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DOI
10.1016/j.apenergy.2022.119759

Publication date
2022

Document Version
Final published version

Published in
Applied Energy

Applied Energy 325 (2022) 119759

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Reducing committed emissions of heating towards 2050: Analysis of scenarios for the insulation of buildings and the decarbonisation of electricity generation

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ARTICLE INFO

Keywords:
Urban heat systems
Committed carbon emissions
Retro-fitting of the building stock
Electrification of heating
Carbon lock-in
Mixed-integer non-linear programming

ABSTRACT

Infrastructure for heat provision in the built environment needs to change remarkably to support lowering carbon emissions and achieving climate mitigation targets before 2050. We propose a computational approach for finding a mix of heat options per neighbourhood that minimises cumulative carbon emissions between 2030 and 2050, referred to as committed emissions, while at the same time adhering to technological constraints at both the household and neighbourhood scales. To establish this approach, we integrated bottom-up heat demand modelling at neighbourhood scale with a mixed-integer non-linear optimisation problem. Nine scenarios with different pathways for the insulation of buildings and the decarbonisation in electricity generation were considered and applied to three neighbourhoods in the city of Amsterdam, the Netherlands. The results show that (i) the committed emissions are ten times lower between 2030 and 2050 in scenarios in which ambitious measures are taken for the insulation of buildings and the decarbonisation in electricity generation, (ii) only in these 'ambitious scenarios' low temperature heat systems, such as heat pumps and low temperature heat networks, are optimal solutions for minimising committed emissions, (iii) if less ambitious insulation and decarbonisation measures are taken, high temperature heat options can be part of the heat mix with lowest committed emissions, and (iv) the minimum heat density for low temperature heat networks is not always achieved, creating risks for carbon lock-ins when applying these heat networks. Our results clearly indicate that pathways for the retrofitting of buildings and the decarbonisation in electricity generation need to be taken into account jointly when designing renewable and low-carbon heat systems to optimally reduce carbon emissions towards 2050 and reduce future carbon lock-ins.

1. Introduction

Transitioning towards low-carbon heat systems is important for attaining globally set targets to abate carbon emissions, mitigating global warming [1]. Heating processes for industrial and domestic purposes generate 40% of the global carbon emissions [2]. Half of this globally produced heat is used for space- and tap water heating in the built environment. According to the Intergovernmental Panel on Climate Change (IPCC), buildings were responsible for 19% of energy-related emissions in 2010 [3]. Although more than a decade later, a notable emission reduction potential is still present, given that still 80% of the currently sold heating appliances still operate on fossil fuels. In the Netherlands specifically, space and tap water heating for the built environment accounts for almost a quarter of the national final energy consumption [4]. Most of this energy, 85%, is generated from natural gas. Heating consequently contributes 13% of the national emissions of greenhouse gases [5]. The national government aims to eliminate the use of natural gas and, simultaneously, reduce carbon emissions to almost zero by 2050 [6]. The national government for example intends to support electrification of heating by stimulating the implementation of hybrid heat pumps, i.e. conventional heating systems such as gas boilers in conjunction with heat pumps, when replacing gas boilers [7]. It is however important to design heat systems that will not only emit net zero carbon emissions by 2050, but also base decisions on the carbon emission reduction potential for the upcoming years. According to the IPCC, the maximum amount of carbon emissions that can be emitted while remaining below 1.5 °C or 2 °C global warming above pre-industrial levels is reached in the upcoming 10 or 25 years, respectively, if the current yearly quantities of carbon emissions are not reduced [8]. In this manuscript, we therefore present an analysis of the cumulative carbon emissions of different scenarios for transitioning towards low carbon heat systems in the built environment.

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https://doi.org/10.1016/j.apenergy.2022.119759
Received 23 December 2021; Received in revised form 10 July 2022; Accepted 23 July 2022
Available online 6 September 2022

Abbreviations

CHP	Combined Heat and Power
COP	Coefficient of Performance
ERE	Energy-required-for-Energy
GIS	Geographic Information System
HP	Heat Pump
HT	High Temperature
IPCC	Intergovernmental Panel on Climate Change
LT	Low Temperature
MINLP	Mixed-Integer Nonlinear Program
MT	Mid Temperature
PHPP	Passive House Planning Package
UTES	Underground Thermal Energy Storage

In order to determine the configuration of heat systems with the lowest cumulative carbon emissions, we propose to use the notion of 'committed emissions'. Different from the main literature body, where the notion of committed emissions is defined as cumulative emissions that occur over the remaining operational lifetime of an asset, we use the notion to indicate the cumulative carbon emissions emitted during a given future planning period [9,10]. This is because infrastructure for heating, such as heat networks, electric heat pumps, and piped networks with fuel gas, have different operational lifetimes, creating difficulties for meaningfully comparing the emissions over the operational lifetime, and assessing the emissions towards 2050.

Up to the author's knowledge, no optimisation studies for determining the configuration of urban heat systems with the lowest cumulative carbon emissions over time however exist. This is in line with an extensive literature review on carbon lock-in induced by long-lived capital in which it was identified that the carbon lock-in in the built environment is insufficiently addressed in the current body of literature [9]. Doing so is however not straightforward, given that urban energy systems comprise large distributed systems, creating many degrees of freedom [11]. Carbon emissions of heating additionally depend on both the spatially heterogeneous heat demand and the infrastructure for thermal energy generation. The heat demand can decrease with the insulation of buildings, which would lead not only to a decrease of carbon emissions for heating but also makes it possible to implement different low carbon heating alternatives. Additionally, the emission factor of heat generation can change when energy carriers or heat sources are replaced. Heat pumps are, for example, considered to be a technology suited for well insulated buildings, but the emission factor of heat pumps is lower if the used electricity is generated with renewable energy sources instead of fossil fuels. To find the mix of heating technologies in urban areas for which the committed emissions are minimised under different scenarios for the insulation of buildings and the decarbonisation in electricity generation, we propose a computational framework combining bottom-up heat demand models with optimisation methods.

Heat demand models, on the one hand, enable policy makers to track whether current goals are realised, to define realistic future goals, and avoid policies that lead to weaker results [12]. High level spatio-temporal data and modelling results are useful for designing future heat systems because recommendations can then be formulated on decision-relevant scales [13,14]. Additionally, information about the heat demand on both the building and neighbourhood scale can inform whether heat systems can be applied or not [15]. Decentralised heat systems such as heat pumps may, for example, require a certain insulation level on the building scale, whereas centralised heat systems do require a minimum heat density in the neighbourhood to be economically preferable and technically feasible [16]. Modelling high level spatio-temporal heat demand for urban areas is however challenging, given that these areas develop over time and are therefore often made up of a heterogeneous building stock. Buildings within cities differ in building age, construction methods, and temporal heat demand patterns associated with current use (e.g. domestic, business, and hospitality) [17].

Bottom-up heat demand models can contribute to high level spatio-temporal heat demand estimation because these models calculate the energy consumption of representative samples and extrapolate this energy demand to represent a larger building stock [18,19]. The work in [20], for example, included modelling each building separately and then applying a Monte-Carlo simulation for estimating future heat load profiles and peak demand under different renovation interventions of buildings. Bottom-up heat demand models can therefore be used to address the challenges of spatially explicit modelling accounting for the diversity in building types, and therefore heat demand, in urban areas [21].

Optimisation studies, on the other hand, are used in combination with heat demand models to inform how to minimise impacts of heat systems on indicators such as costs, carbon emissions and resource use. Some studies focus on optimising one type of heat supply, e.g. on district heating [22], or hydrogen, e.g. [23]. Other studies include modelling multi-energy systems to estimate which technology would be most suitable according to chosen indicators. In [11], for example, a mixed-integer linear program (MILP) tool is offered for modelling both supply side and demand side technologies of residential energy systems in order to minimise costs under different scenarios. Another example is [24], in which a MILP tool is presented to minimise costs and carbon emissions integrating hourly and yearly demand and supply profiles to include seasonal energy storage.

The proposed computational framework is applied to three neighbourhoods in the city of Amsterdam, the capital of the Netherlands. This case study is chosen because insights derived from it can be valuable for other cities; energy infrastructure needed for low-carbon heating in Amsterdam (e.g. heat networks, piped network transporting gaseous energy carriers to heaters in buildings, and the electricity grid providing electricity for electric heat pumps) are also relevant across Europe [14,25–29]. To decide which heat systems are needed in the city, the municipality of Amsterdam has screened which heat sources are affordable and can be available per neighbourhood [16]. They have presented the outcomes of this study in a document and citizens were invited to give their input [16]. Additionally the municipality organises participation processes for decision making on a neighbourhood scale. Because of this neighbourhood based approach, the results of the modelling framework are presented at the neighbourhood level to generate information on a decision-relevant scale [13]. The names of the neighbourhoods analysed, are 'Felix Meritis', 'Molenwijk', and 'Prinses Irenebuurt' (see Appendix A, Fig. A.8 for the location of the neighbourhoods on a map of Amsterdam). The neighbourhoods are chosen for their diversity in building types. Felix Meritis is a historic neighbourhood, consisting mostly of terraced houses and apartment buildings built before 1945. Molenwijk is a neighbourhood consisting only of apartment buildings built between 1946 and 1975, whereas the Prinses Irenebuurt is a neighbourhood with a mix of (semi-)detached houses, terraced houses, and apartment buildings mostly built between 1946 and 1975.

The computational framework with which the neighbourhoods are analysed is presented in Section 2. The results of this analysis are shown in Section 3. Section 4 includes a discussion of the results and is followed by concluding remarks on policy implications in Section 5.

2. Methods

The proposed computational framework, shown in Fig. 1, consists of a bottom-up heat demand model and mathematical optimisation for finding a mix of heat options with the lowest committed emissions. In this section, we will discuss the case study neighbourhoods, the bottom-up heat demand model, the heat systems considered, the studied scenarios, and the optimisation problem we pose and solve.

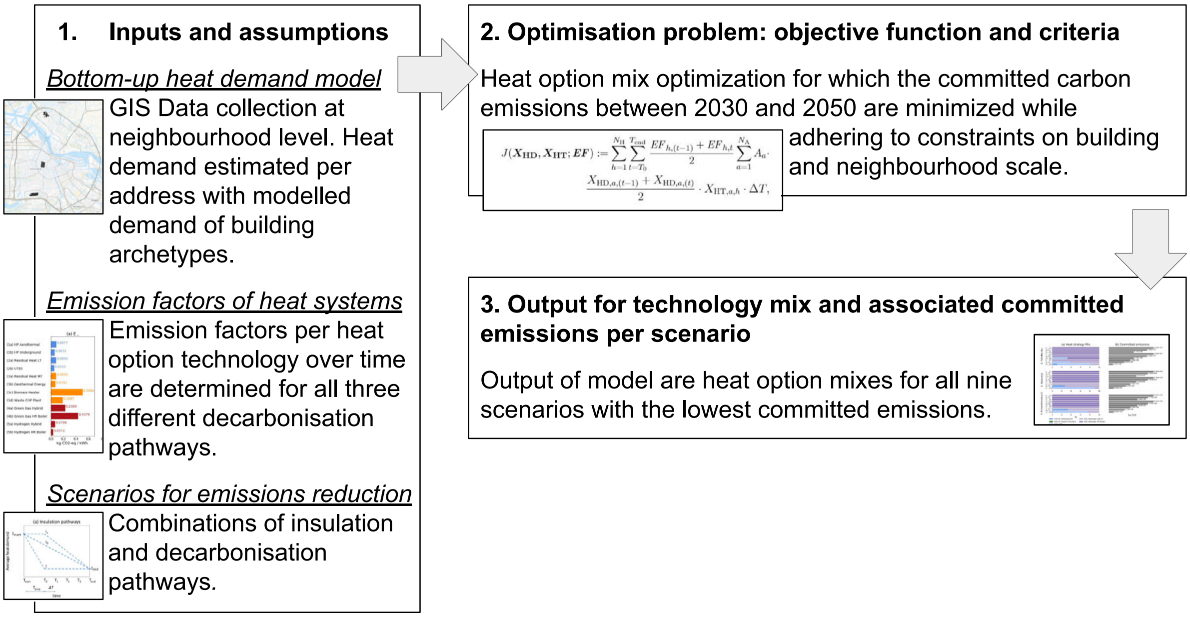

Fig. 1. Modelling framework for minimising committed emissions. The input data needed for the optimisation model are obtained from a bottom-up heat demand model, emission factors per heat option and scenarios for emissions reduction.

2.1. Bottom-up heat demand model

Bottom-up heat demand modelling means that the heat demand is modelled for representative samples and extrapolated to represent a larger building stock [18,19]. In this study sixteen building archetypes were used. The used building archetypes are a combination of four building types and four construction periods (see Fig. 2), and are derived from the report 'Standard and Target values for existing housing' (in Dutch: *standaard en streefwaardes bestaande woningbouw*) [15]. This report is used by the National Government to provide standard insulation references to building owners [15,30]. The four building types represent buildings with a similar number of exterior walls or walls connected to other buildings. The four building types used are 'mid-terrace', 'semi-detached', 'detached', and 'apartments'. The building types cover all building types included in the registration of buildings and addresses by the Netherlands' Cadastre, Land Registry and Mapping Agency [31]. The only difference is that the building types 'end of terrace' and 'semi-detached' were considered as one category in this study because the heat demand of these building types are similar due to a similar amount of exterior walls.

The construction period was also used to define the building archetypes because it can be used as an indicator of the building characteristics related to common insulation measures over time shown in Fig. 2 [15]. Buildings built before 1946 do not often have cavity walls, which means that roof and floor insulation are the main insulation measures that can be applied (a more detailed description of insulation measures used from [15] can be found in Appendix A, Fig. A.9). Buildings built between 1946 and 1975 generically have a cavity wall, so cavity wall insulation is applied additionally to roof and floor insulation. After 1980, building insulation became mandatory, so in these cases the already existing insulation in the cavity can be improved. The four construction periods used in this research are (i) before 1946, (ii) between 1946 and 1975, (iii) between 1976 and 1995, and (iv) after 1995.

For each building archetype, the yearly heat demand per unit of floor area is modelled for standard insulation levels defined in [15]. As input for the optimisation the 'current' and 'advanced' insulation levels were used (see Table 1, and Fig. A.12 in Appendix A for the modelled heat demand for 'basic' and 'intermediate' insulation level). The 'current' insulation level stands for a state in which some regular

Table 1
Modelled heat demand per building archetype for the 'current' and 'advanced' insulation levels expressed in kWh per square metre of floor area per year.

Building type	Construction period	Heat demand [kWh m^{-2} $year^{-1}$]	
		Current insulation level	Advanced insulation level
Apartment	<1946	193	24.2
	1946–1975	159	24.2
	1976–1995	113	24.2
	>1995	79.5	24.2
Detached	<1946	177	30.9
	1946–1975	133	30.9
	1976–1995	107	30.9
	>1995	67.7	30.9
Semi-detached	<1946	143	26.1
	1946–1975	109	26.1
	1976–1995	84.8	26.1
	>1995	58.0	26.1
Terraced	<1946	177	21.3
	1946–1975	156	21.3
	1976–1995	124	21.3
	>1995	79.3	21.3

insulation measures are already undertaken with respect to the original state at construction. The advanced insulation level represents technologically complex improvements that happen less often in practice, but are technologically feasible.

The modelled values for the 'current' and 'advanced' heat demand are static and do not change over time [12]. The optimisation model itself can however be characterised as a dynamic model as it analyses the heat demand over multiple years [12]. In the optimisation model, we first estimate the 'current' heat demand of each address in the neighbourhood and simulate insulation of addresses by lowering the heat demand, keeping the heat demand associated with the 'advanced' insulation level as a minimum heat demand. The 'current' or 'advanced' heat demand per address is determined by associating each address with a building archetype and multiplying the modelled heat demand per square metre floor area of the 'current' or 'advanced' insulation level with the floor area of the associated address. The floor area per address and the information needed to cluster all addresses into building archetypes, i.e. the information on the building type and the construction year, is collected with Geographic Information System

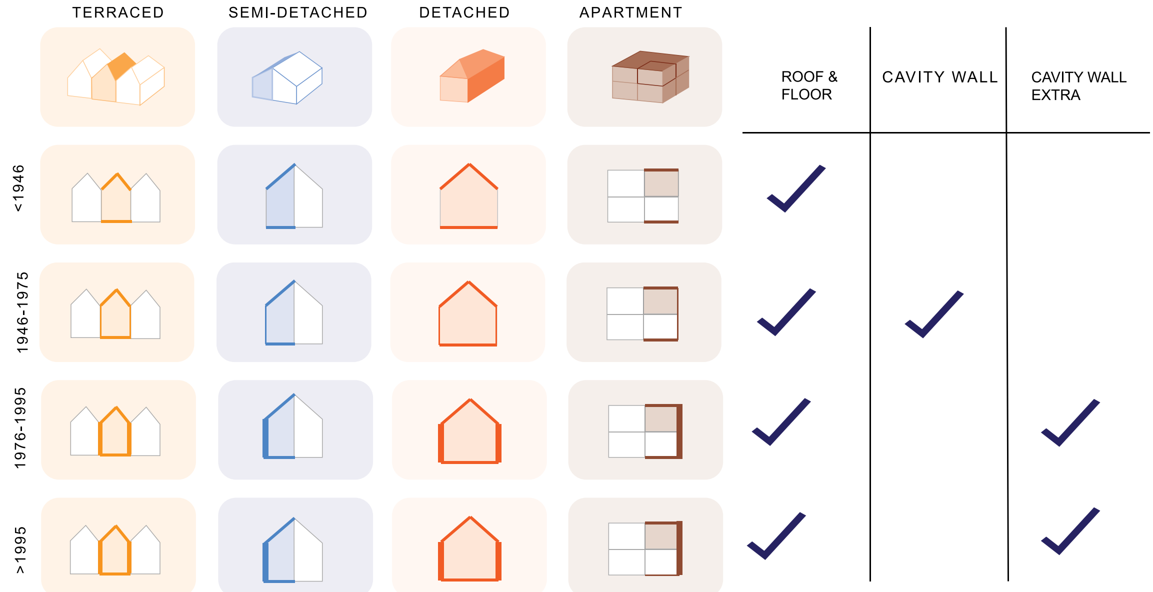

Fig. 2. Overview of the 16 building archetypes used together with possible insulation improvement per construction period.

(GIS) data through ArcGIS pro software. Feature layers are collected from the ArcGIS Living Atlas collection of Esri Nederland Content on the 5th of May 2021 [31] (see Appendix A, Fig. A.8 for an example of the ArcGIS map). The names of the feature layers are: 'BAG - pand', 'Woningtypering', 'BAG - adres', 'BAG - Verblijfsobject'.

The heat demand for the building archetypes is estimated with Passive House Planning Package (PHPP) software (see Table 1). The input data for the PHPP model are the thermal resistance of materials, the area size of the surfaces of the building envelope, the orientation, the infiltration rates and the ventilation mechanism. The thermal resistances, also known as the R-values, of the different materials of the shell of the houses were taken from [15] and presented in Figs. A.10 and A.11 in Appendix A. From [15] we also used the infiltration rates (see Table A.4 in Appendix A) and the insulation measures (see Fig. A.9 in Appendix A). The sizes of the building envelope areas are extracted from a study by Agentschap NL, presently known as RVO The Netherlands Enterprise Agency, and presented in Table A.3 in Appendix A [32]. For this manuscript, we set the height of ceilings at a standard of three metres for all building types. We assume that all terraced housing, semi-detached and detached buildings have two floors while all apartments only have one floor and are in three-storey apartment buildings. The chosen cardinal directions for the building types are 'North' for terraced housing, 'East' for semi-detached houses, 'South' for detached houses and 'West' for apartments to generate a distribution of orientations in the neighbourhoods. Nevertheless, the influence of cardinal direction on the modelled heat demand can be minimal [15].

2.2. Emission factors of heat systems

In this manuscript, we consider a rich mix of supply systems and energy sources that are currently being considered in national policy and in practice. We refer to heat systems as the collection of technologies that generate and distribute heat. Five major heat systems were considered, which are the same as the 'heating strategies' included in the PBL Netherlands Environmental Assessment Agency's decision tool for Dutch municipalities to transition to renewable heating [33]. For each of these five major heat systems listed in Table 2, we have analysed several 'heat options', i.e. heat generation technologies or heat sources from which the thermal energy is sourced.

The first system, i.e. '1. Individual Heat Pump', stands for a heat system in which electric heat pumps are used. The two heat options analysed for this heat system are '(1a) Heat Pump (HP) Aerothermal' and '(1b) HP Underground'. The second heat system is called '2. LT Heat Network'. We define an LT heat network as a heat network that delivers heat at 'Low Temperature' (LT), i.e. 40 °C, following the definition given of the Municipality of Amsterdam [16]. The heat options for such a heat network considered in this manuscript are residual heat from industry, such as from datacenters, and thermal energy withdrawn from Underground Thermal Energy Storage (UTES). The names of the two heat options are: '(2a) Residual Heat LT' and '(2b) UTES'. The third heat system is a 'mid-temperature' (MT) heat network delivering heat at 70 °C [16]. The heat options considered are: '(3a) Residual Heat MT', '(3b) Geothermal energy', '(3c) Biomass Heater', and '(3d) Waste CHP plant'. The latter heat option stands for a combined heat and power (CHP) plant where waste is incinerated. Both heat systems 4 and 5 are decentralised systems at address level that incinerate green gas and green hydrogen respectively. Green gas refers to biogas processed to have the same heat capacity as natural gas and so can be distributed through the existing natural gas grid. Green hydrogen refers to hydrogen produced via water electrolysis with electricity generated by renewable energy carriers. For both systems, we consider two heat options: (a) a hybrid option, and (b) a gas-fired heat condensing boiler. The hybrid option consists of an aerothermal heat pump which covers 60% of the heat supply and a gas-fired heat condensing boiler which supplies 40% of the thermal energy demand, mostly during peak demand. By using gas-fired heat condensing boilers, heat systems 4 and 5 can deliver heat at 'high temperature' (HT), i.e. 90 °C [16].

Table 2
Constraints per heat system defined by [16]. The temperatures of the heat delivery systems for low-temperature (LT), mid temperature (MT) and high temperature (HT) thermal regimes are 40 °C, 70 °C, and 90 °C respectively.

Heat system	Thermal regime	Maximum heat demand [kWh m^{-2} $year^{-1}$]	Minimum heat density [MWh hec^{-1} $year^{-1}$]
1. Individual Heat Pump	LT	50	–
2. LT Heat Network	LT	50	165.75
3. MT Heat Network	MT	80	165.75
4. Green gas	HT	–	–
5. Green hydrogen	HT	–	–

Table 2 also contains two constraints posed in the optimisation problem: one on the addresses and one on the neighbourhood scale.

The first constraint represents the maximum thermal energy demand per square metre of floor area of an address for which a heat option can ‘comfortably’ heat up a space. In practice, whether a heat system can ‘comfortably’ heat up a space depends on a variation of factors such as the indoor heat system and the type of heat pumps installed. However, according to reports from the municipality of Amsterdam, the temperature of the heat source can be used as an indicator for the maximum heat [16,34]. They indicate that buildings with a yearly heat demand below 80 kWh per square metres of floor area can be heated with a heat system which delivers heat at middle temperature [16]. They state a value of 50 kWh m^{-2} $year^{-1}$ as maximum heat demand for LT heat strategies [16]. No maximum heat demand constraint is assigned for HT strategies [16]. The second constraint applies to heat systems operating at the neighbourhood level, i.e. heat systems 2 and 3. Heat networks are more profitable and efficient in areas with higher heat density. Based on the heat demand needed in the neighbourhood to make a heat network economically feasible according to [16], we therefore posed a minimum yearly heat demand density of 165750 kWh per hectare of land as a threshold for heat systems 2 and 3.

In order to model the mix of heat options with the lowest committed emissions between 2030 and 2050, we determined the emission factor per heat option (see Fig. 3). The emission factors are expressed in units of mass of carbon equivalents per unit of thermal energy supplied (kg CO_2-eq / kWh) and are only based on the emissions during the operational phase. In this phase, we accounted for the emissions associated with thermal energy generation including distribution losses. This scope is chosen because currently the operational phase is responsible for the higher share of carbon emissions with respect to the other phases. In the case study on Tuscany for example, the contributions to greenhouse gas emissions of the operational phase are 96.6%, 95.4%, 97.6%, and 96.9% for the considered strategies: natural gas heaters at household level and heat networks distributing thermal energy from geothermal energy, a biomass heater, or a natural gas heater [35].

Emissions associated with thermal energy storage are excluded from the scope. In practice, heat options can be used in combination with energy storage, for example in the form of heat boilers, UTES, electric batteries, or fuel storage. When and how energy is stored can be varied, for example with demand response techniques, increasing the complexity of the heat systems and the assessment of carbon emissions. Additionally, thermal energy for storage can be withdrawn from residual heat sources, making the allocation of carbon emissions non-trivial. It is because of this complexity behind energy storage that carbon emissions associated with the energy needed for charging energy storage systems or storage losses are out of scope of this paper.

In order to determine the emission factors during the operational phase we used the emission factors per energy carrier, those associated with supplying and converting the thermal energy of the energy carrier, and the Energy-required-for-Energy (ERE) factors, which are based on the efficiencies or coefficient of performance (COP) of technologies. The emission factors per energy carrier and the ERE factors used in this study, can be found in Tables B.5 and B.6 in Appendix B.

Three stages in the supply chain of heat were considered: direct emissions, indirect emissions for fuel supply and indirect emissions for electricity supply. Direct emissions take place locally where heat is generated. Indirect emissions, on the other hand, can be emitted elsewhere during different processes in the supply chain of heat. By making a distinction between direct and indirect emissions we aim to stress the multi-scale effects of energy generation. The emission factors for direct emissions and indirect emissions for fuel supply are based on data found in literature (see Appendix B, Tables B.5 and B.6 for input data and references). The magnitude of indirect emissions for electricity consumption, defined as the emission per unit of electricity supply, depends on the power mix of the electricity grid at the time of electricity use and hence the decarbonisation pathway for electricity. We therefore consider different pathways for the decarbonisation of electricity production in our scenarios.

2.3. Scenarios for emissions reduction

To analyse which heat options should be implemented in the neighbourhoods to minimise committed emissions between 2030 and 2050, we consider nine scenarios that span decarbonisation pathways: pathways for the insulation of buildings and the decarbonisation of electricity generation (see Fig. 4). Using scenarios composed of varying pathways for electricity grid decarbonisation and neighbourhood insulation capabilities, we explicitly consider uncertainty in future drivers.

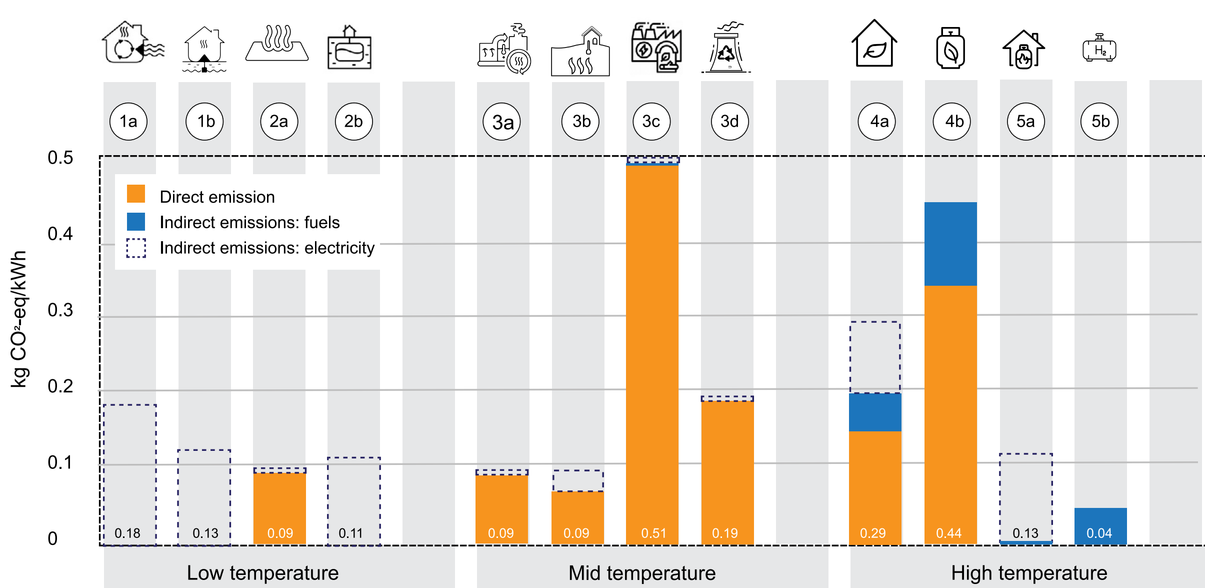

Fig. 3. Emission factors per heat option in terms of kg CO_2 equivalents per kWh of thermal energy supplied. These heat options are considered to replace heating with a natural gas boiler at household level, which has an emission factor of 0.213 kg CO_2-eq kWh^{-1}. Heat options: (1a) Heat Pump (HP) Aerothermal, (1b) HP Underground, (2a) Residual Heat Low Temperature (LT), (2b) Underground Thermal Energy Storage (UTES), (3a) Residual Heat Mid Temperature (MT), (3b) Geothermal Energy, (3c) Biomass Heater, (3d) Waste Combined Heat and Power (CHP) plant, (4a) Green Gas Hybrid, (4b) Green Gas Boiler, (5a) Green Hydrogen Hybrid, and (5b) Green Hydrogen Boiler. The temperatures of the heat delivery systems for low-temperature (LT), mid temperature (MT) and high temperature (HT) thermal regimes are 40°, 70°, and 90° respectively.

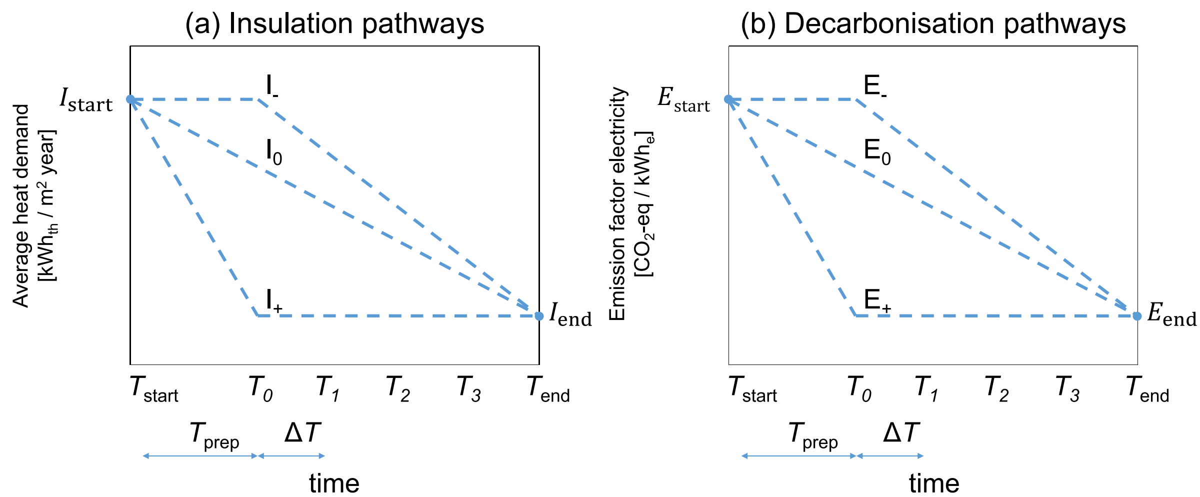

Fig. 4. Pathways for (a) insulation of buildings and (b) decarbonisation of electricity generation. The average heat demand is expressed in kWh of thermal energy per square metre of floor area per year and the emission factor of electricity in kg of CO_2 equivalents per kWh of electricity. T_{start} is the year 2020, T_0 the year 2030 and T_{end} the year 2050. The pathways are annotated with a +, 0 or - representing 'more ambitious', 'linear', 'less ambitious' rates of reaching the goal posed at T_{end}.

The three insulation pathways, I_+, I_0 and I_-, are input for the maximum rate of insulation which can take place per year (Fig. 4a). The start and endpoint of each pathway, i.e. I_{start} and I_{end}, are the same and are expressed as the average areal heat demand in the neighbourhood. The difference between the three is the path in which the endpoint is reached. The average areal heat demand in pathway I_0 decreases linearly between 2020 and 2050. In pathway I_+ we assume a more rapid insulation rate in which the I_{end} is already established by 2030. In pathway I_- buildings only start to be insulated after 2030. In other words, the three pathways represent future situations wherein addresses are insulated linearly, relatively early, or relatively late.

The value of the average heat demand in 2020, i.e. I_{start}, is modelled by multiplying the modelled 'current' heat demand per building archetype with the surface area of that building archetype present in the neighbourhood (as collected previously with the GIS analysis). I_{end} is set equal to 60 kWh m^{-2} year^{-1} based on policy of the municipality to insulate 70% of all addresses to 70 kWh m^{-2} year^{-1} and 30% to 50 kWh m^{-2} year^{-1}. At 70 kWh m^{-2} year^{-1} buildings can be comfortably heated with central heat systems pumping around water at 70 °C [16]. Heating at this temperature is an economic optimum for most existing buildings in Amsterdam according to an economic analysis by [16, pp. 59].

The three pathways for the decarbonisation in electricity generation are defined similarly to the insulation pathways. In pathway E_0, the emission factor for electricity between 2020 and 2050 decreases linearly with time. In pathway E_+ and E_- this linear decrease takes place between 2020 and 2030 and 2030 and 2050, respectively. The emission factor of electricity in 2020 is based on the technology mix for electricity production in the Netherlands [36]. We set the endpoint in 2050 to 14.7 g CO_2-eq/kWh, which is the emissions factor of offshore wind energy [36]. This renewable electricity source is expected to be one of the most important renewable electricity sources in the Netherlands by 2050 [36,37].

2.4. Optimisation of heat options

To find a mix of heat options per neighbourhood that has the minimal committed emissions between 2030 and 2050, while adhering to the two posed technological constraints, we pose a mixed-integer nonlinear program (MINLP) optimisation problem with the following objective function:

$$J(\boldsymbol{X}_{\mathbf{HD}}, \boldsymbol{X}_{\mathbf{HT}}; \boldsymbol{EF}) := \sum_{h=1}^{N_H} \sum_{t=T_0}^{T_{end}} \frac{EF_{h,(t-1)} + EF_{h,t}}{2} \sum_{a=1}^{N_A} A_a \cdot \frac{X_{HD,a,(t-1)} + X_{HD,a,(t)}}{2} \cdot X_{HT,a,h} \cdot \Delta T, \quad (1)$$

where the parameters N_A, N_H, and A_a stand for the number of addresses in the neighbourhood, the number of heat options considered, and the floor area (in m^2) per address a respectively. For each heat option indexed h, the parameter $EF_{h,t}$ represents the emission factor in year t in terms of kg CO_2 equivalents per kWh of thermal energy supplied. The optimisation problem has three sets of indexed variables: $\boldsymbol{X}_{\mathbf{HD}}$, $\boldsymbol{X}_{\mathbf{HT}}$ and $\boldsymbol{x}_{\mathbf{HF}}$. The indexed variables are defined as follows:

$$X_{HD,a,t} \in [HD_{min,a}, HD_{max,a}], \quad \forall a \in [1, N_A]; \forall t \in [T_{start}, T_{end}],$$
$$X_{HT,a,h} \in \mathbb{Z}_{[0,1]}, \quad \forall a \in [1, N_A]; \forall h \in [1, N_H],$$
$$x_{HF,h} \in \mathbb{Z}_{[0,1]}, \quad \forall h \in [1, N_H],$$

where, $X_{HD,a,t}$ stands for the yearly heat demand per m^2 of floor area for address a in year t. The binary variable $X_{HT,a,h}$ represents the heat option at address level — it is equal to 1 if a heat option h is applied at address a and equal to 0 if not. The variable $x_{HF,h}$ stands for whether or not the minimum heat density for heat option h is attained in the neighbourhood. $HD_{min,a}$ and $HD_{max,a}$ are the minimal and maximal yearly heat demand of address a in terms of kWh m^{-2} year^{-1}. They correspond to the modelled heat demand per floor area of the building archetype associated with address a at the advanced and current insulation levels, respectively. The three decision variables are subject to the following constraints:

$$X_{HD,a,t} \leq X_{HD,a,(t-1)}, \; \forall a \in [1, N_A], \forall t \in [T_{start}, T_{end}], \quad (2)$$

$$X_{HT,a,h} \cdot X_{HD,a,t} \leq HS_{max,h}, \; \forall a \in [1, N_A], \forall h \in [1, N_H], \; \forall t \in [T_0, T_{end}], \quad (3)$$

$$\sum_{h=1}^{N_H} X_{HT,a,h} = 1, \; \forall a \in [1, N_A], \quad (4)$$

$$\sum_{a=1}^{N_A} A_a \cdot (X_{HD,a,(t-1)} - X_{HD,a,t}) \leq \sum_{a=1}^{N_A} A_a \cdot (HD_{avg,(t-1)} - HD_{avg,t}), \; \forall t \in [T_0, T_{end}], \quad (5)$$

$$\sum_{a=1}^{N_A} A_a \cdot X_{HD,a,t} \cdot X_{HT,a,h} \geq A_n \cdot x_{HF,h} \cdot HS_{min,h}, \; \forall h \in [1, N_H], \; \forall t \in [T_0, T_{end}], \quad (6)$$

$$x_{\mathrm{HF},h} \cdot N_{\mathrm{A}} \geq \sum_{a=1}^{N_{\mathrm{A}}} X_{\mathrm{HT},a,h},\ \forall h \in [1, N_{\mathrm{H}}]. \tag{7}$$

Eqs. (2)–(4) describe constraints at the address scale. Eq. (2) imposes the heat demand of address a to decrease in time. As described in Section 2.2, the implementation of a heat option at the address level is constrained by the maximum heat demand constraint of that heat option (see the bilinear constraint Eq. (3)). The maximum heat demand per heat option is expressed with the parameter $HS_{\mathrm{max},h}$ and has the unit kWh m^{-2} year^{-1}. The integral constraint in Eqs. (4) enforces that only one heat option is chosen per address. Eqs. (5)–(7) enforce the link between the situation at the address scale and the neighbourhood scale. The heat demand reduction through insulation per time step for an address is constrained by the insulation pathways described in Section 2.3. This is translated into Eq. (5), which states that the decrease in heat demand in the neighbourhood due to insulation at address level cannot be higher than the decrease in the average heat demand, $HD_{\mathrm{avg},t}$, given by the insulation pathway. Eq. (6), which is also bilinear in the decision variables, imposes that the total heat supplied by heat option h in the neighbourhood should be larger than the minimal heat density, $HS_{\mathrm{min,h}}$, in terms of kWh ha^{-1} year^{-1} times the area of the neighbourhood in hectares, A_n. At last, the constraints in Eqs. (6)–(7) together enforce the complementary condition that heat option h is not chosen at neighbourhood and address levels (i.e. $x_{\mathrm{HF},h}$ and $X_{\mathrm{HT},a,h}$, for all addresses a are equal to zero) unless the minimum density requirements for heat option h are strictly met.

All computational experiments were performed using a MacBook Pro computer with a 2.4 GHz QuadCore Intel IntelCore i5 CPU and 16 GB RAM. The optimisation problem is implemented within the python based Pyomo Algebraic Modelling Language and solved using Gurobi. The resulting optimisation problem is a MINLP due to the two sets of indexed nonlinear (i.e. bilinear) constraints and objective, which we solved efficiently with GUROBI 9.1 and an allowable MINLP gap of 1% [38]. The computations took seconds to minutes to converge to the MINLP Gap set per scenario. The results of the MINLP problem are reported in the following section.

3. Results

In Fig. 5 the heat option mixes with the lowest committed emissions between 2030 and 2050 for the different neighbourhoods under different scenarios, are depicted together with the corresponding committed emissions. The heat options presented in the optimal heat option mixes in the left column include the low temperature heat options (1b) HP Underground and (2b) UTES depicted with blue bars, and green hydrogen fuelled heat options represented by the purple bars. The results suggest that low temperature heat options can only be optimal solutions for some addresses in the neighbourhood for scenarios in which more ‘ambitious’ pathways for the insulation of buildings and the decarbonisation of electricity generation, being the scenarios (I_+, E_+), (I_0, E_+), and (I_+, E_0), are applied. For the other scenarios, green hydrogen fuelled heat sources are presented as optimal solutions for minimising committed by the model. The right column, i.e. Fig. 5b, depicts the corresponding committed emission associated with the heat option mixes. The results suggest that the committed emissions in the most ambitious scenarios, i.e. scenario (I_+, E_+) are almost ten times smaller than the committed emissions in the least ‘ambitious’ scenario (I_-, E_-) for each neighbourhood.

Whether or not heat options are included in the mix is a result of the optimisation problem in which cumulative emissions over time are minimised while satisfying the two posed technological constraints. The emission factors over time depend on the different rates of decarbonisation in electricity generation (see Fig. 4). The bar charts in Fig. 6 depict the average carbon emission factors (EF_{average}) per heat option between 2030 and 2050 for the three decarbonisation pathways as used in the optimisation to generate the results as presented in Fig. 5.

For pathway E_- (see Fig. 6a), the heat option with the lowest EF_{average} is heat option (5b) Green Hydrogen Boiler, a HT, decentralised heat system applied at address level and therefore not subject to any constraints in the model (see Table 2). As such, the optimisation chooses this technology for all addresses in the scenarios with decarbonisation pathway E_- (see Fig. 5). The vertical black bars indicate the EF_{average} for if the direct emissions associated with incineration of organic energy carriers is set equal to zero, and will be discussed in Section 4.2.

For pathways E_+ and E_0, the heat option (2b) UTES has the lowest EF_{average} (see Fig. 6b and c). This heat option is a heat system with a LT heat network and can therefore only be applied to addresses with a heat demand lower than 50 kWh m^{-2} year^{-1} (see Table 2). Addresses with a heat demand above 50 kWh m^{-2} year^{-1} cannot be heated by LT heat systems and the model will therefore choose a MT or HT heat option. The heat options with the lowest EF_{average} for pathways E_0 and E_+, which do operate at MT and HT level, are the heat option (5a) Green Hydrogen Boiler and (5b) Green Hydrogen Hybrid respectively. This is why the options (2b) UTES, (5a) Green Hydrogen Boiler, and (5b) Green Hydrogen Hybrid are visible in the heat option mix for the Felix Meritis neighbourhood.

The heat option (2b) UTES is however not applied in the neighbourhoods Molenwijk and Prinses Irenebuurt. Instead, the heat option (1b) HP Underground is applied in scenario (I_0, E_+) even though it has a higher EF_{average} than the heat option (2b) UTES. This is because the heat option (2b) UTES is subject to the heat density constraint (see Table 2). As a consequence, the sum of the heat demand of all addresses that can be connected to this heat option divided by the total area of the neighbourhood needs to be higher than the posed minimal heat density. If the heat density is too low, then this heat option cannot be applied in the neighbourhood. In that case, two different decisions can be made by the optimisation model: either addresses are less insulated so that the heat density is higher, or the heat option with the second lowest carbon emissions, i.e. (1b) Underground HP or (5b) Green Hydrogen Boiler in pathways E_+ and E_0 respectively, are chosen. This is why heat option (2b) UTES is applied in scenario (I_+. E_0) in the Felix Meritis neighbourhood, but not in the Molenwijk and Prinses Irenebuurt neighbourhoods in Fig. 5.

In order to assess how uncertainties in the heat demand model for the existing building stock would affect the heat density for LT Heating, we performed a first-order sensitivity analysis on the two main insulation parameters: I_{start} and I_{end} (see Fig. 4a). Fig. 7 shows the heat density based on summing over the heat demand of all addresses with a LT heat supply suggested by the optimisation when considering different values for I_{start} and I_{end}. The first row in Fig. 7 shows the heat density for the results, called the ‘Reference’ case. The scenarios plotted are the scenarios in which (2b) UTES could be applied, i.e. scenarios (I_0, E_+) and (I_+, E_0) and (I_+, E_+).

As a first step in the sensitivity analysis, we considered varying I_{start} with +30% or -23% with respect to the I_{start} used for the results in Fig. 5. The results (see Fig. 7, rows (b) and (c)) show that varying I_{start} in the Felix Meritis neighbourhood (see Figs. 7.1b and 7.1c) cause the heat density in 2030 for scenario (I_0, E_+) to fall below the minimal heat density required for district heating (i.e. below the red line). In these cases, heat option (2b) UTES can therefore not be in the mix and heat option (1b) HP underground is chosen as heat option for addresses with a LT heat demand. The results of the sensitivity analysis for the neighbourhoods Molenwijk and Prinses Irenebuurt show that it is only in scenario (I_+, E_+) where the heat density for LT heating was above the minimum required heat density as stated by [16] (see Figs. 7.2a-7.2c and 7.3a-7.3c). For the reference case, this is reflected in the results in Fig. 5, where heat option (2b) UTES was only applied in that scenario. The results of the sensitivity analysis show that the heat density in this scenario remains above the minimum heat density for increasing and decreasing I_{start}.

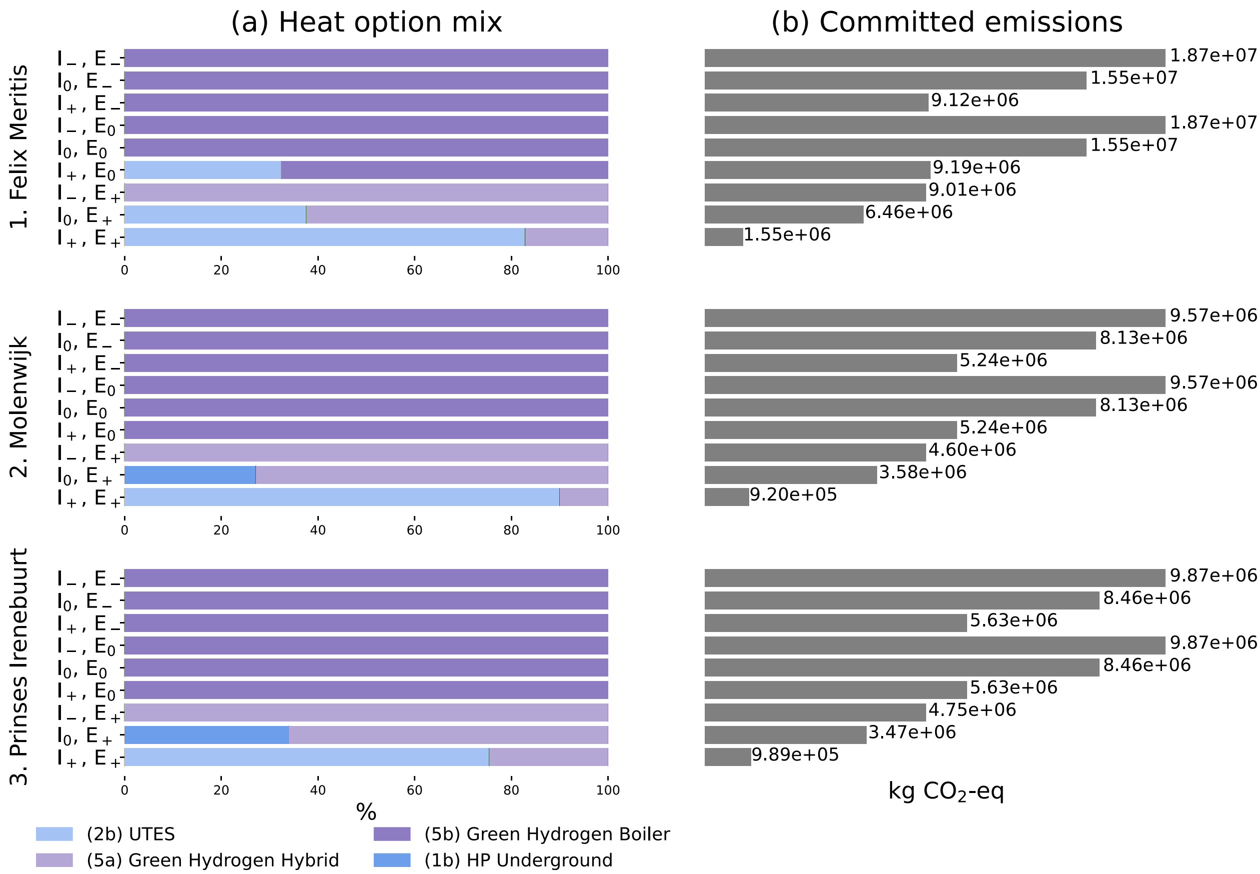

Fig. 5. Mix of heat options in the three case study neighbourhoods. On the left is the heat option mix shown in terms of percentages of addresses connected to a certain heat option. On the right is the total committed emissions between 2030 and 2050.

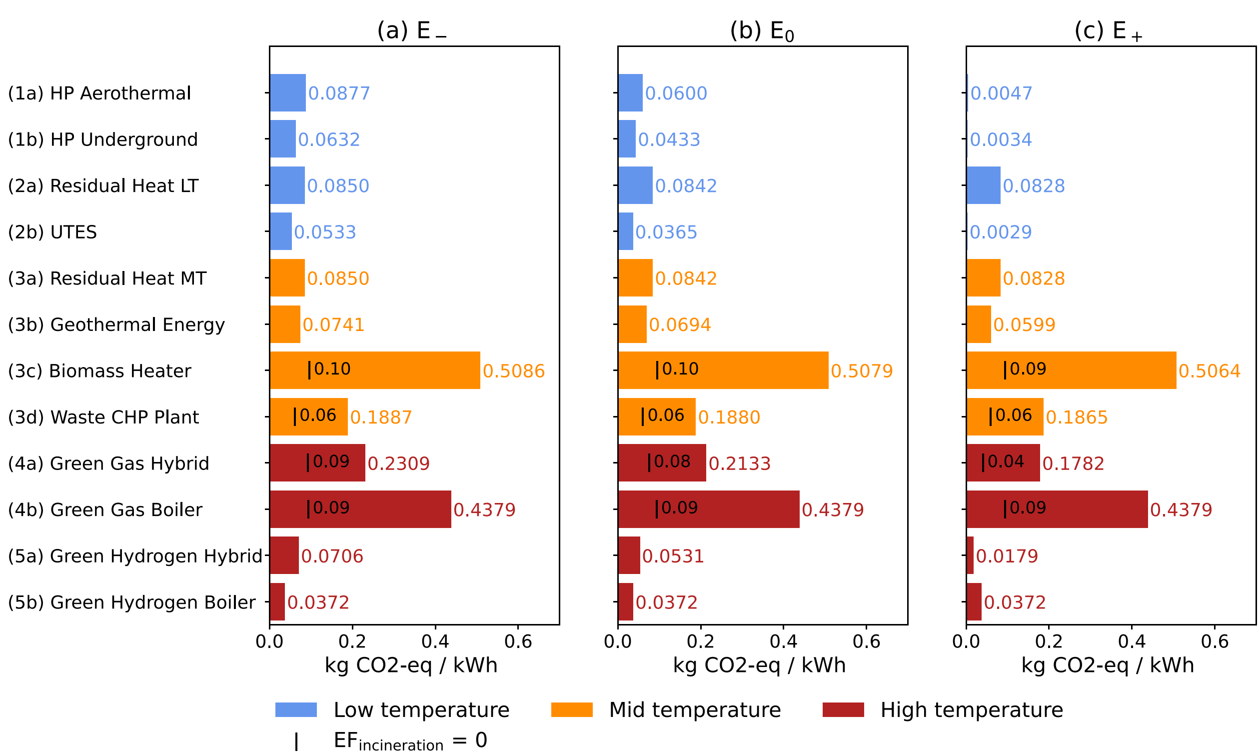

Fig. 6. Average emission factors between 2030 and 2050 expressed in terms of kg CO_2 equivalents per kWh of thermal energy supplied for all heat options. The average is taken for the three decarbonisation pathways. The colours of the bars in the figure indicate the thermal regimes of the heat options. The heat option (3c), (3d), (4a) and (4b) incinerate biomass or biogas. A vertical bar indicates the average emission factors for these four heat options if the carbon emissions associated with the incineration or organic energy carriers is set equal to zero.

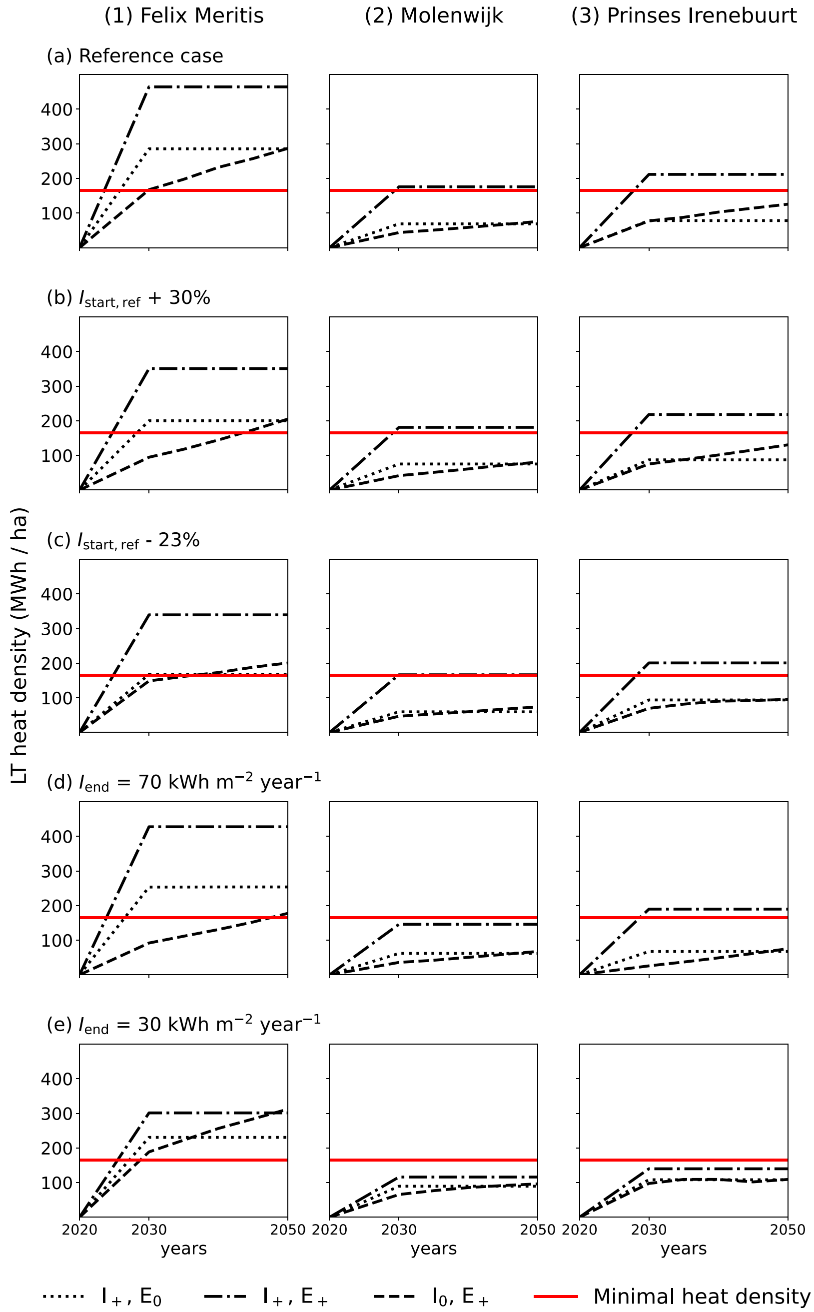

Fig. 7. With insulation, the number of addresses with a heat demand below the maximum heat demand for LT heating increases for the different pathways. This figure shows the LT heat density based on summing over the heat demand of all addresses ready for LT heating for the three neighbourhoods 'Felix Meritis', 'Molenwijk', and the 'Prinses Irenebuurt' for the scenarios (I_+,E_0), (I_+, E_+), and (I_0, E_+). Each row shows the result of a first-order sensitivity analysis: row (b) and (c) I_{start} show the results for varying I_{start} with respect to I_{start} as modelled in the reference case with +30% and −23%. The rows (d) and (e) show the results for choosing the parameter I_{end} to be equal to 70 kWh m^{-2} year^{-1} and 30 kWh m^{-2} year^{-1} respectively.

As a second step in the sensitivity analysis, we varied I_{end}. The results of the reference case were based on target end demand levels of I_{end} = 60 kWh m^{-2} year^{-1}. We also ran the model for I_{end} = 70 kWh m^{-2} year^{-1} and I_{end} = 30 kWh m^{-2} year^{-1}. The first value was chosen because the city of Amsterdam aims to insulate 70% of all addresses to 70 kWh m^{-2} year^{-1} and 30% to 50 kWh m^{-2} year^{-1} [16]. There therefore may be neighbourhoods in which all buildings will be insulated till a heat demand of 70 kWh m^{-2} year^{-1}. The second value was chosen based on our heat demand modelling, where we observed that all addresses could in principle be sufficiently insulated to reduce heat demand to 30.9 kWh m^{-2} year^{-1} (see Table 1). The results of the sensitivity analysis for varying I_{end} are given in Fig. 7, rows (d) and (e). For I_{end} = 70 kWh m^{-2} year^{-1}, the heat density in the Felix Meritis neighbourhood for scenario (I_0, E_+) is lower than the minimum required heat density in 2030. The heat density for a LT heat network can therefore not be high enough for insulation pathway I_0, i.e. when insulation is performed linearly from 2020 till 2050. For I_{end} = 30 kWh m^{-2} year^{-1}, there are no scenarios for which the heat density is high enough for a LT heat network in the Molenwijk and Prinses Irene neighbourhoods. In these neighbourhoods for scenario (I_+, E_+) the optimisation even assigned 100% of the addresses to (1b) HP Underground, meaning that the heat demand of all addresses fell below the maximum heat demand constraint for LT heating. Ambitious insulation targets can thus create 'LT-ready' buildings, leading the heat density in a neighbourhood to decrease below the minimum heat density required for heat networks, possibly creating inefficiencies for in the heat supply by heat networks. If heat networks are therefore applied, an incentive may therefore arise for not applying ambitious insulation, restricting the further reduction of carbon emissions. Additionally, an incentive may be to increase the heat network to a larger area which may however not always be the solution with the lowest carbon emissions and costs. Due to the infrastructural inertia of heat infrastructure, implementing heat networks in neighbourhoods where the heat density can decrease below the minimum heat density required by the heat network can therefore lead to more committed emissions in the future than if other heat options were chosen [10].

4. Discussion

From the results we draw four major insights: (i) the committed emissions between the years 2030 and 2050 can be ten times lower if ambitious measures for both the insulation of buildings and the decarbonisation in electricity generation are taken together, (ii) LT heat options are present in the heat option mix as optimal solutions for minimising committed emissions in these ambitious scenarios, (iii) HT heat options are dominant in the heat option mix as optimal solutions for minimising committed emissions in less ambitious scenarios for the insulation of buildings and the decarbonisation of electricity generation, and (iv) the minimum heat density for low temperature heat networks is not always reached. In short, the results show that the composition of future heat supply with the lowest committed emissions between 2030 and 2050 depends jointly on the rates of insulation of buildings and the decarbonisation of electricity generation. In the following, we discuss how the choice for heat options in the mix depends on the input parameters and modelling objectives.

4.1. Low temperature heat options: carbon emissions and electricity use

The results show that LT heat options can become optimal solutions for minimising the committed emissions between 2030 and 2050 in scenarios with more ambitious measures for the insulation of buildings and the decarbonisation in electricity generation. All LT heat options use electricity and their emission factor therefore depends on the final emission factor for electricity in 2050, E_{end} (see Fig. 4b). In this study we have used the emission factor of the electricity from [36], with E_{start} to be equal to the emission factor of the electricity grid mix in 2018 and E_{end} the emission factor of offshore wind energy, i.e. 14.7 g CO_2-eq kWh^{-1}. According to Dutch policy, electricity is expected to be generated from only renewable energy sources by 2050 [6]. We have taken the value of wind energy as E_{end}, because it likely to become the dominant form of renewable energy in the Netherlands [37]. The renewable energy source with the highest emission factor for electricity generation is however biomass, with an emission factor of 75 g CO_2-eq kWh^{-1} [36]. This number does only account for the supply chain of biomass, and not for the emissions generated during the incineration of biomass. Increasing E_{end} to 75 g CO_2-eq kWh^{-1} only changes the results discussed for pathway E_0, i.e. heat option (2b) UTES does not have the lowest EF_{average}, but heat option (5b) Green Hydrogen Boiler. Electrification of heating may therefore only be an effective way to lower carbon emissions if electricity production is associated with a low emission factor.

In this manuscript, we have used a constant emission factor for electricity per year. The use of heat pumps is however not constant during the year, but fluctuates per season and hour of the day. Additionally, the temporal electricity demand for heat pumps changes when demand response or energy storage is applied. In [39] hourly profiles of heat pumps and generation mix data for the year 2018 of 10 European countries including the Netherlands were analysed, taking into account the weighted emission factor of electricity by analysing the heat demand and the electricity grid on higher-resolution temporal scale [39]. The study concluded that annual weighted emission factors for electricity in the considered European countries is between the -3% and +9.6% different from the unweighted yearly emission factors. We performed a similar analysis to compute the expected weighted emission factor for 2050. We used hourly heat demand profiles of mid-rise apartments from [17], and modelled the weighted emission factor of electricity by weighing it with hourly generation mix data of four major energy mix scenarios presented in [37,40]. The range of difference in the emission factor of electricity for the use of heat pumps was between 3.0% and 10.3%. For these heat demand profiles and scenarios for 2050, the emission factor of heat option (2b) UTES may therefore not be lower than the emission factor of heat option (5b) Green Hydrogen Boiler in the E_0 pathway depending on the mix of renewable electricity sources used (see Fig. 6).

The emission factors for most LT heat options, except heat option (2a) Residual heat LT, depend on the amount of electricity needed to generate and deliver heat, i.e. the COP values (see Table B.6 in Appendix B for the values chosen). A COP of 5.1 was chosen for the heat option (2b) UTES, only accounting for the energy needed to deliver thermal energy and not to charge the storage with thermal energy. This is because heat option (2b) UTES are often used for both heating and cooling. In this paper we only accounted for the energy needed for heating, leaving out the energy needed for cooling. However, during the cooling process thermal energy is stored which can be used for winter. The recharging efficiencies given in [41] vary between the 0.018–0.045 $GJ_{\text{electricity}}$ / $GJ_{\text{thermal energy}}$, which would lead to an increase of 9%–23% of the emission factor of heat option (2b) UTES. By including recharging of the UTES system, heat option (1b) HP underground could thus be the heat option with the lowest emission factor for pathway E_+ and heat option (5b) Green Hydrogen Boiler for pathways E_0 and E_-. LT heating alternatives are thus better suited as low carbon heating alternatives in pathways with ambitious measures for the decarbonisation of electricity production.

4.2. High-temperature heat options: green hydrogen and alternatives

The results in Fig. 5 show that HT heat options are part of the mix in all scenarios, and more dominantly in the scenarios with less ambitious measures for insulation. In most scenarios considered in this study, heating with green hydrogen is the optimal choice for minimising committed emissions between 2030 and 2050 (see Fig. 5). Currently, hydrogen is mostly produced in the Netherlands using natural gas. It is uncertain whether substantial green hydrogen will be available at market-competitive rates in the future; this is because of its dependency on the availability of renewable electricity [1,23,33] and the investments needed for production and storage. The technology for producing green hydrogen, i.e. water electrolysis, can respond rapidly to load variations, but has high operating expenses, making it favourable to apply the technology when renewable electricity is abundant and costs are low [23]. Producing green hydrogen with demand response techniques can therefore support balancing the grid, but however leads to higher levelised hydrogen production cost and extra investments needed in storage [23].

An alternative way to produce hydrogen is by production 'grey hydrogen', i.e. hydrogen produced through steam reforming with the use of natural gas. The EF_{average} for heat option (5a) Hydrogen Hybrid using grey hydrogen is 0.173, 0.209 and 0.226 kg CO_2-eq kWh^{-1} for pathways E_+, E_0 and E_- respectively. Additionally the EF_{average} for heat option (5b) Hydrogen Boiler using grey hydrogen is about 0.427 kg CO_2-eq kWh^{-1} for all pathways. If grey hydrogen is applied in the optimisation instead of green hydrogen, the heat options with the lowest emission factors for LT, MT and HT heating would be (2b) UTES, (3b) Geothermal Energy and (5a) Hydrogen Hybrid relatively for all pathways (see Fig. 6). The emission factor of (5a) Hydrogen

Hybrid using grey hydrogen are however between the 2% and 3% lower than the EF_{average} of heat option (4a) Green Gas Hybrid as shown in Fig. 6 (i.e. 0.178, 0.213 and 0.231 kg CO_2-eq kWh^{-1} respectively). The EF_{average} of heat option (5b) Hydrogen Boilers is also only 3% smaller than the EF_{average} of heat option (4b) Green gas Boiler. Green gas could therefore be used as a renewable energy source for HT heating instead of hydrogen while emitting around the same amount of emissions.

The use of green gas could thus, when available from existing production facilities, be used as a renewable transition fuel from heating with natural gas to heating with green hydrogen, while minimising committed emissions. This is because both heat options using hydrogen or green gas can provide HT heating using parts of existing distribution infrastructure for natural gas [23]. The ranking of heat options with the lowest EF_{average}, if hydrogen based heat options would not be included in the heat mix, would be the same for all three decarbonisation pathways, i.e. (2b) UTES, (3b) Geothermal Energy, and (4a) Green Gas Hybrid for the LT, MT, and HT thermal regimes, respectively. It is however important to note that the only pathway in which the EF_{average} of (4a) Green Gas Hybrid is lower than the emission factor for heating with a natural gas boiler, i.e. 0.213 kg CO_2-eq kWh^{-1}, is E_+. The application of the heat option (4a) Green Gas Hybrid therefore only emits less emissions than heating with natural gas if ambitious measures for the decarbonisation in electricity generation are taken.

Some authors however argue these emissions can be set lower because carbon emissions have already been sequestered from the atmosphere and will be sequestered again as plants grow [42]. Since we assess the operational emissions of heat production in this study, we did account for the direct emissions associated with the incineration of organic materials. The black vertical bar in Fig. 6 shows the EF_{average} for the case in which the emissions associated with the incineration of organic materials are not included in our analysis. The Figure shows that the heat option (3d) Waste CHP Plant becomes the MT heat option with the lowest EF_{average}, instead of (3b) Geothermal Energy. This is also the case in pathway E_+ where the EF_{average} of heat option (3d) Waste CHP Plant is equal to 0.0592 kg CO_2-eq kWh^{-1} and therefore smaller than the EF_{average} of heat option (3b) Geothermal energy. Nevertheless, the EF_{average} of (3d) Waste CHP plant is still higher than the values for the EF_{average} of (5b) Green Hydrogen Boiler in pathways E_- and E_0 and (5a) Green Hydrogen Hybrid in pathway E_+ leaving heating with green hydrogen the preferred heat system for addresses well enough insulated for MT heating in the optimisation and therefore not changing the results as presented in Fig. 5.

4.3. Technological constraints: future research on heat demand modelling and constraints

In this study, we have posed constraints on heat systems on both the building and neighbourhood scale, representing multi-scale considerations for urban heat system design. The constraints were derived from a prominent report on the energy transition by the municipality of Amsterdam, representing relevant knowledge from the field on the case study of this paper [16]. Up to the authors' knowledge, there are no more sophisticated ways in current state-of-the-art literature for assessing the constraints on when a heat technology can 'comfortably' heat up spaces including the height of the peak demand, the heat delivery systems, and the yearly heat demand of those spaces. More research is therefore needed to further validate and generalise these constraints. In the following, we discuss how the constraints influenced the main results of this study.

The constraint of the maximum heat demand on the address level influenced whether LT heating and MT heating could be applied in the mix. The scenarios in which LT heat options are most dominant, are the scenarios with more ambitious insulation pathways, i.e. I_0 and I_+. LT heat options, such as heat pumps, are continuously being improved to provide more heating at higher temperatures. Additionally, changes in indoor heat delivery systems, e.g. replacing radiator heating by floor heating can increase the make buildings more suitable for LT or MT heating systems. To assess the sensitivity of maximum heat demand constraint, the model was run with a maximum heat demand constraint of 65 kWh m^{-2} $year^{-1}$ instead of 50 kWh m^{-2} $year^{-1}$, showing more addresses could be applied to the heat option (2b) UTES in scenario (I_+, E_+) with respect to the results in Fig. 5 if the value of the maximum heat demand constraint was increased (see Appendix C, Fig. C.14). Increasing the maximum heat demand constraint of heat pumps can therefore increase the number of addresses heat pumps can be applied to. The constraint on the minimum heat density influenced whether a heat network can be applied in the neighbourhood. Currently, it is still challenging to model the energy demand of existing neighbourhoods [43,44]. There are for example often differences in existing models (see Appendix A, Fig. A.13, for a comparison between heat demand per building archetype according to the different models of Netherlands Enterprise Agency, PBL Netherlands Environmental Assessment Agency and our results [32,45]). Outcomes depend on assumptions, such as input data, occupancy time, indoor temperature and family size. To give an example of how the heat demand is influenced by model assumptions we discuss the modelled heat demand for apartments. In Table 1, the modelled heat demand for terraced buildings and apartments are higher than the modelled heat demand for (semi-)detached buildings. This may be counterintuitive because these building types often have a smaller useable surface and are adjacent to other buildings, emitting less energy to the outside air. One reason for this result can be that to generate the results of the 'current' heat demand as presented in Table 1, we used as input values [15], a report which is presented to the national government as a source for standardised values for heat demand studies in the Netherlands. The R-values for the current heat demand differ per building type, and are often lower for the building types Terraced and Apartment in this report, leading to higher heat demands (see Figs. A.10, Appendix A). These R-values are based on a database of 4506 households in the WoON 2018 database [15]. Another reason why the values for apartments could be higher is because we modelled apartments in a flat building of three stories, averaging the modelled heat demand of apartments positioned at the ground, mid and top level. The heat demand of apartments positioned at the ground, mid and top level is different because the number of walls adjacent to another apartment or to the outside is different. Increasing the number of floors in the flat building lowers the average heat demand per apartment because there will be more apartments.

To validate the heat demand model itself, more high level data is needed including the insulation measures taken per address. Due to privacy reasons, data needed for calibration, e.g. gas demand data, is often aggregated. This is also true for our case study in which data on gas demand for households (weather corrected data) and businesses is publicly available on postcode level for the year 2019 [46]. Because publicly available gas and electricity demand data is aggregated on postcode level, it is challenging to determine the energy consumption for heating accurately for validation. Although we could assume a fraction of the energy use is for space heating based on national averages for households, this would not be reliable at neighbourhood level. Moreover, differences in modelled heat demand and estimates from measured gas demand are likely to arise because buildings in a neighbourhood can be significantly different from the building archetypes, for example in size or in insulation level, or due to different user profiles per building, including consumption patterns and family size, affecting what fraction of household energy use is for space heating [47]. Additionally, we modelled the heat demand by using the heat demand of the 'current' insulation level for the building archetypes per unit of floor area, simulating a situation where all addresses are insulated to the same state. Accurately estimating the heat demand for a neighbourhood is even more challenging considering that neighbourhoods do not only contain residential buildings but also offices, school, restaurants, etc. [17,20]. Additionally the building energy use can be influenced by inter-building effects [48]. Future research could therefore validate and improve the accuracy of our heat demand model through measurement campaigns of heat demand specifically.

Because of the uncertainty in the heat demand model, the sensitivity analysis was performed, varying I_{start} and I_{end}, presented in Fig. 7. Based on the sensitivity analysis presented in Fig. 7, we argue that the analysis does serve to assess the order of magnitude of the future heat density and therefore to indicate whether or not the future heat density may fall below the minimum required heat density for heat networks, which is needed to check whether there is a change on future carbon lock-ins. The sensitivity analysis also presents that how the difference between the modelled heat density and the posed minimal heat density constraint and therefore the influence of the chosen value for the minimal heat density constraint on the modelling results.

4.4. Other objectives: synergies and trade-offs

In order to legitimise and realise the implementation of low carbon urban heat systems, it is important to analyse the synergies and trade-offs of the decarbonisation strategies for heating with other objectives. One relevant objective is costs. It is important that the implementation of new heat systems leads to affordable energy supply [16]. Costs related to investments and operations can be location specific and also vary over time depending on learning curves and material prices. For a discussion on the expected costs of the implementation of renewable heat systems in the neighbourhoods specifically studied in this paper, we included the results of the expected costs per heat system from a tool developed by PBL Netherlands Environmental Assessment Agency in Appendix D. In general, early installation of low-carbon heat systems can avoid future costs associated with carbon taxes or stranded assets [9,49]. Retrofits of buildings can be economically attractive, sometimes even at net negative costs due to large improvements in performance and costs [50]. Additionally, retrofits can also be beneficial given changes in prices for heating due to future developments in electricity and gas pricing and potentially carbon taxing. However, advanced retrofitting of buildings or the installation of LT heat systems can also be more expensive than implementing MT or HT renewable heat options. To support the implementation of heat systems which are at lowest costs now and in the future, while avoiding a carbon lock-in or stranded assets, we argue for combining projections of the costs of heat systems with assessments of committed emissions as presented in this paper.

Besides costs, it is important that the implementation of low-carbon heat systems does not have an adverse influence on other environmental indicators. Increased use of UTES and hydrogen can, for example, increase the withdrawal of ground and surface water, making collaboration between the energy and water sectors vital [51]. In [21] material versus energy-related impacts of building retrofit were analysed through a process-based Life Cycle Assessment on twenty retrofit scenarios for the Netherlands. They show that improving the retrofitting of existing buildings can contribute to a significant reduction of environmental impacts under the current Dutch energy mix. If more renewable energy will be used, then the energy-related impacts will lower and material impacts will become more important in the assessment of environmental impacts of the retrofitting of buildings. For example, about 10%–12% of the total energy use is currently embodied energy use in standard homes for building materials versus 36%–46% in energy efficient homes, which use less energy [52]. Material-related impacts for retrofitting may therefore become of a bigger importance in future environmental impacts assessments and policy. Additionally, the materials chosen for heat systems, e.g. for the pipes of heat networks, can change whether most environmental impact is made during the operational phase or other phases in the life-cycle of heat networks [53].

At last, policy and design of future urban heating systems can cause trade-offs in the use of energy carriers in other sectors. The heat options presented in the optimal heat option mixes in Section 3 either use electricity for heat pumps or for the production of green hydrogen. Heat pumps with a COP of around 4 can produce more thermal energy from electricity than a green hydrogen boiler with an efficiency of 88% using hydrogen produced via electrolysis with an efficiency between 60%–80% [23,54]. A more efficient and cost-effective use of green hydrogen may therefore be the application of green hydrogen in the decarbonisation of hard-to-electrify sectors, such as long-distance transport and heavy industry [55]. We therefore argue that the reduction of heat demand through the insulation of buildings, increasing the effectiveness of heat pumps and reducing the demand for energy carriers, should therefore be considered in the policy and design of future urban heating systems.

5. Conclusion

To support a transition towards low carbon heating, a computational model is proposed in this study to find a mix of heat options with the lowest committed emissions between 2030 and 2050 under different pathways for the insulation of buildings and the decarbonisation in electricity generation. The computational model consists of a bottom-up heat demand model together with a MINLP optimisation problem for finding an optimal heat supply mix on the neighbourhood scale. From the results we draw four main insights. Firstly, the committed emissions can be ten times lower between 2030 and 2050 if ambitious measures for the insulation of buildings and the decarbonisation in electricity generation are taken together. Secondly, LT heating is only present as solution in the heat option mix in the scenarios with ambitious targets for both insulation and electricity grid decarbonisation. Policies proposing electrification of heating with low temperature heat options should therefore jointly consider measures for building insulation and decarbonisation of electricity supply for minimising committed emissions. Thirdly, the model presents green hydrogen fuelled heat options as optimal solutions for the scenarios with less ambitious targets for the insulation of buildings and the decarbonisation of power supply. In the case that green hydrogen is not included in the analysis, assuming that green hydrogen production and storage will not be available at market-competitive rates, then UTES, geothermal energy and green gas can provide renewable heat sources with relatively low carbon emissions. Finally, LT heat networks may not always be feasible because the minimum heat density is not always reached, creating a risk for not attaining maximal reduction in carbon emissions.

To exploit all four insights, we argue for adaptive planning strategies for future urban heat systems. Given the path dependence and the long life spans of energy infrastructure and building shells, carbon-intensive infrastructure may persist over time, creating a ‘carbon lock-in’, which ‘locks out’ lower-carbon alternatives [9,49]. Adaptive planning that implements heat options in stages can help avoid a carbon lock-in and, consequently, support a transition towards renewable and low-carbon heating systems. An example of an adaptive pathway from HT heating to LT heating is to create hybrid systems with condensing boilers and the installation of heat pumps at the building level. With further insulation of buildings and decarbonisation in electricity generation, the use of fuels can be phased out and replaced with all-electric heating. Another example is designing heat networks in such a way that they can be adapted for LT heating in the future. It is then important to consider the future heat density in a neighbourhood under different insulation pathways to evaluate business cases for heat networks. To improve realistic estimations of current and future heat densities on a high spatial level, heat demand models need to be improved. In our model we assessed the heat demand with a bottom-up heat demand model extrapolating the modelled heat demand of building archetypes of households. This method can be further developed by adding heat demand profiles of other types of users such as shops, restaurants and offices [17]. These heat demand models addressing all types of users can then be calibrated and validated with gas use data at neighbourhood scale [46]. To assess which heat systems can be applied for these users, studies need to be done to indicate the constraints for the maximum heat demand and the minimum heat density of heat systems.

To conclude, the presented four insights on the influence of different pathways for the insulation of buildings and electricity grid decarbonisation on the committed emissions of heat systems are key for supporting policies on sustainable heat systems. They imply that the currently technically feasible heat options with the lowest carbon emissions may not be the solution with the least carbon emissions during the upcoming years. This can lead to less reduction in greenhouse gases or increased costs of heating infrastructure due to stranded assets [9,56]. It is therefore important to take into account pathways for insulation and electricity decarbonisation when designing renewable and low-carbon heat systems to minimise carbon emissions and achieve climate mitigation targets.

CRediT authorship contribution statement

Chelsea Kaandorp: Conceptualisation, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualisation, Project administration. **Tes Miedema:** Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Visualisation. **Jeroen Verhagen:** Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Visualisation. **Nick van de Giesen:** Writing – review & editing, Supervision, Funding acquisition. **Edo Abraham:** Conceptualisation, Methodology, Software, Validation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work. For full disclosure statements refer to https://doi.org/10.1016/j.apenergy.2022.119759.

Data availability

Data will be made available on request.

Acknowledgements

The authors acknowledge the financial support of the Grant from the Netherlands Organisation for Scientific Research (NWO) (Project ID: 438-17- 407), under the Sustainable Urbanisation Global Initiative (SUGI)/Food-Water-Energy Nexus, The Netherlands (Project ID: 11057366).

Appendix A. Bottom-up heat demand model

In this section we present the input and output data of the Bottom-up heat demand model used. The addresses used in the GIS-analysis are presented in Fig. A.8. The input data on the size parameters per building type, the infiltration rates, the insulation specifications, and the thermal resistances are presented in Tables A.3 and A.4, and Figs. A.9, A.10, A.11 respectively. The results of the modelled heat demand per building archetype are presented in Fig. A.12 and compared to results of other models in Fig. A.13.

The input for the infiltration rates and the output for the heat demand per building archetype are presented for different insulation measures. Insulation measures can be performed to different degrees. We therefore define three different insulation levels: the basic, intermediate, and advanced insulation levels. The basic insulation level represents the minimal ordinary improvements that are performed in practice on the original state of buildings after their construction. The intermediate insulation level represents the more elaborate improvements that are still commonly applied in practice. The advanced insulation level represents technologically complex improvements that happen less often in practice, but are technologically feasible.

The results in Fig. A.12 suggest that currently, only building archetypes with a construction year after 1995 can be heated at MT, i.e. the heat demand is lower than 80 kWh m^2 year^{-1} (see Table 2 in the main body of the paper for a description the maximum heat capacities for LT, MT and HT heating). The results also suggest that all building archetypes have a HT heat demand after basic insulation, i.e. the heat demand is higher than 80 kWh m^{-2} year^{-1}. This means that in practice, intermediate or advanced insulation measures need to be taken to bring the heat demand below the HT regime. After intermediate insulation, all buildings built after 1946, except for the detached buildings, have a heat demand below 80 kWh m^{-2} year^{-1} and can therefore be heated with MT heat options. Four out of sixteen building archetypes even have a LT heat demand after intermediate insulation, i.e. the heat demand is lower than 50 kWh m^{-2} year^{-1}. This means that if intermediate insulation is applied to a whole neighbourhood, that MT and even HT heat strategies still need to be applied. The results also show that if advanced insulation is implemented, all building archetype have a heat demand lower than LT level. This means, among other things, that all existing buildings can be retrofitted to a level which is suitable for low-temperature heat systems.

Table A.3
Input data: size parameters per building type. The building envelope areas are extracted from a study by Agentschap NL, presently known as RVO The Netherlands Enterprise Agency [32].

Building type	Number of floors	Floor height [m]	Useable surface [m^2]	Ground floor size[a] [m^2]	Volume[b] [m^3]
Terraced	2	3	87	47	282
Semi-detached	2	3	110	66	396
Detached	2	3	130	93	558
Apartment	1	3	71	71	213

[a] The building footprint is projected to be the ground floor size divided by 0.9.
[b] The volume is calculated by multiplying the number of floors, the floor height and the useable surface.

Table A.4
Infiltration rates ($q_{v;10}$ values) in SI-units of dm^3 s^{-1} m^{-2}. Values are taken from the report 'Standard and Target values for existing housing' (in Dutch: *standaard en streefwaardes bestaande woningbouw*) [15].

Building type	Construction period	Insulation level: Basic	Intermediate	Advanced	Current
Apartment	<1946	1.8	1.8	0.4	1.8
	1946–1975	0.6	0.42	0.4	0.6
	1976–1995	0.6	0.42	0.4	0.6
	>1995	0.6	0.6	0.4	0.6
Detached	<1946	4.2	4.2	0.4	4.2
	1946–1975	1.4	1.4	0.4	1.4
	1976–1995	1.4	1.4	0.4	1.4
	>1995	1.4	1.4	0.4	1.4
Semi-detached	<1946	3.6	3.6	0.4	3.6
	1946–1975	1.2	1.2	0.4	1.2
	1976–1995	1.2	1.2	0.4	1.2
	>1995	1.2	1.2	0.4	1.2
Terraced	<1946	3	3	0.4	3
	1946–1975	1	1.2	0.4	1
	1976–1995	1	1.2	0.4	1
	>1995	1	1	0.4	1

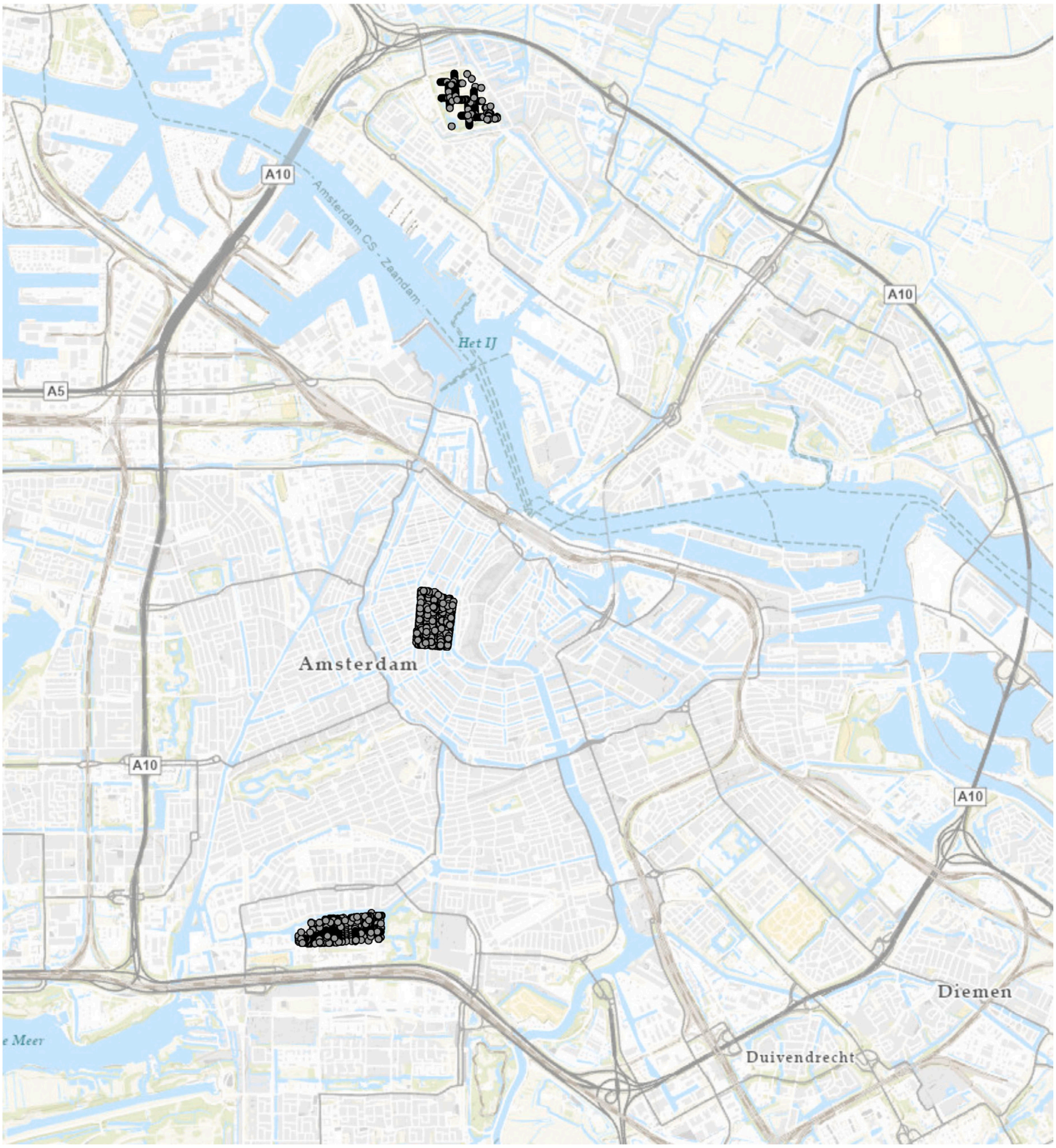

Fig. A.8. Map of Amsterdam with addresses used in ArcGIS Pro. The neighbourhoods analysed are Molenwijk, Felix Meritis and Prinses Irenebuurt (appearing on the map from top to bottom).

		Original state	Basic insulation	Intermediate insulation	Advanced insulation
< 1945	Specificatie	Insulation measures	Insulation measures	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	Non-insulated wooden floor	50 mm insulation under floor	140 mm under floor	140 mm insulation according to ISSO 82.1
Facade	Face without cavitywall	Brickwork no cavity wall	Brickwork no cavity wall	Brickworkd no cavity wall	260 mm insulation according to ISSO 82.1
Panel	Panel with cavity wall	Non-insulated panel	Non-insulated panel	Non-insulated panel	Insulated panel
Roof		Non-insulated roof	50 mm roof insulation	150 mm roof insulation	350 mm roof insulation according to ISSO 82.1
Windows	-	Single glazing, wooden/plastic frame	HR++ glazing, wooden/plastic frame	HR++ glazing, wooden frame	Triple-glazing with new windowframe
Doors	-	Non-insulated door	Non-insulated door	Non-insulated door	Insulated door
Infiltration	-	No gap sealing	Improved gap sealing	Improved gap sealing	Good gap sealing
Koudebruggen	-	-	-	-	-
Ventilation	-	Natural - natural	Natural-mechanical (C2)	Natural-mechanical (C2)	Balanced (D3), with CO2 steering
1945-1975	Specificatie	Insulation measures	Insulation measures	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	Non-insulated wooden floor	50 mm insulation under floor	140 mm under floor	140 mm insulation according to ISSO 82.1
Facade	Face with cavitywall	Brickwork with cavity wall	Brickwork 50 mm cavity wall insulation	Brickwork 50 mm cavity wall insulation	260 mm insulation according to ISSO 82.1
Panel	Panel with cavity wall	Non-insulated panel	Non-insulated panel	Non-insulated panel	Insulated panel
Roof	Roof with cavity	Non-insulated roof	50 mm roof insulation	150 mm roof insulation	350 mm roof insulation according to ISSO 82.1
Windows	-	Single or double glazing, wooden/plastic frame	HR++ glazing, wooden/plastic frame	HR++ glazing, wooden frame	Triple-glazing with new window frame
Doors	-	Non-insulated door	Non-insulated door	Non-insulated door	Insulated door
Infiltration	-	No gap sealing	Improved gap sealing	Improved gap sealing	Good gap sealing
Koudebruggen	-	-	-	-	-
Ventilation	-	natural - natural	Natural-mechanical (C4), CO2 steering in living room	natural-mechanical (C4), with CO2 steering	Balanced (D3), with CO2 steering
1975-1995	Specificatie	Insulation measures	Insulation measures	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	Non-insulated stone-like floor	50 mm insulation under floor	140 mm under floor	140 mm insulation according to ISSO 82.1
Facade	Face with cavitywall	Brickwork with cavity wall	Brickwork 50 mm cavity wall insulation	Brickwork 50 mm cavity wall insulation	260 mm insulation according to ISSO 82.1
Panel	Panel with cavity wall	Non-insulated panel	Non-insulated panel	Non-insulated panel	Insulated panel
Roof	Roof with cavity	Non-insulated roof	50 mm roof insulation	150 mm roof insulation	350 mm roof insulation according to ISSO 82.1
Windows	-	Double glazing	HR++ glazing, wooden/plastic frame	HR++ glazing, wooden frame	Triple-glazing with new window frame
Doors	-	Non-insulated door	Non-insulated door	Non-insulated door	Insulated door
Infiltration	-	No gap sealing	Improved gap sealing	Improved gap sealing	Good gap sealing
Koudebruggen	-	-	-	-	-
Ventilation	-	Natural - mechanical (C1)	Natural-mechanical (C4) with CO2 steering	natural-mechanical (C4), with CO2 steering	Balanced (D3), with CO2 steering
>1995	Specificatie	Insulation measures	Insulation measures	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	Minimal floor insulation	Minimal floor insulation	Minimal floor insulation	Minimal floor insulation
Facade	Face with cavitywall	Brickwork with minimal cavity wall insulation	Brickwork with minimal cavity wall insulation	Brickwork with minimal cavity wall insulation	Brickwork with minimal cavity wall insulation
Panel	Panel with cavity wall	Insulated panel	Insulated panel	Insulated panel	Insulated panel
Roof	-	Minimal roof insulation	Minimal roof insulation	Minimal roof insulation	Minimal roof insulation
Windows	-	HR++ glazing, wooden/plastic frame	HR++ glazing, wooden/plastic frame	HR++ glazing, wooden/plastic frame	Triple-glazing with new window frame
Doors	-	Non-insulated door	Non-insulated door	Non-insulated door	Non-insulated door
Infiltration	-	Minimal gap sealing	Minimal gap sealing	Minimal gap sealing	Good gap sealing
Koudebruggen	-	-	-	-	-
Ventilation	-	Natural - mechanical (C1)	Natural-mechanical (C4) with CO2 steering	Natural-mechanical (C4) with CO2 steering	Balanced (D3), with CO2 steering

Fig. A.9. Insulation specification per construction period (applied to all building types) and insulation levels. Values are taken from the report 'Standard and Target values for existing housing' (in Dutch: *standaard en streefwaardes bestaande woningbouw*) [15].

		Terraced housing	Semi-detached	Detached	Apartment
< 1945					
	Groundfloor	0.77	0.73	0.94	0.56
	Facade	0.7	0.82	0.99	0.58
	Panel	0.46	0.97	0.98	0.36
	Roof	1.24	1.2	1.42	1.00
	Windows	2.96	3.06	2.98	3.11
	Doors	3.36	3.36	3.35	3.32
1945-1975					
	Groundfloor	0.57	0.6	0.66	0.48
	Facade	0.84	1.06	1.1	0.67
	Panel	0.61	0.9	0.86	0.46
	Roof	1.22	1.23	1.40	0.96
	Windows	2.73	2.69	2.66	2.87
	Doors	3.31	3.32	3.31	3.3
1975-1995					
	Groundfloor	1.16	1.25	1.35	1.16
	Facade	1.53	1.61	1.69	1.66
	Panel	1.48	1.61	1.69	1.66
	Roof	1.5	1.59	1.82	1.66
	Windows	2.82	2.72	2.74	2.91
	Doors	3.33	3.33	3.3	3.32
>1995					
	Groundfloor	2.68	2.63	2.64	2
	Facade	2.68	2.59	2.56	2.61
	Panel	2.77	2.56	2.6	2.7
	Roof	2.75	2.69	2.68	2.67
	Windows	2.1	2.16	2.14	2.16
	Doors	3.27	3.25	3.22	3.28

Fig. A.10. The thermal resistances, also known as the *R*-values, of the different materials of the shell for the 'current' insulation level. Values apply for the current insulation level and four different building types, i.e. 'Apartment', 'Detached', 'Semi-detached', and 'Terraced'. Values are taken from the report 'Standard and Target values for existing housing' (in Dutch: *standaard en streefwaardes bestaande woningbouw*) [15].

		Basic insulation level	Intermediate insulation level	Advanced insulation level
< 1945				
	Groundfloor	1.26	3.5	3.5
	Facade	0.19	0.19	6
	Panel	0.23	0.23	2
	Roof	1.33	3.5	8
	Windows	1.8	1.4	1
	Doors	3.4	3.4	1.4
1945-1975				
	Groundfloor	1.26	3.5	3.5
	Facade	1.25	1.5	6
	Panel	0.23	0.23	2
	Roof	1.33	3.5	8
	Windows	1.8	1.4	1
	Doors	3.4	3.4	1.4
1975-1995				
	Groundfloor	1.26	3.5	3.5
	Facade	1.47	1.79	6
	Panel	0.23	0.23	2
	Roof	1.33	3.5	8
	Windows	1.8	1.4	1
	Doors	3.4	3.4	1.4
>1995				
	Groundfloor	1.26	3.5	3.5
	Facade	1.47	1.79	6
	Panel	0.23	0.23	2
	Roof	1.33	3.5	8
	Windows	1.8	1.4	1
	Doors	3.4	3.4	1.4

Fig. A.11. The thermal resistances, also known as the *R*-values, of the different materials of the shell of the houses for three insulation levels. Values apply for three insulation levels and all building types, i.e. 'Apartment', 'Detached', 'Semi-detached', and 'Terraced'. Values are taken from the report 'Standard and Target values for existing housing' (in Dutch: *standaard en streefwaardes bestaande woningbouw*) [15].

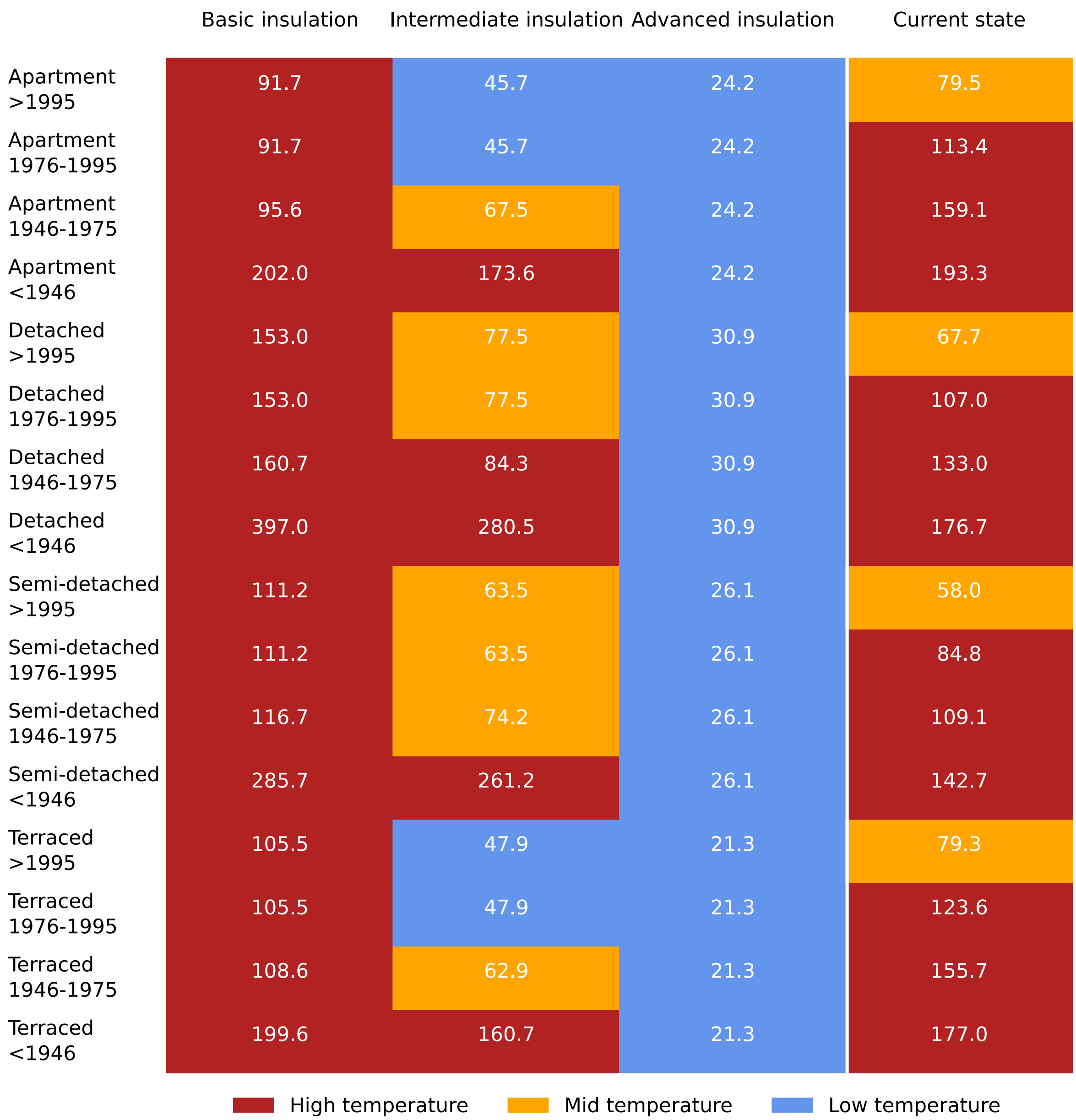

Fig. A.12. Heat demand per building archetype for the four insulation levels in terms of thermal energy demand per square metre of floor area per year (kWh m^{-2} $year^{-1}$). The colours depict the thermal regime in which buildings can be heated. The maximum heat density for low-temperature heating, i.e. below 40 °C, is below 50 kWh m^{-2} $year^{-1}$. Mid-temperature heating at 70 °C can be applied below 80 kWh m^{-2} $year^{-1}$. High-temperature heating, i.e. above 90 °C, can be applied above 80 kWh m^{-2} $year^{-1}$. This heat demand at the current insulation state of a building can be lower than the heat demand for basic or even intermediate insulation because some existing buildings have already been insulated beyond that level.

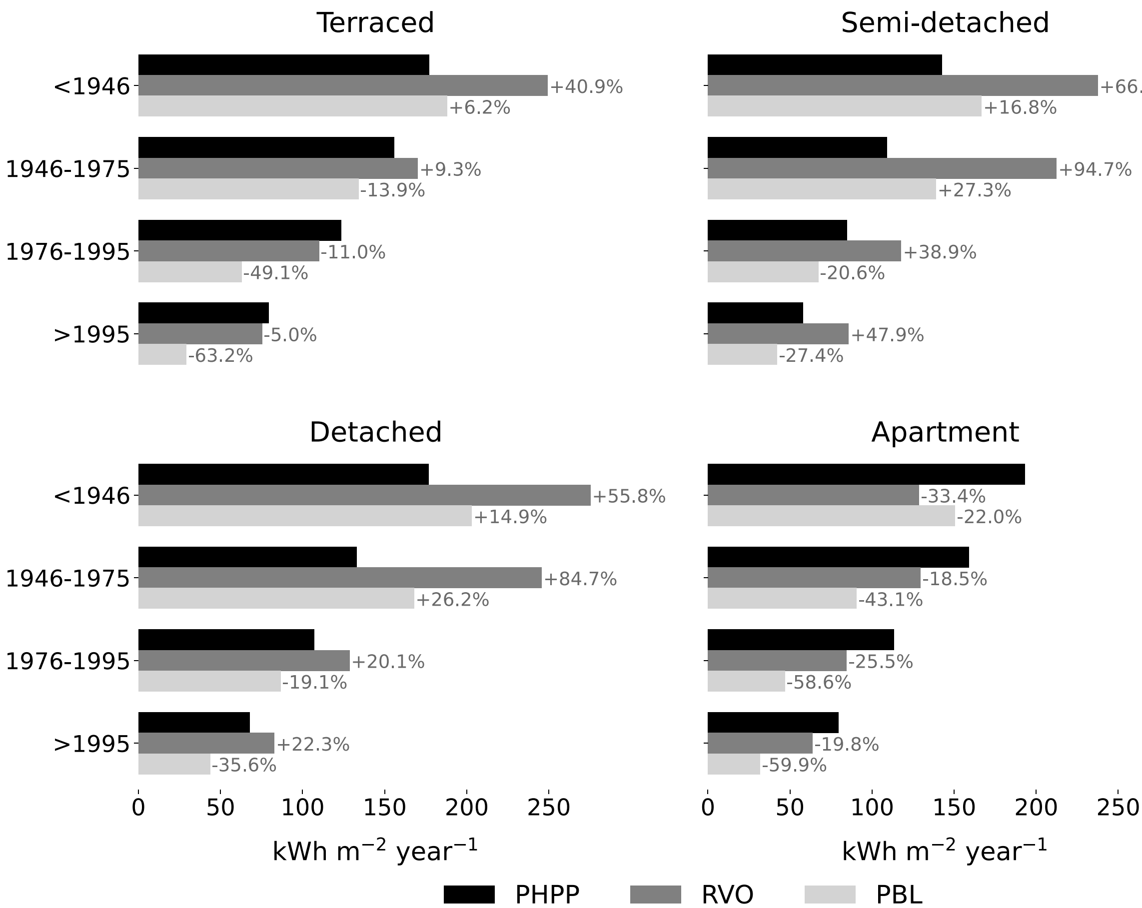

Fig. A.13. Modelled heat demand with PHPP software compared to results from RVO (Netherlands Enterprise Agency) and PBL (Netherlands Environmental Assessment Agency) [32,45]. Heat demand is modelled for four different building types in four different time period. Heat demand is expressed in unit of energy per square metre of floor area per year. The RVO report contains different type of buildings which could be categorised as apartments, i.e. 'maisonette building', 'tenement' and 'other flat' buildings, we used the latter building type in this comparison. There are differences between the time periods defined in this paper and in the RVO report [32]. The time periods used in [32] for terraced buildings are '<1946', '1946-1964', '1965-1974', '1975-1991' and '1992-2005', and for the other building types '<1965', '1965-1974', '1975-1991' and '1992-2005'. The value shown for the construction '<1946' in the figure either corresponds to the time period '<1946' for terraced buildings or '<1965' for the other building types. The value shown for the construction period '1946-1975' corresponds with the average heat demand of time period '1946-1964' and '1965-1974' or '<1965' and '1965-1974' as given in [32]. The values for the construction periods '1975-1995' and '>1995' corresponds with the construction period '1975-1991' and '1992-2005' respectively.

Appendix B. Input tables carbon emission per heat option

See Tables B.5 and B.6 for the emission factors per energy carrier and the Energy-required-for-Energy factors per heat option.

Table B.5
Emissions factors per energy carrier for the fuel supply phase and the operational phase in terms of kg CO_2 equivalents per GJ of thermal energy per energy carrier supplied. A range is given of the values found in the literature applicable to heating technologies in the Netherlands. The value between brackets is the value used for the analysis.

Energy carrier	Fuel Supply [kg CO_2/GJ]	Operational [kg CO_2/GJ]	Reference
Biomass	9.2-17.2 (9.2)	109.6	[57][a]
Electricity 2018	131.94	0	[36]
Electricity Solar PV	2.53	0	[36][d]
Electricity Wind Offshore	4.08	0	[36]
Green gas	12.6 - 32.8(22.8)	84.2 - 100.7 (84.2)	[57], [58][b]
Hydrogen	9.1 - 104.3(9.1)	0	[59][c]
Natural gas	2.9	56.4	[57], [60]
Waste	0	104.4	[57]

[a]Biomass is assumed to be from biomass chips coming from pruning practices in the Netherlands. The value of 17.2 kg CO_2/GJ is the emission factor for wooden chips transported from Canada.

[b]The ranges show the emission factors for different types of green gas produced in the Netherlands, derived from sewage sludge or produced with fermentation of organic waste streams such as domestic and farm waste. The value chosen for fuel supply phase is the weighted average based on the mix of green gas present in the Netherlands in 2020 as given by [58].

[c]In this paper we make the assumption that hydrogen used for heating will be made by electrolysis with green electricity.

[d]Solar panels placed on roofs not fields.

Table B.6
Energy-required-for-Energy (ERE) factors rounded of two decimals places in units of energy needed from energy carrier to generate one unit of thermal energy. Abbreviations: CHP = Combined Heat and Power, HP = Heat Pump, LT = low temperature, MT = Mid Temperature, UTES = Underground Thermal Energy Storage.

Substrategy	Energy carrier	ERE factor	Reference
(1a) HP Aerothermal	Electricity	0.32	[41]
(1b) HP Underground	Electricity	0.23	[41]
(2a) Residual heat LT	Electricity	0.01	[60][a,b]
	Natural gas	0.39	[60][b,c,d]
(2b) UTES	Electricity	0.20	[41][b]
(3a) Residual heat MT	Electricity	0.01	[60][a,b]
	Natural gas	0.39	[60][b,c,d]
(3b) Geothermal Energy	Electricity	0.06	[60][b,d,e]
	Natural gas	0.28	[60][b,c,d]
(3c) Biomass Heater	Biomass	1.05	[60][b,d]
	Electricity	0.01	[60][a,b,d]
	Natural gas	0.28	[60][b,c,d]
(3d) Waste CHP	Electricity	0.01	[60][a,b,d]
	Natural gas	0.28	[60][b,c,d]
	Waste	0.34	[60][b,d,f]
(4a) Green Gas hybrid	Electricity	0.21	[41], [60][g]
	Green gas	0.45	[60][g,h]
(4b) Green Gas Boiler	Green gas	1.14	[60][h]
(5a) Hydrogen Hybrid	Electricity	0.21	[41], [60][g]
	Hydrogen	0.45	[60][g,h]
(5b) Hydrogen Boiler	Hydrogen	1.14	[60][h]

[a]Electricity is needed for the use of heat pumps in the heat network wit a COP of 0.0072.

[b]A distribution loss of 20% for heat networks is included in the ERE factors.

[c]We assume that 0.1 kWh of energy is needed to extract 1 kWh of thermal energy from residual heat sources, and is generated with an efficiency of 85% with natural gas [60].

[d]It is assumed that 20% of the delivered heat comes from a support heater burning natural gas with an efficiency of 85%. The other 80% comes from the main source.

[e]The heat pumps used to extract geothermal energy have a COP of 20.

[f]Per kWh of thermal energy extracted, 0.18 kWh less electricity can be produced in comparison to a power plant with an efficiency of 50%. The amount of extra waste needed is 0.18 kWh_{elec}/kWh_{heat} divided by 0.5 kWh_{elec}/kWh_{waste}.

[g]A heat pump with a COP of 3.1 generates 60% of the heat delivered. The other 40% comes from a boiler which needs 0.0288 kWh of electricity per kWh of heat produced.

[h]An efficiency of 88% was assumed for boilers.

Appendix C. Extended sensitivity analysis

In this section we present the results under different assumptions. In Fig. C.14 if the maximum heat demand constraint of LT heating is put equal to 65 kWh m^{-2} $year^{-1}$ instead of 50 kWh m^{-2} $year^{-1}$.

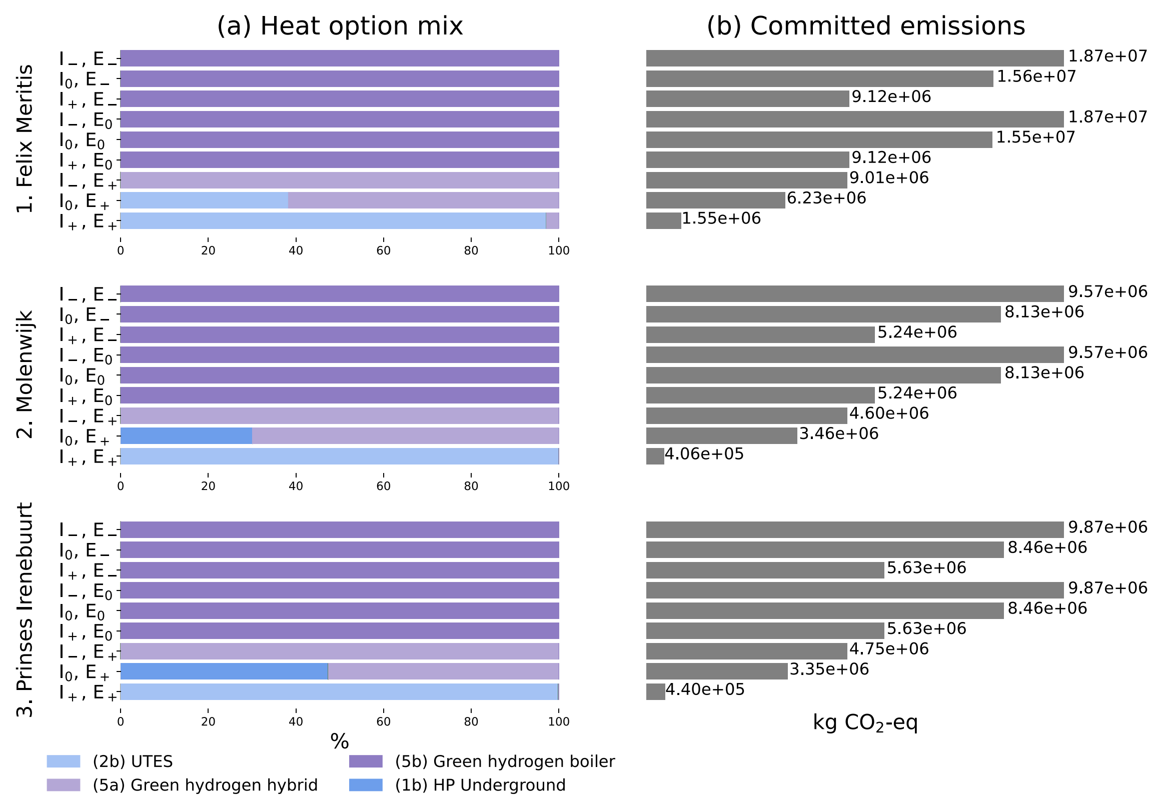

Fig. C.14. Model output for a value of 65 kWh m^{-2} $year^{-1}$ for the maximum heat demand constraint for LT heating instead of the value of 50 kWh m^{-2} $year^{-1}$ which is used in Fig. 5 of the main article.

Appendix D. Perspective on cost for the neighbourhood Felix Meritis, Molenwijk and the Prinses Irenebuurt

An example of an energy model that includes economic factors in the Dutch context, is the VESTA model which is used in a tool developed by PBL Netherlands Environmental Assessment Agency. The tool supports Dutch municipalities to compare the 'national costs' in the provision of heat, i.e. sum of costs for investment in supply infrastructure (generation and distribution), retro-fitting of buildings, fuel supply and operations of different heat options with a reference case for the year 2030 [61,62]. National taxes, subsidies and levies are not included in these 'national costs', because these flows of money do not influence the total costs of all people in the nation.

The tool was developed to support Dutch municipalities to perform a spatially explicit comparison of the costs of different heating systems. In Fig. D.15 is shown that heat system 'LT Heat Network' is often not among the cheapest solution because, according to [61], it was the cheapest to insulate all houses till at least energy label D for all heat options except for heating system 'Individual heat pump', which requires insulation to energy label B. For heat options in heating systems 'LT Heat Network' they include the costs for extra heat pumps to increase delivered heat by the heat network to 70°C. In this way, the costs for LT heating systems 'Individual heat pump' and 'LT Heat Network' can be higher than for other heating systems. However, the results in this manuscript suggest that insulation of houses is an effective way of reducing carbon emissions and moreover is often a no-regret measure for decreasing carbon emissions of heating [21]. Heating systems without insulation further than energy label D may therefore be cheaper now, but will have additional costs if further insulation measures will be taken in the future.

In this reference case, the variable costs are different to current costs for heating due to assumed climate change driven changes in outdoor temperatures and costs of natural gas. Moreover, no capital costs are assumed because potential changes to building shells, or heating infrastructures are disregarded. The costs per neighbourhood can vary due to factors such as number of buildings, building types and proximity to heat sources. The costs for heating in the reference case for the year of 2030 are 4.2, 1.4 and 2.0 million euros for the neighbourhoods Felix Meritis, Molenwijk and the Prinses Irenebuurt respectively [61].

To assess how much each low-carbon heat option would cost in 2030, the costs were calculated for different insulation levels using the tool in [61], which considers similar heat options to the ones presented in this paper, making it straightforward to use the definitions of heat options as given in this paper. The costs for the heat options are presented in Fig. D.15 and labelled with the name of the heat system of that heat option. In the following we will give the names of the heat options used.

The costs for different heat options vary per neighbourhood due to multiple factors such as the insulation measures needed, the amount of energy demand, and the extra costs for improvement or implementation of a electricity, gas or heat grids. According the PBL analysis, heat option '(4b) Green Gas Boiler' is the cheapest heat option in the Felix Meritis neighbourhood with yearly additional costs of 1.6 million euros compared to a 'business-as-usual' case in which a natural gas heating system is maintained until 2030 [61]. Heat options '(5b) Hydrogen Boiler', '(2a) Residual Heat LT', '(1a) HP Aerothermal', and '(3a) Residual Heat MT' are more expensive with a yearly additional cost of 2.1, 2.6, 2.7 and 2.7 million euros respectively. The cheapest heat option in Molenwijk neighbourhood is '(3a) Residual Heat MT' with 0.62 million euros. Heat options '(4b) Green Gas Boiler', '(5b) Hydrogen Boiler', '(2b) UTES', and '(1a) HP Aerothermal' are more expensive with a yearly additional cost of 0.82, 1.2, 1.4 and 1.5 million euros respectively. The results from this manuscript, however, suggest that heat option '(3b) Residual heat MT' is not the solution with the lowest EF_{average}. Additionally, we have seen in Fig. 5.2a that heat option (2b) UTES can be applied to more than 30% of the addresses in this neighbourhood if ambitious rates of insulation and decarbonisation in electricity generation are applied. In the case for the Molenwijk neighbourhood, we thus see that the cheapest solution is not necessarily the solution with the least committed emissions. For the neighbourhoods Prinses Irenebuurt '(4b) Green Gas Boiler' is the cheapest option with 0.8 million euros additional costs according to [61]. Other options are '(5a) Hydrogen Hybrid', '(3b) Geothermal Energy', '(1a) HP Aerothermal' and '(2b) UTES' with 1.1, 1.28, 1.31, 1.31 million euros additional costs. For this neighbourhood, the prices of some heat options are thus close to each other.

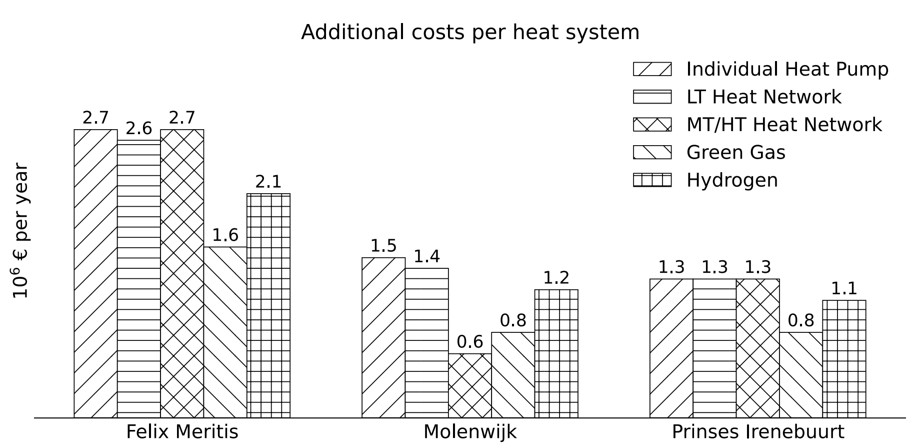

Fig. D.15. Additional yearly costs per heat system in 2030 in comparison to keeping the status quo in the three neighbourhoods Felix Meritis, Molenwijk and the Prinses Irenebuurt. *Source:* The values are taken from [61].

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