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HIGHLIGHTS

- Agent-based modelling of multi-criteria individual and group decisions in heat transitions.
- Combinations of fiscal policies, heat networks' regulation, and subsidies could influence transitions.
- Steering heat transitions mainly with financial policies could prove ineffective.
- Different preferences of households can influence energy transitions.

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ABSTRACT

Natural gas for heating is widespread in the built environment of The Netherlands, where the government aims at limiting heat demand and reducing natural gas consumption over the coming decades. In the owner-occupied residential sector, this transition is complex and requires cooperation and coordination of individuals and groups that make investment decisions. We use agent-based modelling to explore the effect that various financial policies could have in an illustrative neighbourhood, given that households make multi-criteria and group decisions. In the scientific literature, this type of energy model seldom focuses on the adoption of competing technologies by households as individual and collective agents grouped in homeowner associations in multi-family buildings. To address the problem and knowledge gaps, we model individual preferences with a multi-criteria perceived lifetime utility submodel, and decisions as outcomes of individual preferences and a threshold voting system. We explore energy taxes (natural gas and electricity), regulated price of heat from networks, and subsidies (insulation and heat pumps). Under our assumptions, we found that combinations of fiscal policies, regulated heat prices, and subsidies can sometimes create incentives for households to disconnect from natural gas, but that steering the transition mainly with financial policies could prove ineffective. We also found that, in terms of collective CO_2 reduction, some transitions in which only some households phase out natural gas could have results similar to some scenarios in which households only improve their dwellings' insulation levels.

1. Introduction

In The Netherlands, where natural gas for heating is widespread in the built environment [1], a complex energy transition is taking place. The national government has set goals to limit heat demand and reduce natural gas consumption over the coming decades [2]. Municipalities and regions are proposing ways to phase out natural gas in documents known as "Heat transition visions" [3] and "Regional Energy Strategies" [2], and the public sector has implemented and continues to explore policies to enable this transition. These policies include, for example, subsidies for insulation [4] or heat pumps [5], changes in the taxes of electricity and gas [2], and changes in the implementation and management of heat networks [6–8].

Phasing out natural gas in the residential built environment is a multi-actor challenge. Homeowners are responsible for energy renovations in their individual dwellings [9]. However, as explained in our

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Table 1
KPIs used in the agent-based model.

KPI	Abbreviation	Units	Description
Natural gas consumption	NG	MWh	Annual natural gas consumption; computed before households make technology changes.
CO_2 emissions	CO_2	Ton	Cumulative CO_2 emissions from the operation of heating systems; computed before households make technology changes.
Households with natural gas	HwNG	Number of households	Number of households connected to the natural gas network; computed after households make technology changes.
Household costs	HC	Million Euros	Cumulative investment costs (IC) (which include reinvestment) and operation costs (OC) by all households; computed after households make technology changes.
Subsidy costs	SC	Thousands of Euros	Cumulative costs of subsidies for insulation and heat pumps; computed after households make technology changes.

Table 2
State variables of households agents in the agent-based model.

Subject	State variable	Type	Description
Dwelling (technology)	Type of dwelling	Static	Apartment, semi-detached, or terraced house.
	TS	Variable	TS from the TS available (see Table 3).
	Previous TS	Variable	TS that the household had before its current TS.
Resident (actor)	Profile	Variable	4-tuple of numbers representing the relative quantitative importance of each decision-making criteria for a household.

within HOAs are relevant for energy transitions [12]. Moreover, because the feasibility and affordability of projects such as heat networks depend, among others, on density of demand or numbers of users [13,14], group decisions between HOAs and individual homeowners are also relevant. HOAs are also present in other countries, where they are also relevant to energy transitions [15].

Agent-based models (ABMs) are often used for exploring energy transitions [16]; however, few works have explored the heat transition [17], and few works have focused on competing technologies [18]. These limitations are not exclusive to case studies of The Netherlands; they extend to international literature on ABMs. Some exceptions in which authors studied heat transitions include [19–24]; the technologies studied in these works include micro-cogeneration, natural gas boilers, heat pumps, electric and wood-pellet heating, insulation measures, district heating, geothermal heat, and electric boilers.

Moreover, in their agent-based models and simulations, [25] and [26] incorporate the notion of a necessary minimum density of demand or number of households for heat projects to be feasible. However, organisations that instigate projects, instead of active individual household agents, are included in the work by [25], and in the work by [26], HOAs are not mentioned. Further, [27] propose a framework to assess scenarios to extend a heat network; they account for household behaviour to predict heat demand, and for a building's likelihood to connect to a heat network. Although they consider multi-family buildings and private or public ownership, HOAs are not discussed. In [10] we explore the effect of group decisions on heat transitions. To the best of our knowledge at the time of writing, this study was the only ABM work of energy transitions that explicitly represented and focused on group decisions within and between HOAs.

Scientific literature concerning agent-based studies of adoption of alternatives to natural gas in The Netherlands is also limited. A search in the engine Scopus [28] retrieved only 11 publications[1]; in addition to these publications, our work in [29] also addresses this topic. From these publications, only [20,26], and our works in [10,29] study the adoption of alternatives to natural gas, and two additional publications [19,30] study adjacent topics.

In this paper, we continue our line of research from [10,29,31]. In the ABM in [10], households are decision-makers with bounded financial rationality and they determine their preferences via net present value (NPV) calculations using implicit discount rates (IDRs). IDRs are a

Table 3
Conceptualization of the TSs available in the illustrative neighbourhood.

TS	Type	Heating system	Insulation	Appliances
1:GB3	Individual [a]	Natural gas boiler	3:Low	Natural gas
2:GB2	Individual [a]	Natural gas boiler	2:Medium	Natural gas
3:GB1	Individual [a]	Natural gas boiler	1:High	Natural gas
4: BN1[b]	Collective: Neighbourhood [c]	Green gas network and an individual hybrid heat pump	1: High	Electric
5:medHN2	Collective: Neighbourhood [c]	Medium temperature heat network	2:Medium	Electric
6:HP1	Collective: HOAs [d]	Heat pump	1:High	Electric
7:lowHN1	Collective: Neighbourhood [c]	Low temperature heat network and an individual heat pump	1:High	Electric
8: HH1[b]	Collective: Neighbourhood [c]	Hydrogen network and an individual hybrid heat pump	1: High	Electric
9:medHN1	Collective: Neighbourhood [c]	Medium temperature heat network	1:High	Electric

[a] In the ABM, changes in insulation are treated as individual decisions for apartments too; in practice, renovation projects may require approval from an HOA. See the website of the municipality of The Hague [66] as an example.
[b] In the ABM, TS4:BN1 and TS8:HH1 are available to households only after 2030.
[c] We assume that all collective projects at the level of the neighbourhood require changes in buildings that need approval from the building's HOA.
[d] In the ABM, TS1:HP6 are treated as collective TSs for HOAs also for self-standing houses, which are modelled as part of an HOA with a one member, i.e. themselves.

previous work [10], coordination and cooperation are specially relevant in owner-occupied multi-family or strata buildings, which have more than one dwelling and potentially more than one owner. In strata buildings, households are organized in homeowner associations (HOA). HOAs are governed by rules and regulations [11] and group decisions

[1] We searched for entries with the following keywords in the publication's title, abstract, or keywords: (heat OR heating OR thermal) AND (netherlands or dutch) AND (energy) AND (agent-based).

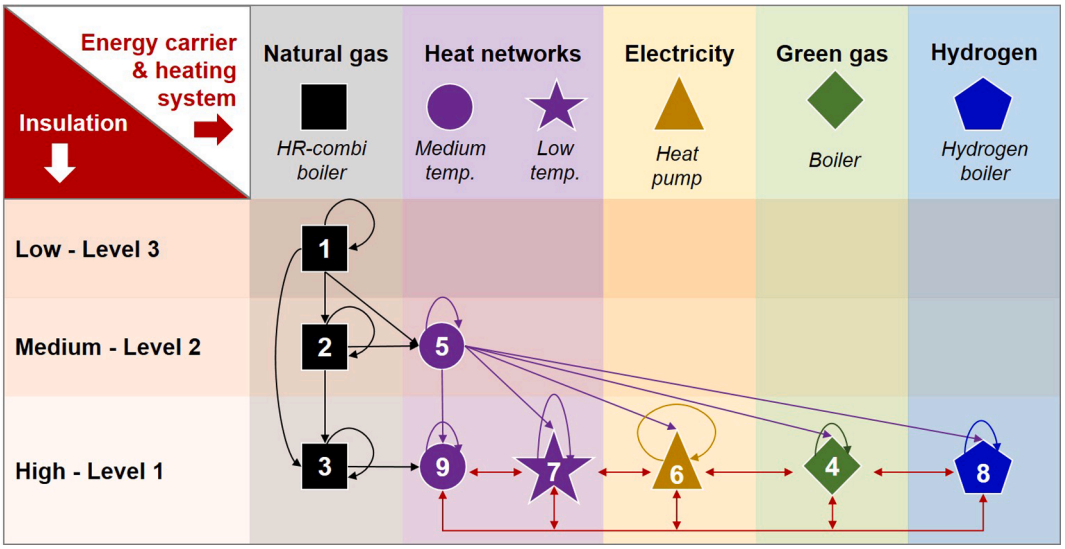

Fig. 1. TSs that are available to households based on their current TS.

Table 4
Initialization of dwellings in the neighbourhood.

Area	Type of dwelling	Number	TS
Old	Semi-detached	50	TS1:GB3
	Terraced	150	TS1:GB3
New	Semi-detached	22	TS3:GB1
	Terraced	50	TS3:GB1
	Apartments	228	TS3:GB1

quantitative way of representing financial and non-financial factors that influence preferences [32]. Because non-financial factors are implicit in the discount rate in [10], the possibilities to explore the performance of various financial policies on multi-criteria decisions were limited.

The objective of this article is to address the following knowledge gap. Based on the aforementioned literature, an agent-based study that focuses on heat transitions, incorporates multiple competing alternatives to the incumbent heating system, explicitly represents individual and group decisions within and between HOAs, and explores the performance of financial policies while representing multi-criteria decisions by households, is still missing from the international scientific literature.

Thus, our present work is novel due to the combination of the following aspects, which are relevant to The Netherlands and also to energy transitions in other countries:

Focus on the emerging challenge of a heat transition in which natural gas is to be phased out from the residential built environment and various combinations of insulation and heating systems compete to replace incumbent natural gas boilers.
Representation of an illustrative neighbourhood with both single-family and multi-family buildings, in which each agent represents one household in one dwelling, households in multi-family buildings are grouped in HOAs, and there are explicit group constraints and decisions both within and between HOAs.
Exploration of the performance of financial policies for the phase-out of natural gas while explicitly representing multi-criteria decisions by households.

By integrating these aspects in an ABM, we explored a heat transition in an illustrative neighbourhood. We found that under our assumptions, combinations of fiscal policies, regulated heat prices, and subsidies can sometimes create opportunities to incentivize households to disconnect from natural gas. Furthermore, we found that steering the transition mainly with financial policies could prove ineffective, and that, in terms of collective CO_2 reduction, some transitions in which only some households phase out natural gas could have results similar to some scenarios in which households only improve their dwellings' insulation levels. This approach can be applied to international case studies in which energy transitions are taking place.

The remaining parts of this paper are structured as follows. In Section 2, we specify our materials and methods. Then, we describe our ABM and simulation work in Section 3. In Section 4, we present and discuss our results, and in Section 5, our conclusions.

Table 5
Household preference profiles.

Profile	Criteria (%)				Profile	Criteria (%)			
	Finances	Environment	Space	Duration		Finances	Environment	Space	Duration
A	25	50	0	25	M	50	0	0	50
B	25	50	25	0	N	50	25	25	0
C	25	25	25	25	O	50	25	0	25
D	25	25	50	0	P	50	0	25	25
E	25	25	0	50	Q	75	25	0	0
F	25	75	0	0	R	75	0	25	0
G	25	0	50	25	S	75	0	0	25
H	25	0	25	50	T	100	0	0	0
I	25	0	75	0	U	0	100	0	0
J	25	0	0	75	V	0	0	100	0
K	50	50	0	0	W	0	0	0	100
L	50	0	50	0					

Table 6
Preferred TSs at the beginning of the simulation for single-criteria household preference profiles (HPPs).

Criteria	Dwellings				
	Old		New		
	Semi-detached	Terraced	Semi-detached	Terraced	Apartments
Finances HPP=100-0-0-0	RE = XXXIX, TS2:GB2. RE = XXX0X, TS1:GB3.	TS1:GB3	TS3:GB1	TS3:GB1	TS3:GB1
Environment HPP=0-100-0-0	TS9: medHN1	TS9: medHN1	TS9: medHN1	TS9: medHN1	TS9: medHN1
Space HPP=0-0-100-0	TS5: medHN2	TS5: medHN2	TS9: medHN1	TS9: medHN1	TS9: medHN1
Duration HPP=0-0-0-100	TS1:GB3	TS1:GB3	TS3:GB1	TS3:GB1	TS3:GB1

2. Materials and methods

In line with our previous work [10,29,31], we use an approach that integrates the perspectives of STS [34–36] and CAS [37–39]. We describe the problem with the concepts of actors, technology, and institutions. Actors include individuals or organizations [40], and their rationality can be bounded [41,42]. Interactions between and within actors and technology, which form networks [36], are complex and involve institutions, i.e. rules and regulations [43]. Based on these concepts, we formalize the problem in an ABM. Agent-based modelling builds on CAS and STS, and in this method, actors can be seen as individual components that shape the system as a whole [44].

As explained in our previous works [10,29], ABMs have agents, environment, and time [44]. The environment contains the agents [44]. Agents have parameters, known as "state variables", which describe them at each point in time [45,46], and agents and environment influence each other over time. The behaviour of the system, including interactions between agents, is based on knowledge or assumptions regarding individual agents [47–50].

Our ABM represents the adoption of combinations of heating systems and insulation by households in an illustrative neighbourhood under different socio-technical conditions. These conditions are household preferences –defined as household preference profiles (HPP)– and combinations of policies –defined as regulatory environments (RE)–, described in Section 3. Our selection of financial policies is based on previous or existing financial energy measures; namely, taxation for electricity and gas, price regulation for heat from networks, and subsidies for insulation and heating systems.

We observe the effects of HPPs and REs on five key performance indicators (KPIs): number of households using natural gas (HwNG), natural gas consumption (NG), CO_2 emissions from heating systems' operation (CO_2 emissions), household costs (HC) as cumulative investment (IC) and operation costs (OC) by households, and subsidy costs (SC) as cumulative costs of subsidies for insulation and heat pumps.

We use our ABM to simulate developments in the neighbourhood under experimental scenarios, i.e. combinations of an HPP and a RE that define the input conditions for the simulation. For simplicity, we only explore instances of the neighbourhood in which all households have the same profile. To compare initial preferences with simulation outcomes, we study the preferences of households at the beginning of the simulation and the actual combinations of heating systems and insulation after 30 simulated years.

Table 7
Sufficient HPPs for households to prefer a disconnection from natural gas at the beginning of the simulation.

Preferences	HPPs sufficient?	Profile	Criteria (%)				Preferred TS of dwellings		
			Finances	Environment	Space	Duration	Old semi-detached	Old terraced	New area
Medium temperature heat network	Yes	A	25	50	0	25	TS5:mHN2	TS5:mHN2	TS9:mHN1
		C	25	25	25	25	TS5:mHN2	TS5:mHN2	TS9:mHN1
		B	25	50	25	0	TS5:mHN2	TS9:mHN1	TS9:mHN1
		D	25	25	50	0	TS5:mHN2	TS9:mHN1	TS9:mHN1
		F	25	75	0	0	TS5:mHN2	TS9:mHN1	TS9:mHN1
		K	50	50	0	0	TS5:mHN2	TS9:mHN1	TS9:mHN1

Table 8
Household profiles that were sufficient or necessary conditions for full transitions after 30 years in the set of nominal results, according to our ABM.

Transition?	HPPs as condition	Profile	Criteria (%)				Additional REs required
			Finances	Environment	Space	Duration	
Partial	Necessary	T	100	0	0	0	GEXXX or G0XXP
		Q	75	25	0	0	GXXXX
		O	50	25	0	25	GXHIX or GE0IP
Full	Sufficient	A	25	50	0	25	None
		B	25	50	25	0	
		C	25	25	25	25	
		D	25	25	50	0	
		F	25	75	0	0	
		K	50	50	0	0	
	Necessary	E	25	25	0	50	GXHXX
Insulation	Sufficient	N	50	25	25	0	None
	Necessary	T	100	0	0	0	0XXIX or G0XX0
		I	25	0	75	0	GXXXX or 0XXIX
		L	50	0	50	0	GXXXX or 0XXIX
		P	50	0	25	25	G0HIX or GEHI0
		O	50	25	0	25	G00IX or GE0I0
		S	75	0	0	25	GXXIX
		R	75	0	25	0	0XXIX or GXXXX
		Q	75	25	0	0	0XXXX

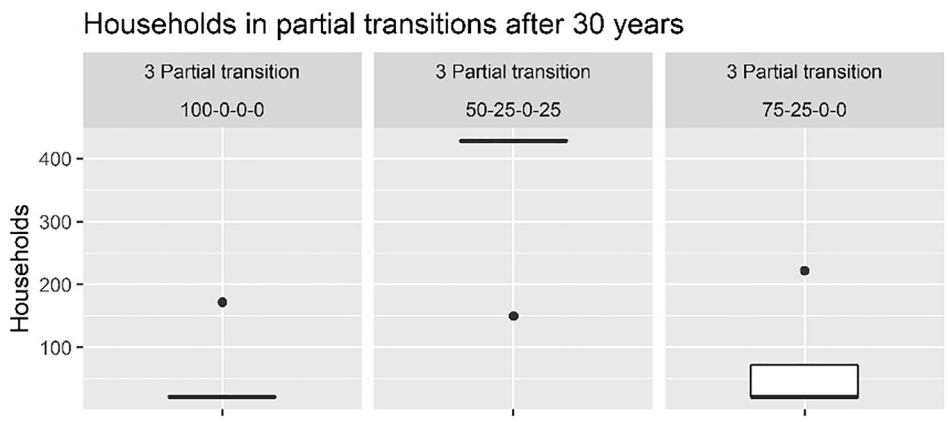

Fig. 2. Boxplot of the number households that disconnected from natural gas by the end of the simulation, when the simulation run was classified as a partial transition.

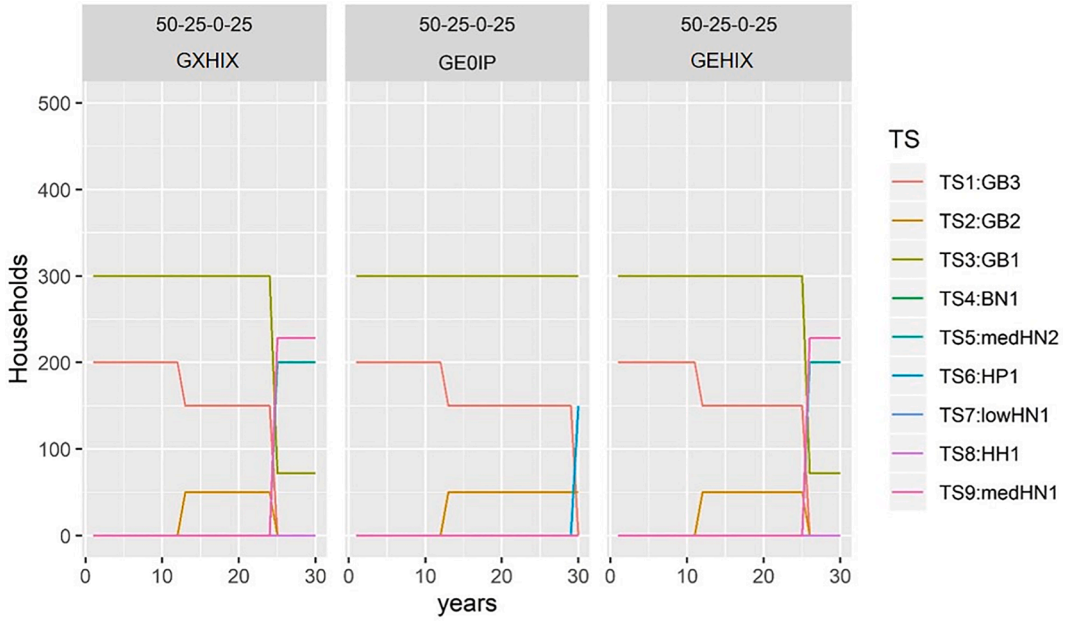

Fig. 3. TSs of households in partial transitions when HPP = 50-25-0-25 per RE.

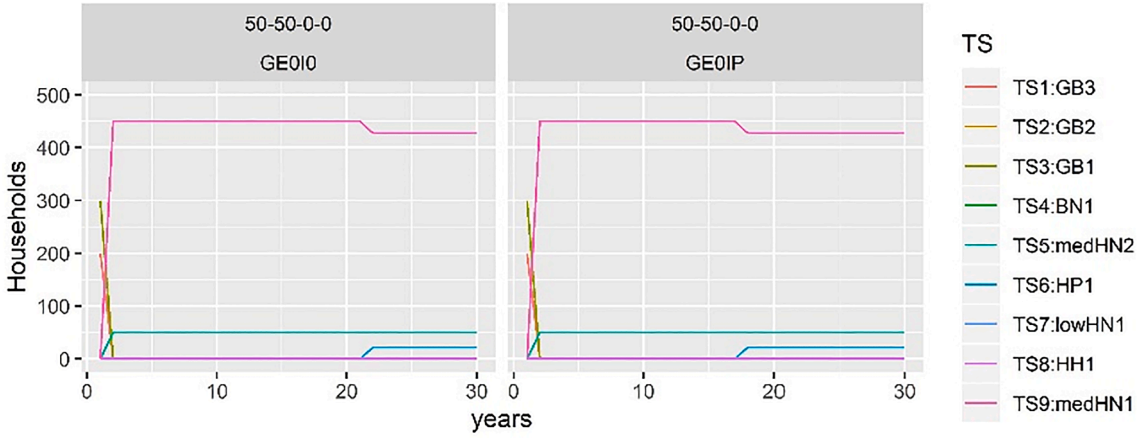

Fig. 4. TSs of households in full transitions when HPP = 50-50-0-0 per RE.

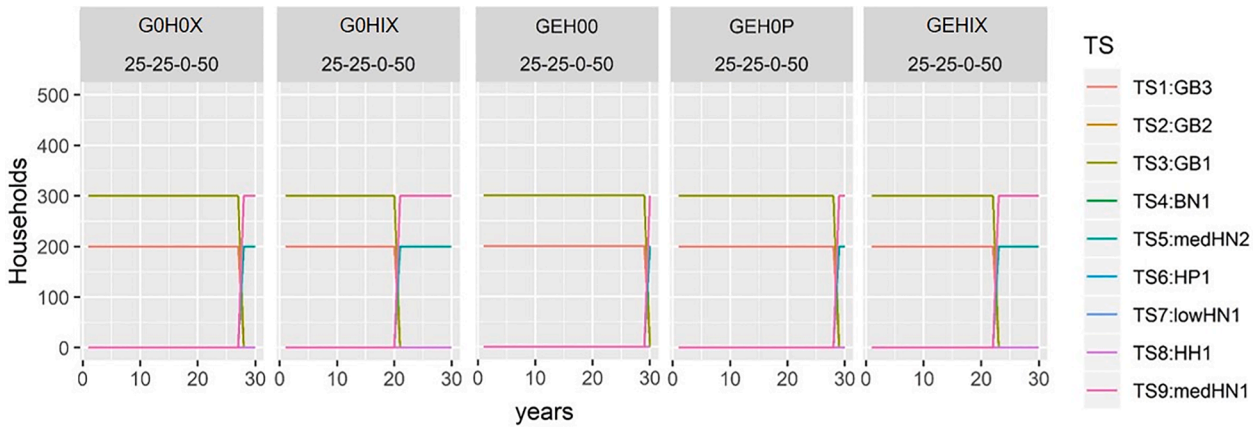

Fig. 5. TSs of households in full transitions when HPP = 25-25-0-50 per RE.

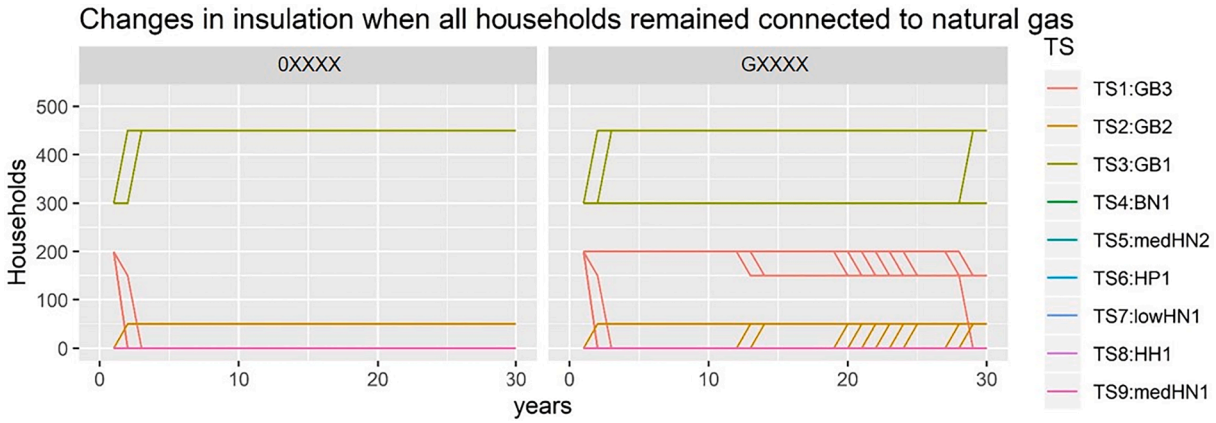

Fig. 6. TSs of households when only changes in insulation took place, by increase in natural gas tax.

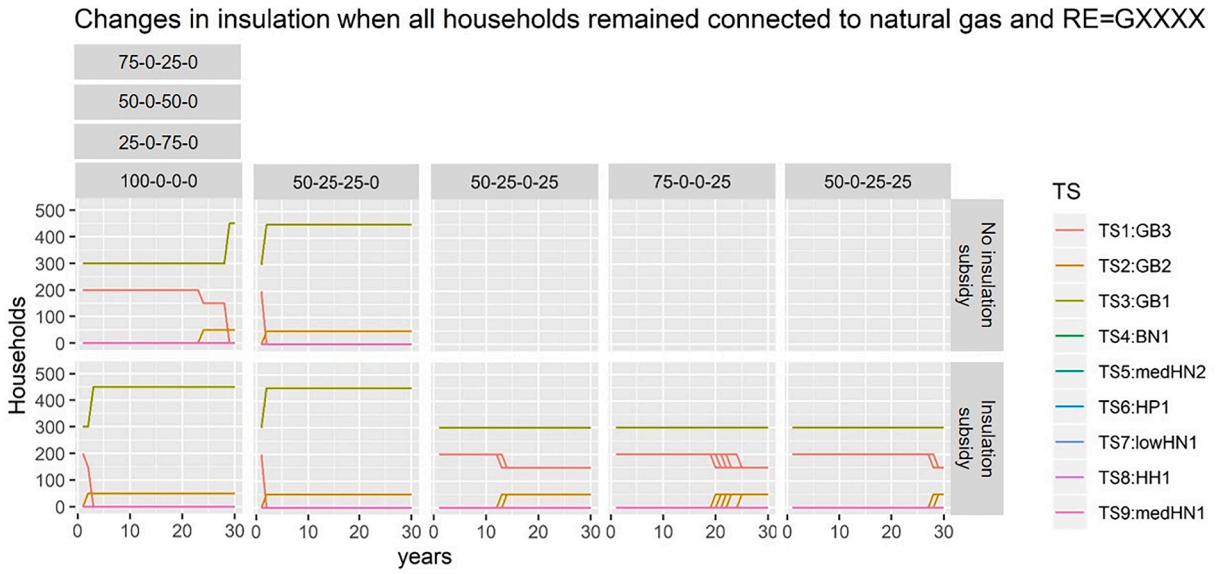

Fig. 7. TSs of households when only changes in insulation took place and RE = GXXXX.

We use the following modelling questions to guide our work:

(1) *What were households' preferences at the beginning of the simulation?*
(2) *Under which socio-technical conditions,* i.e. *household preference profiles and regulatory environments, were heat transitions possible?*
(3) *How did heat transitions influence CO_2 emissions and costs?*

We analyse output data with R Project 3.2.6 [51] via R Studio 1.1.463 [52] with ggplot2 3.2.1 [53], sqldf 0.4-11 [54], and car 3.0-2 [55]. Our methods are visual inspection and non-parametric statistical

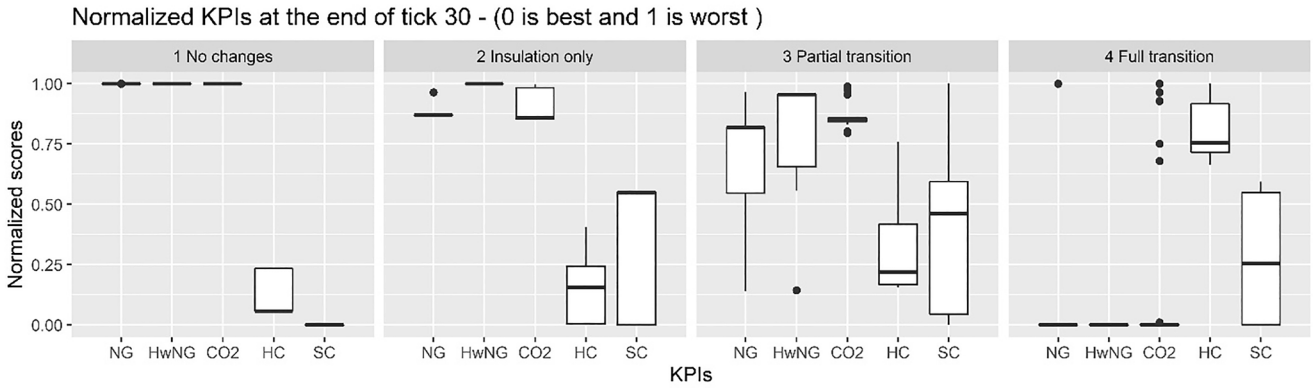

Fig. 8. Normalized KPIs in the ABM nominal results.

Table 9
Results for statistical tests to assess the effect of heat transitions on CO_2 emissions between four groups: "1 No changes", "2 Insulation only", "3 Partial transition", and "4 Full transition".

Variable compared	Levene's[a] (p-value)	Shapiro-Wilk[b] (p-value)	Kruskal-Wallis rank sum[c] (p-value)	Wilcoxon rank sum (summary of findings)
Normalized CO_2 emissions	0.00	0.00	0.00	Differences between all groups
Annual CO_2 emissions	0.00	0.00	0.00	Differences between all groups
Subsidy costs per annual CO_2 reduction after 30 years	0.00	0.00	0.00	Differences between most groups, except for 2&3.

[a] We assume homogeneity of variances only if p-values are lower than the significance level of 0.05.
[b] We assume normality only if values are higher than the significance level of 0.05.
[c] We use this test as a non-parametric alternative to one-way ANOVA. A p-value lower than the significance level of 0.05 indicates significant differences between treatment groups.

tests due to lack of normality and presence of outliers.

We address validation in two ways: a sensitivity analysis based on the One-factor-at-a-time (OFAT) method [56], and a reflection on publications regarding the heat transition.

We use desk research to parameterize our ABM; estimates and assumptions for input data are described in Appendix A: input data. We use some elements and parameters that we also used in [10,29].

To identify relevant decision-making factors, gather information to conceptualize an illustrative neighbourhood, and gather data for some parameters, we conducted a research project at Delft University of Technology. As part of the project, two of the authors supervised a graduate thesis [57] on a multi-criteria assessment; methods included literature reviews, desk research, and interviews. We use four factors that were selected in [57]: finances, environment, space (occupy by the heating system in the dwelling), and duration (of the works in the dwelling required to install the new technology). In [57], reliability of experts to support the change of TS was also included; however, we exclude this factor to represent a situation in which, by 2030, there are reliable experts in each of the TSs. The literature that was consulted in [57] included, among others, [58–61].

The neighbourhood that we simulate is illustrative, i.e. while it contains elements of the residential built environment in The Netherlands, it does not represent any specific neighbourhood. For example, the cost-effectiveness of different heating systems can vary as it depends of multiple factors [62,63]; here, we represent heat networks as having higher upfront costs than heat pumps. We make this choice to explore tensions between heating systems that may be preferred on the basis of finances, and other heating systems that may be preferred on the basis of environment, space, or duration of the works.

3. Description of the agent-based model

Our ABM represents an illustrative neighbourhood. It expands our previous work in [10] by explicitly representing households' multi-criteria decisions under combinations of policies. In this section, we present our ABM's overview and initialization, based on the ODD protocol that is commonly used to describe ABMs [45].

3.1. Model overview

3.1.1. Purpose

The purpose of our ABM was described in Section 1, i.e. to explore the effect of various financial policies on the heat transition given that

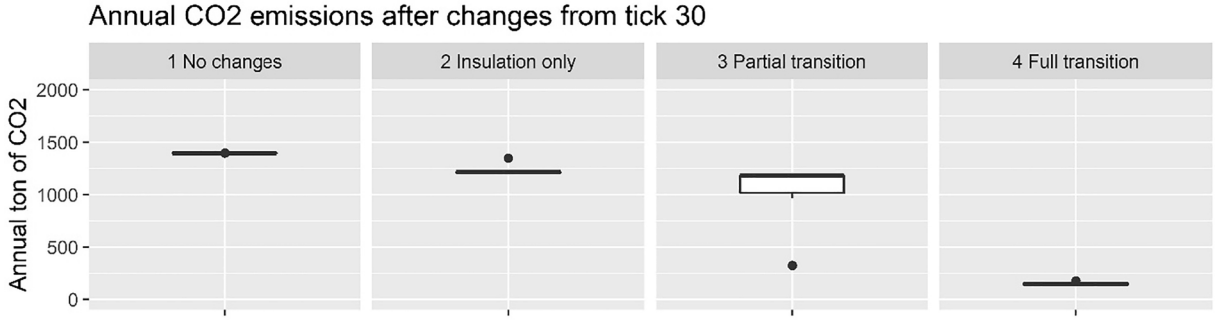

Fig. 9. Annual CO_2 after changes from tick 30, according to our ABM.

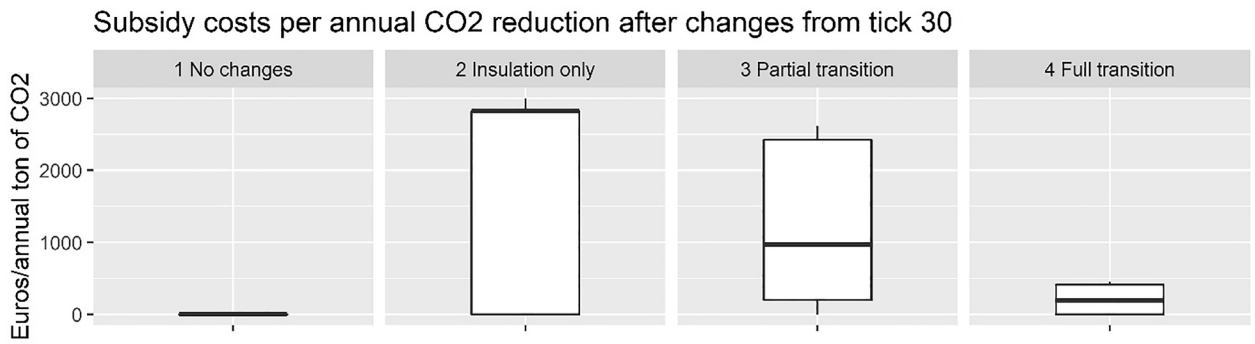

Fig. 10. Subsidy costs per annual CO_2 emissions reduction, according to our ABM.

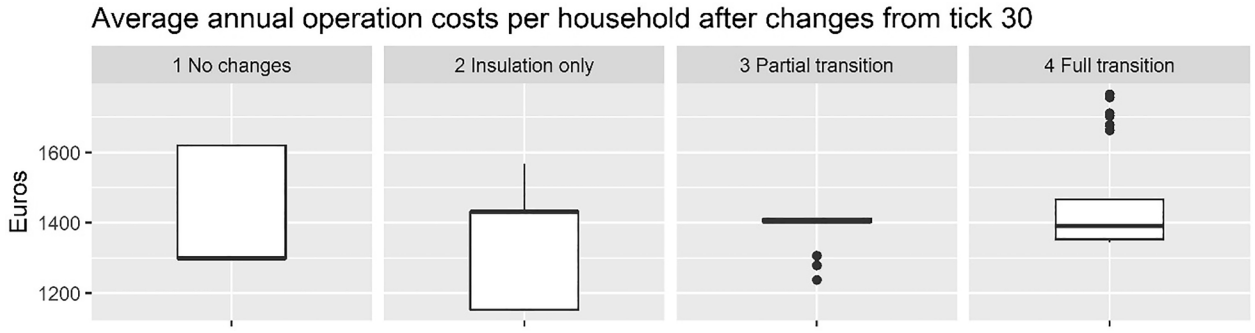

Fig. 11. Annual OC after changes from tick 30, according to our ABM.

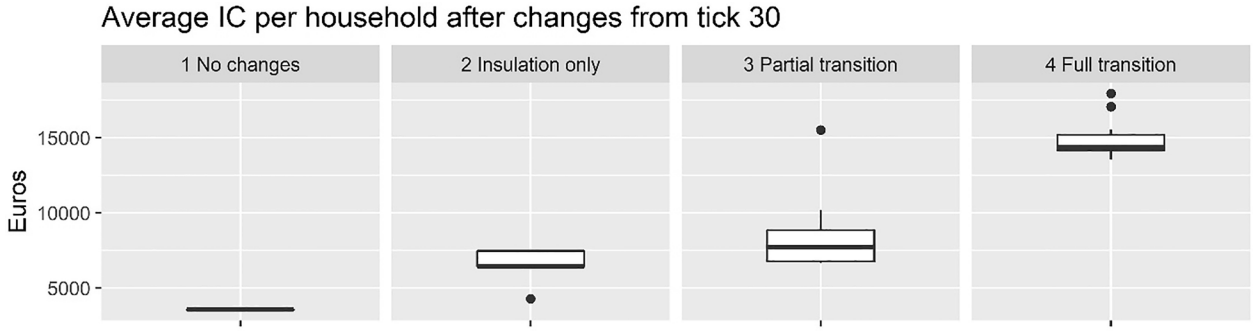

Fig. 12. Average IC after changes from tick 30, according to our ABM.

household decisions are multi-criteria. We use the KPIs from Table 1.

3.1.2. *Entities, variables, and scales*

Agents are households, the environment has market conditions and policies, and time consists of annual time steps. We study 30 simulation years, from 2019.

Households - Households have technology and actor components. The technology is the dwelling with its heating system, insulation, and appliances. The actor represents humans and their preferences.

State variables (Table 2) describe a household. A household's "type of dwelling" describes whether its dwelling is self-standing (semi-detached or terraced house) or in a strata building (apartments); the type

Table 10
Results for statistical tests to assess the effect of heat transitions on costs between four groups: "1 No changes", "2 Insulation only", "3 Partial transition", and "4 Full transition".

Variable compared	Levene's[a] (p-value)	Shapiro-Wilk[b] (p-value)	Kruskal-Wallis rank sum[c] (p-value)	Wilcoxon rank sum (summary of findings)
Annual OC after changes in tick 30	0.00	0.00	0.00	Differences between:1&2, 1&4, 2&4 No differences between:1&3, 2&3, 3&4
Average IC per household after changes in tick 30	0.00	0.00	0.00	Differences between all groups.

[a] We assume homogeneity of variances only if p-values are lower than the significance level of 0.05.
[b] We assume normality only if values are higher than the significance level of 0.05.
[c] We use this test as a non-parametric alternative to one-way ANOVA. A p-value lower than the significance level of 0.05 indicates significant differences between treatment groups.

Table 11
Conditions for partial transitions that differed from the nominal results in the sensitivity analysis.

Profile	Criteria (%)				Nominal REs that were required	Change in the variable with respect to its nominal value				REs required in the sensitivity analysis
	Finances	Environment	Space	Duration		Gas	DHN	INS	HPS	
T	100	0	0	0	GEXXX or G0XXP	0.9	1	1	1	GEXXX
					GEXXX or G0XXP	1	1	1	0.9	GEXXP
C	75	25	0	0	GXXXX	0.9	1	1	1	GEXXX or G0XXP
O	50	25	0	25	GXHIX or GE0IP	0.9	1	1	1	GXHIX
					GXHIX or GE0IP	1.1	1	1	1	G0HXX or GE0IP or GEH0P or GEHIX
					GXHIX or GE0IP	1	2026	1	1	GEHIP
					GXHIX or GE0IP	1	1	0.9	1	GXHIX
					GXHIX or GE0IP	1	1	1	0.9	GXHIP

Table 12
Conditions for full transitions that differed from the nominal results in the sensitivity analysis.

Profile	Criteria (%)				Nominal REs that were required	Change in the variable with respect to its nominal value		REs required in the sensitivity analysis
	Finances	Environment	Space	Duration		Gas	DHN	
E	25	25	0	50	GXHXX	0.9	1	GXHIX
					GXHXX	1	2026	GXHIX

of dwelling is linked to an energy demand and, potentially, group constraints. Households are part of the building's HOA, which have one member for self-standing dwellings. Each household has a technology state ("TS"), i.e. a combination of heating system and insulation, and appliances. Each household remembers its own "previous TS" and has a "profile" representing its preferences.

The ABM has nine TSs (Table 3). Three TSs have natural gas boilers and four TSs have alternative heating systems. We assume that hydrogen and green gas become available only from 2030 onwards. The website of the Expertise Center for Heat in The Netherlands states that hydrogen is not expected to play a significant role in the Dutch built environment until 2030 [64]. The website also states that the availability of green gas (which is processed biogas or syngas [108]) is limited, and that the green gas sector has the ambition of having increased its production by 2030 [65]; however, that for hydrogen and green gas, the future remains uncertain [64,65].

The TS of a household is dynamic. Households consider changing their TS annually. There are two restrictions based on a household's current TS (Fig. 1). First, insulation levels can only improve. Second, after being disconnected, a dwelling cannot reconnect to natural gas.

Five TSs (TS4:BN1, TS5:medHN2, TS6:HP1, TS7:HN1, and TS8:HH1) are simplified representations of combinations of heating systems and insulation that have already been represented in energy models for The Netherlands [57,63].

We conceptualized the remaining TSs as follows. A study by [20], which explored competition between incumbent natural gas boilers and micro-cogeneration that also uses natural gas, found that the adoption of the alternative could be inhibited if demand for natural gas decreased, for example, via insulation. Therefore, we include TSs that only require changes in insulation while maintaining a natural gas boiler (TS2:GB2 and TS3:GB1). This allows us to explore combinations of policies that aim at reducing heat demand, such as subsidies for insulation, and policies that aim at phasing out natural gas, such as subsidies for heat pumps. Similarly, we include a TS in which households would join a medium temperature heat network but would also insulate their dwelling and reduce their heat demand (TS9:medHN1).

The decision-making criteria are operationalized as follows. "Finances" is the lifetime cost of adopting and using a TS. "Environment" is the CO_2 emissions from operation of a TS, based exclusively on the amount of energy carrier used by the TS during its lifetime. "Space" is the area of the dwelling (in m^2) that a TS would occupy. "Duration" is the number of hours required to change TSs. Details on these calculations are provided in Appendix B.

Profiles are 4-tuples of numbers with values 0, 25, 50, or 100. Each number represents the relative importance that a household gives to each decision-making criteria. The sum of all numbers in a profile is always 100. Each household uses its profile to determine its preferred TS relative to each current TS. To do this, households use the numbers in their profiles as the weights of the four decision-making criteria when computing a weighted average over the normalized criteria scores. The resulting weighted average or score is considered to be the multi-criteria perceived lifetime utility of each TS relative to the current TS. This calculation is defined as the Submodel: Individual multi-criteria perceived lifetime utility from Appendix B.

Market conditions – We include sales prices (retail price plus tax) of energy and prices of changing TSs. Energy prices include gas, electricity, and heat from networks. To focus on the effect of fiscal policies, we maintain retail prices constant during the simulation, with the exception of the regulated price of heat from networks. Taxes change based on REs. Input data for this and other variables in the ABM are presented in Appendix A.

Policies – Regulatory environments (REs) are combinations of five policies; each policy can be active or inactive. These policies are an annual increase in natural gas tax after 2026 (G), annual decrease in electricity tax after 2026 (E), cap on the price of heat from networks (H), insulation subsidy (I), and heat pump subsidy (S). When a policy is inactive, it means that the annual increase or decrease is zero, that there is no price cap, or that there is no subsidy, respectively. We represent a RE as a string of length five; if a policy is active, we represent it with a letter (as just indicated), and if it inactive, with a zero. For example, in RE = GEHIP all policies are active; in RE = GEH0P there is no insulation subsidy but the other policies are active; in RE = 00000 all policies are inactive. We write RE = GXXXX to denote the collection of all REs where the increase in natural gas tax after 2026 is active and each of the remaining policies is either active or inactive.

Our policies are simplified representations of existing measures and expectations for future policies. Taxes on gas and electricity have increased and decreased, respectively [67]. Based on the Climate Agreement, further increases and decreases until 2026 can be expected [2]. The price of heat from networks is regulated [68] and alternative forms of regulation are also expected [8]. Subsidies for insulation [4] and heat pumps [5] have been available.

Group decisions – Households' preferences are constrained by group

decisions via a system of thresholds[2]. In our ABM, if households are part of an HOA, a threshold percentage of households must first approve such project within the HOA. If the threshold is met, the TS becomes the preference of all households in the HOA, and if the threshold is not met, the households that preferred the project no longer pursue it. Note that this is a simplified representation of legal systems and decision-making processes in place, which are more intricate and varied. In The Netherlands, HOAs are regulated by the Civil Code [69] and by their deed of division and rules [70]. See [12] for a tentative framework to describe group decisions within HOAs in energy transitions.

In our ABM, collective TSs for HOAs also require a percentage of households in the neighbourhood to be willing to join the project in order for the project to be realized. This reflects the fact that the costs or feasibility of energy infrastructure such as heat networks are linked to number of users or density of demand [6,14,71]. We define these percentages as "HN Threshold" for heat networks (including TS5:medHN2, TS7:lowHN1, and TS9:medHN1); "HH Threshold" for TS8:HH1; and "BN Threshold" for TS4:BN1.

We represent an additional prerequisite for hydrogen and green gas projects. Based on [64], we assume that there is only one network infrastructure for gas and that it can only transport either hydrogen or other types of gas. We do not account for a mix of natural gas and green gas. In our ABM, the corresponding threshold must be met and households with one of the other energy carriers must prefer to change their TS to a TS that uses the energy carrier in question.

3.1.3. Process overview and scheduling

The main processes in our ABM are as follows (see Table 1 with KPIs).

(1) In every time step, market conditions are updated based on the RE. In the first time step, HwNG is computed. In every subsequent time step, heating systems age, households consume heat, NG and operation costs are recorded, and the procedures below take place.
(2) Households determine their preferred TSs using Submodel: Individual multi-criteria perceived lifetime utility (see Appendix B).
(3) Thresholds for collective projects are assessed and projects for which thresholds are met are built and become operational the following year. The steps below are followed for heat networks, heat pumps, green gas networks, and hydrogen networks, in that order.
    (a) The ABM determines if the HOA Threshold for a collective project in each building is met. In each HOA, if the HOA Threshold was met for a neighbourhood project, either all households in the HOA count towards the required threshold in the neighbourhood, or none of them does (*winner-takes-all*). For heat networks, preferences for TS5:medHN2, TS7:lowHN1, and TS9:medHN1 are counted together; only later is it determined which TS with a heat network each household implements.
    (b) The ABM determines if the neighbourhood threshold is met (HN Threshold, HH Threshold, or BN Threshold).
    (c) If a neighbourhood threshold is met or a neighbourhood project of that type exists from a previous tick, the households in HOAs in which the HOA threshold was met for that type of neighbourhood project maintain their current TS if they had already adopted that type of neighbourhood project or replace their current TS if they had not. If the HN Threshold is met, each HOA determines whether a low and medium temperature network is implemented, based on which type is preferred by most households in the HOA. The constraints from Fig. 1 are also considered when determining whether a household will install TS5:medHN2 or TS9:medHN1.
(4) Individual TSs are implemented as follows.
    (a) Households that preferred collective TSs that were not feasible determine their preferred individual TS (including TS6:HP1 for self-standing houses) and implement it.
    (b) Households that initially preferred TSs with natural gas and who did not join a collective project in that time step adopt their preferred TS.
(5) Each household replaces its heating system if such heating system has reached the end of its lifetime.
(6) HwNG is updated and CO_2, HC and SC are computed.

3.2. Initialization

Our illustrative neighbourhood has 500 dwellings and one household per dwelling. The neighbourhood has a new and an old area where dwellings initially have high and low insulation, respectively. There are three types of dwellings: terraced and semi-detached houses, and apartments. The energy demand is determined by the dwelling type and its insulation. The type of dwelling and insulation are based on a set of dwellings conceptualized in [57]. At the beginning of the simulation, all dwellings are connected to natural gas and their boilers are 14 years; their expected lifetime is assumed to be 15 years. Old boilers are a known problem in the European Union [72].

The initial configuration of the neighbourhood is summarized in Table 4. Moreover, we use an HOA Threshold of 70% and HN Threshold, HH Threshold, and BN Threshold of 75%.This initialization is constant across experimental scenarios. We point out that this is not meant to correspond to any specific real-world neighbourhood.

We use experimental scenarios that differ in terms of household preferences and REs. There are 32 REs resulting from all combinations of the five policies. We study 23 HPPs, summarized in Table 5. Four HPPs are single-criteria. To explore the effect of financial policies, in the remaining 20 HPPs finances has at least 25% weight. For simplicity, we only explore instances of the neighbourhood in which all households have the same profile.

4. Results and discussion

This section is structured as follows. In Section 4.1, we discuss household preferences at the beginning of the simulation, and in Section 4.2, results from the entire simulation. In Section 4.3, we discuss the effect of heat transitions on the KPIs, and in Section 4.4, we address validation. Finally, we discuss limitations and future work in Section 4.5. Simulation data is available as supplementary material.

Throughout the section we use three concepts to classify simulation runs. First, *partial transitions*, in which some but not all households disconnected from natural gas by the end of the simulation. Second, *full transitions*, in which all households disconnect from natural gas. Third, *insulation-only*, in which all households remained connected to natural gas and a positive nonzero number of households improved their insulation level.

4.1. Household preferences at the beginning of the simulation

We use household preferences at the beginning of the simulation as a baseline to understand the effect of our dynamic simulation on the TSs that were adopted in the neighbourhood. Table 6 is an overview of the most preferred TS of households with single-criteria household preference profiles (HPPs). As illustrated in the row with HPP = 100-0-0-0, a cost-neutral transition was not possible under the initial conditions. All households preferred to remain connected to natural gas and only households in old semi-detached dwellings preferred to improve their

[2] The word "threshold" replaces the word "quorum" from our previous work in [10].

insulation to level 2 when a subsidy for this purpose was available. Similarly, when households based their decisions on duration, they preferred to maintain their existing TS. In contrast, when households based their decisions on a single criteria other than finances and duration, they preferred medium temperature heat networks with varying levels of insulation.

Results differed when households had multi-criteria HPPs. Under most HPPs, households preferred natural gas, with varying insulation levels. There were six exceptions in which all households preferred medium temperature heat networks, summarized in Table 7. In those HPPs, environment is weighted at least as much as finances, and duration is weighted 25% or 0%.

4.2. Heat transitions over 30 years

Partial and full transitions were possible over 30 years. HPPs were the single most influential condition enabling transitions. While no RE was a sufficient condition for a partial transition, the same six HPPs from Table 7 were sufficient conditions for full transitions. The remaining HPPs under which either type of transition took place had to be combined with specific REs. Conditions are summarized in Table 8.

4.2.1. Partial transitions

Partial transitions took place under three HPPs (T, Q, or O). No HPP was a sufficient condition; they always required RE = GXXXX, and in some cases, additional policies. In those HPPs, finances had the highest weight, followed by environment in multi-criteria HPPs.

The number of households that disconnected from natural gas varied, as well as the TSs that they adopted. In most cases, households adopted heat pumps. As shown in Fig. 2, the median of the number of disconnected households was highest with HPP = 50-25-0-25. The median (428) occurred for RE = G0HIX: households joined a medium temperature heat network, and in the old area, households made only small insulation improvements. Outliers when HPP = 50-25-0-25 occurred under RE = GE0IP: 150 households adopted heat pumps. In the other HPPs households also adopted heat pumps, with higher outliers for HPP = 100-0-0-0 and RE = GEX0P, and HPP = 75-25-0-0 and RE = GEXXP. REs in which outliers occurred had favourable conditions for heat pumps: increasing natural gas taxes, decreasing electricity taxes, and heat pump subsidy.

During partial transitions, households disconnected from natural gas over the last two thirds of the simulation; the earliest ones occurred under HPP = 75-25-0-0. Changes in insulation preceding a natural gas disconnection were also possible. For example, Fig. 3 illustrates two types of transitions when HPP = 50-25-0-25. Under GXHIX, households that disconnected from natural gas adopted heat networks towards the end of the simulation (note that the changes in G0HIX and GEHIX took place one year apart). Under GE0IP, they adopted heat pumps.

4.2.2. Full transitions

In most full transitions, disconnections took place at the beginning of the simulation, when varying numbers of households adopted medium temperature heat networks. Under HPP = 25-25-25-25 and 25-50-0-25, households in old dwellings made only small insulation improvements (TS5:medHN2). Under HPP = 25-25-50-0, 25-50-25-0, 25-75-0-0, and 50-50-0-0, most households improved their insulation further (TS9: medHN1), except for households in old semi-detached dwellings (TS5: medHN2). However, under 50-50-0-0 and RE = GX0XX, the 22 households in new semi-detached houses that had adopted TS9:medHN1 changed to TS6:HP1; this change occurred in the second half of the simulation, as illustrated in the two examples from Fig. 4. Under HPP = 25-25-0-50, disconnections occurred in the last third of the simulation and all households adopted a heat network, as shown in Fig. 5.

4.2.3. Insulation only

Households that never disconnected from natural gas sometimes improved their insulation. Fig. 6 shows the following. Under RE = 0XXXX, by the end of the second year, 250 households improved their insulation to level 3, and 50 households, to level 2. Fig. 7 illustrates that when RE = GXXXX, changes took place in different years. Changes were at the beginning of the simulation for HPP = 50-25-25-0, towards the middle for 50-25-0-25, and towards the end for 75-0-0-25 and 50-0-25-25. For the remaining HPPs, changes were at the beginning when there was an insulation subsidy, and when such a subsidy was not available, changes occurred towards the end. In Fig. 7, empty boxes indicate that this was not an insulation-only run.

4.3. Effects of transitions on natural gas consumption, CO_2 emissions, and costs

We normalized the KPIs and classified simulation runs in four groups ("1 No changes", "2 Insulation only", "3 Partial transition", and "4 Full transition"), as illustrated in Fig. 8.

In Fig. 8, the medians of NG, HwNG and CO_2 appear at their lowest in "4 Full transition". By definition, when the entire neighbourhood disconnected, no natural gas was consumed. Moreover, all households changed to TSs with the lowest emissions. In "4 Full transition", outliers for NG indicate that changes in TSs took place at the end of the last year and they would only influence heat consumption on the following year. Outliers in CO_2 correspond to transitions under HPP = 25-25-0-50, which took place in the last third of the simulation. Notably, the median of CO_2 appears to be similar for "3 Partial transition" than for "2 Insulation only"; nonetheless, their small difference is significant (see Table 9).

The median of HC was higher for "4 Full transition" than for "1 No changes". However, as described in Table 1, NG and HwNG are annual measures, and CO_2, HC, and SC are cumulative measures. When households made changes in TSs in different years, the lifetime of some TSs was not finished by the end of the simulation. As a result, a comparison of CO_2 and HC between groups that include "2 Insulation only" and "3 Partial transition" is incomplete. In those cases, investment costs would be overrepresented in HC and CO_2 emissions could be either under- or overrepresented. This indicates that, unless households changed their TSs from the beginning of the simulation, a horizon of 30 years would be insufficient to observe the effects of partial transitions and changes in insulation on KPIs without using annualized measures.

Therefore, we further examined the effect of transitions on CO_2 emissions after 30 years as follows. Firstly, we compared the expected annual CO_2 emissions of different groups, based on the final state of households (Fig. 9). Here too was the median for "3 Partial transition" close to that of "2 Insulation only"; nonetheless, they were statistically different (see Table 9). Secondly, we estimated the subsidy costs of annual CO_2 reduction after 30 years with respect to the initial conditions. Fig. 10 illustrates no used subsidies for "1 No changes", and otherwise, the lowest median for "4 Full transition" and the highest for "2 Insulation only" and "3 Partial transitions"; the difference in the medians of groups 2 and 3 was not statistically significant (see Table 9).

Finally, since HC were not annualized, we compared the average annual OC per household at the end of the simulation for every group (Fig. 11), and the average IC per household (Fig. 12). Not all groups had significant differences in the medians of average annual OC between each other (Table 10). Differences in IC were greater, as illustrated in Fig. 12, and were the cause of "4 Full transition" having higher HC that the other groups; these differences were statistically significant (see Table 10).

4.4. Validation

The heat transition is ongoing and possibilities for validation with historical data or with experiments are limited. Therefore, in this section, we address validation in the form of a sensitivity analysis (4.4.1) and a discussion of our results in the light of expert reports and news

(4.4.2).

4.4.1. Sensitivity analysis

We identified differences in the preferences of households with HPP = 100-0-0-0 at the beginning of the simulation, and in the HPPs and REs required for partial and full transitions. We explored changes in the annual increase of the natural gas tax and electricity tax, in the size of the insulation subsidy, and in the size of the heat pump subsidy. For each variable, we repeated simulations with values of 90% and 110% of the nominal value. For the active mode of the regulated price of heat from networks (RE = XXHXX), instead of being equal to the 2020 price, the price cap was equal to the 2026 price.

The insulation subsidy influenced the preferences of some households with HPP = 100-0-0-0 at the beginning of the simulation. When the insulation subsidy was 110% of its nominal value, households in old terraced houses preferred TS3:GB1 instead of the TS1:GB3 from Table 6. In contrast, the conditions under which households preferred to disconnect from natural gas at the beginning of the simulation, reported in Table 7, did not change.

In the simulations, partial transitions still took place under HPP = T, C, or O; however, changes in each policy except for the decrease in the electricity tax resulted in some changes in the REs that were necessary for partial transitions. The required REs that differed from the nominal results are summarized in Table 11. For example, in the nominal results, RE = GXXXX was necessary for partial transitions when HPP = Q; in contrast, in the sensitivity analysis, the transition was also possible if the increase in natural gas tax was only 90% of the nominal value, as long as RE = GEXXXX or G0XXP. Overall, as the values of the policies increased or decreased, partial transitions were possible under more or less REs, and the number of households that disconnected from natural gas sometimes varied. Results were robust with respect to changes in the value of the electricity tax, but they were often influenced by changes in the value of natural gas tax, and less often, by changes in the value of the remaining policies.

For full transitions, only HPP = 25-25-0-50 was sensitive to changes in the values of policies, and only to increases in the natural gas tax and in the regulated price of heat from networks. If the increase in the natural gas tax was smaller or the price cap on heat from networks was higher, the transition only took place when an insulation subsidy was in place. These findings are summarized in Table 12. Overall, results were robust with respect to changes in all policies except for a decrease in the natural gas tax and an increase in the regulated price of heat from networks.

4.4.2. Reflection on publications regarding the heat transition

As explained in our previous works [10,29], the heat transition in The Netherlands is complex. Recently, [73] found that, under their assumptions, the costs of disconnecting from natural gas would seldom be recovered via energy savings. Moreover, although the government has supported areas known as "testing grounds" to explore ways to disconnect from natural gas [74], national numbers indicate that the percentage of dwellings that did not use natural gas at the beginning of 2019 was 5.7% [75].

However, heat transition projects are yielding lessons [76,77] and some testing grounds are in an implementation phase [78]. The challenge of actor heterogeneity and the resulting need to customize projects and measures to disconnect from natural gas was noted by an alderman in the testing ground of Garyp [79] and by a project leader in the testing ground of Loppersum [80]. Furthermore, [76] higlights, among other points, that working at the level of neighbourhoods makes both problems and solutions identifiable. Moreover, that customization is necessary, that social preferences may not always lead to the lowest social costs, and that structural national solutions to potential bottlenecks will be needed. According to a dashboard from the testing grounds which we consulted on October 6, 2021, 29 testing grounds are in a planning phase and 17 testing grounds are in an implementation phase [78].

Our work echoes some of the previously mentioned situations. Firstly, that a cost-neutral transition was not possible under the initial conditions of the simulation (see Section 4.1). Secondly, that actor heterogeneity, in our case in the form of HPPs, is a determining factor for successful transitions. This resonates with the need to consider customization and multiple factors in the testing grounds [79,80]. Moreover, in some testing grounds, differences have been found between dwellings with different ages. Namely, in Loppersum and Nagele, heat networks have been found to be interesting in older areas [80,81]. Our results also showed situations in which different TSs were attractive to different types of dwellings. See variations in initial preferences in Section 4.1, and variations in TSs at the end of the simulation for partial transitions in Section 4.2.1, and in Section 4.2.2, for full transitions.

4.5. Limitations and future work

For simplicity, we only explore situations in which all households had the same HPP. Although we represent different types of dwellings, we also expect the preferences of households to vary. Therefore, it would be more realistic to simulate a neighbourhood in which households also have different HPPs. However, the present study allows us to identify HPPs under which households would prefer to change their initial state. Future work can build on this identification to explore combinations of HPPs and type of dwellings in neighbourhoods.

We incorporate elements of the Dutch built environment, decisions by households, and relevant policies in our ABM. However, since our work is exploratory, we use simplified representations of policies, group and multi-criteria decisions, and input data based on desk research, as well as assumptions. For instance, we expect our results to be different for neighbourhoods in which heat networks are more cost-effective than heat pumps: multi-criteria decisions might more often lead to disconnections from natural gas, provided that heat networks are preferred based on non-financial criteria. We also exclude effects of TSs on public space or infrastructure. Future studies can incorporate empirically validated representations and parameters –including for example of group decisions and varying energy prices-, quantitative models that are technologically accurate, study specific neighbourhoods and their alternatives to natural gas, adopt broader perspectives, and incorporate stakeholder participation.

The following changes can improve our ABM. Firstly, as described by [25], infrastructure requires a development process rather than instantaneous adoption. Our ABM could incorporate more realistic timelines and decision processes. For example, when comparing TSs, our households decide whether to change their TS on an annual basis and they do not take into account the age of their heating system, whether they have recovered previous investments, or whether they have sufficient capital to make a new investment. In reality, households are more likely to make an investment decision during dwelling renovation, change of residents, or breakdown of heating systems [76]. Secondly, a dynamic submodel for the business case of collective infrastructure depending on the number of users or heat demand -such as the model in [62,82]- could be used to determine costs for households.

Finally, our work is exploratory and our quantitative findings are only valid under the assumptions of our model. Therefore, instead of providing quantitative conclusions, with this work we seek to advance the study of the heat transition while accounting for group and multi-criteria decisions and to provide directions for future research in these lines. Our approach can be applied further to case studies concerning energy transitions in which various technologies compete to replace an incumbent technology, and in which both individual and collective decisions play a role in their adoption. This is for example relevant to the challenge of improving the energy performance of buildings and reducing greenhouse gas emissions in the built environment in the European Union, as described in [72].

5. Conclusions

Household preference profiles were more influential in the transition than financial policies; while no combination of financial policies was sufficient to enable the transition, six household preference profiles were sufficient conditions. Moreover, our results showed that combinations of policies can have different outcomes depending on household preference profiles, and transitions may require specific combinations of financial policies.

In simulations over 30 years, full transitions occurred when household preference profiles were as follows. Environment and finances were each weighted 50%. All criteria were weighted 25%. Finances and environment had nonzero weights but environment was weighted higher than finances. Finances and environment were weighted 25%, duration was weighted 50%, natural gas tax increased, and there was a cap on the price of heat from networks.

Partial transitions occurred under specific household preference profiles and policies, and the number of households that disconnected from natural gas varied: it could be as low as 22 and as high as 428. Moreover, the benefits of partial transitions were debatable. When comparing medians, annual CO_2 emissions at the end of the simulation were lower for partial transitions than for simulation runs in which only changes in insulation took place; however, the difference was small. Moreover, the difference between the medians of the subsidy costs per annual CO_2 reduction of partial transitions and of simulation runs with only changes in insulation was not statistically significant. In other words, in terms of CO_2 emissions and subsidy costs relative to the reduction in CO_2 emissions, similar results could be obtained from partial transitions and insulation-only.

Full transitions also posed challenges. In terms of medians, although they led to lower CO_2 emissions, they also led to higher investment costs. Heat networks were often adopted by households in full transitions and our assumptions represented a situation in which heat networks had high costs. However, full transitions did not have the highest average annual operation costs per household. Therefore, we recommend to use our model on a case-by-case basis and include validated business cases for heat networks and for other technologies. Lower upfront costs and other ratios between the costs of different alternatives could reveal different favourable socio-technical conditions for full transitions.

Our work is exploratory and should not be used as a quantitative analysis nor to select technologies or policies. However, we make the following recommendations for policy analysis. These recommendations are intended for heat transitions in the built environment in which various technologies compete to replace an incumbent technology, and in which both individual and collective decisions play a role in their adoption.

Firstly, combinations of ex-ante regulation of heat prices, fiscal policies for other energy carriers, and subsidies are relevant for the transition; theoretically, they could incentivize households to disconnect from natural gas. Therefore, we recommend to further explore interaction effects of these policies.

Secondly, full transitions might not happen with financial policies alone; instead, only some households might disconnect from natural gas. In case of partial transitions, the difference in CO_2 emissions with insulation-only scenarios might be small. For these reasons, in analyses and discussions, we recommend to include scenarios in which households maintain natural gas and different levels of insulation, as well mixes of dwellings with and without natural gas.

Thirdly, we encourage authors and decision-makers to also consider non-financial measures. To this aim, we recommend to continue to explore factors that are relevant for households, the impact of heterogeneity on the performance of financial policies, and the influence of natural moments in which households may decide to improve their insulation or replace their heating system.

Finally, we recommend to continue to explore the costs that the transition and its financial policies could have for different actors, implications for energy poverty and vulnerability, for the business case of energy projects, and for public expenditures.

CRediT authorship contribution statement

Graciela-del-Carmen Nava-Guerrero: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Helle Hvid Hansen:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration. **Gijsbert Korevaar:** Conceptualization, Methodology, Data curation, Writing – review & editing, Supervision, Project administration. **Zofia Lukszo:** Conceptualization, Methodology, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A. Input data

In this appendix we summarize input data used in the ABM. Some of the content of this appendix is similar to our previous work [10] because our ABM is an expansion of the previous one. Other assumptions and input data are based on the work by [57].

Table 13
Assumptions for the heat capacity used for the calculation of CO_2-equivalents per energy carrier in $kgCO_2/kWh$.

Energy carrier	Heat capacity	Source
Natural gas	35.17 MJ/m3	[87]
Green gas	We assume that it has the same heat capacity than natural gas.	
Hydrogen gas	0.03 kgH2/kWh	[88]
		A similar value of 33.33 kWh/kg was discussed in [89]

A.1. Considerations

In line with the exploratory purpose of our ABM, input data was gathered via desk research and includes estimates and assumptions. Developing a quantitative model to compare combinations of heating systems and insulation measures was not a purpose of our work. See [83] for an overview of energy models used for decision making in the heat transition in The Netherlands.

Our compilation does not represent any specific neighbourhood. To apply our ABM to a case study, input data needs to be validated in order to improve its quantitative accuracy.

We summarize some of our modelling choices as follows.

- We use the higher heating value (HHV = 35.17 MJ/m^3) for natural gas and an ideal heat capacity for hydrogen gas (see Table 13). Future work can use different values or explore the sensitivity of our calculations to these values.
- Input data was consolidated from different sources and we did not standardize the costs that are included in the estimates. For instance, upfront costs based on [63] do not include value-added tax, while sources such as [57] do not discuss value-added tax. Standardizing costs to include or exclude value-added tax, or using existing models that are already validated, can be part of future work. Similarly, the estimated costs that we use are not detailed estimates, but general assumptions for our exploratory purposes. See sources such as [63] and [84] for a technical and financial model.
- We focus on the costs, duration, and space of TSs that directly affect users in their dwellings during the lifetime of the TSs. See the works of [63,84], and [57] for broader perspectives.
- We simulate 30 years, and assume that heat networks do not require reinvestment during this time and that other heating systems require one reinvestment. A lifetime of 30 years with reinvestments after 15 years is often the starting point of business cases for heat networks [6]. A lifetime of 30 years has also been used in the scientific literature [85,86]; however, [85] explain that different lifetimes are expected depending on the specifications of the technology. See [85] for an overview of various estimated lifetimes.

Table 14
Assumptions for thermal efficiency the primary heating system of each TS.

TS	Thermal efficiency [fraction]	Sources	Thermal efficiency relative to natural gas boilers [fraction]
1:GB3	0.87	[68]	1.00
2:GB2	0.87	[68]	1.00
3:GB1	0.87	[68]	1.00
4:BN1	0.87	We assume the same value than natural gas boilers.	1.00
5:medHN2	1.00	[68]	1.15
6:HP1	3.81	[63]	4.28
7:lowHN1	1.00	[68]	1.15
8:HH1	0.87	We assume the same value than natural gas boilers.	1.00
9:medHN1	1.00	[68]	1.15

Table 15
Assumptions for thermal efficiency of the secondary heating system.

TS	Thermal efficiency [fraction]	Sources	Thermal efficiency relative to natural gas boilers [fraction]
4:BN1	4.4	[63]	5.06
8:HH1	4.4	[63]	5.06
7:lowHN1	6.1	[63]	7.01

Table 16
Assumptions for the lifetime of heating systems.

TS	Lifetime of primary heating systems [years]	Lifetime of secondary heating systems [years]	Sources
1:GB3	15	Not applicable	Assumptions. See [108] for heat pumps and natural gas boilers. See section B.1 for heat networks.
2:GB2	15	Not applicable	
3:GB1	15	Not applicable	
4:BN1	15	15	
5:medHN2	30	Not applicable	
6:HP1	15	Not applicable	
7:lowHN1	30	15	
8:HH1	15	15	
9:medHN1	30	Not applicable	

A.2. Technical specifications

We study nine TSs, described in Section 4.2.2. TSs have a heating system (defined as "primary heating system"), insulation level, and appliances. We conceptualize the primary heating system of TS4:BN1 and TS8:HN1 as boilers. We assume that TS4:BN1, TS7:lowHN1, and TS8:HN1 require additional heat pumps (defined as "secondary heating system"), in line with [63]. We do not account for separate heat demand or systems for space heating and tap water; we only make a difference between heat demand for cooking and for space heating.

Each TS is associated with the following parameters: thermal efficiency, lifetime of the heating system, and heat demand (cooking, primary, and secondary). Thermal efficiency and lifetime of the heating system are summarized in Tables 14–16.

Assumptions for the heat demand for TS1:GB3 and TS4:GN1 to TS8:HG1 were based on [90] and [57]. The work in [57] used theoretical estimates from [91] and adjusted those estimates to account for the energy performance gap described in [92], in which actual energy consumption after a renovation tends to be higher than theoretically estimated.

The resulting demand consisted of cooking demand (when natural gas is used) and demand for heating to be fulfilled by the primary and, if

Table 17
Assumptions for cooking demand of TSs.

TS	Cooking demand	Sources
1:GB3	37 m^3/year	Based on the average consumption of stoves natural gas and induction stoves by [90]
2:GB2	37 m^3/year	
3:GB1	37 m^3/year	
4:BN1	175 kWh/year	
5:medHN2	175 kWh/year	
6:HP1	175 kWh/year	
7:lowHN1	175 kWh/year	
8:HH1	175 kWh/year	
9:medHN1	175 kWh/year	

Table 18
Semi-detached houses: assumptions for heat demand.

TS	Heat demand from the primary heating system [kWh/year]	Heat demand from the secondary heating system	Sources
1:GB3	20,936	Not applicable	See description in text.
2:GB2	15,963	Not applicable	
3:GB1	15,358	Not applicable	
4:BN1	7295	8063	
5:medHN2	15,963	Not applicable	
6:HP1	15,358	Not applicable	
7:lowHN1	3839	11,518	
8:HH1	7295	8063	
9:medHN1	15,358	Not applicable	

Table 19
Terraced houses: assumptions for heat demand.

TS	Heat demand from the primary heating system [kWh/year]	Heat demand from the secondary heating system	Sources
1:GB3	16,794	Not applicable	See description in text.
2:GB2	14,029	Not applicable	
3:GB1	12,378	Not applicable	
4:BN1	5879	6498	
5:medHN2	14,029	Not applicable	
6:HP1	12,378	Not applicable	
7:lowHN1	3094	9283	
8:HH1	5879	6498	
9:medHN1	12,378	Not applicable	

Table 20
Apartments: assumptions for heat demand.

TS	Heat demand from the primary heating system [kWh/year]	Heat demand from the secondary heating system	Sources
1:GB3	Not applicable	Not applicable	See description in text.
2:GB2	Not applicable	Not applicable	
3:GB1	9984	Not applicable	
4:BN1	4743	5242	
5:medHN2	Not applicable	Not applicable	
6:HP1	9984	Not applicable	
7:lowHN1	2496	7488	
8:HH1	4743	5242	
9:medHN1	9984	Not applicable	

Table 21
Assumptions for Connection fee for primary and secondary heating systems.

TS	Primary heating system		Secondary heating system	
	CoF	Source	CoF	Source
1:GB3	159.56	Based on the 2020 fees of a natural gas supplier in The Netherlands [93].	NA*	NA*
2:GB2	159.56			
3:GB1	159.56			
4:BN1	159.56	We assume the same cost as for natural gas.	656.78	Based on the 2020 fees of an electricity supplier in The Netherlands [93].
5:medHN2	371.73	Based on the 2020 fees of a district heating supplier [94].	NA*	NA*
6:HP1	656.78	Based on the 2020 fees of an electricity supplier in The Netherlands [93].	NA*	NA*
7:lowHN1	371.73	Based on the 2020 fees of a district heating supplier [94].	656.78	Based on the 2020 fees of an electricity supplier in The Netherlands [93].
8:HH1	159.56	We assume the same cost as for natural gas.	656.78	Based on the 2020 fees of an electricity supplier in The Netherlands [93].
9:medHN1	371.73	Based on the 2020 fees of a district heating supplier [94].	NA*	NA*

*NA = Not applicable.

applicable, secondary heating systems. Demand is summarized in Tables 17–20. The heating demand that is to be fulfilled by the primary heating system for TS4:BN1 and TS8:HN1 was determined using the fraction 0.525 from [63], as used by [57]. For TS7:lowHN1 we used the fraction 0.75, which is mentioned by [63] as the fraction of the heat demand delivered by the individual heating system rather than the heat network. Not that we assume that all the demand after subtracting cooking demand is demand for space heating, and do not consider tap water demand.

Furthermore, to represent situations in which insulation measures are improved but natural gas is maintained, we assume that the heat demand of TS2:GB2 and TS5:medHN2 are equal, as well as the heat demand of TS1:GB1 and of TSs without natural gas and with the highest insulation.

A.3. Market conditions

Annual costs (AC), fixed costs (FC), and variable costs (VC) are expressed in Eqs. (7)–(10). In Eq. (8), *CoF* is a connection fee for both primary and secondary heating systems, and *MeF* is a measuring fee. In Eq. (10), *d, e,* and *f* are the prices (including taxes) of the corresponding energy carrier.

$$AC = FC + VC \tag{7}$$

Equation 7 Annual costs.

$$FC = CoF + MeF \tag{8}$$

Equation 8 Fixed costs.

$$CoF = CoF_{primary} + CoF_{secondary} \tag{9}$$

Equation 9 Measuring fee for primary and secondary heating systems.

$$VC = d^{*}Primary\ \ heat\ \ demand + e^{*}Secondary\ \ heat\ \ demand + f^{*}Cooking\ \ demand \tag{10}$$

Equation 10 Variable costs.

We assume that all households have a connection to the electricity network regardless of their TS and pay a measuring fee for this energy carrier. Therefore, we exclude MeF for electricity from our analysis. However, we assume that when households adopt a TS with an electric component (TS4:BN1, TS6:HP1, TS7:lowHN1, or TS8:HH1) they require a larger connection to the electricity network, which requires higher CoF. As mentioned in our previous work [10], in practice, a smaller connection without higher CoF could be sufficient. We only include the difference between the CoF of a larger connection (assumed to be 3x35A) and the CoF that households already had (assumed to be between 1x35A). The values for MeF and CoF are summarized in Table 21 and Table 22.

A.3.1. Upfront and reinvestment costs

We define upfront costs (UC) in Eq. (11), where HC are the costs of heating systems, IC are the costs of insulation measures, IS are the insulation subsidies, HS are the heat pump subsidies, and RE is the regulatory environment. Assumptions for HC, RC, and IC are summarized below (Table 23, 24, 25, 26 and 27), and for IS and HS, in Section A.4.

$$UC(s, s^{'}, RE) = HC(s, s^{'}) + IC(s, s^{'}) - IS(s, s^{'}, RE) - HS(s, s^{'}, RE) \tag{11}$$

Equation 11 Upfront costs (UC).

A.3.2. Energy prices

We define energy (sales) prices as the sum of retail prices and energy taxes. Retail prices of natural gas, electricity, hydrogen and green gas were constant throughout the simulation. This allowed us to focus our analysis on the effects that financial policies, including taxes and regulated price of heat from networks, could have on the transition. We represent a situation in which there are no taxes on green gas and

Table 22
Assumptions for Measuring fee.

TS	MeF	Source
1:GB3	22.40	Based on the 2020 fees of a natural gas supplier in The Netherlands [93].
2:GB2	22.40	
3:GB1	22.40	
4:BN1	22.40	Assumed to be the same as for natural gas.
5:medHN2	26.63	Based on the 2020 fees of a district heating supplier [94].
6:HP1	0.00	Excluded because all households use electricity.
7:lowHN1	26.63	Based on the 2020 fees of a district heating supplier [94].
8:HH1	22.40	Assumed to be the same as for natural gas.
9:medHN1	26.63	Based on the 2020 fees of a district heating supplier [94].

Table 23
Assumptions for HC of the primary heating system.

TS	HC [Euros]	Sources
1:GB3	NA*	NA*
2:GB2	1775.8	[63] for HR boilers, which we assume to be applicable to natural gas, green gas, and hydrogen.
3:GB1	1775.8	
4:BN1	1775.8	
8:HH1	1775.8	
6:HP1	7458.0	Adapted from [57], which was based on [84] and [63] for a 6 kW heat pump.
5:medHN2	12000.0	Assumption selected to represent a situation in which the upfront costs of heat networks are higher than those of other TSs.
7:lowHN1	12000.0	
9:medHN1	12000.0	

*NA = Not applicable

Table 24
Assumptions for HC of the secondary heating system.

TS	HC [Euros]	Sources
4:BN1	6638.0	Adapted from [57], which was based on [84] and [63] for a 4 kW heat pump.
8:HH1	6638.0	
7:lowHN1	4500.0	Assumption based on [63].

Table 25
Assumptions for RC.

TS	RC [Euros]	Sources
1:GB3	1775.8	Equal to UC of the primary heating system.
2:GB2	1775.8	
3:GB1	1775.8	
4:BN1	8413.8	Equal to sum of UCs of primary and secondary heating systems.
8:HH1	8413.8	
6:HP1	7458	Equal to UC of the primary heating system.
5:medHN2	0	We assume that no reinvestments are necessary.
9:medHN1	0	
7:lowHN1	4500	Equal to UC of the secondary heating system.

Table 26
Assumptions for the insulation measures required by each type of old dwelling. .

Change in insulation level	Type of dwelling	
	Semi-detached houses	Terraced houses
Low to medium	HR++ glass Roof insulation Cavity wall insulation	HR++ glass Roof insulation
Low to high	HR+++ glass Roof insulation Floor insulation Cavity wall insulation	HR++ glass Roof insulation Floor insulation Cavity wall insulation
Medium to high	HR+++ glass Roof insulation Floor insulation Cavity wall insulation	Floor insulation Cavity wall insulation
Source	Based on [57].	

Adapted from [57]

Table 27
Assumptions for the cost of insulation measures per type of old dwelling. .

Change in insulation level	Type of dwelling	
	Semi-detached houses	Terraced houses
HR++ glass	3770	3103
HR+++ glass	6240	NA*
Roof insulation	2768.5	2005.5
Floor insulation	2640	1880
Cavity wall insulation	1956	846
Source	Based on [57].	

*NA = Not applicable.
Adapted from [57]

Table 28
Assumptions for sales prices of energy carriers.

Energy carrier	Assumption [Euros/kWh]	Source
Natural gas	0.04	Estimated value for 2019 and 2020 [95].
Electricity	0.14	Estimated value for 2019 and 2020 [96].
Green gas	0.07	Based on an estimated low price in [63].
Hydrogen	0.06	Based on estimated low prices when produced with energy carriers other than natural gas, as discussed by [97].

Table 29
Assumptions for the available insulation subsidies. .

Change in insulation level	Type of dwelling	
	Semi-detached houses	Terraced houses
Low to medium	2981	1895
Low to high	5133	2436
Medium to high	2152	541
Source	Based on [57].	

Adapted from [57]

hydrogen and their prices are low. Our assumptions for the sales prices of energy carriers are summarized in Table 28. Energy taxes, and the regulated price of heat from networks, are described in Section 8.3.

A.4. Financial policies

A.4.1. Natural gas and electricity taxes

The taxes for the first two time steps, corresponding to 2019 and 2020, were based on data from The Netherlands [67]. The natural gas tax was rounded to 0.030€/kWh for 2019 and 0.034€/kWh for 2020. The electricity tax was rounded to 0.099€/kWh for 2019 and 0.098 for 2020€/kWh.

After 2020 and before 2027, changes in taxes were based on the content of the Climate Agreement [2]. Natural gas tax increased by 0.01€/m^3-year (0.001€/ kWh-year). Electricity tax decreased about 0.05€/kWh, a decrease that we implemented linearly: 0.0083€/year.

After 2026, energy taxes depended on the RE. When G was inactive (RE = 0XXXX), natural gas taxes remained constant. When E was inactive (RE = X0XXX), electricity taxes remained constant. When G was active (G = GXXXX), natural gas taxes continued to increase by 0.001€/ kWh-year. When E was active (E = 0EXXX), electricity taxes continued to decrease by 0.0083€/year until they reached zero.

A.4.2. Regulated price of heat from networks

The regulated price of heat from networks for 2019 and 2020 is 0.09 Euros/kWh, based on the price of a heat supplier for 2020 [94]. After 2020, if the policy is active (RE = XXHXX), the price remains constant. After 2020, when the policy is inactive (RE = XX0XX), the price continues to increase in proportion to the sales price of natural gas, as expressed in Equation (12). In Equation (12), RHP is the regulated price of heat from networks, t is the time step, and SPG is the sales price of natural gas. This is a simplified representation of a price cap.

$$RHP(t) = \left(1 + \left(\frac{SPG(t) - SPG(t-1)}{SPG(t-1)}\right)\right) * RHP(T-1) \quad (12)$$

Equation 12 Regulated price of heat from networks under RE = XX0XX.

A.4.3. Insulation subsidy

Our insulation subsidy is based on the former policy SEEH (Subsidie energiebesparing eigen huis) that was in place until the end of 2020 [98,99]. Currently, insulation subsidies are available via a different policy. Following our conceptualization, we assume that old dwellings, which have low insulation, can improve to medium or high level, and that new dwellings already have the highest insulation. Our assumptions for the insulation subsidies are summarized in Table 29.

A.4.4. Heat pump subsidy

Our heat pump subsidy is based on the existing policy ISDE (Investeringssubsidie Duurzame Energie) [100]. We assume that a subsidy of 1700 Euros is granted for hybrid heat pumps (TS4:BN1 and TS8:HH1) and a subsidy of 1900 Euros for regular heat pumps (TS6:HP1). These assumptions are based on online examples such as [101,102], and [103].We assume that the subsidy is granted only for the first time that a heat pump is installed and not for future reinvestments.

A.5. Factors for the multi-criteria calculations

A.5.1. Environmental computation

We limit the environmental calculation to an estimate of the CO_2-equivalents linked to the energy carrier during the operational phase of the

Table 30
Factors used for the calculation of CO_2-equivalents per energy carrier. .

Energy carrier	Factor	Source	Factor in $kgCO_2$/kWh
Natural gas	56.6 $kgCO_2$/GJ	[104]	0.20
Electricity	0.475 $kgCO_2$/kWh	[105]	0.48
Green gas	0.723 $kgCO_2$/m3	[105]	0.07
Hydrogen gas	1.5 $kgCO_2$/kg	[57], which assumed that 50% is produced from wind and 50% is produced from PVs, and used factors from [106]	0.05
Low temperature heat network	8.60 $kgCO_2$/GJ	[107], assuming a geothermal source and including only direct emissions from the main source.	0.03
Medium temperature heat network	5.7 $kgCO_2$/GJ	[107], assuming residual heat and including direct emissions only from the main source.	0.02

Adapted from [57]

Table 31
Space factor (s') in m^3.

TS	1:GB3	2:GB2	3:GB1	4:BN1	5:medHN2	6:HP1	7:lowHN1	8:HH1	9:medHN1
Space factor	0.584	0.584	0.584	1.83	0.584	5.746	5.49	1.83	0.584
Source	Based on [57].								

Table 32
Duration factor (s') for semi-detached houses in hours.

TS	TS'								
	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9
1:GB3	0	26	46	54	26	54	54	54	46
2:GB2	NA	0	46	54	4	54	54	54	46
3:GB1	NA	NA	0	12	NA	12	12	12	4
4:BN1	NA	NA	NA	0	NA	12	12	12	4
5:medHN2	NA	NA	NA	54	0	54	54	54	42
6:HP1	NA	NA	NA	12	NA	0	12	12	4
7:lowHN1	NA	NA	NA	12	NA	12	0	12	4
8:HH1	NA	NA	NA	12	NA	12	12	0	4
9:medHN1	NA	NA	NA	12	NA	12	12	12	0
Source	Based on [57].								

*NA = not applicable.

Table 33
Duration factor (s') for terraced houses in hours.

TS	TS'								
	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9
1:GB3	0	20	38	46	20	46	46	46	38
2:GB2	NA	0	22	30	4	30	30	30	22
3:GB1	NA	NA	0	12	NA	12	12	12	4
4:BN1	NA	NA	NA	0	NA	12	12	12	4
5:medHN2	NA	NA	NA	30	0	30	30	30	18
6:HP1	NA	NA	NA	12	NA	0	12	12	4
7:lowHN1	NA	NA	NA	12	NA	12	0	12	4
8:HH1	NA	NA	NA	12	NA	12	12	0	4
9:medHN1	NA	NA	NA	12	NA	12	12	12	0
Source	Based on [57].								

*NA = not applicable.

Table 34
Duration factor (s') for apartments in hours.

TS	TS'								
	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9
1:GB3	NA	NA	NA	NA	NA	NA	NA	NA	NA
2:GB2	NA	NA	NA	NA	NA	NA	NA	NA	NA
3:GB1	NA	NA	0	12	NA	12	12	12	4
4:BN1	NA	NA	NA	0	NA	12	12	12	4
5:medHN2	NA	NA	NA	NA	NA	NA	NA	NA	NA
6:HP1	NA	NA	NA	12	NA	0	12	12	4
7:lowHN1	NA	NA	NA	12	NA	12	0	12	4
8:HH1	NA	NA	NA	12	NA	12	12	0	4
9:medHN1	NA	NA	NA	12	NA	12	12	12	0
Source	Based on [57].								

*NA = not applicable.

Table 35
Duration factor (s') in hours for all dwellings, when a reinvestment was necessary.

TS	1:GB3	2:GB2	3:GB1	4:BN1	5:medHN2	6:HP1	7:lowHN1	8:HH1	9:medHN1
Space factor	4	4	4	12	0	12	12	12	0
Source	Based on [57].								

heating system. The factors are summarized in Table 30.

A.5.2. Space computation

The space computation required a space factor (s') for each TS, summarized in Table 31.

A.5.3. Duration computation

The duration computation required a duration factor (s') for each TS, summarized in Tables 32–34. When a reinvestment was necessary, we used the values of Table 35.

Appendix B. Design concepts and submodel

In this appendix, we discuss the design concepts of our ABM and the submodel for individual multi-criteria perceived lifetime utility.

B.1. Design concepts

Our ABM has three basic principles:

- Multi-criteria decisions in the form of households having profiles with their preferences.
- Group decisions in the form of a system of thresholds.
- Heterogeneity in the form of dwellings with different characteristics.

Further, our ABM has the following design concepts:

- Objectives: households try to maximize their utility by preferring the TS with highest score.
- Prediction: households have imperfect prediction of future financial policies and use current prices and taxes in their estimates.
- Sensing: households in an HOA know whether the HOA Threshold was met and all households know whether the HN Threshold was met. No other interactions are formalized.
- Observation: takes place via the computation of KPIs.
- Collectives: households are grouped into HOAs, which condition their decisions.

B.2. Submodel: Individual multi-criteria perceived lifetime utility

Households use this submodel to determine the score of each TS with respect to the household's current TS. It consists of five computations: four single-criteria computations that are later normalized (finances, environment, space, duration), and the computation of a score or weighted average based on the single-criteria computations and the household's profile. We first proposed and used the finances computation in [10] as a lifetime cost calculation (LTC). The remaining computations are based on the static multi-criteria assessment model by [57].

The financial cost (FC) is the lifetime-cost (LTC) of changing from the current TS (s) to a new TS (s'), discounted with a market discount rate (ρ) to account for differences in present and future cash-flows, and starting on the current time step (t). The FC and the LTC are expressed in **Eq.** (1), where UC are upfront costs, AC and RC are annual costs and reinvestment costs, β is a uniform horizon equal to the lifetime of the heating system with the longest lifetime, and τ is the lifetime of the heating system of s' for which **Eq.** (1) is being used. Input data is presented in Appendix A (Sections A.2 and A.3).

Equation 1 Financial cost

$$FC_{s,s'} = LTC(s,s',\rho,\mathrm{t}) = UC(s,s') + \sum_{k=0}^{\beta} \frac{\mathrm{AC}(s',t+k)}{(1+\rho)^{\mathrm{k}}} + \sum_{j=1}^{\left\lfloor \frac{\beta-1}{\tau} \right\rfloor} \frac{RC(s')}{(1+\rho)^{j\tau}} \tag{1}$$

Note that households do not consider the lifetime of their current heating system in the calculation of UC and RC. For instance, if s' uses the same heating system as s, regardless of the age of s, households consider the standard: no investment costs required for heating system of s' and only one reinvestment throughout 30 years. This is however only accurate when the heating system of s is at the beginning of its lifetime. Therefore, households could be underestimating RC of s' that use the same heating system as s does. A more accurate representation would have households consider the age of their current heating system in the calculation of UC and RC.

The environmental cost (EC) is the CO_2 emissions of the energy carrier used during the lifetime of a TS. It is expressed in **Eq.** (2), where *a*, *b*, and *c* are emission factors in kg of CO_2/kWh, HD is heat demand, CD is cooking demand, nH is the efficiency of heating systems, and the energy demands are expressed in kWh/year (see Appendix A, section A.5.1). Note that we use the concept "environmental cost" in a rather narrow sense.

Equation 2 Environmental cost

$$EC = \left(a^{*} \frac{HD_{primary}}{nH_{primary}} + b^{*} \frac{HD_{secondary}}{nH_{secondary}} + c^{*}CD \right)^{*}\beta \tag{2}$$

We assume that the space that the heating system occupies in the dwelling does not change over time, and the works to install the TSs take place

only once. Therefore, the spatial cost (SC) and the duration cost (DC) are equal to a constant space factor or duration factor for every TS. As expressed in **Eq.** (3), the value of the space factor depends only on s', and the value of the duration factor depends on both s and s', as expressed in **Eq.** (4) (see Appendix A, Sections A.5.2 and A.5.3).

Equation 3 Space computation

$$SC_{s'} = space\ \ factor(s') \tag{3}$$

Equation 4 Duration computation

$$DC_{s,s'} = duration\ \ factor(s, s') \tag{4}$$

After the FC, EC, SC, and DC are computed for all TSs, results are normalized as expressed in **Eq.** (5), where N stands for normalized, X is a placeholder for F, E, S, or D, and minimums (min) and maximums (max) are taken over the values of s'.

Equation 5 Normalization computation

$$NXC = \frac{XC - XC_{min}}{XC_{max} - XC_{min}} \tag{5}$$

Finally, for each TS, a score is calculated as expressed in **Eq.** (6), where FW, EW, SW, and DW indicate the weights given to each criteria in the HPP. The TS with the highest score becomes the most preferred TS by the household.

Equation 6 Score computation

$$Score_{s,s'} = FW*NFC_{s,s'} + EW*NEC_{s,s'} + SW*NSC_{s,s'} + DW*ND_{s,s'} \tag{6}$$

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.118118.

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