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Research Article

The effect of group decisions in heat transitions: An agent-based approach

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ABSTRACT

The Netherlands aims at reducing natural gas consumption for heating in the housing sector. Although homeowners are responsible for replacing their heating systems and improving dwelling insulation, they are not always able to make individual decisions. Some projects require group decisions within and between buildings. We use an agent-based modelling and simulation approach to explore how these individual and group decisions would influence natural gas consumption and heating costs in an illustrative neighbourhood, under a set of assumptions. We model individual household preferences over combinations of insulation and heating systems as a lifetime cost calculation with implicit discount rates, and we use quorum constraints to represent group decisions. We model three fiscal policies and a policy to disconnect all dwellings from the natural gas network. Results show that the disconnection policy was the only necessary and sufficient condition to incentivize households to replace their heating systems and that group decisions influenced the alternatives that were chosen. Since results were influenced by group decisions within buildings and by the market discount rate, we recommend further research regarding policies around these topics. Future work can apply our approach to case studies, incorporate new empirical knowledge, and explore group decisions in other contexts.

1. Introduction

A heat transition is taking place in The Netherlands. Natural gas is widely used in the country to heat the built environment (Beurskens and Menkveld, 2009). However, the national government has the ambition of reducing the consumption of this fuel over time (Rijksoverheid, 2019a). Since July 2018, buildings with a relatively low energy consumption for space heating, i.e. houses and small commercial buildings, should be built without being connected to the natural gas grid (RVO, n.d.). Moreover, the national government aims at making all existing homes free of natural gas by 2050 (Rijksoverheid, 2019a). These goals are in line with those of the European Union to improve the energy performance of buildings and increase the share of renewable energy sources that are used to heat the built environment (European Commission, 2016).

To enable this transition, national authorities are revising laws and policies. For instance, a new version of the Heat Act, which concerns heat networks, was approved in 2019 (Lavrijssen and Vitez, 2019; Warmtewet - BWBR0033729, 2019); a Heat Act 2.0 is also expected (Rijksoverheid, 2019b). Another example is the adjustment of fiscal policies. In 2020, taxes on natural gas and electricity increased and decreased, respectively, compared to their values in 2019 (Rijksoverheid, 2019c). Price caps for heat delivered by heat networks are also being revised. Until now, regulatory authorities have set heat price caps that depend on the price of natural gas; however, authorities are now revising such caps and considering their potential decoupling from the natural gas price (Voortgangsoverleg Klimaatakkoord, 2019). In addition, public and private actors produced the Climate Agreement, a document with climate-related measures for the coming years (Rijksoverheid, 2019d).

Nevertheless, the responsibility to formulate heat transition plans lies at the local level. Since 2019, an amendment to The Dutch Crisis and Recovery Act (Crisis- en herstelwet—BWBR0027431) allows municipalities to carry out experiments to phase out natural gas in areas such as testing grounds (PAW, 2019). A testing ground, or “proeftuin” in the Dutch language, is a location where a group of households organize and

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Abbreviations: ABM, Agent-based model; AC, Annual costs; CAS, Complex adaptive systems; HN, Heat network; HOA, Homeowner association; IDR, Implicit discount rate; LTC, Lifetime-cost; NPV, Net present value; RC, Reinvestment costs; RE, Regulatory environment; RES, Regional energy strategy; STS, Socio-technical systems; TS, Technology state; UC, Upfront costs.

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receive a contribution from the central government to test solutions for the transition towards a natural gas-free future (PAW, n.d.). Moreover, municipalities are required to prepare visions for their local heat transition before 2022 (Rijksoverheid, 2016a). In accordance with the Climate Agreement, local authorities are organizing at a regional level to achieve this goal. Municipalities were grouped in 30 regions, and each region is to prepare a Regional Energy Strategy (RES) for the transition (Rijksoverheid, 2019d).

The implementation of a RES will not be trivial: it will require multiple actors to coordinate their decisions. In the housing sector, individual owners and groups of owners would have to make joint decisions. Building owners are responsible for investments to improve energy efficiency and replace heating systems (Filippidou et al., 2017). However, they are not always able to start a project on their own. Projects such as heat networks (or their expansion) require sufficient heat demand in order to be feasible or remain affordable (Lund et al., 2014; Mahapatra and Gustavsson, 2009); therefore, such projects would require building owners to coordinate their decisions.

A second complication is that some buildings, known as strata buildings, consist of multiple dwellings and can have more than one owner. Owners must organize in homeowner associations (HOA, in Dutch language called Vereniging van Eigenaren), which are regulated by the Book 5 of the Civil Code (Burgerlijk Wetboek Boek 5—BWBR0005288) and by the HOA's individual deed of division. Formally, members make group decisions using voting systems with quorums; therefore, owners of dwellings in strata buildings are responsible for individual investments as well as for reaching agreements regarding joint investments in energy efficiency (Roodenrijs et al., 2020). As a result, depending on the scope of a RES, its implementation would require group decisions within and between HOAs, and potentially, between neighbourhoods.

It follows that group decision-making is a key aspect of energy transitions because it can constrain household individual decisions. However, literature exploring this phenomenon is limited and studies often focus on individual decision-makers (Roodenrijs et al., 2020). For instance, Klöckner and Nayum (2017) explore psychological and structural facilitators and barriers to energy upgrades by private households in Norway, but they exclude households living in strata buildings. Michelsen and Madlener (2013) investigate motivational factors behind homeowner's decisions between residential heating systems in Germany, but exclude households living in multi-family dwellings, classified as more than two dwellings. In an empirical analysis of the decision-making process of homeowners for energy renovation measures in The Netherlands, Broers et al. (2019) exclude condominiums. The focus on individual decision-makers rather than strata buildings extends to agent-based modelling and simulation studies, which we discuss in Section 2.

Our aim is to explore how group decision-making in strata buildings could affect the heat transition in the owner-occupied share of the housing sector in The Netherlands. Since new buildings must comply with energy performance standards and are therefore built without a natural gas connection, we focus on the stock of buildings that currently uses natural gas for heating. We study the problem at the level of a neighbourhood and its HOAs. Our main research question is:

How could individual and group decisions between building owners, and within HOAs in strata buildings, influence the course of the heat transition in a neighbourhood in The Netherlands, under different policy interventions?

We explore the question from a computational modelling and simulation approach. In particular, we use an agent-based approach that we proposed in Moncada et al. (2017) and Nava Guerrero et al. (2019), which is based on the perspectives of socio-technical systems (STS) and complex adaptive systems (CAS). We conceptualize and build a computational model to explore possible developments in an illustrative neighbourhood over time, under a set of assumptions regarding households' decision-making. We conceptualized the illustrative neighbourhood by including dwelling features that are present in the Dutch residential built environment. We observe whether households disconnect from natural gas, what their heating costs are, and whether their individual decisions are influenced by group decisions.

The remaining parts of this paper are structured as follows. In Section 2, we discuss knowledge gaps in agent-based studies of energy transitions. We further explain our research approach in Section 3 and present our agent-based model (ABM) in Section 4. Then, in Section 5, we present results and discussion. Finally, in Section 6, we conclude by answering the main research question and discussing policy implications.

2. Knowledge gaps in ABMs of energy transitions

As explained in our previous work (Moncada et al., 2017; Nava Guerrero et al., 2019), we use the perspectives of STS (Cooper and Foster, 1971; Herder et al., 2008; Trist, 1981) and CAS (Holland, 1988; Waldorp, 1993) throughout our work. These perspectives allow us to describe the multi-actor and multi-level nature of the heat transitions. Through the lens of STS, actors are individuals and organizations (Enserink et al., 2010) who make decisions and affect each other or the system. They may cooperate or compete (Bengtsson and Kock, 1999), and might have bounded rationality (March 1978; Simon, 1997). Actors and technology are described as networks with complex interactions, which take place under rules and regulations, defined as institutions (North and Macal, 2007). Through the lens of CAS, actors can be conceptualized as agents, i.e. low-level components of a system whose actions, interactions, and reactions lead to the system's behaviour.

Both STS and CAS are used in agent-based modelling, a method for computational modelling and simulation in which systems are represented through knowledge of (assumed) behaviour of individual agents (Grimm and Railsback, 2004; North and Macal, 2007; Railsback and Grimm, 2019; Borshchev and Filippov, 2004). An ABM has agents, environment, and time (Dam et al., 2013). Agents represent actors, exist within the environment (van Dam, 2009), and are described at any time by their state, i.e. a set of parameters or state variables (Grimm et al., 2010; Wooldridge and Jennings, 1995). Agents and environment are influenced by their current and previous states and those of each other.

Although agent-based modelling has been widely used to model and simulate energy transitions due to its suitability for representing STS and CAS (Li et al., 2015), in this work, we seek to address the following three knowledge gaps within ABMs of adoption of technologies.

First, as noted by Hansen et al. (2019), studies have seldom had an explicit or exclusive focus on the heating sector. Authors have focused on inquiries regarding the electricity sector and fewer studies have investigated the adoption of either heating systems or insulation measures. Some exceptions include the exploration of competing micro-CHP and incumbent condensing boilers by Faber et al. (2010), insulation activity by Friege (2016), wood-pellet heating by Maya Sopha et al. (2011) and Maya Sopha et al. (2013), heat pumps by Snape et al. (2015), and a neighbourhood's transition towards heating without natural gas in our earlier work (Nava Guerrero et al., 2019).

Second, as noted by Hesselink and Chappin (2019), studies have seldom explored the adoption of multiple and competing technologies. Instead, works have usually explored the adoption of individual technologies, e.g. photovoltaic cells. Some exceptions include the previously mentioned work by Faber et al. (2010) and the works by Mittal et al. (2019) and Mittal, Krejci, Dorneich, et al. (2019). The latter two concern multiple solar-based energy models in the context of residential renewable energy systems and zero energy communities, respectively. Another exception is our earlier work (Nava Guerrero et al., 2019), which includes competing combinations of heating systems (micro-CHPs, electric radiators, aerial heat pumps, and geothermal heat-pumps) and insulation measures.

Third, to the best of our knowledge, group decision-making within and between HOAs has not yet been explicitly incorporated in ABMs of energy transitions. Instead, authors have represented other ways in which households influence each other's decisions. As noted in the review by Hesselink and Chappin (2019), authors have often used social network theory to model the spread of information, perception, or innovations. Examples include the previously mentioned Friege (2016), Maya Sopha et al. (2011) and Maya Sopha et al. (2013), and Mittal et al. (2019) and Mittal, Krejci, Dorneich, et al. (2019), to mention a few. Similarly, authors have accounted for social factors without the explicit use of network theory. For instance, Snape et al. (2015) model a distribution of positive and negative opinions as a proxy for a local social network influence. Similarly, in Nava Guerrero et al. (2019), agents that are socially oriented are triggered to adopt a technology when a fraction of their peers has also changed its technology.

Moreover, instead of modelling group decisions to collectively adopt a technology, authors have limited the technology options that are available to households in strata buildings. For instance, from the previous works, Mittal, Krejci and Dorneich (2019) explore household adoption of different renewable energy models. They distinguish households, which are agents, as home-owners, tenants, and apartment-owners. They assume that both tenants and apartment-owners are unable to buy or lease rooftop PV panels, and that only 57% of house-owners are able to do so due to physical constraints of the building.

Busch et al. (2017) model the emergence of heat networks as a multi-actor and multi-stage process that can be instigated, for example, by a community organisation. In their model, density of demand, among others, influences the feasibility of heat network projects. Their implementation depends on factors such as the capabilities of their instigator (which is an agent) and whether sufficient heat demand remains available.

We address these knowledge gaps in the following ways. First, we have an explicit focus on heat provision in the owner-occupied share of the housing sector. Second, we include multiple and competing combinations of heating systems and insulation measures. Third, we propose a way to account for the effects of group decisions in strata buildings on the transition towards heating without natural gas.

3. Research approach

Our approach consists of three steps, as proposed in Moncada et al. (2017) and Nava Guerrero et al. (2019). First, we structure the problem in terms of actors, technology, institutions, and interactions. Second, we conceptualize and formalize an agent-based model (ABM). Finally, we use the ABM to simulate changes to heating systems and insulation levels in the illustrative neighbourhood over 30 years. The simulation and analysis of results was guided by the following sub-questions:

1) In an ABM of an illustrative neighbourhood in The Netherlands,
   a) how to represent individual household preferences?
   b) how to represent group decisions between and within HOAs?
2) Under which socio-technical conditions would the illustrative neighbourhood phase out natural gas?
3) Under different socio-technical conditions:
   a) how would household individual preferences vary?
   b) how would household individual and group decisions vary?
   c) how would the costs of the transition vary?

The ABM represents an illustrative neighbourhood that includes dwelling features that are present in the residential built environment in The Netherlands, as described in 4.2.3.1. The model is parameterized using desk research, estimates, and assumptions. When applying our ABM to specific neighbourhoods, parameters and assumptions can be validated on a case by case basis.

We implement the ABM using the NetLogo software (version 6.0.4) (Wilensky, 1999).

We analyse simulation results using the statistical computing software R Project (version 3.6.2) (R Core Team, 2018) through R Studio (version 1.1.463) (RStudio Team, 2016), where we loaded the packages ggplot2 (version 3.2.1) (Wickham, 2016) and sqldf_0.4–11 (Grothendieck, 2017). Our analysis consists of visual inspection of numerical trends. As validation, we conduct a sensitivity analysis and consult expert publications and news.

4. Agent-based modelling of heat transitions

4.1. Heat transitions in the Dutch housing sector as a structured problem

In this section, we present our conceptualization of heat transitions in the owner-occupied share of the Dutch housing sector, at the level of one neighbourhood, from the perspectives of STS and CAS. We illustrate this view in Fig. 1, and describe it below.

First, we conceptualize technology as dwellings, buildings, and external infrastructure. Some dwellings are independent buildings, such as terraced houses, and others are part of strata buildings, such as apartments. Each dwelling has an insulation level, a heating system, and heat-related appliances, such as stoves. Dwellings are connected to external infrastructure: the natural gas network to fuel their heating systems and appliances, and the electricity network. Dwellings can also be connected to a heat network. In Fig. 1, technology is part of the technical subsystem, in green (in the web version).

Second, we conceptualize actors as households, energy suppliers, and contractors. Households in strata buildings are grouped in HOAs. Energy suppliers include suppliers of natural gas, electricity, and heat from networks. Contractors sell and install heating systems and insulation measures in dwellings. In Fig. 1, actors are part of the social subsystem, in blue (in the web version).

Third, we conceptualize institutions as contracts between households and suppliers and between households and contractors, regulations within and between HOAs, and public policy interventions. Institutions permeate both the technical and social subsystems. In Fig. 1, they are illustrated in magenta (in the web version).

Policy interventions are included at the bottom-right of Fig. 1 and are external to the neighbourhood, i.e. they influence the social and technical sub-systems but these sub-systems do not influence the policies. Market conditions, i.e. prices of energy, heating systems, and insulation measures, are external factors for the same reason.

4.2. Model description

The description of the ABM is based on the ODD protocol by (Grimm et al., 2010), which has been found useful to clarify content and features, and to provide input for further analysis. Accordingly, we present a model overview (4.2.1), design concepts (4.2.2), and details (4.2.3).

4.2.1. Model overview

4.2.1.1. Purpose. The purpose of this ABM is to explore how group decisions by households could influence household adoption of competing combinations of insulation measures and heating systems without natural gas under policy interventions. We explore a residential and owner-occupied illustrative neighbourhood with independent and strata buildings, where households have perfect or bounded financial rationality.

We use the key performance indicators (KPIs) from Table 1 to measure the influence of group decisions on natural gas connections and use, heating costs, and "group lock out". A household has group lock out when it was not able to adopt its preferred option due to a group decision.

4.2.1.2. Entities, variables, and scales. The ABM has agents, objects, environment, and time. Agents are households; the environment is

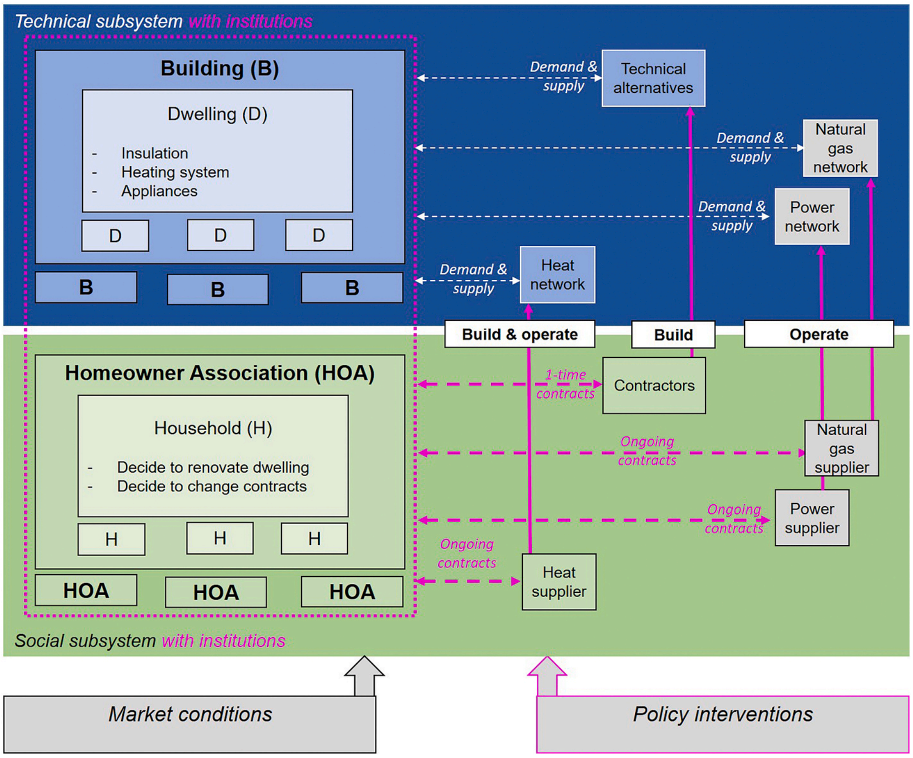

Fig. 1. Illustration of our view of the problem at the level of one neighbourhood, from the perspective of STS and CAS.

Table 1
KPIs.

KPI	Units	Description
Households using natural gas	Number of households	Number of households that are using natural gas.
Natural gas consumption	MWh	Cumulative sum of natural gas consumption of all households.
Heating costs	k€	Cumulative sum of investment and running costs. Investment costs are upfront costs to change states. Running costs include annual fees and fuel costs.
Households with group lock out	Number of households	Number of households with group lock out at a given point in time.

Table 2
State variables of households.

State variable	Type	Description
Type of dwelling	Static	Apartment or terraced house.
Building ID	Static	Identifier that links a household to its HOA.
TS	Variable	Current TS, from the 7 possible TS from Table 4.
Previous TS	Variable	Previous TS different to its current TS.
IDR	Static	Market discount rate (ρ_{market}) for households with perfect financial rationality, and a higher discount rate (ρ_{bnd}), for households with bounded financial rationality.

information from quorums, market conditions and policy interventions, and one time step models a year. We study simulation results for 30 years, starting in 2019.

Households – The state variables[1] that describe households are summarized in Table 2. Households live in dwellings that are either independent (terraced house) or part of strata buildings (apartment), as described by the *type of dwelling*. Apartments are grouped in HOAs, identified by the *building ID*. For implementation reasons, terraced houses are part of a HOA with a single member (themselves). The technology state (*TS*) of a household describes its dwelling's combination of heating system, insulation level, and appliances. At all times, households can choose between seven TSs, summarized in Table 4. We selected these TSs to explore the situations from Table 3.

A household's *previous TS* is the last TS that a household had before its current TS.

Finally, a household's *IDR* is an implicit discount rate that the household uses when comparing and selecting its preferred TS. An

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[1] State variables, also known as properties, may be static or change over time.

Table 3

Situations that we explore with our chosen TSs.

Situation	Motivation
TSs that involve one household vs TSs that require coordination between and within HOAs	As discussed in the previous sections (1–4.1).
TSs that require smaller renovations vs those that require major ones	Filippidou et al. (2017) argue that deep renovations rather than individual improvements in energy efficiency are needed for the non-profit housing sector in The Netherlands to meet its targets.
TSs with lower upfront costs vs TSs with higher ones	Upfront costs have a greater marginal impact on NPV calculations compared to cash flows at later times, with discount rates greater than zero; however, large upfront investments could also reduce future operation costs.
TSs consisting only of demand reductions vs those consisting of the phasing out of natural gas	Available policies target different objectives. For example, there are subsidies for insulation (Rijksoverheid, 2016b) and also subsidies for heat pumps (Rijksoverheid, 2017).

implicit discount rate (IDR) represents financial and non-financial factors that influence household decisions. Schleich et al. (2016) explain that IDRs are estimates based on observed technology adoption choices; they are the discount rate that would render a specific choice reasonable in a net present value (NPV) calculation. In other words, they represent the opportunity costs of capital and additional barriers that prevent optimal financial decision making. As noted by Schleich et al. (2016), authors have found IDRs to be typically higher than the costs of capital in studies of the adoption of energy technologies by households (Dubin and McFadden, 1984; Hausman, 1979; Train, 1985).

Quorums – We define two quorums: HOA Quorum and HN (heat network) Quorum. The former represents the percentage of households in a HOA that must approve a collective project in order for the project to be binding for all households in the HOA. The latter represents the percentage of households in the neighbourhood that must be willing and able to join a heat network for such heat network to be constructed.

Market conditions – Market conditions consist of electricity, natural gas and heat retail prices of energy suppliers, and contractors' fees for carrying out changes in heating systems and insulation.

Policy interventions – We include two types of public policy interventions: fiscal and disconnection. We base these policies on the Climate Agreement (Rijksoverheid, 2019d) and national laws (PAW, 2019; *Warmtewet - BWBR0033729*, 2019). The fiscal policies are assumptions of an annual linear increase in taxes on natural gas (P-TXG), an annual linear decrease in taxes on electricity (P-TXE), and regulated price of heat from networks in the form of heat prices that are coupled to natural gas prices (P-RHP). The disconnection policy would require households to replace heating systems and appliances that use natural gas. We include the disconnection policy as a thought experiment based on the amendment to The Dutch Crisis and Recovery Act (Crisis- en herstelwet—BWBR0027431) and the hypothetical disconnection of a testing ground (PAW, 2019).

Each policy intervention has a reference and an alternative mode. In the reference mode of the disconnection policy, households are not required to disconnect from the natural gas network, and in the alternative mode, they are. The fiscal policy interventions are operationalized as follows. In both modes of P-TXG and P-TXE, real data is used for 2019 and 2020. This data is presented in Appendix A. From 2021 to 2026, taxes on natural gas increase as suggested by the Climate Agreement: 1 Eurocent per cubic meter per year, equivalent to 0.001024€/kWh per year. After 2026, in the reference mode of P-TXG, taxes on natural gas remain constant, and in the alternative mode, they continue to increase at the same rate. Between 2021 and 2026, taxes on electricity decrease by a total of 5 Eurocents per kWh, as suggested by the Climate Agreement. In our ABM, this decrease is linear: 0.833 Eurocents per year. After 2026, in the reference mode of P-TXE, they remain constant, and in the alternative mode, they continue to decrease at the same rate until zero. In the reference mode of P-RHP, the heat price increases in proportion to the sales price of natural gas (SPG), which we define as the sum of its retail price and taxes (see **Equation (1)** and **Equation (2)**). In the alternative mode of P-RHP, the regulated heat price remains constant.

$$SPG\ (t) = retail\ price\ of\ natural\ gas(t) + tax\ on\ natural\ gas(t) \tag{1}$$

Equation (1) Sales price of natural gas

$$Heatprice(t) = \left(1 + \frac{SPG(t) - SPG(t-1)}{SPG(t-1)}\right) {*} Heatprice(t-1) \tag{2}$$

Equation (2) Heat price in the reference mode of P-RHP.

Based on the two modes of each of the four policy interventions, 16 combinations of modes are possible. We refer to these combinations as regulatory environments (REs). In the name of each RE, the alternative mode of each policy intervention is indicated with a suggestive letter: G for P-TXG, E for P-TXE, H for P-RPH, and D for the disconnection policy. The reference mode is always indicated with 0. We fix the order of the policy interventions as just mentioned. For instance, we denote by GEHD the RE where all policy interventions are in alternative mode, and we denote by GE00 the RE where P-TXG and P-TXE follow the alternative mode, but P-RHP and disconnection policy follow the reference modes.

4.2.1.3. Process overview and scheduling. Process overview – The main processes in the model, which take place every time step, are:

1) Households compute their individual preferences over TSs under the current market conditions and RE. See the individual preferences submodel in section 4.2.3.3 for details.
2) The group decision-making process takes place in two steps.
    a. The first step takes as input the individual preferences of the households in the HOA and outputs whether there is HOA Quorum for a heat pump (TS6:HP1) or a heat network (TS5:HN2

Table 4

TSs available to households.

TS	Type	Heating system	Insulation level[a]	Appliances
1:GB3	Individual	Natural gas boiler	3	Natural gas
2:EB3	Individual	Electric boiler	3	Electric
3:GB2	Individual	Natural gas boiler	2	Natural gas
4:EB2	Individual	Electric boiler	2	Electric
5:HN2	Collective: neighbourhood	Heat network	2	Electric
6:HP1	Individual (for terraced houses) Collective: HOA (for apartments)	Heat pump	1	Electric
7:HN1	Collective: neighbourhood	Heat network	1	Electric

[a] Where an insulation level of 3 is the lowest and 1 the highest.

   and TS7:HN1). For heat networks, we count households with preferences for either TS5:HN2 and TS7:HN1.
   b. In the second step, towards the HN Quorum we count all households in HOAs in which the HOA Quorum was met for heat networks (*winner-takes-all* in each HOA).

3) Households determine their TS in the next time step based on their individual preferences and the outputs of the group decision-making process. This individual process has three steps.
   a. If the HN Quorum was met or a heat network from a previous time step exists, HOAs with HOA Quorum for heat networks decide between TS5:HN2 and TS7:HN1 as follows. If most households prefer TS5:HN2, all households with insulation level of 2 or lower adopt TS5:HN2 and households with an insulation level of 1 adopt TS7:HN1. Otherwise, all households adopt TS7:HN1.
   b. Households in HOAs with HOA Quorum for TS6:HP1 (heat pump) adopt TS6:HP1.
   c. Households in HOAs in which the HOA Quorum was not met for a collective TS adopt their most-preferred individual TS.

Scheduling – In the first time step, the households using natural gas are computed to record the initial conditions of the neighbourhood. Every following time-step, energy prices are updated and the ABM records the neighbourhood's natural gas consumption. After that, the main processes take place: households compute (in random order) their individual preferences, the group decision-making processes are carried out, and once these have all completed, their results are observed by households and households' next TS is determined. Households replace heating systems that reached the end of their lifetime and broke down. Finally, households using natural gas, heating costs, and households with group lock out are computed.

4.2.2. Design concepts

Our ABM incorporates the following design concepts: heterogeneity, objectives, prediction, group decisions, sensing, interaction, stochasticity, collectives, and observation.

Heterogeneity is the first design concept. Households are heterogeneous because they have different types of dwellings and different IDRs. Their objective is to minimize heating costs via NPV calculations (see 4.2.3.3). We model households that have perfect prediction of future market conditions and policy interventions and that are grouped in HOAs, which are collectives.

Group decisions are a second design concept. As part of the group decision-making process, households can sense the outcome of group-decisions within their HOA and between HOAs in the neighbourhood. These are the only interactions between households in the ABM.

Observation and stochasticity are also part of the ABM. Observation takes place via the KPIs from Table 1. Stochasticity is part of the model initialization: IDRs are assigned uniformly at random to households. Therefore, the distribution of IDRs in a HOA may not be representative of the entire population.

4.2.3. Details

4.2.3.1. Initialization. We conceptualize and model an illustrative neighbourhood in which heat networks are a financially competitive option with respect to other alternatives to natural gas, but are not yet present in the neighbourhood. Our illustrative neighbourhood has 520 dwellings: 160 terraced houses, 5 buildings of 60 apartments each, and 10 buildings of 6 apartments each. We selected this set to represent both independent dwellings and dwellings in strata buildings of different sizes. We represent a HN Quorum of 75% and a homogeneous HOA Quorum of 70% for all HOAs.

Table 5
Initial annual natural gas consumption of dwellings in the ABM.

Type of dwelling	Natural gas consumption
Apartment	980 m^3
Terraced house	1330 m^3

Table 6
Factors for the simulation.

Factor	Description	Variations	Values
RE	Combination of policy interventions	16	G000, G0H0, GE00, GEH0, G00D, G0HD, GE0D, GEHD, 0000, 00H0, 0E00, 0EH0, 000D, 00HD, 0E0D, 0EHD
Population of IDRs	Fraction of households with ρ_{bnd} and fraction of households with ρ_{market}.	3	0–1 0.25–0.75 1–0

Initially, households have TS1:GB3, i.e. low insulation and natural gas-fuelled boiler and appliances. For simplicity, we assume that all boilers need to be replaced after the first time step because they reached the end of their lifetime. These features roughly represent dwellings from the period between 1965 to 1974, with energy labels C to D, and annual natural gas use from Table 5. Description and estimates are loosely based on (CBS, 2019) and the online tool (Milieu Centraal & Rijksoverheid, n.d.).

We assume a ρ_{market} of 2.33%. This value is the average interest rate for 30 annuity mortgage products in the Netherlands, on March 10, 2020, for existing buildings at 100% of market value over 30 years (De Hypotheker, 2020). We assume that households would be able to complement their mortgage with an additional loan for energy-related renovations, and that such additional loans would have the same discount rate used for mortgages.

We assume a ρ_{bnd} of 36%, which was the value of ρ_{bnd} in an empirical case study of a UK district heating scheme by Burlinson et al. (2018). They used traditional and behavioural theories to explore decision-making of energy consumers, which they found to undervalue future energy costs. The high IDR was partially explained by consumer inattention and heuristics.

We use the ABM to simulate the changes in the TS of households in the neighbourhood over time, and study simulation results for 30 years, starting from 2019. We use the simulations to compute the KPIs over time, under different combinations of factors (see Table 6). Each combination is one of 48 experimental scenarios. When the ABM is initialized, each household randomly gets a discount rate. When discount rates are homogeneous, the model is deterministic; otherwise, there is stochasticity. To account for this stochasticity, we simulate the former scenarios only once, and the latter, 10 times.

4.2.3.2. Input data. Input data consists of market conditions, i.e. energy prices and prices of TSs (see Appendix A).

4.2.3.3. Individual preferences submodel. Households compare available TSs to determine their preferred one. As illustrated in Fig. 2, a household's TS constrains the TSs from which the household can choose. There are three constraints: (1) an improvement in insulation cannot be undone, e.g. insulation cannot go from level 2 to level 3, so it is not possible to transition, for instance, from TS4:EB2 to TS2:EB3; (2) after a dwelling was disconnected from natural gas, it cannot be reconnected; (3) under the disconnection policy, TSs that use natural gas are unavailable.

Households use the lifetime-cost (LTC) sub-model from **Equation (3)** to compute their preferences over TSs. Our LTC submodel can be seen as a refinement of the LTC submodel by Burlinson et al. (2018), which is based on Hausman (1979).

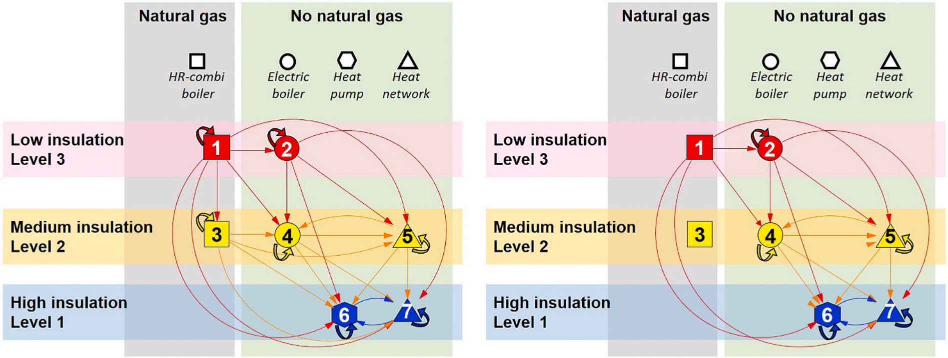

Fig. 2. Possible changes in household TSs. (a) Possible changes without the disconnection policy. (b) Possible changes under the disconnection policy.

$$LTC(s,s',\rho,t) = UC(s,s') + \sum_{k=0}^{\beta} \frac{AC(s',t+k)}{(1+\rho)^{k}} + \sum_{j=1}^{\frac{\beta}{\tau}-1} \frac{RC(s')}{(1+\rho)^{j\tau}} \tag{3}$$

Equation (3) LTC submodel.

We define *LTC(s,s',ρ,t)* to represent the net present value (NPV) of changing from TS *s* to TS *s'* with heating system lifetime given by *τ*, and maintaining *s'* over time horizon β, while using discount rate ρ. The LTC of a TS is calculated via the upfront costs (*UC*), the annual costs (*AC*), and the reinvestment costs (*RC*) of a household.

AC can change over time as a result of fiscal policy interventions, and we let *AC(s,t)* denote the annual cost of a household with TS *s* at time step *t*. We assume that households have perfect knowledge of future market conditions and regulatory environments and therefore they can access *AC(s,t)* for future time steps *t* in their LTC-calculation. We provide a detailed breakdown of *AC* in Appendix A.

Each household uses the LTC calculation to compare the lifetime-cost of all TSs available to them, including the current one. Heating systems can have different lifetimes and would therefore require different time horizons for the LTC. Following van den Boomen et al., 2017, to enable their comparison, we include reinvestment costs (*RC*) in addition to *UC* and *AC*. For instance, if a heating system *h1* has a lifetime of 30 years and another heating system *h2* has a lifetime of 15 years, we compute the LTC over 30 years without *RC* for *h1* and with one reinvestment for *h2* in year 15. We let *RC(s)* denote the cost of reinvesting in the heating system of TS *s*. We exclude *RC* for insulation and appliances: we assume that no *RC* are required for insulation and that *RC* for appliances are equal for all TS and would therefore have no differential effect. Furthermore, in order to compare LTC-values for all TSs, we take a uniform horizon β equal to the lifetime of the available heating system with the longest lifetime. For simplicity, we assume that maintaining the same TS requires an initial reinvestment. Finally, *UC(s,s')* denotes the upfront cost of switching from TS *s* to TS *s'*, and we assume this cost remains constant during the simulation.

Each household uses either $\mathrm{LTC_{ideal}}$ or $\mathrm{LTC_{bnd}}$ to determine its individual preferences. They prefer TSs with lower LTCs. We ignore that if a household were to improve its insulation without changing its heating system (TS1:GB3 to TS3:GB2 or TS2:EB3 to TS4:EB2), the heating system might no longer be at the beginning of its lifetime and might have to be replaced earlier than anticipated. When the change is implemented, the age of the new TS is set to zero.

Operationally, a household has group lock out in a TS *s* after having made an adoption decision in time step *t* if there is a TS *s'* such that *LTC(s,s',ρ,t)* < *LTC(s,s,ρ,t)*. In other words, it could not adopt its preferred TS due to a group decision.

Households use the LTC submodel to compute ideal estimates ($\mathrm{LTC_{ideal}}$) and bounded estimates ($\mathrm{LTC_{bnd}}$). They use a market discount rate (ρ_{market}) in the former, and a higher discount rate (ρ_{bnd}) in the latter, that is:

$LTC_{\mathrm{ideal}}(s,s',t) = \mathrm{LTC}(s,s', \rho_{\mathrm{market}}, t)$ and $LTC_{\mathrm{bnd}}(s,s',t) = \mathrm{LTC}(s,s', \rho_{\mathrm{bnd}}, t)$

4.3. Discussion of modelling choices

Our modelling choices affect the way in which the model can be used and its results. In this subsection, we discuss our main modelling choices and alternative ways of modelling.

4.3.1. Household prediction of future policies and prices

We assume that households have perfect knowledge of future market and policy developments in their LTC calculation. As a result, households have the same preferred TS over most of the simulation, and hence the only changes in TS happen in the initial years. It would be more realistic to drop this assumption and let households make predictions for annual costs based on current taxes, and let energy taxes (and potentially prices) fluctuate as opposed to using a simple linear growth in taxes. This could lead to more dynamic outcomes where households change their TS more often.

4.3.2. Input data for market conditions and the technological subsystem

Input data for market conditions, such as *UC*, *RC*, and technical specifications for each TS, influences the preferred TSs of households. As noted in Appendix B, variations in input data could lead to households preferring a different TS. This is also the case for the prices of natural gas and electricity, which we assume to be constant but can in reality be uncertain and fluctuating.

Moreover, we would expect some *UC* to be different than we estimated. We parameterized the model using estimates and assumptions rather than, for example, requesting commercial quotes. Moreover, we explicitly modelled a neighbourhood in which heat networks could be financially competitive with respect to other alternatives to natural gas. This choice allowed us to explore the effect of group decisions via the HN Quorum and HOA Quorum. However, we expect the cost of building or expanding a heat network, and the *UC* for households, to be case specific.

A third remark concerns our use of input data for demand reduction associated with a change of TS. Implicitly, we consider theoretical rather than actual demand reduction when households improve dwelling insulation. In practice, researchers have observed a phenomenon known as the energy performance gap. When energy renovations are carried out, households tend to have a higher energy demand than theoretically expected (Filippidou et al., 2019; Majcen et al., 2013). Accounting for the energy performance gap in our ABM could lead to different results.

Finally, we conceptualized and modelled a heat network that can provide medium (TS5:HN2) and low temperature (TS7:HN1) heating to different dwellings. In future research, it would ideally be replaced by a heat network design that accounts for physical constraints specific to the neighbourhood.

4.3.3. *Modelling of policy interventions*

We model simplified policy interventions. In reality, the regulated heat price is published every year by The Netherlands Authority for Consumers and Markets (ACM), a national regulator. The calculations published by the ACM (ACM, 2019) go beyond our assumption of the heat price changing in the same percentage as the natural gas price. Moreover, our disconnection policy requires households to replace their heating systems the year after the policy is implemented. However, this transition could take place over multiple years. A more realistic way of representing these policies would be to have a more detailed calculation for the regulated heat price and a disconnection policy that allows households to replace their heating systems over a longer time frame.

4.3.4. *Individual preferences*

Schleich et al. (2016) recommend the use of different IDRs per household and technologies. In this work, we model a population of households with different IDRs (ρ_{market} or ρ_{bnd}). We assumed that households had a ρ_{bnd} of 36%, a number determined in a case study by Burlinson et al. (2018) regarding heat networks. We expect that this percentage, and even its order of magnitude, can vary on a case by case basis. Instead of assuming a percentage, one could determine the IDR empirically, and instead of using a single value, one could explore how individual preferences would change within a wide range of IDRs. Further, in our ABM, each household uses the same IDR to compare competing TSs; instead, as recommended by Schleich et al. (2016), household could use different IDRs per TS. Finally, because discount rates do not necessarily make the barriers of technology adoption explicit, their use can hamper the design of effective policies to target non-financial preferences (Schleich et al., 2016).

Accordingly, our use of IDRs constrains the purposes for which our ABM can be used. We represent household decisions under the assumption that IDRs are static, and equal for different TSs. Therefore, this ABM can be used in an "if … then/how …" manner. For instance, a suitable modelling question would be: *if* 50% of households in a neighbourhood had ρ_{market} and 50% had ρ_{bnd}, *how* would financial policies, or the disconnection policy, influence natural gas consumption over time, under our set of assumptions? Using our ABM to explore policies to increase adoption would require the explicit inclusion of underlying factors that explain ρ_{bnd}, and policies that could effectively influence those underlying factors.

In addition, we model households that are always financially able to change their TSs. After a change, they do not wait to recover their investment. In reality, households that recently made an investment might not make a new investment, even if it would reduce their future LTC.

In the LTC, we ignore that when a change in TS improves insulation but does not replace a heating system, the remaining lifetime of the heating system would not be as long as if it were a new heating system. This could overestimate the financial attractiveness of changing from TS1:GB1 to TS3:GB2 or from TS2:EB3 to TS4:EB2. Finally, instead of assuming that maintaining the same TS requires an initial reinvestment, the age of the heating system could be considered.

Table 7
Individual household preferences in the initial TS, under each RE and using ρ_{market}.

RE	Preferred TS	Subsequent preferred TSs
XXX0	TS3	TS1, TS7, TS5, TS6, TS4, TS2
XXXD	TS7	TS5, TS6, TS4, TS2

Table 8
Individual household preferences in the initial TS, under each RE and using ρ_{bnd}.

RE	Preferred TS	Subsequent preferred TSs
XXX0	TS1	TS3,TS2, TS4, TS5, TS7, TS6
XXXD	TS2	TS4, TS5, TS7, TS6

4.3.5. *Group decisions*

Our use of quorum constraints is a simplified representation of group decisions, including the realization of a heat network. Other factors, such as leadership and information processes, have been found to play a role in group decision-making (Roodenrijs et al., 2020). There are also various ways to realize heat networks (den Dekker et al., 2020; Busch et al., 2017). Moreover, our ABM has the implicit assumption of household preferences not being influenced during group decision-making processes, and the explicit assumption that all HOAs always use the same quorum. However, preferences may be influenced and type and value of quorums can vary between HOAs and types of decisions. Future work can include an empirically grounded conceptual model for group decisions in our ABM.

5. Results and discussion

In the following subsections, we answer the second and third sub-questions from Section 3. Datasets with simulation results are included as supplementary material.

5.1. *Socio-technical conditions for the transition*

The disconnection policy was the only necessary and sufficient condition for households to disconnect from natural gas. This outcome was independent of the population of IDRs. Hence, no combination of fiscal policies enabled the heat transition, and without the disconnection policy, group decisions did not have a differential influence on households' decision to stop using natural gas.

5.2. *Initial individual household preferences*

In Table 7 and Table 8, we summarize households' individual preferences at the beginning of the simulation. We rank TSs based on their LTC, from lowest to highest. The letter "X" indicates both the reference and alternative mode of a policy. Appendix B contains detailed quantitative results.

Firstly, the preferences of households using ρ_{market} were as follows. Without the disconnection policy, households preferred to maintain their natural gas boiler and improve their insulation level from 3 to 2 (TS3:GB2). Under the disconnection policy, households preferred a low temperature heat network with insulation level 1 (TS7:HN1). However, the ranges across REs of the LTC of their first and second most preferred TSs (TS7:HN1 and TS5:HN2) overlapped. These ranges are shown in Table 9, where cells with a single number indicate a range smaller than 100€.

Uncoupling the heat price from the price of natural gas reduced the financial attractiveness for households to reduce their heat demand by selecting a low temperature heat network (TS7:HN1) rather than a medium temperature one (TS5:HN2). When the heat price remained coupled with the natural gas price, the difference between the LTC of these TSs ranged between 0.6 and 1.4k€ for apartments and 0.9–1.9k€ for terraced houses. When the heat price was decoupled, the difference was 0.2k€ for apartments and 0.3k€ for terraced houses. These

Table 9
Ranges of the LTCs in the initial TS.

Source	TS	Apartments		Terraced houses	
		Ideal estimates (k€)	Bounded estimates (k€)	Ideal estimates (k€)	Bounded estimates (k€)
Natural gas	TS1:GB3	26.1 - 28	5.7	33.7 - 36.3	7.4 - 7.5
	TS3:GB2	24.7 - 26.3	6.4	31.8 - 34	8.4
Electricity	TS2:EB3	53.9 - 60.5	15.1 - 15.3	67.5 - 76.5	19.5 - 19.7
	TS4:EB2	52.6 - 58.3	17.1 - 17.2	65.7 - 73.5	22.2 - 22.4
	TS6:HP1	45.7 - 46.5	24.1	56.3 - 57.3	31.6
Heat from network	TS5:HN2	36.9 - 39.5	17.7 - 17.8	46.7 - 50.1	23.4 - 23.5
	TS7:HN1	36.7 - 38.1	23.1	46.4 - 48.2	30.6 - 30.7

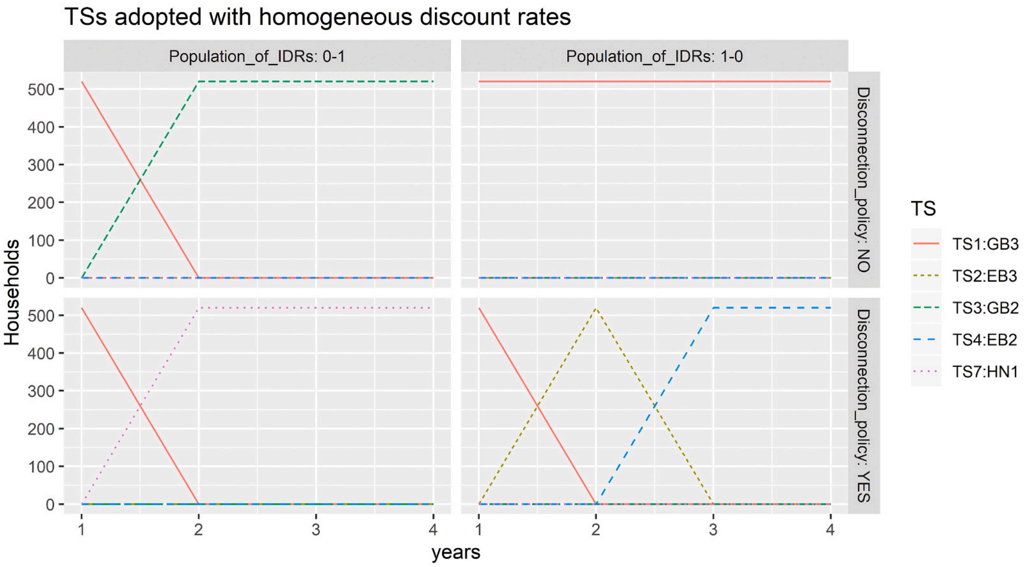

Fig. 3. TSs adopted in the neighbourhood when households had homogeneous discount rates. The left column represents populations in which all households had ρ_{market} (0–1), and the right, ρ_{bnd} (1–0).

differences are equivalent to less than 4% (reference mode) and 1% (alternative mode) of the LTC of TS7:HN1. Although TS7:HN1 was always the cheapest option, in order for households to save 0.6–1.9k€ over 30 years with respect to TS5:HN2, they would have to make an additional investment of *UC* of 6.5k€ to 8.8k€.

Fig. 4. TSs when households had heterogeneous discount rates, without the disconnection policy.

Secondly, the preferences of households using ρ_{bnd} were as follows. Without the disconnection policy, households preferred to remain in their current TS1:GB3. Under the disconnection policy, households preferred TS2:EB3. High IDRs drove these households to prefer a TS with high *AC* and low *UC*.

Finally, to enable the transition without the disconnection policy, the LTC of TS3:GB2 would have to be at least as high as the LTC of TS7:HN1. This could be theoretically achieved, for example, by changing the fiscal policies or subsidizing *UC*.

In the case of households using ρ_{market}, assuming that there is also a cap on the price of heat from networks after 2020, the tax on natural gas after 2026 would have to be in the order of 0.1€/kWh for the LTC of TS3:GB2 to match the LTC of TS7:HN1. Alternatively and theoretically, a subsidy for *UC* would have to be in the order of 10–15k€.

We also explore the case of households using ρ_{bnd}. For the LTC of TS1:GB3 to match the LTC of TS7:HN1, assuming that there is also a cap on the price of heat from networks after 2020, the tax on natural gas after 2026 would have to be in the order of 3€/kWh. Alternatively and theoretically, a subsidy for *UC* would have to be in the order of 17-23k€. We consider these calculations to be a thought experiment because the required taxes and subsidies could be unaffordable.

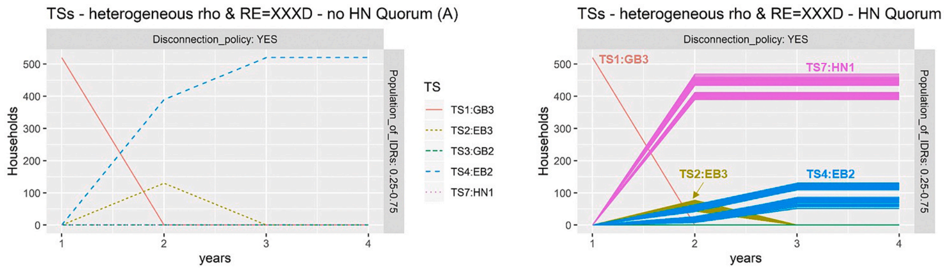

Fig. 5. TSs when households had heterogeneous discount rates, under the disconnection policy.

Fig. 6. TSs adopted in the neighbourhood after 2 years under RE = GEHD and Population of IDRs = 0.25–0.75. In each pair of boxplots, the boxplot to the left represents the households with each TS that had group lock out, and the boxplot to the left, those that did not.

5.3. Household decisions and group lock out

When households had homogeneous discount rates, either TS2:EB3 or TS7:HN1 were preferred by all households. As a result, households were able to adopt their preferred TS because it was individual or because they agreed to adopt the same collective TS. Therefore, there was no group lock out. Fig. 3 illustrates those choices depending on whether the disconnection policy was active and whether all households had ρ_{market} or ρ_{bnd}. Fig. 3 shows only the first four years of simulation because there were no further changes afterwards. Note that when all households had ρ_{bnd}, they first replaced their natural gas boiler for an electric one (TS2:EB3) and only later improved their insulation (TS4:EB2).

Results differed when households had heterogeneous discount rates (75% had ρ_{market} and 25% had ρ_{bnd}). When there was no disconnection policy, as shown in Fig. 4, households with ρ_{market} were able to adopt their preferred TS4:EB2, which was individual, and there was no group lock out. However, when the disconnection policy was in place, HOA Quorums and the HN Quorum were not always met. When the HN Quorum was not met (Fig. 5 A), households with ρ_{market} were not able to adopt their preferred TS7:HN1. Instead, they chose their preferred individual option (TS4:EB2) and experienced group lock out. This was also the case when the HN Quorum was met in the neighbourhood but the HOA Quorum was not met in a given HOA (Fig. 5 B). The thicker lines in Fig. 5 B represent results from different experimental scenarios in which there was stochasticity (see 4.2.3.3). Households with ρ_{bnd} who were able to make individual decisions initially replaced their natural gas boiler for an electric one (TS2:EB3) and improved their insulation the year after (Fig. 5 A and B).

Therefore, in spite of 75% of households preferring TS7:HN1, group decisions resulted in instances in which the HN Quorum was not met. In these cases, the adoption decisions in the neighbourhood were not a simple mix of individual preferences; instead, the model behaviour

Table 10
Values for the sensitivity analysis.

Parameter	Units	Nominal value	New values	Population of IDRs	Repetitions
HOA Quorum	%	70	63, 77	0.25–0.75	10
HN Quorum	%	75	67.5, 82.5	0.25–0.75	10
ρ_{market}	%	2.33	2.1, 2.56	0–1	1
ρ_{bnd}	%	36	32.4, 39.6	1–0	1

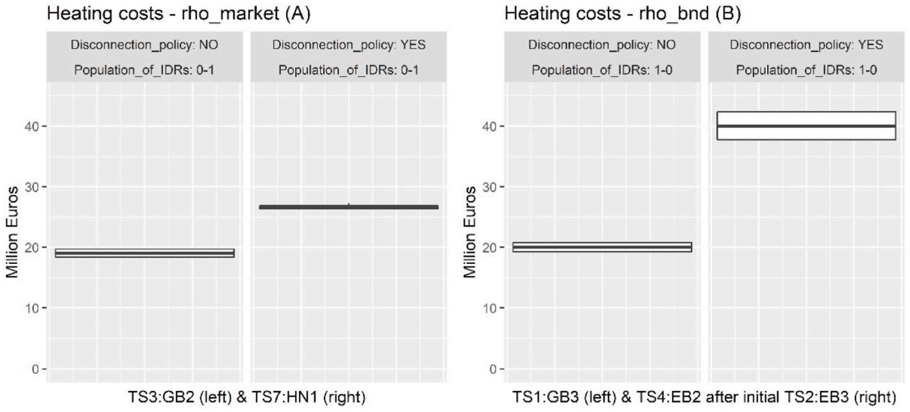

Fig. 7. Heating costs when all households had ρ_{market} (A) or ρ_{bnd} (B), after 30 years.

displayed emergence.

The boxplots in Fig. 6 illustrate one of these situations at the end of 2 years of simulation and under the disconnection policy. In each pair of boxplots, the boxplot to the left represents the households with each TS that had group lock out, and the boxplot to the right, those that did not. The large green (in the web version) boxplot to the right indicates that in most simulation runs, households that chose TS7:HN1 were able to choose their preferred TS, and the small green (in the web version) boxplot to the left indicates that some households that chose TS7:HN1 had group lock out, i.e. they had to choose such TS because it was the preferred by 70% or more of their HOA peers. Likewise, the large red (in the web version) boxplot to the left and flat red (in the web version) boxplot to the right, at zero, indicate that TS4:EB2 was chosen only by households unable to choose their preferred TS (TS7:HN1).

5.4. *Heating costs of the transition*

The heating costs of the transition depended on the TSs that households adopted and the REs. Different REs established different combinations of natural gas taxes, electricity taxes, and price of heat from networks. Therefore, the same choices of TSs could lead to different heating costs depending on the REs. In Fig. 7, we plot the neighbourhood's cumulative heating costs after 30 years of simulation when households had homogeneous IDRs. Each boxplot represents the heating costs that resulted from household decisions under a group of REs and discount rate. For instance, the first boxplot of Fig. 7 A represents the heating costs under RE = XXX0, when all households used ρ_{market} and selected TS3:GB2. Note that we ignore that the LTC period of different TSs might not yet be complete (see Figs. 4 and 5 for the years in which TSs were initially adopted).

As discussed in 5.1, we confirmed that the heating costs of the transition were higher than the heating costs of using natural gas. In spite of fiscal policy interventions, disconnecting a dwelling from natural gas was never financially advantageous. Fig. 7 also confirms that, when there was a transition (XXXD), heating costs were lower when all households used ρ_{market} than when all used ρ_{bnd}.

6. Validation

In the following subsections we discuss the sensitivity analysis and consultation of expert publications and newspaper articles as forms of validation.

6.1. *Sensitivity analysis*

We conducted one-factor-at-a-time (ten Broeke et al., 2016) sensitivity analysis on the four variables from Table 10. The sensitivity values were determined as 10% lower or higher than the nominal value.

6.1.1. *HN quorum and HOA quorum*

We explored different percentages for the HN Quorum and HOA Quorum when 75% of households used ρ_{market}. HN Quorums of 67.5% and 82.5% did not qualitatively affect the ways in which the transition could happen: under the disconnection policy, heat networks were sometimes but not always adopted by some households. In contrast, HOA Quorum variations did have a qualitative effect. When the HOA Quorum was 63%, heat networks were always adopted by some households, and when it was 77%, only in some random repetitions.

Table 11

Changes in household preferences when 0.23% < ρ_{market} =< 4.66%.

Household choices	RE	ρ_{market} (%)
Households adopted TS7:HN1 towards the end of the simulation.	G0H0	0.23, 0.47, 0.7
	GEH0	0.23, 0.47, 0.7, 0.93
By the end of the second year, households adopted TS5:HN2.	XXHD	2.8, 3.03, 3.26, 3.5, 3.73, 3.96, 4.19, 4.43, 4.66
	0X0D	3.26, 3.5, 3.73, 3.96, 4.19, 4.43, 4.66
By the end of the second yednar, households adopted TS5:HN2, maintained it for one or more years, and adopted TS7:HN1.	GX0D	3.96, 4.19, 4.43, 4.66

6.1.2. *Market discount rate*

A 10% decrease or increase in ρ_{market} (2.1 or 2.56% instead of 2.33%) did not change households' individual preferences nor their choices over time. However, the actual value of ρ_{market} could vary beyond the range that we explored. We assumed that households could receive a loan for energy renovations with the same interest rate as their mortgage. Other loans for house renovations can have higher interest rates, e.g. 4.2% on the basis of 15 years (Green Loans, n.d.) or 4.5% or higher on the basis of 8 years (ING, n.d.).

Therefore, we explored 18 additional values of ρ_{market} by further increasing and decreasing its nominal value in intervals of 0.233, i.e. from 0.23% to 4.66%. We only explored scenarios in which all households used ρ_{market}. The sensitivity results that were qualitatively different from the nominal results are summarized in Table 11.

6.1.3. *Implicit discount rate*

A 10% increase or decrease in ρ_{bnd} did not change households' individual preferences nor their choices over time. In practice, the value of ρ_{bnd} could vary further. As noted by Burlinson et al. (2018), authors have found implicit discount rates as low as 25% and higher than 100% (Train, 1985).

6.2. *Expert publications and newspaper articles*

Whether disconnecting dwellings from natural gas can be cost neutral, i.e. recovering investments via savings in the energy bill, is a known concern in The Netherlands. In August 2020, Schilder and van der Staak, 2020 reported that such cost neutrality is often not feasible. Although their study excluded collective solutions, this conclusion is in line with our own: in our ABM, the transition took place only under the disconnection policy. Furthermore, they highlighted the importance of the interest rate in the calculations: alternatives to the *status quo* became attractive for most of the households that they modelled under a hypothetical interest rate of 0% instead of 2%. These findings are also in line with ours: we found that under discount rates lower than or equal to 0.93% and under certain RE, the disconnection policy was no longer necessary. Furthermore, they also expect interest rates related to future building-related financing to be higher, as we discuss in 6.1.2.

Moreover, Schilder and van der Staak (2020) explain that even if savings compared to the *status quo* could be achieved over the lifetime of the alternatives, those savings would not necessarily justify the large upfront investment. In other words, cost neutrality might not be a sufficient incentive for households to transition. We represent this possibility by using a discount rate of 36%. They explain that although neighbourhood-oriented approaches could lead to cost-reduction due to economies of scale, such approaches pose coordination challenges.

Newspaper articles describe examples of such challenges. In *Het Financieele Dagblad*, McDonald (2020) reported that after two years of consultation, residents of owner-occupied dwellings in an Amsterdam neighbourhood preferred to postpone the decision to phase out natural gas. According to van den Berg (2021), an inventory conducted by *De Volkskrant* showed that only 206 houses in four of 27 testing grounds had been disconnected from natural gas. In the same year, McDonald (2021) discussed examples of dwellings that did phase out natural gas, and their costs varied. Our representation of group decisions is a step towards accounting for coordination challenges by using ABMs.

Our choice to model a disconnection policy is validated by McDonald's (2020a) reporting of potential future obligations to disconnect from natural gas in *Het Financieele Dagblad*. According to Verhelst (2019) in the same newspaper, a mandatory connection was described by the director of a Danish heat network as the most important condition for project success; otherwise, the necessary investments would not be possible. In our ABM, the transition was indeed achieved only with the disconnection policy. However, experts have raised concerns regarding such a potential obligation in the context of The Netherlands and about potential legislation (Huygen and Akerboom, 2020; van Vlerken, 2019).

7. Conclusions and policy implications

7.1. Conclusions

The main research question of this work is: How could individual and group decisions between building owners, and within HOAs in strata buildings, influence the course of the heat transition in a neighbourhood in The Netherlands, under different policy interventions? To answer this question, we took an agent-based approach and applied it to an illustrative example of a residential neighbourhood. We modelled three fiscal policies and a disconnection policy and explored how they would influence the adoption of alternatives to natural gas by households that make group decisions, under a set of specific assumptions.

We found that no combination of the fiscal policies that we explored incentivized households to disconnect from the natural gas network. The fiscal policies were based on the Climate Agreement (Rijksoverheid, 2019d), an amendment to The Dutch Crisis and Recovery Act (Crisis- en herstelwet—BWBR0027431), and the potential disconnection of a testing ground (PAW, 2019). The disconnection policy was the only necessary and sufficient condition for households to stop consuming natural gas.

Notably, under the disconnection policy, uncoupling the price of heat from networks from the price of natural gas decreased the incentive for households to further insulate their dwellings and decrease their energy demand. Households with bounded financial rationality preferred an electric boiler, and only later improved dwelling insulation. Households with perfect financial rationality preferred a low temperature heat network with high insulation. Because the heat price remained constant, the savings that households would have had by adopting a low temperature heat network with high insulation, compared to a medium temperature heat network with medium insulation, were smaller.

Group decisions influenced choices in the neighbourhood when there was a mix of households with perfect and bounded financial rationality. Although there were in principle sufficient households that preferred a heat network, group decisions sometimes resulted in unmet quorums. In those cases, households had to adopt their best individual option, i.e. an electric boiler with either low or medium dwelling insulation, depending on their implicit discount rate.

We found that our results were qualitatively sensitive to changes in two variables. First, the percentage of households that need to agree to a project within a homeowner association for that project to be realized. Second, to the discount rate that was used in lifetime cost calculations. When discount rates were equal or lower than 0.93%, and in combination with taxes on natural gas that continued to increase after 2026 and a cap on the price of heat from networks, the transition was possible without the disconnection policy, but only towards the end of the simulation.

It must be noted that the quantitative power of our ABM is limited. Our conclusions should not be used to select specific policy interventions or changes in technology because the nature of this work is exploratory. Instead, this work paves the way for future research in two directions. First, regarding the application of our approach to specific case studies. Second, regarding how to include group decisions between and within home owner associations in agent-based modelling studies of heat transitions and other types of transitions that involve group decisions between heterogeneous actors.

To use or adapt our agent-based model to study a neighbourhood, we recommend the following. Use input data specific to the neighbourhood. Consider the inclusion of decreased efficiency of heating systems due to ageing, reinforcement of the electricity network, and relevant transaction costs. Explore the sensitivity of the lifetime cost model to the financial data.

Future research to improve our agent-based model includes the following. Account for uncertainties in future prices. Use empirically determined implicit discount rates, different implicit discount rates for competing technologies and for different households, and model non-financial preferences of households explicitly. Account for heterogeneous quorums between and within homeowner associations, and for factors that influence group decisions. Account for the energy performance gap. Model policy interventions in more detail; in particular, the regulated heat price and the disconnection policy.

7.2. Policy implications

Under the assumptions of our agent-based model, we make the following observations.

A cost-neutral transition towards heating without natural gas would require additional policy intervention. We recommend to further explore potential subsidies for upfront costs, much higher taxes on natural gas, or relatively higher taxes on natural gas in combination with interest rates approaching zero and a cap on the price of heat from networks. However, their implications for affordability should also be considered.

Assuming financial rationality, policies that target upfront rather than operation costs could be more effective, e.g. initial subsidies rather than subsequent taxes. The fiscal policies that we modelled could, in theory, incentivize households to replace their natural gas-based heating systems or to choose one heating system over another. These policies artificially increase or decrease the operation costs associated to energy consumption. However, in our model, the difference between the lifetime costs of a heat network with medium insulation and one with high insulation was less than 5%, and the upfront costs of the former were about a third lower than those of the latter. Because future cash flows are discounted in a lifetime cost assessment, a change of X€ in the upfront costs would have a greater impact in the value of the project than a change of X€ in the operation costs over time.

Fiscal policies could have unexpected consequences, such as reducing the attractiveness of an option that might be desirable at a system level. In our model, uncoupling the heat price reduced the incentive for households to join a low rather than a medium temperature heat network. Therefore, policy makers should account for the interaction effects of policies that aim at enabling the transition. In particular, we recommend policy analysts and policy makers to focus on the interaction between incentives for insulation and incentives to phase-out natural gas.

Finally, because group decisions can influence adoption decisions, group decisions within and between homeowner associations should be taken into consideration in the design of policies.

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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Annex. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2021.112306.

Appendix A. Input data

In this Appendix, we describe input data regarding (1) technical specifications of TSs, (2) costs of TSs, (3) annual costs of TSs, and (4) energy taxes for 2019 and 2020. Input data is based on desk research, estimates, and assumptions.

10.1 1. Technical specifications of TSs

Each TSs is further described by cooking demand (kWh/year), thermal efficiency (fraction), lifetime of the heating system (years), heat demand of apartments, and heat demand of row houses. We consider the following:

- Cooking demand is assumed to be 361.47 kWh/year for natural gas, and 175 kWh/year for electrical appliances. See for example Milieu Centraal (n.d.).
- We define insulation levels in the following way:
  1. Level 3: lowest level; equivalent to energy label C to D.
  2. Level 2: medium level; equivalent to Level 3 plus windows with HR++ glass.
  3. Level 1: highest level; equivalent to Level 2 plus façade, floor, and roof insulation.
- Heat demand is expressed as the natural gas demand for apartments and row houses that have a natural gas boiler. It is based on (CBS, 2019) and (Milieu Centraal & Rijksoverheid, n.d.), and depends on insulation levels, as summarized in Table 12.
- We assume the following values for thermal efficiency of heating systems: 87% for natural gas boilers, based on (ACM, 2019), which we also assume for electric boilers; 100% for heat networks, based on (ACM, 2019), and 3.81 for heat pumps, based on (Hoogervorst et al., 2020). However, in the ABM, we use thermal efficiency of heating systems relative to natural gas boilers and use the following values: 100% for natural gas and electricity boilers, 1.15% for heat networks, and 4.38 for heat pumps.
- The lifetime (τ) of heating systems is assumed to be 30 years for heat networks and 15 years for all other heating systems.

Table 12
Assumptions for heat demand in kWh/year per insulation level

Type of dwelling	Units	Level 3	Level 2	Level 1
Apartments	kWh/year	9574	8235	4269
Terraced houses	kWh/year	12,993	11,176	5793

10.2 2. Upfront and reinvestment costs of TSs

For each dwelling, changing or maintaining their TSs has upfront costs (*UC*) and reinvestment costs (*RC*), as described in 4.2.3.3 Individual preferences submodel. *UC* is the sum of the costs of appliances (AP), insulation (IN), and heating systems (HS). *RC* is equivalent to HS. These costs are described in **Equation A.1**.

$$UC = AP + IN + HS \tag{A.1}$$

Equation A.1 Upfront costs.

To parameterize the model, we make the following assumptions:

- That the costs of a collective heat pump are proportional to those of an individual heat pump. For example, that a collective heat pump for a HOA of 6 members would be 6 times more expensive than an individual heat pump for one of its members.
- That the costs for apartments are approximately 74% of the costs for terraced houses, based on the differences in their heat demands from Table 5.
- That replacing a natural gas stove for an electric or induction stove costs 2500€ (AP).
- The values of IN for all TSs and HS for TS6:HP1 are loosely based on data from a publicly available tool to estimate renovation options and costs in the Netherlands (Milieu Centraal & Rijksoverheid, n.d.), as summarized in Tables 13 and 14.
- The value of HS for TS5:HN2 and TS7:HN1 is assumed to be 12000€ linked to an assumed HN Quorum of 75%. Note that, in practice, we expect both numbers to vary, with the former in the order of thousands of Euros (Vereniging Eigen Huis., n.d.; ACM n.d.; GreenHome, 2019). We selected a value of 12000€ to represent a situation in which HS for TS7:HN1 are lower than those of TS6:HP1, and both TS5:HN2 and TS7:HN1 are

financially attractive options over their lifetime compared to other TSs that do not use natural gas.

- For TS1:GB3 and TS3:GB2, we base HS on the costs of natural gas boilers reported in (Homedeal). Similarly, we base the costs of HS of TS2:EB3 and TS4:EB2 on (Feenstra, 2018; Fleiter et al., 2016).
- An overview of *UC* is provided in Table 16.

Table 13
Assumptions for the costs of changing insulation level (IN)

Change in insulation level	IN
Level 3 to Level 1	12,801
Level 3 to Level 2	3957
Level 2 to Level 1	8844

Table 14
Assumptions for the costs of heating systems (HS)

Heating system	HS
Natural gas boiler	2400
Electric boiler	5000
Heat network	12,000
Heat pump	12,501

Table 15
Assumptions for reinvestment costs (RS)

Heating system	*RC*
Natural gas boiler	2400
Electric boiler	5000
Heat network	0
Heat pump	12,501

Table 16
Assumptions for*UC* of changing from TS to TS'

TS	TS′							
		TS1:GB3	**TS2:EB3**	**TS3:GB2**	**TS4:EB2**	**TS5:HN2**	**TS6:HP1**	**TS7:HN1**
TS	**TS1:GB3**	0	7500	3957	11,457	18,457	27,802	27,301
	TS2:EB3	NA[a]	0	NA[a]	3957	15,957	25,302	24,801
	TS3:GB2	NA[a]	NA[a]	0	7500	14,500	23,845	23,344
	TS4:EB2	NA[a]	NA[a]	NA[a]	0	12,000	21,345	20,844
	TS5:HN2	NA[a]	NA[a]	NA[a]	5000	0	21,345	20,844
	TS6:HP1	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	0	12,000
	TS7:HN1	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	12,501	0

[a] NA = Not applicable.

10.3 3. Annual costs of TSs

Households have annual costs (*AC*) that are linked to their TS. *AC* are the sum of fixed costs (FC) and variable costs (VC). FC is the sum of an annual connection fee (CoF) and measuring fee (MeF). We exclude a maintenance fee (MaF) which in the case of heat networks, would include a rental fee for the equipment in the dwelling. VC is the product of the energy price and the annual heat demand of the dwelling. These costs are described in **Equation A.2** to **Equation A.4**.

$$AC = FC + VC \tag{A.2}$$

Equation A.2 Annual costs

$$FC = CoF + MeF \tag{A.3}$$

Equation A.3 Fixed costs

$$VC = energy\_price * annual\_heat\_demand \tag{A.4}$$

Equation A.4 Variable costs.

FC are summarized in Table 17, and we considered the following:

- For TS1:GB3 and TS3:GB2, connection and measuring fees are based on the fees from a natural gas supplier in The Netherlands for 2020, for a consumption between 500 < 4000 m^3/year (Stedin, n.d.). The connection fee includes periodical and transport fees, which in turn, includes fixed and capacity fees.
- For the electric TSs, TS2:EB3, TS4:EB2, TS6:HP1, connection and measuring fees are also based on the fees from an electricity supplier in The Netherlands for 2020 (Stedin, n.d.). However, we assumed that regardless of their TS, households would have a connection to the electricity network, but if they adopted an electric TSs, they would have to have a different and more expensive connection. We assume that a non-electric TS requires a connection of type 1X35A, while an electric TS requires a connection of type 3X35A. However, the necessary connection is case specific, and in reality, a connection smaller than 3X35A and with a lower connection fee could be sufficient. Such change would result in lower annual costs for TS2:EB3, TS4:EB2, and TS6:HP1.
- For the heat network TSs, TS5:HN2 and TS7:HN1, connection and measuring fees are based on a heat supplier in The Netherlands for 2020 (HVC, n.d.).

Table 17
Assumptions for annual connection and measuring fees

	Units	Technology state						
		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
CoF	€/year	159.56	656.78	159.56	656.78	371.73	656.78	371.73
MeF	€/year	22.39	24.20	22.39	24.20	26.63	24.20	26.63

Energy prices are an input for VC. Natural gas and electricity prices for 2019 are based on the estimated average prices for the second half of 2019 [9]: 0.04806824 €/kWh and 0.1218 €/kWh, respectively. After 2019, these prices remain constant in the model. Heat price is based on the fees of a heat supplier in The Netherlands for 2020, with a value of 24.77 €/GJ, equivalent to 0.089172 €/kWh (HVC, n.d.).

10.4 4. Energy taxes for 2019 and 2020

Taxes for natural gas and electricity for 2019 and 2020 were based on real data for The Netherlands (Rijksoverheid, 2019c). The taxes for natural gas were 0.2931 €/m3 and 0.333 €/m3, equivalent to 0.030002 and 0.034086 €/kWh, respectively. The taxes for electricity were 0.0986 €/kWh and 0.0977 €/kWh, respectively.

Appendix B. Results from the individual preferences submodel

In this appendix, we provide the results of the individual preferences submodel in year 2020, for 2021 to 2050. Table 18 is an overview of estimates for each TS under each RE, in k€. The remaining tables contain the LTC estimates for each TS, per RE. All tables contain LTC estimates for both apartments and terraced houses when houses used ρ_{market} (ideal estimates) and ρ_{bnd} (bounded estimates). In Table 19 to Table 26, the colour gradient in each column shows the TS with the highest (red) and lowest (green) LTC, and the underlined number in bold indicates the TS without natural gas with the lowest LTC.

Table 18
LTC estimates for each TS, per RE

Source	TS	RE	Apartments		Terraced houses	
			Ideal Estimates (k€)	Bounded Estimates (k€)	Ideal Estimates (k€)	Bounded Estimates (k€)
Natural gas	TS1:GB3	GXXX	28.0	5.7	36.3	7.5
		0XXX	26.1	5.7	33.7	7.4
	TS3:GB2	GXXX	26.3	6.4	34.0	8.4
		0XXX	24.7	6.4	31.8	8.4
Electricity	TS2:EB3	XEXX	53.9	15.1	67.5	19.5
		X0XX	60.5	15.3	76.5	19.7
	TS4:EB2	XEXX	52.6	17.1	65.7	22.2
		X0XX	58.3	17.2	73.5	22.4
	TS6:HP1	XEXX	45.7	24.1	56.3	31.6
		X0XX	46.5	24.1	57.3	31.6
Heat	TS5:HN2	GE0X	39.3	17.8	50.0	23.5
		G00X	39.5	17.8	50.1	23.5
		0E0X	37.9	17.8	48.0	23.5
		000X	38.0	17.8	48.1	23.5
		XEHX	36.9	17.7	46.7	23.4
		X0HX	37.0	17.7	46.8	48
	TS7:HN1	GE0X	38.0	23.1	48.1	30.7
		G00X	38.1	23.1	48.2	30.7
		0E0X	37.2	23.1	47.1	30.7
		000X	37.3	23.1	47.2	30.7
		XEHX	36.7	23.1	46.4	30.6
		X0HX	36.9	23.1	46.5	30.6

Table 19

LTC estimates in 2020, for 2021 to 2050, when RE = GE0X.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	28.0	53.9	26.3	52.6	39.3	45.7	38.0
	Bounded estimates	5.7	15.1	6.4	17.1	17.8	24.1	23.1
Terraced houses	Ideal estimates	36.3	67.5	34.0	65.7	50.0	56.3	48.1
	Bounded estimates	7.5	19.5	8.4	22.2	23.5	31.6	30.7

Table 20

LTC estimates in 2020, for 2021 to 2050, when RE = G00X.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	28.0	60.5	26.3	58.3	39.5	46.5	38.1
	Bounded estimates	5.7	15.3	6.4	17.2	17.8	24.1	23.1
Terraced houses	Ideal estimates	36.3	76.5	34.0	73.5	50.1	57.3	48.2
	Bounded estimates	7.5	19.7	8.4	22.4	23.5	31.6	30.7

Table 21

LTC estimates in 2020, for 2021 to 2050, when RE = 0E0X.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	26.1	53.9	24.7	52.6	37.9	45.7	37.2
	Bounded estimates	5.7	15.1	6.4	17.1	17.8	24.1	23.1
Terraced houses	Ideal estimates	33.7	67.5	31.8	65.7	48.0	56.3	47.1
	Bounded estimates	7.4	19.5	8.4	22.2	23.5	31.6	30.7

Table 22

LTC estimates in 2020, for 2021 to 2050, when RE = 000X.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	26.1	60.5	24.7	58.3	38.0	46.5	37.3
	Bounded estimates	5.7	15.3	6.4	17.2	17.8	24.1	23.1
Terraced houses	Ideal estimates	33.7	76.5	31.8	73.5	48.1	57.3	47.2
	Bounded estimates	7.4	19.7	8.4	22.4	23.5	31.6	30.7

Table 23

LTC estimates in 2020, for 2021 to 2050, when RE = GEHX.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	28.0	53.9	26.3	52.6	36.9	45.7	36.7
	Bounded estimates	5.7	15.1	6.4	17.1	17.7	24.1	23.1
Terraced houses	Ideal estimates	36.3	67.5	34.0	65.7	46.7	56.3	46.4
	Bounded estimates	7.5	19.5	8.4	22.2	23.4	31.6	30.6

Table 24

LTC estimates in 2020, for 2021 to 2050, when RE = G0HX.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	28.0	60.5	26.3	58.3	37.0	46.5	36.9
	Bounded estimates	5.7	15.3	6.4	17.2	17.7	24.1	23.1
Terraced houses	Ideal estimates	36.3	76.5	34.0	73.5	46.8	57.3	46.5
	Bounded estimates	7.5	19.7	8.4	22.4	23.4	31.6	30.6

Table 25

LTC estimates in 2020, for 2021 to 2050, when RE = 0EHX.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	26.1	53.9	24.7	52.6	36.9	45.7	36.7
	Bounded estimates	5.7	15.1	6.4	17.1	17.7	24.1	23.1
Terraced houses	Ideal estimates	33.7	67.5	31.8	65.7	46.7	56.3	46.4
	Bounded estimates	7.4	19.5	8.4	22.2	23.4	31.6	30.6

Table 26

LTC estimates in 2020, for 2021 to 2050, when RE = 00HX.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	26.1	60.5	24.7	58.3	37.0	46.5	36.9
	Bounded estimates	5.7	15.3	6.4	17.2	17.7	24.1	23.1
Terraced houses	Ideal estimates	33.7	76.5	31.8	73.5	46.8	57.3	46.5
	Bounded estimates	7.4	19.7	8.4	22.4	23.4	31.6	30.6

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