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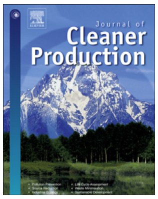

Exploring the pathways towards a sustainable heating system – A case study of Utrecht in the Netherlands

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ABSTRACT

Heating accounts for about half of the final energy demand in the member states of the European Union. The challenges of a transition to a sustainable heat supply vary greatly at the local level indicating the need for incorporating local data for determining solutions. Current studies vary in the inclusion of heat savings, the level of details, and energy efficiency improvements of heat supply. The interactions between the heating system and the rest of the energy system are often ignored. In this study, coherent methodological steps are proposed to identify, develop, and assess the pathways of sustainable heating systems at the local level. It combines data on the application of generic sustainable heating strategies with the collection and usage of local data and allows the analysis of the impacts of a heat transition on the local energy system. A case study is carried out in the city of Utrecht, the Netherlands. The computer tool EnergyPLAN is applied to simulate the current and future energy system in 2050, including three fossil fuels-free heating scenarios, that depict different share of collective and individual heating. The individual heating scenario leads to 17% of annual energy-saving in comparison to the future reference scenario while the mixed-options and collective heating scenarios achieve 7% and 3% respectively. The individual scenario is, however, the most expensive option as its annualized costs are 170% and 80% higher than the costs of the collective and mixed-options scenario. To achieve a fossil fuels-free heating system, annual costs per building was calculated to be 375, 665, and 1030 euro in the collective, mixed-options, and individual scenario respectively. It is concluded that the most techno-economic pathway is a mixture of energy savings, individual and district heating technologies. The optimal balance should be determined at a neighbourhood level.

1. Introduction

1.1. Background and motivation

Heating accounts for about half of the final energy demand in the member states of the European Union (EU) (Connolly, 2017). A sustainable heating system is crucial for the development of a sustainable energy system and plays an important role in combating climate change. It facilitates the achievement of sustainable development goals (SDGs) such as affordable and clean energy. Sustainable heating systems include measures that lower fossil fuel intensity by energy-savings on the demand side, energy efficiency improvement on the supply side, and replacing fossil fuel with renewable heat sources and recoverable heat sources, e.g. industrial waste heat (Liu et al., 2011).

A sustainable heating system can be classified according to the heat source used, the temperature of heat delivered, and whether it is an individual or collective system. The current district heating (DH) systems, a typical collective system, have the characteristics of 1) having one central heat source, such as biomass boilers, deep geothermal wells, industrial waste heat, and incineration plants, and 2) supply temperatures of just below 100 °C (Lund, H. et al., 2014). For individual heating systems, electricity is the heat source with the adoption of technologies such as domestic heat pumps (HPs). Its application requires better insulation and often floor heating instead of heat radiators.

The transition towards a sustainable heating system is challenging for many reasons. There are for instance uncertainties about the availability of sustainable heating sources, spatial restrictions, reinforcement of electricity grids, and high investments

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Table 1
Characterization of selected studies focusing on modelling a sustainable heating system at the city level.

Study	City/region	Objectives of sustainable heating	Time horizon	Modelling approach	Modelling time interval	Inclusion of sectors (heat/ power/entire energy system)	Inclusion of strategies (insulation/ efficiency improvement/ renewables)	Inclusion of collective/ individual system	Level of detail of heat supply	Inclusion of impacts on the energy system
Zhang et al. (2019)	Beijing/CN	Lower CO_2 emissions	2030	Simulation	hourly	+/ ±	+/−/+	+/+	M	No
Zhao et al. (2017)	Beijing/CN	100% renewable	2030	Simulation	hourly	+/+/+	−/−/+	+/+	L	Yes
Hast et al. (2018)	Helsinki/FI, Warsaw/PL, Kaunas/LT	Zero CO2 emission	2050	Simulation	hourly	+/−/-	+*/+/+	+/−	H	No
Quiquerez et al. (2017)	Geneva/CH	Lower CO_2 emissions,	2035	Simulation	hourly	+/−/-	+/+/+	+/+	H	No
Popovski et al. (2019)	Herten/DE	Lower CO_2 emissions,	2050	Simulation	hourly	+/−/-	+/−/+	+/+	H	No
Ben Amer-Allam et al. (2017)	Helsingør, DK	Lower CO_2 emissions, higher energy efficiency	2030	Optimization	hourly	+/−/-	+/+/+	+/−	M	No
Rämä and Wahlroos (2018)	Helsinki/FI	Lower CO_2 emissions, higher Net Present Value	2030	Simulation	hourly	+/−/-	−/−/+	+/−	M	No
Köfinger et al. (2018)	Linz/AT	Lower CO_2 emissions, higher revenue	2015	Simulation	hourly	+/−/-	−/−/+	+/−	H	No
Popovski et al. (2018)	Matosinhos/PT	Lower CO_2 emissions, lower heat costs	2015	Simulation/ Optimization	hourly	+/−/-	−/−/+	+/+	H	No
Zivkovic et al. (2016)	Nis/RS	Lower CO_2 emissions, higher energy efficiency, better energy security	2030	Simulation	Annually	+/−/-	+/−/+	+/+	M	No
Pavičević et al. (2017)	Zagreb/HR	Lower CO2 emissions, lower heat costs	2014	Optimization	hourly	+/−/-	+/−/+	+/−	H	No
Büchele et al. (2019)	Romania/RO	higher energy efficiency, lower heat costs	2020	Optimization	hourly	+/ ±	+/−/+	+/+	L	No
Lund, R. et al. (2017)	Copenhagen/DK	higher energy efficiency, lower heating system costs	2050	Simulation	hourly	+/−/-	+/+/+	+/−	M	Yes
Bach et al. (2016)	Copenhagen/DK	Lower CO2 emissions, lower heat costs	2025	Simulation	hourly	+/−/-	+/−/+	+/−	M	NO

(L ≙ low; M ≙ medium; H ≙ high; + ≙ included; - ≙ not included; *energy saving due to building renovation is considered only in the city of Kaunas).

in heating technologies and infrastructure (e.g. insulation measures, HPs, heat network, and electricity grids). These difficulties vary greatly at the local level. For determining local solutions, there is a need for incorporating local data and placing the heat transition in the context of the energy system.

1.2. Local heating system in the context of energy systems

An overview of the most recent studies on sustainable heating systems at the city level is provided in Table 1. These studies explore, model and assess the heating systems with different research scopes: focusing on only DH systems, residential heating systems and, placing the heating systems in the context of local energy systems.

Decarbonization is the common objective of having sustainable heat supplies. Other objectives include decreasing primary energy supply, increasing the share of renewables and, promoting economic feasibility. In terms of modelling methods, simulation is often applied to 1) deploy single (Popovski et al., 2019) or multiple (Hast et al., 2018; Popovski et al., 2018; Zhang et al., 2019; Zhao et al., 2017) heat supply technologies, 2) to implement heating strategies (Lund, R. et al., 2017; Quiquerez et al., 2017), e.g. energy-savings, collective and individual heating, as well as 3) to assess their effects on decarbonization. Existing studies also optimize the operation of the designed heating systems to minimize the levelized cost of heat (Ben Amer-Allam et al., 2017), heating system costs (Pavičević et al., 2017), and the combined cost of heat savings and supply (Büchele et al., 2019). The time interval of 1 h is applied in the modelling in most studies to ensure an hourly match between heat supply and demand.

The inclusion of different sustainable heating strategies differs in the existing studies. Replacing fossil fuels with locally available renewable heat sources is often applied, however other strategies, such as efficiency improvement on the supply side are often not included in the techno-economic assumptions of defining future heating systems. Energy-saving is also not always considered in determining future heat demand. For example, energy and heating system analyses were carried out to explore the renewable energy systems and low carbon development in Beijing in 2030, however, the potential of energy saving in the built environment was not addressed (Zhao et al., 2017). The level of detail of heat supply varies depending on the research scope and objectives. There is a lack of analysis of the impacts of heat demand electrification on the rest of the energy system. For example, the cost-optimal mix between district heating, individual heating, and heat savings was identified for the city HelsingØr in Denmark (Ben Amer-Allam et al., 2017). The technical, economic, and environmental impacts of implementing domestic and large-scale HPs such as the increase in power load and reinforcement of electricity grids were not discussed.

1.3. Own contribution

As follows from the discussion before, previous studies on the development of sustainable heating systems at the local level vary in focus, e.g. in terms of the sustainable heating strategies included, as well as in the level of detail. The sector interactions and impacts of the sustainable heat transition on the rest of the energy system are often ignored. A step-based methodology is needed to identify, develop, and assess sustainable heating systems at the local level, while taking into account energy system impacts. The hypothesis is that using such methodological steps give better guidance for the selection and design of sustainable heating technologies and a better assessment of their impacts on the overall energy system. These steps may help future studies in combining the application of generic sustainable heating strategies with local data collection and usage as well as placing the assessment of the sustainable heating system in the context of local energy systems.

The objective of this study is therefore to propose such methodological steps and to illustrate their application in a case study of Utrecht, the fourth largest city in the Netherlands. The main contributions of this study are summarized below:

- It proposes comprehensive and detailed methodological steps that place the sustainable heating system in the context of local energy systems.
- The methodological steps combine data on the application of generic sustainable heating strategies with the collection and usage of local data and allow the analysis of the interaction between sustainable heating systems and the rest of the energy system.
- It is the first time that a transition to a sustainable heating system (natural gas-free) is explored in a Dutch city, where natural gas infrastructure is well deployed."

This paper is structured into five parts: the introduction (1); methodological steps, input data of the current energy system, scenario development, and energy system modelling (2); results from technical, economic and environmental analyses as well as the sensitivity analysis (3); discussion (4) and conclusion (5).

2. Method

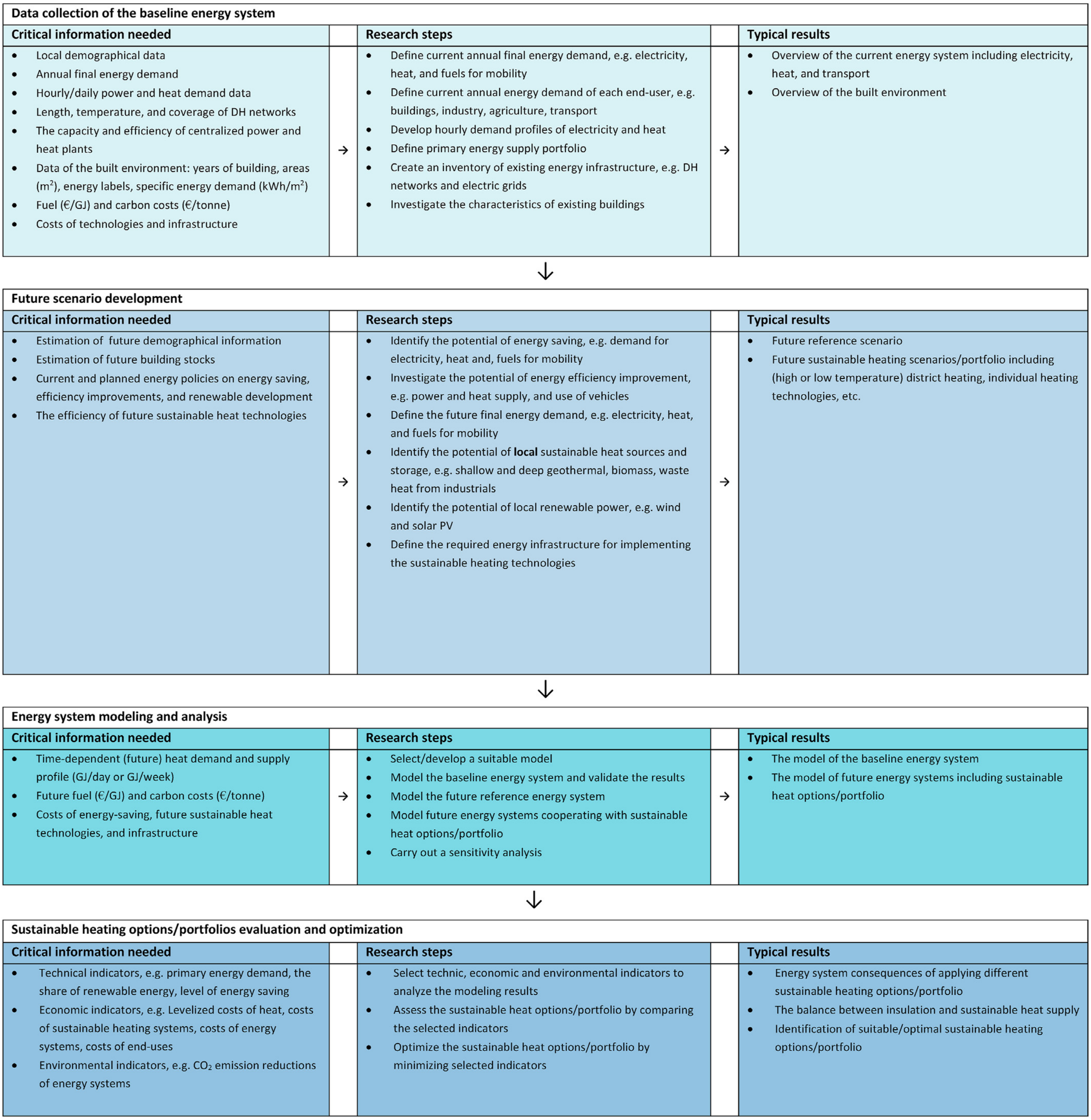
2.1. Methodological steps

The proposed methodological steps aim to identify, develop, and assess sustainable heating systems at the local level. These are presented in Fig. 1. The first step is the collection of techno-economic data regarding the baseline energy system and the building stock. The second step is the future scenario development aimed at understanding the potential of energy savings, efficiency improvement, local sustainable heat sources and specific costs. The data from step 1 and 2 are inputs into step 3, which consists of the energy system modelling and analysis. A suitable tool needs to be developed or selected to model the baseline and future energy systems with a detailed focus on the heating system. Finally step 4 is about the evaluation and optimization of sustainable heating options/portfolios. It aims to answer the questions of what the most techno-economic sustainable heating options are and the extent to which a sustainable heating system contributes to the decarbonization of the energy system.

2.2. Current energy system and the built environment of Utrecht

Next to climate change concerns, the extensive use of natural gas (NG) has raised social and economic concerns in the Netherlands. The Dutch government has set the goal to remove NG supply to the built environment and transit to sustainable heating systems by 2050 (Rijksoverheid, 2017). Utrecht, the fourth-largest city of the country, is a densely populated area and the production industry constitutes a small part of the economy.

The energy system of 2015 is selected as the baseline because data for this year is more complete compared to more recent years. Table 2 presents the comparison of population, economy, and energy between Utrecht and the Netherlands. The built environment in Utrecht consists of both residential and utility buildings covering about 90% of the total heat demand, which to a great extent varies from the situation of the overall country (where 48% of residential and utility buildings make up the total heat demand). The city has the oldest and largest DH system in the country supplying 28% of



Data collection of the baseline energy system

Critical information needed

- Local demographical data
- Annual final energy demand
- Hourly/daily power and heat demand data
- Length, temperature, and coverage of DH networks
- The capacity and efficiency of centralized power and heat plants
- Data of the built environment: years of building, areas (m^2), energy labels, specific energy demand (kWh/m^2)
- Fuel (€/GJ) and carbon costs (€/tonne)
- Costs of technologies and infrastructure

→

Research steps

- Define current annual final energy demand, e.g. electricity, heat, and fuels for mobility
- Define current annual energy demand of each end-user, e.g. buildings, industry, agriculture, transport
- Develop hourly demand profiles of electricity and heat
- Define primary energy supply portfolio
- Create an inventory of existing energy infrastructure, e.g. DH networks and electric grids
- Investigate the characteristics of existing buildings

→

Typical results

- Overview of the current energy system including electricity, heat, and transport
- Overview of the built environment

↓

Future scenario development

Critical information needed

- Estimation of future demographical information
- Estimation of future building stocks
- Current and planned energy policies on energy saving, efficiency improvements, and renewable development
- The efficiency of future sustainable heat technologies

→

Research steps

- Identify the potential of energy saving, e.g. demand for electricity, heat and, fuels for mobility
- Investigate the potential of energy efficiency improvement, e.g. power and heat supply, and use of vehicles
- Define the future final energy demand, e.g. electricity, heat, and fuels for mobility
- Identify the potential of **local** sustainable heat sources and storage, e.g. shallow and deep geothermal, biomass, waste heat from industrials
- Identify the potential of local renewable power, e.g. wind and solar PV
- Define the required energy infrastructure for implementing the sustainable heating technologies

→

Typical results

- Future reference scenario
- Future sustainable heating scenarios/portfolio including (high or low temperature) district heating, individual heating technologies, etc.

↓

Energy system modeling and analysis

Critical information needed

- Time-dependent (future) heat demand and supply profile (GJ/day or GJ/week)
- Future fuel (€/GJ) and carbon costs (€/tonne)
- Costs of energy-saving, future sustainable heat technologies, and infrastructure

→

Research steps

- Select/develop a suitable model
- Model the baseline energy system and validate the results
- Model the future reference energy system
- Model future energy systems cooperating with sustainable heat options/portfolio
- Carry out a sensitivity analysis

→

Typical results

- The model of the baseline energy system
- The model of future energy systems including sustainable heat options/portfolio

↓

Sustainable heating options/portfolios evaluation and optimization

Critical information needed

- Technical indicators, e.g. primary energy demand, the share of renewable energy, level of energy saving
- Economic indicators, e.g. Levelized costs of heat, costs of sustainable heating systems, costs of energy systems, costs of end-uses
- Environmental indicators, e.g. CO_2 emission reductions of energy systems

Research steps

- Select technic, economic and environmental indicators to analyze the modeling results
- Assess the sustainable heat options/portfolio by comparing the selected indicators
- Optimize the sustainable heat options/portfolio by minimizing selected indicators

Typical results

- Energy system consequences of applying different sustainable heating options/portfolio
- The balance between insulation and sustainable heat supply
- Identification of suitable/optimal sustainable heating options/portfolio

Fig. 1. Methodological steps of developing techno-economic pathway(s) of sustainable heating systems.

Table 2
Comparison between Utrecht and the Netherlands in 2015 (CBS, 2016; Rijkswaterstaat, 2018).

	Indicator	Unit	Utrecht city	The Netherlands
Area Population	Land area	km^2	94	33,700
	Population density	Person/km^2	3658	488
Economy	GDP per capital	Euro/capita	49,776	40,740
	Income per capita	Euro/capita	42,500	39,600
Energy	Energy demand composition: electricity, transport, and heat	–	1:1.4:1.9	1:1.4:2.7
	Share heat demand built environment in total heat demand	%	89	48
	Share DH in heat demand of the built environment	%	29	2
Transport	Private vehicle ownership	Vehicle/1000 person	396	485

Table 3
Energy demand and consumption in Utrecht in 2015 (Rijkswaterstaat, 2018).

Primary energy use in Utrecht

Energy demand	Primary energy use (PJ)				Share NG consumption in energy demand (%)
	NG*	Gasoline/diesel	Renewable	Total	
Heat	10.6	–	–	10.6	100
Electricity	6.2	–	0.1	6.3	98
Transport	0.1	7.5	0.2	7.8	1
Other	0.8	–	–	0.8	100
Total	14.3	7.5	0.3	25.5	56

Heat and electricity demand per sector

Energy demand	The sector of energy end-user (PJ)				Share energy demand built environment in total heat and electricity demand (%)
	The built environment	Industry & Agriculture	Transport	Total	
Heat	7.4 (DH:2.1; NG boiler: 5.1; HP: 0.2)	0.9	–	8.3	89
Electricity	4.5	0.7	0.1	5.3	85

(*the NG consumption of the two CHP plants (11.2 PJ) is not included as the plants also supply heat and electricity to consumers outside of the municipality).

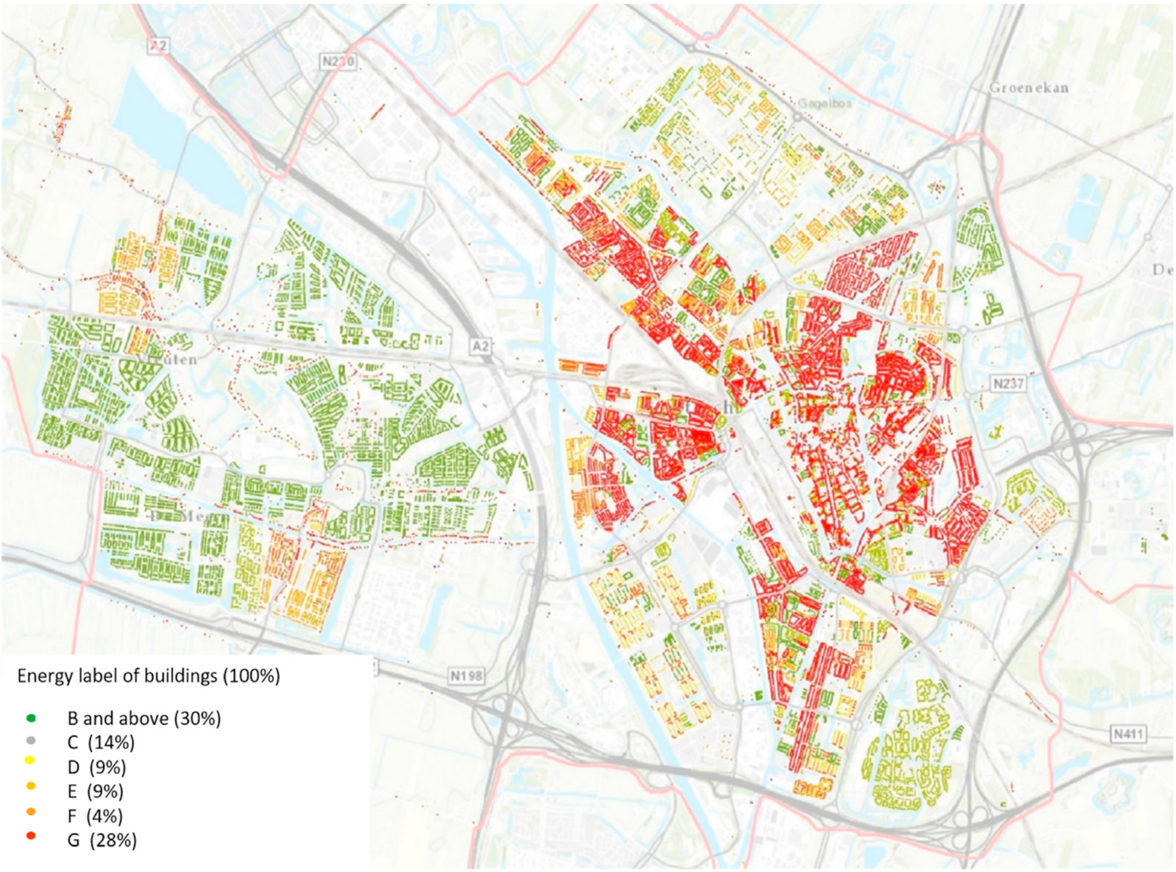


Fig. 2. Energy labels of residential buildings in 2015 (van den Wijngaart et al., 2018).

heat demand in the built environment, while this share is only 2% at the country level.

An overview of primary and final energy demand is indicated in Table 3. Total primary energy use of Utrecht was 25.5 PJ in 2015 resulting in 1.5 Mt CO_2 emissions (Utrecht, 2018a). Heat demand has the largest share (44%) in energy demand and NG dominates energy demand in all energy sectors except transport. On average, annual energy demand per household in 2015 was 780 m^3 NG and 2560 kW h of electricity (CBS, 2016). The use of NG is much lower compared to the national average of 1300 m^3 per household since a large part of the heat is delivered by a DH system. The DH networks connect over 39,000 residential (25% of housing stock) and 1500 non-residential buildings (CBS, 2016). Heat via the DH networks is provided by two CHP plants fueled by NG (180 MW_{th} and 248 MW_e). Besides, there are multiple auxiliary NG boilers with a total thermal capacity of 174 MW_{th}. The two CHP plants together used approximately 11 PJ natural gas in 2015 and produced 3.3 PJ heat and 5.7 PJ electricity (CBS, 2016). A part of the electricity output is sold to the national grid and part of the heat output is delivered to Nieuwegein, a city next to Utrecht, via the DH networks.

Table 4
Overview of future heating scenarios for 2050 and associated assumptions.

Scenario name	Reference	Collective	Individual	Mix of options
Scenario description	The energy system will develop based on established and planned policy measures	Focus on the expansion of DH with geothermal as its main heat source	High demand reductions and focus on individual solutions	High demand reductions combined with district and individual heating technologies
Min. Energy label	C	B	A	A
DH (%)	45%	75%	21%	55%
Individual heating (%)	55%	25%	79%	45%
Heat supply (main technologies*)	CHP and individual boilers based on NG	Geothermal and absorption HPs (AHPs)	Domestic HPs with solar PV	A combination of collective and individual options

(*Note that all scenarios are a combination of multiple heating technologies however only the main technologies are mentioned in the table).

Of the electricity demand in Utrecht in 2015 (5.3 PJ), 85% can be attributed to the built environment. Within the municipality, there are no installed wind turbines while the installed solar PV has increased dramatically over the years. In comparison to 1 MW installed capacity in 2011, more than 11 MW of solar PV was installed on the roof of buildings in 2015. There were 132,250 registered vehicles in Utrecht of which 1% were electric vehicles (EVs) (CBS, 2018b). Fuel demand for road transport was estimated to be 7.8 PJ in 2015.

Utrecht counted 161,866 buildings in 2015 and 91% of these are residential buildings (CBS, 2018c). The other buildings, e.g. commercial and public buildings are referred to as utilities. Fig. 2 indicates the distribution of energy labels for residential buildings in 2015 (van den Wijngaart et al., 2018). The average current energy label in Utrecht is D. An overview of the number of dwellings per energy label and associated heat demand in 2015 is given in Appendix A (Table A1).

2.3. Future scenario development

The design of a sustainable heating system involves at least three technological changes including energy saving, efficiency improvement, and replacing fossil fuels, NG in the case of the Netherlands, by sustainable heating sources (Lund, H., 2018). These changes are all applied in the scenario development.

The future energy system refers to 2050 and includes a description of heat, electricity, and transport. Next to it, sustainable heating scenarios are developed focusing on collective, individual heating technologies, and a combination of both. The development of electricity and transport in three sustainable heating scenarios is kept the same as in the future reference scenario. Some general assumptions are made including 1) each scenario aims for a fossil-free heating system in 2050, 2) electricity and fuels used for heating purposes are 100% produced from renewables, e.g. solar PV and biomass, and 3) all energy is obtained from or produced by the sources within the municipal borders as much as possible.

The potential sources of sustainable heat within the borders of Utrecht municipality including geothermal heat, waste heat, biomass, and organic waste, solar PV and wind power. The most important features of the future scenarios can be found in Table 4.

2.3.1. Reference scenario

The development of a *reference scenario* is based on national and local policy measures. Assumptions on the population growth and building expansion in 2050 apply to each scenario. The average annual growth of population and buildings is assumed to be 1.3% and 1% respectively (CBS, 2018b). Three strategies for energy label upgrading are applied, i.e. low, medium and high level of renovation. A detailed explanation of the strategies and associated costs are provided in Appendix A.

In the reference scenario, the minimum requirement for existing buildings is assumed to be a C label (Utrecht, 2018b). Total heat demand for existing buildings will decrease from 7.38 PJ to 6.45 PJ. New buildings must comply with BENG requirements indicating a maximum annual heat demand of 25 kW h/m^2 in the residential buildings (RVO, 2019). It means that new buildings have an annual heat demand of 0.7 PJ and total heat demand in 2050 is 7.15 PJ. After 2030, all NG pipelines older than 30 years will be replaced by new technologies and no new gas infrastructure will be constructed in order to facilitate the heat transition (CBS, 2018b). Furthermore, 55% of new buildings built till 2020 are not connected to NG infrastructure (Ministry of Economic Affairs and Climate Policy, 2017; van 't Hof and Wim, 2018). These plans imply that 95,000 buildings will still be connected to an NG infrastructure until 2050 which is 43% of the total building stock. Based on this, it is assumed that 43% of heat demand is covered by individual NG boilers consuming in total 3.07 PJ. The adoption of HPs is assumed to increase at the same pace as in the last 6 years. In 2015, 2% of heat demand was covered by HPs, whereas in 2050 this will add up to 12% (CBS, 2018c). For both residential and utility buildings this is equal to 0.89 PJ of heat provided by HPs. Heat pumps will require 0.22 PJ of electricity assuming a COP of 4[1] (Van Melle et al., 2015). The remaining heat demand will be covered by DH (45% of heat demand) corresponding to a heat demand of 3.19 PJ. Currently, a new biomass heat-producing facility (BWI) is being built and expected to start generating heat from 2020. It is assumed that the BWI will cover 40% production from the DH boilers, while the other 60% is still covered by NG (Eneco, 2018). Biomass within the municipal borders of Utrecht is derived from the available organic waste, which is calculated as 0.22 PJ per year in 2050 (CBS, 2018a). A schematic overview of heat supply is presented in Fig. 3. A 15% heat loss in the DH networks is assumed (Van Melle et al., 2015).

The overall electricity and fuel demand for transport are listed in Table 5. Electricity demand is assumed to slightly increase in 2050 as a result of efficiency improvement and increased use of electric appliances (ECN, 2017). The fuel demand in transport will decrease in 2050 caused by the stricter European policies for passenger cars on fuel efficiency and traffic volume (ECN, 2017).

2.3.2. Collective scenario

The *collective scenario* is based on the expansion of the DH system which will cover 75% of heat demand and the domestic HPs provide the remaining heat demand (25%). The minimum energy label for existing buildings is assumed to be a B label and total heat demand is decreased to 6.85 PJ.

Geothermal heat is the most important local heat source.

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[1] 70% for space heating with a COP of 4.5 and 30% for hot tap water with a COP of 2.8, air-source HP.

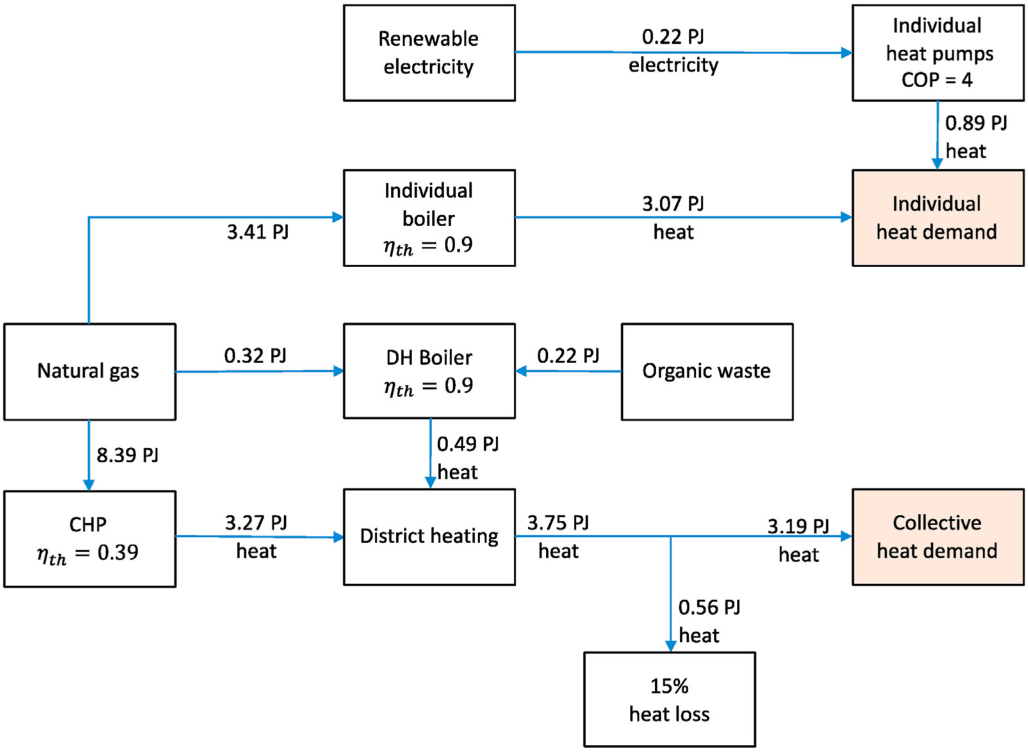

Fig. 3. Schematic overview of heat supply in the reference scenario in 2050.

Table 5
Electricity demand and fuel demand in transport towards 2050 in PJ (ECN, 2017).

Electricity demand	2015	2050	Fuel demand in transport	2015	2050
Residential buildings	1.30	1.30	**Oil products**	7.35	5.66
Non-residential buildings	3.13	3.10	**NG**	0.03	0.21
Industry	0.71	0.74	**Electricity**	0.10	0.28
Agriculture	0.01	0.02	**Biofuels**	0.21	0.99
Total	5.15	5.16	**Total**	7.68	7.05

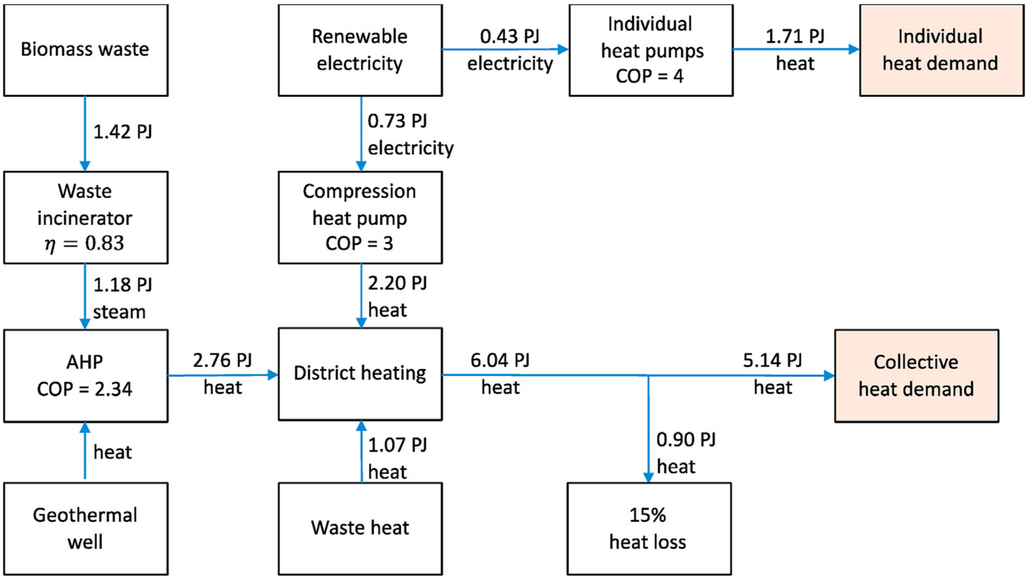

Fig. 4. Schematic overview of heat supply in the collective scenario in 2050.

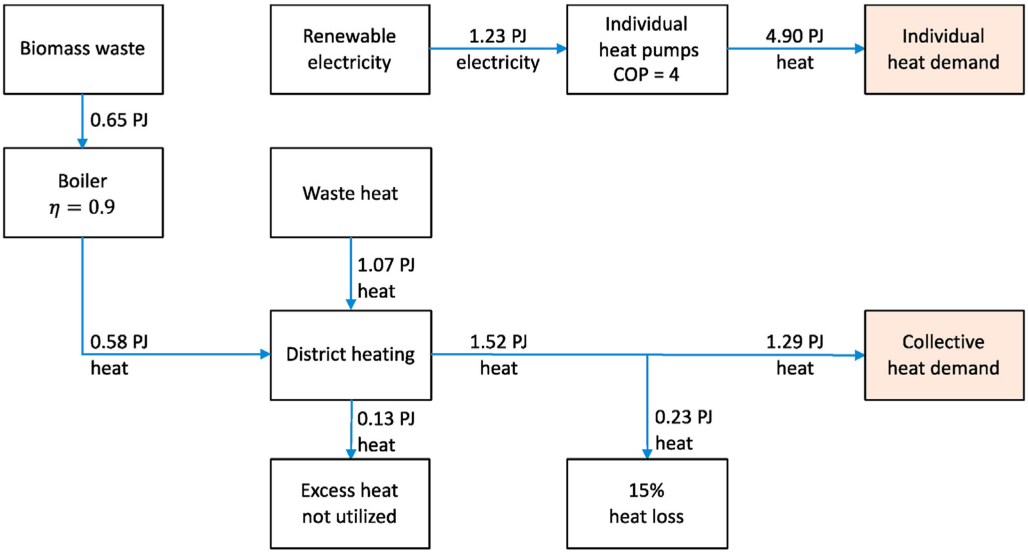

Fig. 5. Schematic overview of heat supply in the individual scenario.

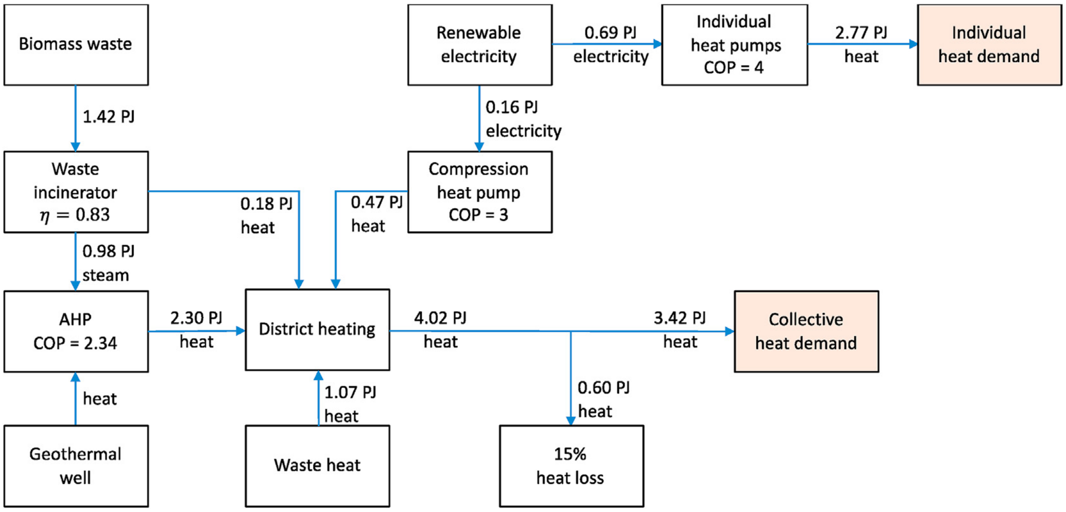

Fig. 6. Schematic overview of heat supply in the mix of options scenario.

Ongoing research with preliminary results indicates that the technical potential of geothermal heat in Utrecht is 2.76 PJ (Operators, 2018). Heat is extracted from the geothermal well by AHPs with a combined capacity of 259 MW. To drive the AHPs with a COP of 2.35 (Østergaard, 2013), 1.18 PJ of steam is required and obtained from organic waste incineration. Biomass to steam conversion has an efficiency of 0.83 (Ryu and Shin, 2012) and results in organic waste demand of 1.42 PJ. This indicates that the amount of biomass within municipal borders (estimated as 0.22 PJ) is not sufficient, which means that the remaining demand must be imported from outside the municipality.

Additional DH demand (1.07 PJ) is covered by waste heat from the asphalt factory within the borders of the municipality (Eneco, 2018; van den Wijngaart et al., 2018). Seasonal demand peaks are covered by large-scale HPs with a capacity of 75 MW and a COP of 3 (Østergaard, 2013). The total heat delivered by the DH system is 5.14 PJ. The remaining heat demand of 1.71 PJ is met by domestic HPs with a COP of 4 (Van Melle et al., 2015). Total electricity demand for both the large-scale and domestic HPs is 1.04 PJ. To cover this, on-shore wind turbines are used to their full potential of 60 MW (Dooper et al., 2010). The remaining part is covered by the installation of building-integrated solar panels with a combined capacity of 185 MWp. In order to compensate for a temporal mismatch between renewable electricity and demand, power from the electric grids is used. A schematic overview of heat supply is presented in Fig. 4.

2.3.3. Individual scenario

In the individual scenario, domestic HPs are adopted by a large part of society. Heating through heat pumps is an example of low temperature (LT) heating. It is implemented together with an LT heating system such as floor heating. The minimum requirement for existing buildings is therefore assumed to be label A (Kieft et al., 2015) and total heat demand is decreased to 6.19 PJ. The share of houses connected to DH stays the same as in the baseline in 2015 leading to a heat demand of 1.29 PJ covered by waste heat from the asphalt factory. Seasonal discrepancies are covered by a 75 MW biomass boiler with an efficiency of 90% and annual demand of biomass of 0.65 PJ.

To cover electricity demand for heating purposes, 400 MWp of

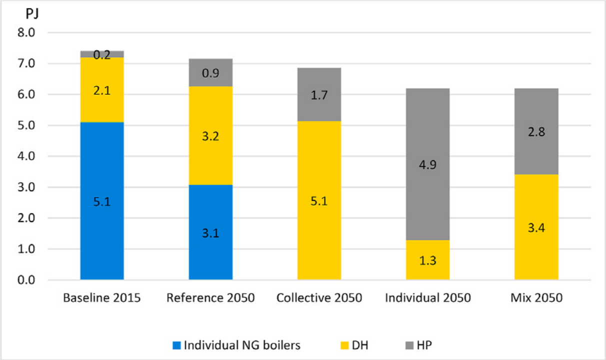

Fig. 7. Final heat demand in the built environment in baseline and 2050 scenarios.

solar panels are required. This is 57% of the total potential of PV in 2050 (CBS, 2018d). A schematic overview of heat supply is presented in Fig. 5.

2.3.4. Mix scenario

The *mix of options scenario* is based on a mixture of both district and individual heating technologies. The minimum requirement for existing buildings is assumed to be an A label and total heat demand is decreased to 6.19 PJ. The percentage of heat demand covered by DH is based on the potential of geothermal and waste heat. Seasonal discrepancies are compensated by a 25 MW compression HP requiring 0.16 PJ of electricity annually and producing 0.47 PJ of heat. Together these sources can supply 3.42 PJ of heat, which results in a demand coverage of 55%. The AHPs will require steam from biomass incineration. This leads to a biomass demand of 1.42 PJ. Additional demand is covered by domestic HPs with a total electricity demand of 0.69 PJ. It requires an installed solar capacity of 278 MWp, which is 40% of the total PV potential (CBS, 2018d). A schematic overview of heat supply is presented in Fig. 6. An overview of the heat demand of each future scenario is presented in Fig. 7.

2.4. Energy system modelling

2.4.1. EnergyPLAN tool

The main purpose of the EnergyPLAN model is to analyze the energy, environmental and economic impacts of various energy strategies (Aalborg University, 2018). EnergyPLAN has been widely applied in the research field of energy system analysis at the regional (Østergaard, 2013; Xiong et al., 2016), national (Liu et al., 2011; Lund, H., 2018) and EU level (Connolly et al., 2014; David et al., 2017). Two main features make the EnergyPLAN tool suitable for modelling diverse heating systems from an energy system point of view. First, it incorporates all energy sectors in the energy system, e.g. electricity, heating, cooling, and transport; and second it is an hour-by-hour simulation tool that can calculate hourly, weekly, monthly, or seasonal energy balances instead of an aggregated annual demand and production. A schematic overview of the model can be found in Fig. 8. A more detailed description of the model can be found in (Aalborg University, 2018).

2.4.2. Techno-economic inputs

The hourly profiles of electricity and NG demand were obtained from the distribution system operator Alliander. The hourly heat demand data of the DH system was provided by the heat supply company Eneco. For confidentiality reasons, these hourly profiles are not presented in the paper.

Costs calculated by the EnergyPLAN model are total annual energy system costs. These have been calculated based on investment costs, flexible and fixed operation and management costs (FO&M and VO&M) as well as an annuity factor which includes the economic lifetime and interest rate (see Table 6 (Agency, 2012; Agency, 2016; Van Melle et al., 2015)). The interest rate is assumed to be 3% (Kienlen, 2015). Future fuel and carbon price developments are based on projections made by the Netherlands Environmental Assessment Agency (PBL) (ECN, 2017). An overview of fuel and

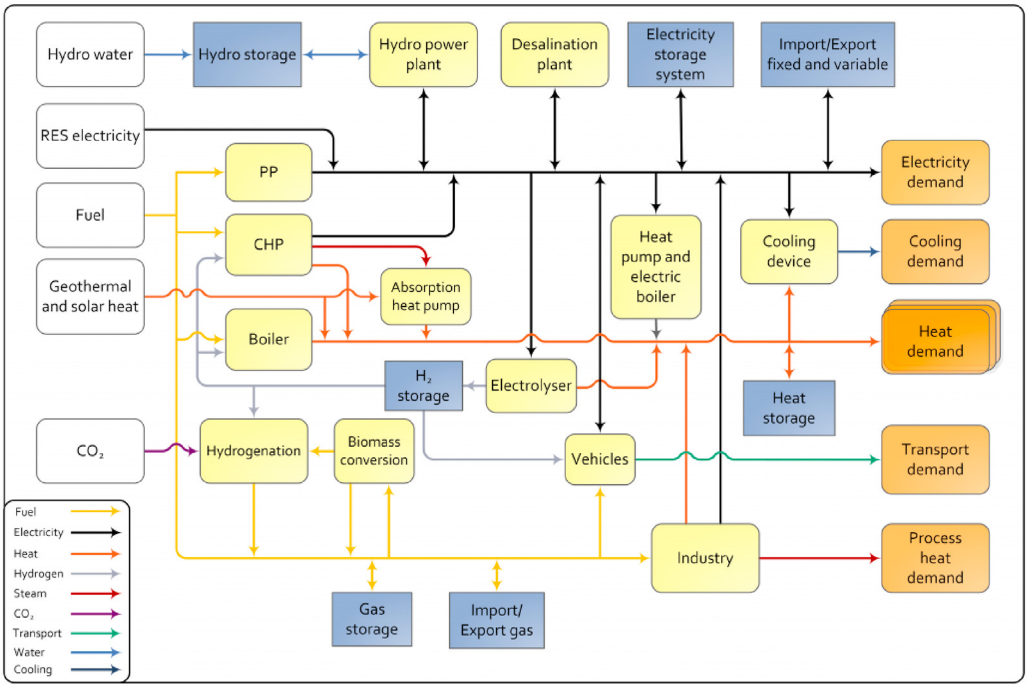

Fig. 8. Schematic overview of the EnergyPLAN model (Aalborg University, 2018).

Table 6
DH, renewable and individual heating technology costs in 2015 and 2050 (Agency, 2012, 2016; Van Melle et al., 2015).

	Investment (M€/unit)			Life time	FO&M (% of Investment)		VO&M (€/MWh)	
	Unit	2015	2050		2015	2050	2015	2050
DH								
CHP	M€/MWe	0.9	0.8	25	3.3	3.4	4.5	4.0
Boilers	M€/MWe	0.06	0.05	25	3.3	3.4	1.1	1.0
Compression HP	M€/MWe	0.7	0.5	25	0.3	0.4	3.3	3.9
Large power plant	M€/MWe	0.9	0.8	25	3.3	3.4	4.5	4.0
Biomass boiler	M€/MWe	0.7	0.6	25	4.7	5.0	1.0	1.0
Waste CHP	M€/TWh	215.6	215.6	25	7.4	7.4		
Geo. AHP	M€/MWe	2.00	2.0	25	2.5	2.5	0.9	1.4
Renewable								
Wind onshore	M€/MWe	1.1	0.8	25	2.4	2.6		
Photovoltaics	M€/MWe	1.6	0.6	30	1.0	1.6		
Waste heat	M€/TWh/y	40.0	40.0	25	1.0	1.0		
Individual								
Boilers	M€/1000-units	1.5	1.2	15	2%	2%		
Domestic HPs	M€/1000-units	12.5	7.2	15	2%	2%		

Table 7
Fuel and carbon prices in 2015 and 2050 (ECN, 2017).

	Coal (€/GJ)	Crude oil (€/GJ)	Diesel/Gasoil (€/GJ)	Petrol (€/GJ)	NG (€/GJ)	LPG (€/GJ)	Biomass waste (€/GJ)	Carbon (€/tonne)
2015	2.4	8.1	33.9	47.2	5.6	27.4	3.9	7.7
2050	3.5	18.5	51.0	66.0	10.8	40.4	13.5	35.1

Table 8
Distribution and connection costs for infrastructure development (Valk et al., 2018; Van Melle et al., 2015).

Infrastructure	Electricity grids		Gas grids		DH grids		Floor heating (€/m^2)	Electric cooking (€/hh)
	Connection (€/hh)	Distribution (€/kW)	Connection (€/hh)	Distribution (€/kW)	Connection (€/hh)	Distribution (€/kW)		
Costs	975	2200	650	5280	450	1204	72	900

(*hh: household).

Table 9
Values for the sensitivity analysis of NG and carbon price (Brink, 2015; ECN, 2017).

	2015-level	Sensitivity analysis (2050)		
		Lower	Mid	Upper
NG price (€/GJ)	5.75	6.83	10.83	15.65
Carbon price (€/tCO$_2$)	7.66	15.64	35.10	116.20

Table 10
Comparison of the actual data of the baseline energy system in 2015 and the simulation results in EnergyPLAN.

Validation items	Unit	Baseline	EnergyPLAN	Difference (%)
Natural gas consumption	PJ	25.33	16.99	−33.3%
Heat production	PJ	7.37	7.31	0.1%
Electricity production	PJ	5.15	5.15	–
CO$_2$ emissions	Mt	1.47	1.49	1.4%

carbon prices in 2015 and 2050 can be found in Table 7.

Costs for infrastructures are presented in Table 8 below. A distinction is made between connection and distribution costs (Van Melle et al., 2015). Furthermore, in-house distribution is included covering costs for floor heating and electric cooking (Valk et al., 2018).

2.4.3. *Model validation*

Once the hourly and annual data of techno-economic inputs have been collected, the baseline and future scenarios were simulated by the EnergyPLAN tool. The accuracy of the baseline model was examined by comparing the simulation results of natural gas consumption, electricity and heat production, and CO$_2$ emissions with the actual data.

2.5. *Sensitivity analysis*

A sensitivity analysis is carried out to identify the influence of scenario designs and assumptions of key parameters as well as to illustrate the uncertainty of the model outcomes. For each scenario, the influence of a different interest rate, NG, and carbon prices are examined. In the sensitivity analysis, the interest rate is changed from 3% to 6%. An overview of parameter values in the sensitivity analysis is presented in Table 9.

3. Results

3.1. *Baseline energy system validation*

To validate the baseline model, a comparison was made between the simulation results of natural gas consumption, electricity and heat production, and CO$_2$ emissions with the actual data. The results are shown in Table 10.

The largest difference is found in natural gas consumption. The

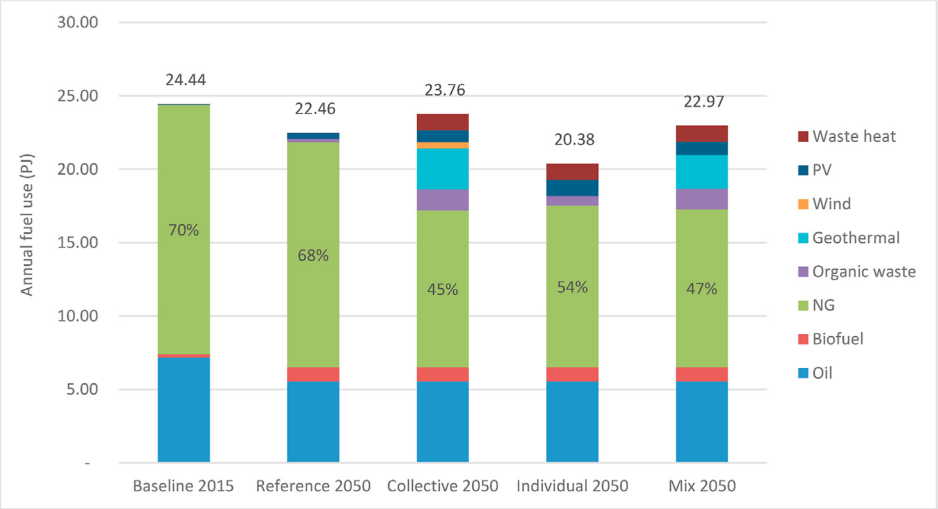

Fig. 9. Annual primary energy demand by fuel types.

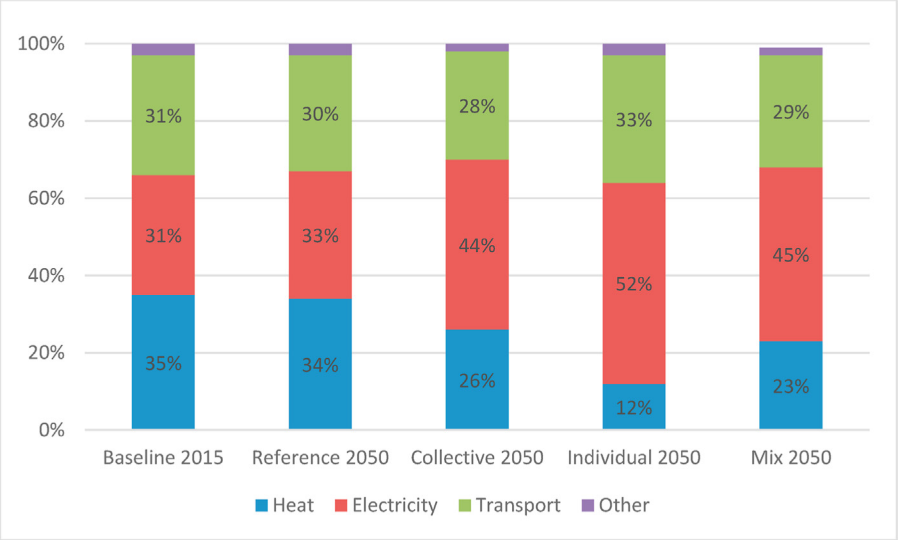

Fig. 10. The share of primary energy demand per sector.

natural gas use in the baseline energy system is the sum of the use in vehicles, agriculture, industry, individual heating boilers, and large-scale CHP plants. The difference is caused by electricity and heat generation from CHP plants. There are two CHP natural gas plants in the municipality of Utrecht consuming 11.76 PJ natural gas annually which is included in Table 10. However, these two plants also supply heat and electricity to consumers outside the municipality (see descriptions in section 2.2). Natural gas consumption in the EnergyPLAN model is calculated based on final energy demand within the municipality and therefore is lower.

The comparison result of CO_2 emissions (1.4%) is not influenced by the difference in natural gas consumption as CO_2 emissions monitoring in Utrecht is done based on final energy demand. In EnergyPLAN, emissions are based on the primary fuel use. The differences between electricity and heat production are very small. To summarize, the baseline model correctly simulated the existing energy system in 2015.

3.2. *Technical analysis*

Annual primary energy use by fuel types is presented in Fig. 9. Fig. 10 shows the share of primary energy demand per sector. Note that electricity produced for heating purposes falls under the heating sector instead of the electricity sector. Compared to the baseline in 2015, the NG use decreases with 10% in the reference scenario in 2050 due to the inclusion of a biomass boiler for fuelling the DH system and an increase in domestic HPs. Furthermore, the use of oil products in the transport sector is decreased in 2050. The main reason for this is the adoption of electric vehicles and the blending of biofuels as a reaction to governmental regulation and policies. In the sustainable heating scenarios, no NG is used for heating purposes. Its use in the total energy system is thereby lowered with approximately 30%, compared to the reference scenario. Because of the electricity sector, NG remains a widely used fuel in the energy system.

Within the sustainable heating scenarios, the collective and mixed scenarios use more energy than the reference case, although

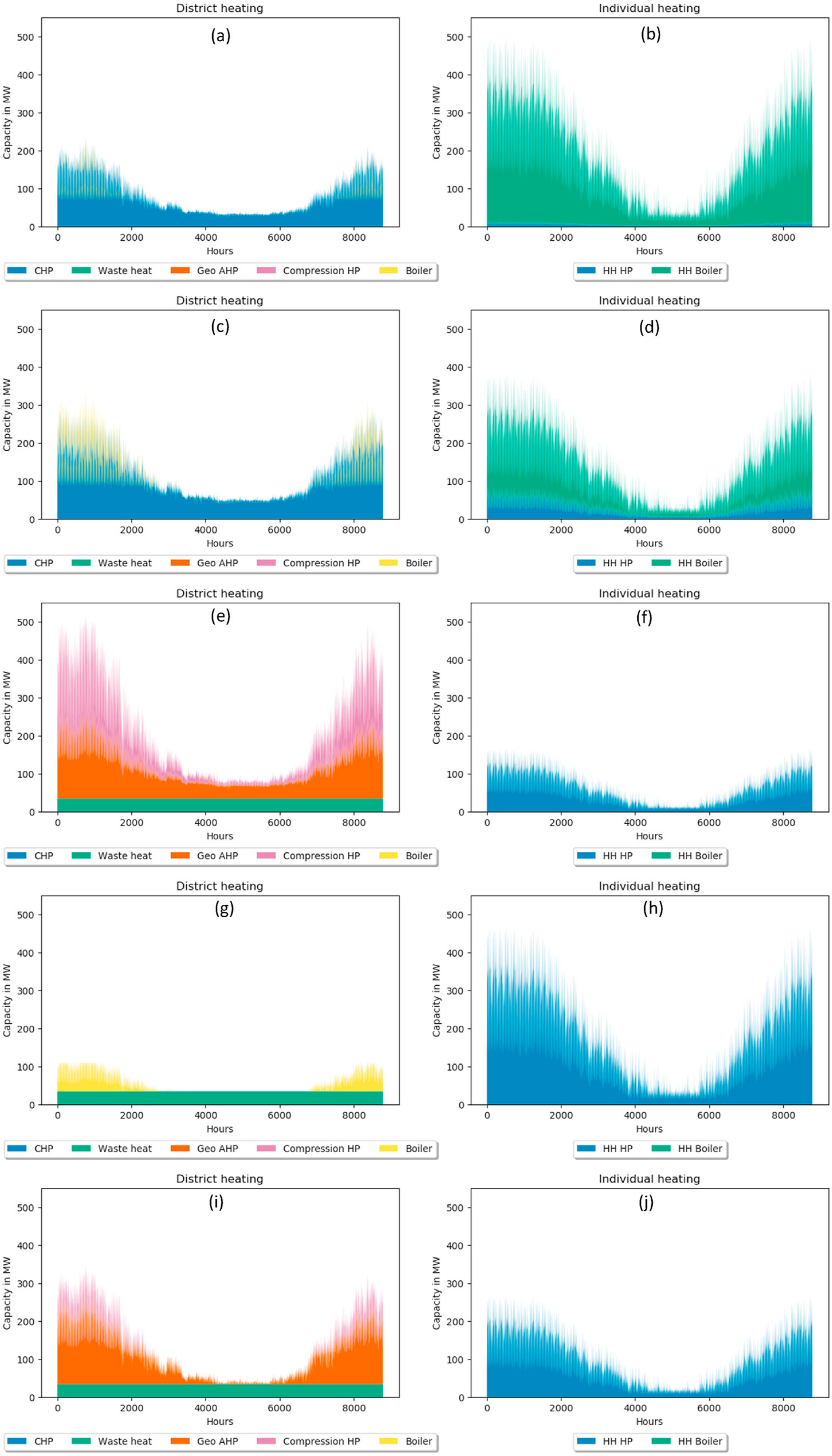

Fig. 11. Heat supply in different scenario (baseline: (a) and (b); reference scenario: (c) and (d); collective scenario: (e) and (f); individual scenario: (g) and (h) and mix of options scenario: (i) and (j)).

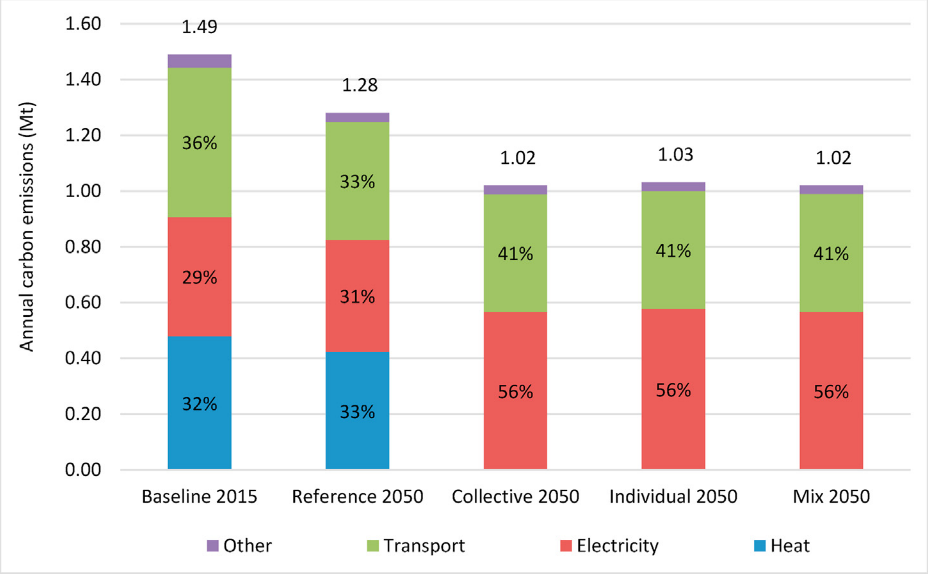

Fig. 12. Annual CO_2 emissions by sector.

less than in the base year. An explanation for this is that NG boilers and CHP plants have a high efficiency. Replacing those technologies with geothermal heat extraction and biomass incineration requires more primary energy. The individual scenario has the lowest primary energy requirement due to the high adoption of domestic HPs.

Load profiles of heat supply in the base year and all scenarios are presented in Fig. 11. A distinction is made between DH and individual heating as all scenarios are a combination of both, although in different ratios. The heat supply profiles of the base year (Fig. 11 (a) and (b)) and reference scenario (Fig. 11 (c) and (d)) are much alike. However, in the reference scenario, heat demand covered by DH is increased and more heat comes from a biomass boiler. In the collective scenario (Fig. 11 (e) and (f)), industrial waste heat is used as baseload and is accompanied by geothermal heat and large-scale compression HPs. All technologies are operated during all hours of the year following a variable pattern. The heat balance is maintained at all times. In the individual scenario (Fig. 11 (g) and (h)), industrial waste heat is included as baseload. However, from the heat balance, it is found that waste heat is lost during the summer months, as DH demand is too low. This results in a heat loss of 13% annually. In the mix of options scenario (Fig. 11 (i) and (j)), industrial waste heat is again used as baseload. Geothermal heat is used to accommodate heat demand and a large-scale compression HP of 25 MW is included to cover demand peaks during winter months.

3.3. *Environmental analysis*

Fig. 12 shows the CO_2 emissions by sector in each scenario. In 2015, total CO_2 emissions were 1.5 Mt. Approximately 32% of the emissions were caused by heating demand, 29% by electricity production, and 36% by transportation. In the reference scenario, carbon emissions are reduced by 14% in 2050. This reduction is caused by the inclusion of a biomass boiler, more electric vehicles, and the blending of biofuels. In the three sustainable heating scenarios CO_2 emissions are reduced by 32% compared to the base year. This can be perceived as the contribution of the sustainable heat transition to the energy system decarbonization.

3.4. *Economic analysis*

The annual energy system costs and investment costs of sustainable heating are presented in Table 11. Higher fuel and carbon prices in the future are the main contributor to the cost increase in the reference scenario compared to the base year. Besides, infrastructure needs expansion due to an expansion of the building stock. The sustainable heating scenarios have higher annual energy system costs compared to the reference scenario. The individual scenario is the most expensive with additional costs of 228 Million euros per year. For the mix of options and collective scenario, additional costs of 147 and 83 million euros are required annually.

Table 11
The annual cost of the energy system and investment costs of sustainable heating.

	Unit	Baseline	Reference	Collective	Individual	Mix
Annual costs of the energy system and sustainable heating						
Annual energy system costs	(M€/year)	465	691	774	919	838
Additional annual costs of sustainable heat development	(M€/year)	–	–	83	228	147
Additional costs of sustainable heat delivered	(€/kWh heat delivered)			0.04	0.13	0.09
Additional annual costs per building	(€/building)			375	1030	664
Annual costs of CO_2 emission reductions	(€/tCO_2 reduction)			319	916	565
Investment costs of sustainable heating						
Infrastructure	M€		285	673	382	481
Renovation	M€		790	1220	2135	2135
Individual technologies	M€		657	1055	2926	1765
DH technologies	M€		251	692	56	222
Total investment	M€		1983	3640	5499	4603

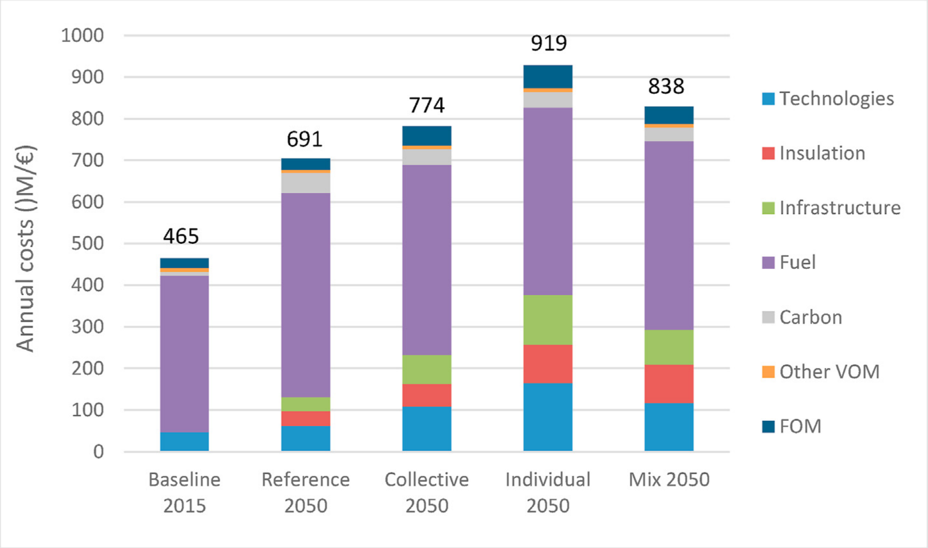

Fig. 13. Annual energy system costs per cost item.

The additional annual costs per building vary between 375, 1,030, and 664 euros. The investment of insulation is the largest cost item.

A visual representation of the total annual energy system costs per cost item can be found in Fig. 13. Technology costs make up 9–18% of annual energy system costs in future scenarios, with the lowest share in the reference scenario and the highest share in the individual scenario. It is because domestic HPs are more expensive than collective technologies or NG boilers per kWh of heat delivered. Insulation costs depend on the chosen insulation level. Accordingly, the individual and mix of options scenario have the highest share of insulation costs. In the reference scenario, an increase in electricity demand leads to the necessity of grid reinforcement. Also, a part of the NG grid will be demolished. In sustainable heating scenarios, infrastructural costs will rise accordingly. A detailed overview of infrastructure costs can be found in appendix B (Table B1). The carbon costs increase substantially in the 2050 reference scenario, due to a carbon price increase. Other fixed and variable operations and maintenance costs are very small.

3.5. Sensitivity analysis

The detailed results of sensitivity analysis are presented in Appendix B (Figure B1 to Figure B3). The main impacts of the sensitivity changes (i.e. higher interest rate and higher NG and CO_2 prices) are:

- A higher interest rate (6% instead of 3%) results in higher annual investment costs due to a larger interest payment. Compared to the reference scenario, the sustainable heating scenarios react more significantly to a change in interest rate as they require more investments (e.g. insulation, infrastructure, and technologies).
- Increasing the NG price lowers the cost difference between the reference and sustainable scenarios. As NG increases in price, it becomes more interesting to switch to sustainable technologies.
- A similar effect is caused by variations in the carbon price. The effect is the largest in the individual scenario and the lowest in the collective scenario.

4. Discussion

The input data, system boundaries, and assumptions determining the scenarios have an important influence on the results. The approach of being transparent on data and assumptions is adopted to give insight into uncertainties. In comparison with other studies, some similar results are found in the economic analysis. For example, the costs of CO_2 emission reduction in the collective, individual, and mix scenarios are found as 319, 916, and 565 euro per tCO_2 respectively. Decarbonization effectiveness of DH and HPs was calculated as 370 and 630 euro per tCO_2 respectively (Koelemeijer et al., 2017). The additional annual costs per building amount to 375, 1030, and 664 euros in the collective, individual, and mix scenarios, respectively. CE (CE, 2018) found comparable additional costs per building of about 1000 euro/y. The difference is probably because of the scenario assumptions and the exclusion of energy taxes in this study.

Future scenario design entails assumptions and system simplifications, leading to uncertainties. The technical potential of geothermal heat in Utrecht (2.76 PJ) is sufficient for the uses in the collective scenario (Operators, 2018). Due to the complexity and interdisciplinarity of geothermal projects, the worst case is that a disappointing outcome of heat extraction occurs. The local biomass potential is assumed to be 0.22 PJ which is illustrated by the development of a new biomass heat-producing facility (BWI). In the sustainable heat scenarios, biomass needs to be imported from elsewhere outside of the municipality. Therefore the worst case is that sustainable heat sources from geothermal and biomass are not available. Such worst-case is similar to the reference scenario and leaves two potential solutions: 1) large-scale electrification of heat demand and 2) finding new sustainable heat sources/technologies which may be less mature (e.g. hydrogen).

A methodological choice was made in this study to keep the electricity and transport sector constant in all future scenarios as this study focused on the sustainable heating system. However, to investigate the interconnection and synergies among the energy sectors and to model a 100% renewable energy systems, the electricity and transport sectors should be included as well.

The transition of sustainable heating systems facilitates sustainable development in general and the achievement of SDGs such as affordable and clean energy. General assumptions made in developing future scenarios/pathways (see section 2.3) lead to renewables dominated heating systems and can result in 32% of CO2 emission reductions from the local energy system perspective. It contributes to increase the share of renewables in the energy mix and to promote the upgrade of energy infrastructure and clean energy technologies. On the other hand, the collective and mixed scenarios need more primary energy use than the reference. Replacing high efficient NG boilers and CHPs with geothermal heat and biomass incineration, plus the heat losses in the DH systems lead to lower energy efficiency in the heating system. Also, a large number of investments are required for technology replacements and infrastructure upgrades. Making a business case for the relevant stakeholders, e.g. house owners and utilities is crucial.

Two main limitations arise in this study. The first is the ratio of DH and individual heating technologies. Various ratios were examined, however, finding the optimal balance is difficult to determine at the city level. In practice, both individual and collective solutions will be necessary whereas the ratio should be determined on a neighbourhood-level, taking into account the local characteristics and aging of buildings. For future research, it is therefore recommended to search for optimal balances on a neighbourhood scale. The second research limitation is not considering the ownership of the investments. The economic consequences of scenarios are given as annual system costs without differentiating costs between different parties (e.g. individuals, housing corporations, utility, distribution system operators or the municipality).

5. Conclusion

Heating accounts for about half of the final energy demand in the member states of the European Union. The sustainable heat transition serves as one of the important strategies for combating climate change and achieving sustainable development. The difficulties of the transition vary greatly at the local level indicating the need for incorporating regional data for determining local solutions. The current studies on the development of sustainable heating systems at the local level vary in focus, the included sustainable heating strategies and the level of detail. Sector interactions and impacts of the heat transition on the rest of the energy system are often ignored. To fill these knowledge gaps, this study proposes comprehensive methodological steps, that can be used to identify, develop and assess sustainable heating systems at the local level, including the impact on the rest of the energy system. To illustrate the application of the proposed methodological steps, a case study is carried out in the city of Utrecht, the Netherlands. The computer tool EnergyPLAN is applied to simulate the current and future energy system in 2050 including three fossil-free heating scenarios.

The technical analysis shows that it is possible to achieve a maximum annual energy saving of 17% in the individual heating scenario due to the high adoption of domestic HPs (79%) and efficient use of renewable energy. The collective heating scenario with 75% of DH systems is less efficient due to a lower insulation level and distribution losses. However, it has the potential to include more sustainable heat sources. The economic analysis shows that the individual scenario is the most expensive and requires three times as much investment costs compared to the reference scenario. The lowest investments are found in the collective scenario which is, however, still two times more expensive than the investment in the reference case.

The proposed methodologies aim to facilitate future studies in exploring local solutions for sustainable heat supply. The case study in the Utrecht city indicates its applicability in densely populated urban areas where fossil fuel-based heating infrastructure is planned to be phased out. The insights into different directions of the heat transition and the implications of the results may be beneficial to other studies at a similar geographic scale. It shows that the most techno-economic pathway at the city level is always a mixture of energy savings and individual and DH technologies. The optimal balance should be determined at a neighbourhood level.

CRediT authorship contribution statement

Wen Liu: Methodology, Writing - original draft, preparation, Visualization, Supervision, Writing - review & editing. **Faye Best:** Data curation, Investigation, Validation. **Wina Crijns-Graus:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Energy labels and renovation strategies

Table A1
Final heat demand of the built environment per energy label (van den Wijngaart et al., 2018)

Energy label	Number of residential buildings	Heat demand [PJ]	Utility buildings area in m^2	Heat demand [PJ]
A or higher	21,507	0.22	2,708,917	0.57
B	26,270	0.36	651,220	0.19
C	23,786	0.40	854,290	0.30
D	17,116	0.37	551,200	0.25
E	13,600	0.37	393,312	0.23
F	13,043	0.44	258,754	0.18
G	32,190	1.43	669,123	0.62
Total	147,511	3.59	6,086,817	2.33

(note for utility buildings, the total area in each energy label is given instead of the number of buildings).

Table A2
Renovation strategies for residential and utility buildings (Majcen, 2016) (Schepers et al., 2016)

Strategy	Minimum level	buildings		Annual renovation rate (%)		Heat demand reduction		Total costs (M€)
		Residential (number)	Utility (m^2)	Residential	Utility	In PJ	In %	
Low	C	75,948	1,872,390	1.5%	0.9%	0.94	−16%	790
Medium	B	99,735	2,726,680	1.9%	1.3%	1.24	−21%	1220
High	A	126,004	3,377,900	2.4%	1.6%	1.90	−32%	2135

Appendix B. Additional results

Table B1
Infrastructural costs per scenario

	Reference	Collective	Individual	Mix
NG grids				
Additional connections	3474	–	–	–
Connection costs [M€]	2.26	–	–	–
Capacity costs [M€]	18.34	–	–	–
Demolition costs [M€]	21.04	91.40	91.40	91.40
Total costs [M€]	41.64	91.40	91.40	91.40
Electric grids				
Additional connections	59,466	59,466	59,466	59,466
Connection costs [M€]	57.98	57.98	57.98	57.98
Additional capacity [MW]	18	31	106	56
Capacity costs [M€]	39.60	68.20	233.20	123.20
Total costs [M€]	97.58	126.18	291.18	181.18
DH grids				
Additional connections	52,722	119,953	–	76,313
Connection costs [M€]	23.72	53.98	–	34.34
Additional capacity [MW]	118	334	–	145
Capacity costs [M€]	142.07	402.14	–	174.58
Total costs [M€]	165.80	456.11	–	208.92
Floor heating				
Area [m^2]	2,323,961	3,972,829	14,783,675	8,347,390
Total costs [M€]	167.33	286.04	1064.42	601.01
Electric cooking				
Buildings	116,642	204,371	204,371	204,371
Total costs [M€]	104.98	183.93	183.93	183.93

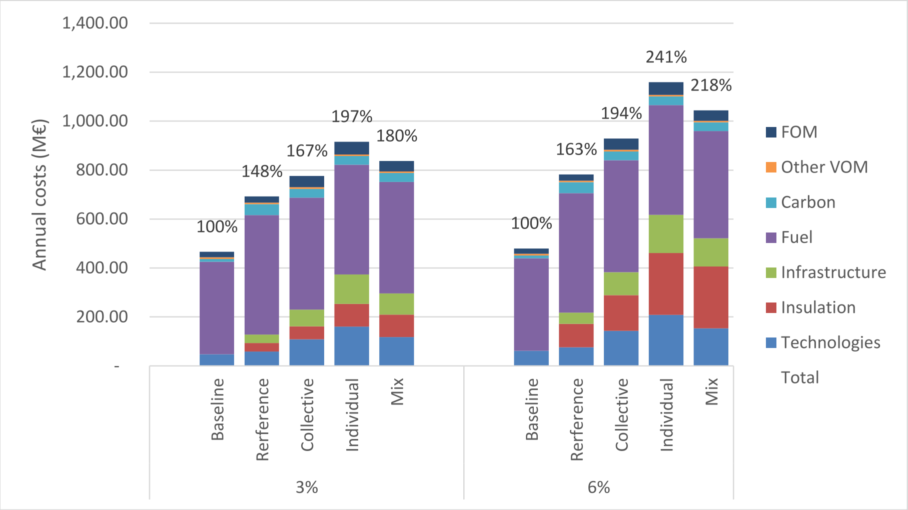

Fig. B1. Influence of the interest rate on annual system costs.

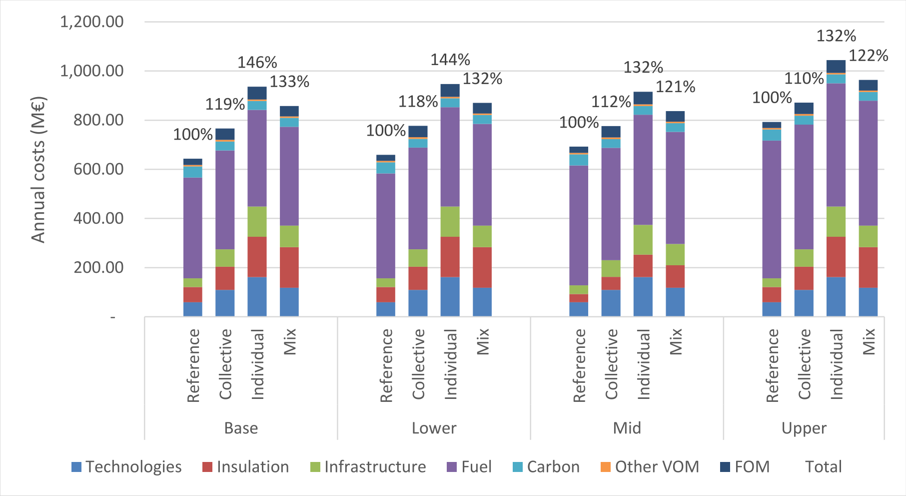

Fig. B2. Influence of the NG price on annual system costs.

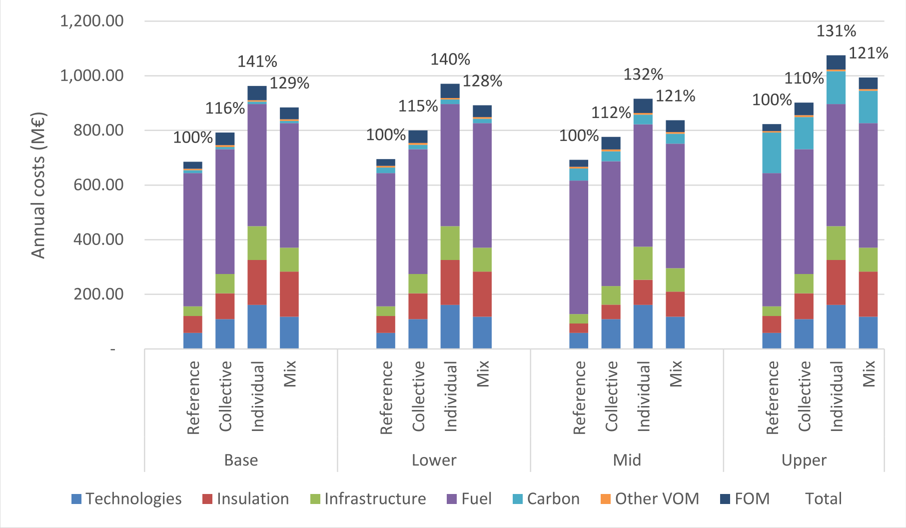

Fig. B3. Influence of the carbon price on annual system costs.

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