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Fouladvand, Javanshir; Ateş, Emre; Sarı, Yasin; Okur, Özge

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Does the availability of alternative energy choices lead to more environmentally friendly outcomes? The case of thermal energy communities and natural gas consumption

Javanshir Fouladvand [a,*], Emre Ateş [b], Yasin Sarı [c], Özge Okur [b]

[a] Copernicus Institute of Sustainable Development, Utrecht University
[b] Multi-Actor Systems department, Technology, Policy and Management faculty, Delft University of Technology (TU Delft)
[c] Enterprise Application Systems, Group IT, Nationale-Nederlanden (NN Group)

HIGHLIGHTS

- Agent-based modelling and simulation is used to study thermal energy transition.
- Multi-level governance is used as a theoretical backbone in an agent-based model.
- The importance of the availability of alternative energy choices is demonstrated.
- The availability of several natural gas sources leads to more sustainable outcomes.
- The establishment of thermal energy communities is vital for the energy transition.

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ABSTRACT

Individual households, responsible for 25% of total energy consumption in Europe, are crucial actors in the energy transition. Although various policies and energy choices are available for such actors (e.g., individual solar photovoltaic or community energy systems), they are usually restricted to municipal governance, and public opinion towards national energy policy is not strongly presented. This study explores and describes the influence of the availability of alternative energy choices on different levels of governance to facilitate households' energy transition. An agent-based model is conceptualised through multi-level governance, the institutional analysis and development framework and the social value theory. To also address the ongoing energy crisis, the study focuses on the Dutch thermal energy transition and the thermal energy communities as a collective action for generating, distributing, and consuming renewable thermal energy and, therefore, three layers of energy choice alternatives are provided for households: national level (i.e., sources of natural gas), municipal/community level (i.e., collective renewable energy technologies), and individual level. The results delineated the importance of the availability of alternative energy choices in the suggested multi-level governance collective action system. Such systems consumed only 12% natural gas, while they covered their thermal demand by increasing the capacity of collective thermal energy systems (83% on average) and adopting more individual thermal energy systems (heat pump, approximately 85%). Although the performances on voluntary blackouts/discomfort (2.7% on average) and CO_2 emissions (85% reduction approximately) were also positive, this was reflected in a significant price increase.

1. Introduction

Addressing climate change and the pivotal need to reduce greenhouse gas emissions (GHG, such as CO_2) requires significant transformation in the energy sector [1]. Such transformation, mainly referred to as the energy transition, has various facades, such as energy demand reduction strategies, energy efficiency and deployment of renewable energy technologies (RETs), which include and influence different actors (e.g., individual households, industries and businesses) across the globe [2].

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* Corresponding author.
E-mail addresses: j.fouladvand@uu.nl, javanshir.fouladvand.work@gmail.com (J. Fouladvand).

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Individual households are responsible for approximately one-fourth of total energy consumption in Europe [3], making their participation crucial for a successful energy transition [4]. However, as illustrated in studies such as [5,6], it is impossible to suggest a one-size-fits-all solution that facilitates the households' energy transition due to different reasons, such as heterogeneity in their motives and demands. Therefore, various studies explored the behaviour and preferences of individual households regarding different energy sources and strategies.

From the individual households' perspective, the influence and importance of values on evaluating different energy alternatives and adopting them in the Netherlands are investigated in [7]. By employing behavioural economics and exploring the influence of psychological and behavioural conditions, the households' energy-related decision-making and behaviour are studied in [8]. The importance of the attitude and knowledge of saving behaviours in the residential sector is explored in [9]. Dutch households' energy efficiency decisions and CO_2 emission reduction strategies are explored in [10], showing the importance of natural gas prices in adopting energy-efficient technologies. Factors influencing energy efficiency investments in existing Swedish residential buildings are explored in [11], and the influence of knowledge and economic incentives for such decisions is highlighted. The adoption of renewable heating systems in Italy is investigated in [12] by employing the diffusion of innovation theory. Studies such as [12–14] explored the influence of user profiles, socio-economic factors and values on households' energy consumption. In addition, various studies have focused on the influence of policies and regulations on households' energy transition. The influence of decarbonisation policies in the residential sector in central and southern eastern Europe is studied in [15]. The impact of taxing households' energy consumption in Spain is investigated in [16]. Along with such studies focusing on individual households' behaviours, various studies studied households' collective action for energy generation and consumption within their neighbourhood, namely community energy systems (CESs).

As an overarching term, CES is defined based on the collective action of individual households to generate, distribute and consume renewable energy resources (RECs) [17,18]. In this context, by collecting empirical data, studies such as [19,20] explore the role of institutional and socio-psychological factors in participating in CESs. The perceptions towards natural gas consumption and import in Europe are presented in [21], and it highlights the importance of knowing the natural gas sources for households. Factors influencing the adoption of renewable heating systems and participating in (thermal) energy communities are studied in [22]. The role of behaviour and leadership in the emergence of CESs in the Dutch context is explored in [23]. Studies such as [24,25] investigated the role of renewable heating systems, namely thermal energy communities (TEC initiatives), in the heat transition in Germany and the Netherlands. The influence of the different institutional factors (e.g., regulations and policies) and internal and external networks (e.g., relationships and dynamics within the neighbourhoods) are investigated in [20,26]. By employing computational social simulation approaches such as agent-based modelling and simulation (ABMS), [27,28] explore different settings for the collective decision-making processes for TEC initiatives, demonstrating the potential of such systems in reducing natural gas consumption. The influence of different technical, institutional and behavioural settings on the energy security of CESs and TEC initiatives are also explored in [29,30]. Therefore, this branch of literature, namely the (individual and collective) behaviour of households, is expanding, and the participation of households in the energy transition is studied from different angles. However, no study systematically explores the influence of the availability of different alternative energy choices on the households' energy transition and their decision-making processes. Furthermore, no study specifically investigates the potential influence of the availability of different natural gas sources on energy-related behaviours.

This gap is crucial as the availability of different RECs, technological developments, and climate change goals urges the households' energy transition to take place faster. This is particularly highlighted in the context of the European households, considering the energy crisis resulting from the ongoing Russian-Ukrainian conflict, to reduce their natural gas consumption (and re-think about the sources of the natural gas imports) and eventually fasten the thermal energy transition [21]. However, the literature has not investigated the households' opinions towards all the alternative energy choices and to what extent the availability of different alternative energy choices (such as different natural gas from different countries/ origins) could potentially influence the (thermal) energy transition. For instance, the households should only have choices about the individual renewable energy systems that they adopt (e.g., individual heat pump), or they should be given choices on the municipality-level decision-making (e.g., collective renewable energy systems they can adopt) and national level decision-making (i.e., natural gas import sources). In the real world, this can be translated as to what extent public opinion should be involved in making national-level energy choices and how such choices could contribute to the energy transition as a whole. In other words, it is unclear whether the importance and potential of providing alternative energy choices for households at different levels could add to the energy transition.

To address this gap, this study aims to explain and describe the influence of the availability of alternative energy choices at different levels on individual decision-making to facilitate households' energy transition. To capture the decision-making processes and choices while including the heterogeneity of motives and behaviour of households, the research employs agent-based modelling and simulation (ABMS) instead of other simulation approaches such as System Dynamics [31], Discrete Event Simulations [32] and Equilibrium Modelling [33], that mainly focus on system processes and outcomes. Also, to address the ongoing energy crisis due to the Russian-Ukrainian conflict, the study focuses on the thermal energy choices of households within thermal energy communities (TEC initiatives) [17,34]. In this sense, the current study can be seen as an extension of existing models, such as [28,30,35], which are focused on establishing and functioning of TEC initiatives. Therefore, the model contributes to the existing literature by adding alternative energy choices at different levels to understand their influence on the individual's decision-making. The alternative energy choices at different levels considered in this study are: national level (i.e., sources of natural gas), municipal/ community level (i.e., collective renewable energy technologies, such as geothermal valves and biogas combined heat and power), and individual level (e.g., solar thermal and heat pump). Lastly, to address the research objectives concretely, this study uses input data from the Netherlands, a European country with unique characteristics for the thermal energy transition, as elaborated in [28,36]. Along with bringing structured insights, the developed model could potentially be used for other countries. To summarise, the study has the following contributions:

- Explaining and describing the influence of the availability of different alternative energy choices, particularly natural gas sources, on households' behaviour and their contribution to energy transition,
- Demonstrating the value of using (and expanding existing) ABMS to study new questions/ topics (e.g., different technical and policy choices),
- Providing concrete insights on thermal energy communities and thermal energy transition, particularly in Europe.

The study also aims to provide concrete insights and recommendations to relevant actors, particularly the policy-makers and individual households, along with scientific contributions. In addition, such insights and recommendations could contribute to the energy and geopolitical agendas at a higher level. More specifically, the study can be seen as a response to concerns in relation to the energy and geopolitical crisis in Europe and around the world.

The structure of the paper is as follows: Section 2 explains the theoretical background of this research. Section 3 elaborates on the research approach, ABMS. Section 4 delineates the model conceptualisation. Section 5 describes the simulation results. Section 6 presents the discussions and limitations. Finally, Section 7 concludes the main findings and provides recommendations.

2. Theoretical background

This section introduces the theories and frameworks used as the backbone of the modelling exercise. Multi-level governance (MLG) is used to conceptualise and investigate different alternative energy choices. While the collective action perspective (i.e., the institutional analysis and development framework) is used to structure and understand the decision-making processes, the social value orientation theory is employed to structure individuals' heterogeneous behavioural attributes and motivations.

2.1. Multi-level governance for the Dutch public opinion in thermal energy transition

Multi-level governance (MLG) aims to capture and understand the political and institutional processes to describe the political processes and governance structures (such as the establishment of the European Union) [37,38]. The MLG structures such processes on different levels (e.g., global, continental, national and regional levels) from the perspective of different actors (e.g., public, government and businesses) and different sectors (e.g., energy, transport and agriculture) [37,38]. Various studies, such as [39–41], explored the MLG in the context of European integration and governance and expanded its applications. In recent years, the application of the MLG has expanded further and included climate and energy governance. For instance, [42] explored the challenges and uncertainty of natural resource management through the MLG, and [43] structured global climate governance by using the MLG. On the other hand, various studies such as [44–46] applied the MLG to study and facilitate energy transition. The deployment of solar energy for China's sustainable development processes and goals through the MLG is explored in [47]. Germany's energy efficiency policies are studied using the MLG in [48]. The multi-level governance of renewable energy in England is presented in [49]. Particularly at the local level, [45,46] studied the community energy systems through the MLG lens.

Following such studies, three levels of governance and policy and their representative choices are structured for this study:

- National level/ EU level- natural gas import sources and consumption: This level focuses on public opinion about the sources of natural gas available for individual household consumption. In a broad sense, there are three alternative choices: (i) the current mixture the natural gas grid offers, (ii) specifically choosing a natural gas from an ally country (in the case of the Netherlands, a European or North American country), or (iii) natural gas from a non-ally country (Russia and Qatar in the case of the Netherlands).
- Regional level- collective renewable thermal energy systems: This level focuses on the available renewable thermal energy systems the city or province could use to cover the thermal energy demand. In the case of the Netherlands, three systems are prominent, namely: aqua thermal energy storage (ATES), biogas combined heat and power and electric boilers (i.e., electrification) [28,35].
- Individual level- individual renewable heating systems: This level focuses on the available renewable thermal energy systems for implementation within a single household to cover the thermal energy demand. Following studies such as [30,35], the following systems are suitable for the case of the Netherlands: heat pumps, small bio-energy heaters (i.e. wood pallets) and photovoltaic thermal hybrid solar collectors (i.e., Solar PVT)

Considering these three levels (and their representative choices) could potentially contribute to capturing the influence and application of multi-level governance and the availability of alternative energy choices for individual households. Therefore, the MLG is employed to structure the three levels of the decision-making processes and choices (i.e., individual, municipal and national levels) rather than focusing on investigating the governmental institutions. Furthermore, by employing and applying MLG and the three representative levels, such an approach contributes to studies such as [45] investigating the governance and policy processes for sustainability transitions.

2.2. Collective action: The institutional analysis and development (IAD) framework

As presented in [17,35], CESs can theoretically be seen as a form of collective action where the generation, distribution and consumption of renewable energy is the common goal of different actors (e.g., individual households). Therefore, by breaking a system down into simpler and manageable components, the institutional analysis and development (IAD) framework investigates the dynamics of the decision-making processes in such a system [50,51], as presented in Fig. 1.

The IAD framework investigates collective action problems from an institutional perspective, which are the rules of the game that govern the activities of the actors [52,53]. As a conceptual space, the action situation is the main component of the IAD framework, where actors make decisions while considering the trade-offs, take actions and experience the consequences [53]. The action situation component leads to a pattern of interactions that generate specific outcomes (e.g., establishment of TEC initiatives), which can be objectively assessed based on evaluation criteria (e.g., generated renewable energy and cost) [51]. A feedback loop connects the outcomes to the exogenous variables, ultimately influencing the action situation (and all the other components). The exogenous variables are classified into three main components: (i) biophysical conditions, which refer to the physical resources and capabilities available within the system's boundaries (e.g., available RETs); (ii) community attributes, include the cultural norms accepted by the community, shared values and beliefs (e.g., environmentally friendly behaviour); and (iii) rules-in-use; include the formal rules such as policies and regulations that officially govern the system (e.g., available subsidies and Carbon emissions tax) [30,53].

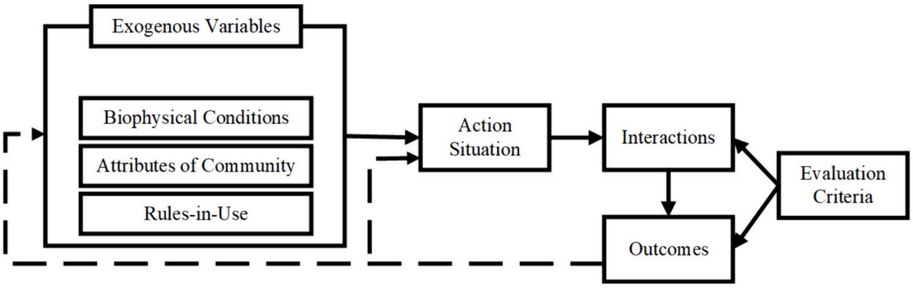

Fig. 1. *The IAD framework* [51].

The IAD has proven useful for building agent-based models, along with its analytical power and being highly instrumental in studying thermal energy communities (TEC initiatives) as a collective action problem [54]. Therefore, various studies used the IAD framework for conceptualising their experimental settings (e.g., [28,35,55]).

2.3. Individual behaviour: The social value orientation (SVO) theory

As presented in [56,57], individual households join an energy community to fulfil specific concerns (e.g. environmental) or to achieve certain goals (e.g. financial benefits). In this context, the social value orientation (SVO) theory explains the individuals' motivations, concerns and goals for making a specific decision, such as joining a CES [58]. SVO theory provides measurement tools as it hypothesises that people vary in their motives and goals when evaluating different resource allocations and alternative choices [59]. Therefore, SVO theory classifies individuals' personalities into four groups as follows:

- Altruistic: individuals are selfless, focusing on maximising joint benefits regardless of the impact on their payoff; the opportunity to help others is their motivation;
- Cooperative: individuals aim to maximise one another's outcome together with their own;
- Individualistic: individuals are mainly concerned with their outcomes, focusing on their payoff without having a specific motive for minimising another one's benefits;
- Competitive: individuals aim for maximum results and strive to minimise other individuals' benefits [59].

By such classification, SVO theory helps capture real-life decision-making situations while considering various motivations and goals [58]. As SVO theory is highly instrumental, various studies have employed it to study energy-related behaviours. [60,61] employed SVO theory to empirically explore the individuals' decision-making to adopt and invest in renewable energy technologies and energy efficiency. On the other hand, several studies used SVO theory as the theoretical backbone of their ABMS. For instance, [23] used SVO to explore the influence of behavioural attitudes and leadership on the deployment of CESs based on solar photovoltaic systems in the Netherlands. [30] used SVO theory to investigate the importance of the behavioural attributes towards collective energy security in TEC initiatives.

There are other frameworks which could potentially be useful. For instance, socio-ecological systems (SES framework) [62] could be used to delve into collective action and institutional analysis details. However, such a framework has been mainly applied to the (collective) systems that have already existed for some time rather than studying new and emerging systems and complex phenomena (such as thermal energy transition and TEC initiatives). The multi-level perspective (MLP) [63] could also be beneficial for studying the procedures and conceptualising TEC initiatives as niche innovations. However, the study focuses on the individual and collective decision-making processes for local energy transition rather than on dynamics for making TEC initiatives, as an established innovation, to become the dominating system for thermal energy generation and heat transition.

To summarise, the three elaborated theoretical concepts are used as a backbone of agent-based modelling and simulation (ABMS). Thermal energy communities (TEC initiatives) are seen as collective actions, and therefore, decision-making processes are conceptualised using the IAD framework. The SVO theory is employed to capture and categorise individual households' motivations and values for participating in TEC initiatives. The suggested multi-level governance approach (MLG) captures the different policy levels and their importance for establishing and functioning TEC initiatives. Using the mentioned theories as the backbone of ABMS serves the research aim, namely explaining and describing the influence of the availability of alternative energy choices on different levels for facilitating the households' energy transition.

3. Agent-based modelling as a computational simulation method

Performing real-world experiments would be time-consuming and costly, with not necessarily beneficial impacts on individuals' lives. However, computer simulation is often used to conduct experiments in a virtual simulation environment [64,65]. In this branch of literature, computational social simulation is a well-established field of research, integrating different scientific fields such as computer science, social sciences and technological design [66,67]. Agent-based modelling and simulation (ABMS) is specifically promising for this research as it facilitates the exploration of artificial societies of autonomous agents as representatives of the real world [68,69].

In an ABMS, “An agent is the software representation of some entity that completes an action or takes a decision, by which it effectively interacts with its environment” [70]. Therefore, agents are heterogeneous, autonomous and individual decision-making entities (such as individual households) that are able to learn and interact with each other and their environment [68,71]. In addition to studying and capturing individuals' behavioural choices, using ABMS provides the opportunity to study the emergent behaviour of the system [72]. Moreover, ABMS inherently adds the time dimension, which allows the examination of different scenarios under different input settings over time [69,72].

For these reasons, the investigative power is enhanced, and therefore, ABMS is considered a suitable approach for studying the dynamics and interactions within TEC initiatives to explain and describe the influence of the availability of alternative energy choices. Although considering the complexity of the real world, an ABMS cannot represent all the details of real-world decision-making processes, different studies argue for and use ABMS to study different topics in the context of energy transition. Studying value conflict for acceptance of decentralised energy systems [73], simulating behavioural attitudes [74] and leadership in the energy communities [23], exploring the social acceptance of sustainable heating systems [75], studying local heating systems [76,77], indoor heating and cooling and built environment systems [78–80], modelling and simulating zero energy communities [81–83], and studying the renewable energy technology adoption [84,85], renewable energy market design and price reforms [86,87], are examples of such studies in this branch of literature. A detailed overview of studies that employed ABMS for studying (thermal) energy communities is presented in [88].

4. Model conceptualisation

This section describes the model conceptualisation and implementation using the IAD framework, as presented in Section 2.2, starting with agents, followed by exogenous variables (i.e., biophysical conditions, attributes of community and rules in use), action situation and interactions, evaluation criteria and outcomes.

4.1. Agents

The model represents a municipality with multiple neighbourhoods, each one of which can only form and implement one thermal energy community (TEC initiatives). The following two types of agents are included in the model:

(i) Individual households who initially are connected to the national grid to cover their thermal demand by consuming natural gas. Following studies such as [30,35], individual households (i.e., agents) have the following internal motivations to participate in TEC initiatives: (i) energy independence, (ii) a sense of community, (iii) environmental concern and (iv) economic benefits, which independently from each other, each of them have a value between 0 and 10 (i.e., 0 is the weakest and 10 is the strongest). Based on their interaction, individual households in a neighbourhood can influence each other's internal motivation. Individual households make decisions related to participating in TEC initiatives and adopting renewable heating systems based on their SVO type, which is captured based on these four internal motivations as following:

$$\text{Level of motivation} = (\text{environmental concern} + \text{sense of community}) - (\text{financial concerns} + \text{energy independence}) \tag{1}$$

- If Level of motivation >1: SVO-type 1 (i.e., altruistic),
- If Level of motivation < -1: SVO-type 3 (i.e., individualistic),
- If Level of motivation ≥ -1 and ≤ 1, and sense of community <5: SVO-type 4 (i.e., competitive),
- If Level of motivation ≥ -1 and ≤ 1, and sense of community ≥ 5: SVO-type 2 (i.e., cooperative).

In addition to [19], following studies such as [89–91], individual households also have two other internal motivations which potentially influence their connection and consumption from the national grid (in this case, natural gas consumption): national energy independence and awareness/care towards the energy source they consume. These two internal motivations will be used for the decision-making process described in Section 4.5. (the data is presented in Appendix E, from [21]). Finally, following [28], among all the individual household (i.e., agents in the model), the top five most environmentally friendly ones whose other motivations are also higher than the median value (i.e., $\geq$ 5) are considered to be the community board, who are representatives of individual households in the neighbourhood and are responsible for initiating, deciding and leading the establishment and functioning of TEC initiatives.

(ii) The municipality represents the national government (in this case, the Dutch government; depending on the context, it could be any government), which is responsible for the thermal energy transition and supporting TEC initiatives that are being formed and implemented. In this modelling exercise, the municipality performs its responsibilities by checking the eligibility requirements for and distributing the available subsidies among the TEC initiatives. This is in line with municipalities' role in different (European) countries, as presented in [35,92]. As the municipalities' resources (such as available budget) are limited, following [28,35,93], municipalities have four strategies to perform, namely: environmentally driven (meaning supporting the TEC initiative with the most CO_2 reduction option), economically driven (meaning supporting the TEC initiative with the least economic burden for the municipality itself), socially driven (meaning supporting the TEC initiative with the most involved participants in a neighbourhood) and a trade-off between the three. Individual households have been aware of the municipality's strategy since the beginning of the simulation. The municipality strategy has been known for the individual households since the beginning of the simulation. In the real world, this means the municipality (and/or the national government) has transparently communicated the criteria for granting subsidies to TEC initiatives, and the individual households are aware of the criteria for granting subsidies TEC initiatives.

4.2. Biophysical conditions: Alternative energy choices

Following studies such as [35], the agents in the model (i.e., individual households) have the following alternative energy choices to select from (based on their internal values and interactions, as explained in detail in Section 4.5.):

- Adopting renewable thermal energy systems:
  - o Collective renewable thermal energy systems: the choices are biogas heaters, aquifer thermal energy systems (ATES), and electric boilers (will be distributed through medium-temperature district heating);
  - o Individual renewable thermal energy system: the choices are heat pumps, small bio-energy heaters (i.e. wood pallets) and photovoltaic thermal hybrid solar collectors (i.e., Solar PVT).
- Continuing consuming natural gas from:
  - o the current mixture of the natural gas grid (i.e., natural gas from different origins and countries) for the individual households who are indifferent to the natural gas source;
  - o an ally country (in the case of the Netherlands, a European or North American country) for the individual households who care about national energy independence;
  - o another country that is not an ally (e.g., Russia and Qatar in the case of the Netherlands) for individual households who are economically driven

4.3. Attributes of community

Each individual household lives in a neighbourhood with its own specific TEC initiative (meaning each individual household can only participate in one TEC initiative). Each month (i.e., each time step in the model represents a month), the households in a neighbourhood can interact with each other randomly in monthly residential meetings that are held for decision-making related to CES. These interactions can be translated as a form of information exchange, peer pressure and influence on each other in the real world. The small world network is used to capture and simulate such interactions [94]. The 'small world' is commonly used in modelling the interactions in neighbourhoods, particularly for studying CESs (e.g. [23,28,95]).

Such interactions lead to influencing each others' motivations in the following manner as presented in [30,96]: for each internal motivation (i.e. energy independence, trust, environmental concern, economic benefits, national energy independence and awareness/care), if the value is not extreme, between 2 and 8 (meaning not hard to be changed), they will be updated and leaning one value towards the interacting agent's opinion, for better or worse. If the value of internal motivations is higher than 8 or lower than 2 (meaning they are extreme and hard to change), the agent will not update its own values during the interaction and, therefore, will not be influenced.

4.4. Rules-in-use

Three types of rules are considered: (i) supportive policies such as subsidies, (ii) prohibiting policies such as CO_2 tax, and (iii) flexibility in natural gas import sources. The Dutch subsidy schemes such as 'Stimuleringsregeling Duurzame Energie' (SDE++) and reports from the Dutch Environmental Assessment Agency (PBL) are used to collect data related to the policies. The model assumes that sources are available for natural gas imports and that they can be used depending on households' choices. The current mixture of national natural gas grid data is extracted from PBL, Statistics Netherlands (CBS) and Eurostat.

4.5. Action situation and interactions

The households have a period to exchange information to know each others' motivations and align them. Individual households consume natural gas from the national gas grid during this information exchange period (and before deciding on alternative energy choices). These interactions are based on the description in Section 4.3. Decisions 2, 3, 4 and 5 (type and amount of collective and individual renewable thermal energy systems and the choice of natural gas consumption) are based on the MLG (see Section 2.1). After a period of information exchange among the individual households, the following decisions need to be made:

(i) The project leadership: to choose the project leader, between the community board or municipality, who is responsible for organising the TEC initiative formation and implementation; individual households check the municipality's strategy, which will be one of the following:

- Environmentally driven strategy: if the individual households' environmental concern is higher than 5 and belongs to first and second SVO-types (meaning being altruistic or cooperative), it votes for the community board leadership. If the environmental concern is higher than 5 and belongs to third and fourth SVO-types (meaning being individualistic or competitive), the individual household checks its “sense of community” value, which, if it is higher than 5, votes for the community board leadership.
- Societally driven strategy: the procedure is the same as that described for the environmentally driven strategy. The only difference is that the households first check the “sense of the community” value, and then if needed, they check the “environmental concern” value.
- Economically driven strategy: if the individual households' economic benefits are higher than 5 (regardless of its' SVO-type), it votes for the municipality leadership.
- Trade-off strategy: randomly, with an equal chance, the individual households opt for one of the above-mentioned strategies.

(ii) Type of the collective renewable thermal energy system: Depending on the project leadership, the decision-making process for the collective renewable thermal energy goes through two different processes for choosing between biogas heaters, ATES, and electric boilers as collective technologies.

- If the municipality is the leader, depending on its strategy (i.e., environmental, economic, social and trade-off), the municipality chooses one of the collective renewable thermal energy systems and then communicates its choice with the individual households. Therefore, it is more of a top-down approach. As presented in Appendices A and B, the municipality calculates and normalises values for each technology's annual CO2 emissions, costs and minimum participants to make this decision.
- If the community board is the leader, they first go through a multi-criteria decision-making process (MCDM) to select a collective renewable thermal energy system based on the board members' internal motivation (and by following calculations presented in Appendices A, B, and D). The board suggests the technology with the highest MCDM score as the alternative thermal technology for the community. After this suggestion, each individual household conducts an individual MCDM based on its own internal motivations and values, and if the suggested technology fulfil the following conditions, it would be accepted: (i) the suggested technology is the one that is rated as the highest by more than half of the neighbourhood; (ii) the suggested technology by the community board is not the technology that is rated as the lowest by more than one-third of the neighbourhood. If the first technology proposed by the community board does not meet these conditions, the same procedure takes place for the next collective energy technology.

(iii) Capacity of the collective renewable thermal energy system: After choosing the type of the collective renewable thermal energy system (between biogas heaters, ATES, and electric boilers), individual households select the capacity of such a system, which is calculated in terms of the percentage of the total thermal demands of the individual households. The capacity is determined as the average percentage value of all the individual households, corresponding to the share of each individual household's thermal demand covered by the collective renewable thermal energy. The two conditions for this choice are the budget and SVO type of an individual household. The upper limit is how much an individual household can afford to invest in the collective renewable thermal energy within its budget. If the household belongs to the SVO-type 1 (i.e., altruistic), it prefers to meet all its demands collectively (i.e. 100%). For the other SVO-types, the preferences to cover their energy demand collectively is as follows: Households with SVO-type 2 (i.e., cooperative) 90%, households with SVO-type 3 (i.e. individualistic) 80%, and households with SVO-type 4 (i.e. competitive) 70%. If the collective renewable thermal energy does not cover the entire demand within the TEC initiative, the individuals, depending on their internal motivations, have other choices to address their thermal demand.

(iv) Type and capacity of individual renewable thermal energy system: after selecting a collective renewable thermal energy system, if the individual households' environmental concerns are higher than economic benefits, it goes through the following processes:

- If its budget is sufficient, it should adopt one of the individual renewable thermal energy systems (between heat pump, wood pellet, and solar PVT) to cover its remaining thermal energy demand.
- If its budget is insufficient, it chooses to face blackout/ discomfort voluntarily; this means it reduces its demand and, therefore, saves money to install individual renewable thermal energy systems in the future.

When the individual household equally values environmental concerns and economic benefits, the sense of community value serves as a tiebreaker, meaning if the sense of community is lower than 5 the household withdraws from adopting collective and individual renewable thermal energy systems.

(v) Choice of natural gas consumption: after selecting a collective renewable thermal energy system, if an individual household has economic benefits higher than environmental concerns, it chooses to use natural gas as the energy source for the remaining demand that is not covered by the selected collective heating energy system and goes through the following processes:

- If it is less concerned/ aware of the natural gas sources (i.e., does not care about the source of natural gas), it will continue with what the current natural gas grid offers (meaning the current equal mixture of natural gas from ally countries and non-ally countries collected from CBS and Eurostat; 50% from ally countries and 50% from non-ally countries).
- If it is highly concerned/ aware of the natural gas sources (i.e., cares about the source of the natural gas) and has higher national energy independence concerns than economic benefit, it selects to get the natural gas from its own country (in this case, the Netherlands). If its country does not have natural gas resources, it chooses to get it from an ally country (in this case, a European or North American country). If this were also impossible (the allied country does not have natural gas), the individual household would voluntarily face a blackout/ discomfort, reducing its demand and saving money for the future. Depending on its interactions in the next ticks (see Section 4.3), the individual household might grow towards investing its savings in (collective and individual) renewable thermal energy systems.

(vi) Financing, establishing and maintaining TEC initiatives: after selecting the technical configurations (i.e., natural gas sources, collective and individual renewable thermal energy systems), the final financial feasibility of the system, including applying for the subsidies, takes place. In this phase, the project leader (either the municipality or community board) calculates the renewable generation (including collective and individual technologies), CO_2 emissions, number of adopters of RETs and costs. Then, the subsidy amount is calculated. Every 12 ticks in the simulation (meaning once a year), the municipality considers all the subsidy applications and ranks them based on its own strategy. The municipality distributes the subsidy from the top of the list until its subsidy is finished. If a TEC does not receive the subsidy (as it might not meet the municipality's criteria for receiving the subsidy or as it might be low in the municipality's ranking while the subsidy is finished), it waits for the next year and applies again.

After the investment is fulfilled (including receiving a subsidy and individual households' investment), the construction of the infrastructure and energy systems will take one year (12 ticks in the simulation).

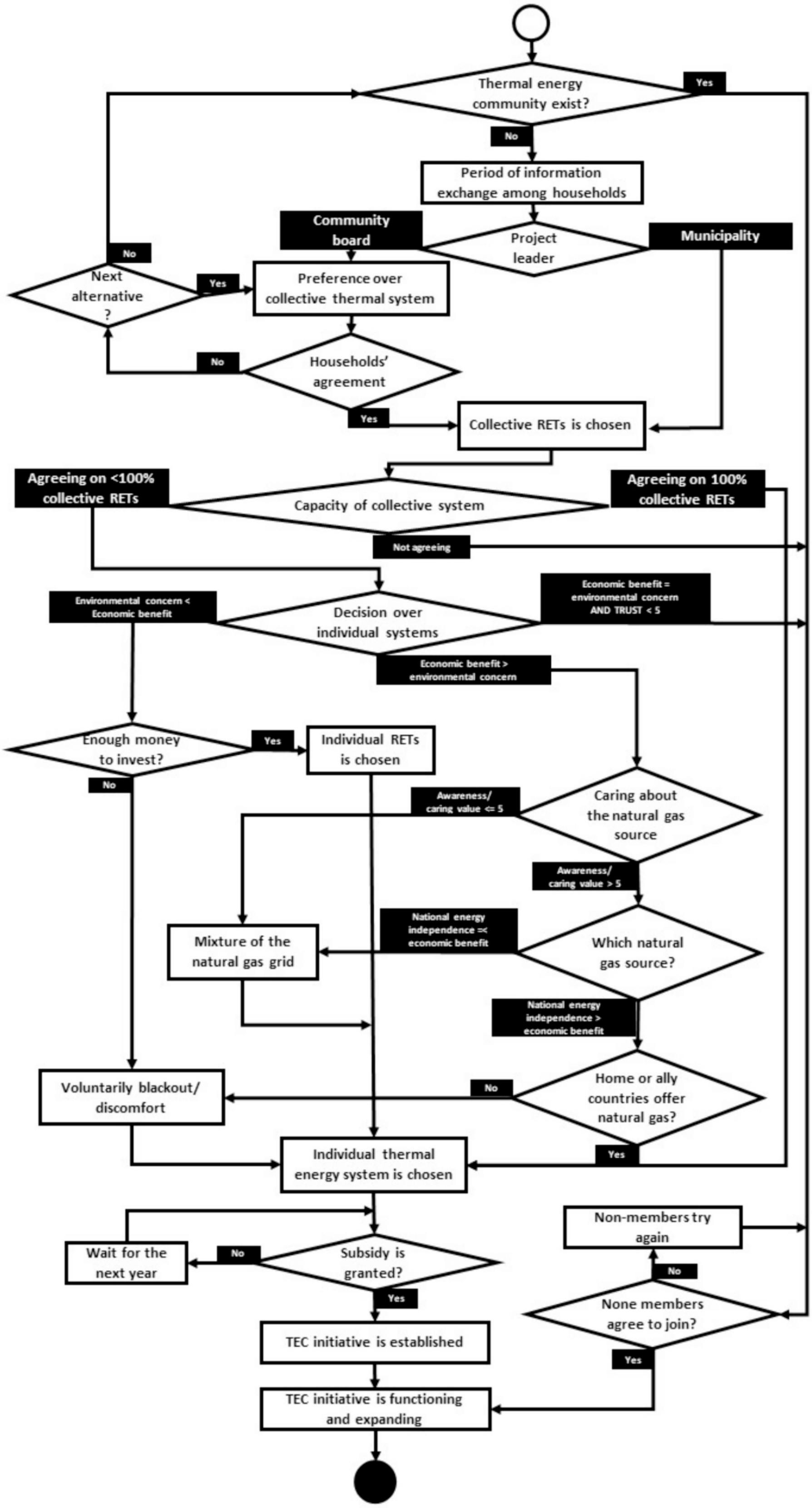

Fig. 2. Conceptual framework of model flowchart.

After establishing, every year, the project leader checks whether they have reached the end of their project time horizon (i.e., 20 years in the simulation). As the agents continue to interact with each other and influence each others' values during the simulation, "non-adopters" in the neighbourhood (i.e., non-members of TEC initiatives) can re-evaluate their participation and can potentially add to the community initiative over time. Fig. 2 presents these six main decision-making processes as a conceptual model flowchart.

4.6. Evaluation criteria and outcomes

The evaluation criteria and outcomes are considered key performance indicators (KPIs) in the simulation. In order to explain and describe the importance of the availability of choices for individual households, along with analysing the alternative energy choices (including the technical configurations and average natural gas consumption), the following KPIs are used (and their calculations are presented in Appendix C):

- Average voluntary blackout/ discomfort per household (%): this KPI is the average voluntary blackout/ discomfort for individual households. As presented in Section 4.5., an individual household might face voluntary blackout/ discomfort due to technical, economic and behavioural conditions.
- Average CO_2 emission per household per year ($KgCO_2$/year): the average CO_2 emission per year of an individual household is based on the CO_2 intensity of the selected energy choices.
- The average costs per household (€/month): The average cost per year for each individual household is calculated based on three energy costs: collective renewable thermal energy system, individual renewable thermal energy system and natural gas consumption.

4.7. Parameters and experiment setting

For capturing the Dutch individual households' internal motivations, the results from [19] are used. Table 1 delineates the model's parameter configurations based on these parameters and the one-factor-at-a-time (OFAT) sensitivity analysis approach [97]. These are also in line with the previous studies, such as [28,30,35], that studied the TEC initiatives in the Dutch context.

As the goal of this study is to explain and describe the importance of the availability of choices for individual households (and TEC initiatives) at different decision-making levels (rather than focusing on understanding technical and social conditions), the model adopted its parameters and experimentation settings from relevant studies such as [28,30,35], which are proven to be useful and instrumental for presenting the Dutch complex thermal energy system. Such parameter setting could facilitate comparing the results with the previous studies where the possibility of choosing natural gas sources is not included as an alternative energy choice. The parameters presented in Table 2 are used to conduct the simulation, which led to 48,600 simulated TEC initiatives (and 29,160,000 individual households in total).

Table 1
Input parameter configuration settings.

Parameter	Value	Unit
Duration of information exchange	7	Months
Neighbourhood size	600	households
Number of connections each household has	3	Number
Number of neighbourhoods in a municipality	3	Neighbourhood

Table 2
Experimentation settings.

Parameter	Value	Unit
Increasing rate of the natural gas price	0.01, 0.02, 0.03	(€/kWh)
CO_2 taxes	0.002, 0.004, 0.006	(€/kg)
Ambient temperature changes	Mild, High, Severe	–
Available subsidy	2, 4, 6	Million €
Municipality subsidy policy	Environment, social, economic, a trade-off	–

5. Results

This section presents the simulation results in two main categories: (i) an overview of the alternative energy choices and technical configurations and (ii) an overview of environmental, costs and discomfort indicators.

5.1. Overview of alternative energy choices and technical configurations

Fig. 3 demonstrates that individual households who joined thermal energy communities (TEC initiatives) adopted collective and individual renewable thermal energy systems, and overall, the simulated TEC initiatives drastically reduced their natural gas consumption. Few TEC initiatives continue consuming around 30% of their thermal demand from natural gas, while, on average, including all the 48,600 simulated TEC initiatives, the average natural gas consumption is 12.6% per initiative. These results are considerably lower than those of the previous study (where the individual households/ agents did not have the opportunity to choose their natural gas import source), as presented in [30,35]. In these studies, the alternative energy choices are only on two levels (i.e., collective and individual renewable thermal energy systems), and the average TEC initiatives natural gas consumption is 37% in [30] and around 20% in [35]. As the main difference between the studies is related to the possibility of choosing natural gas sources, this demonstrates the importance of giving individual households such a choice. In other words, the possibility of choosing the source of natural gas could lead to consumption reduction and, eventually, its imports. Overall, these results could translate to a higher contribution of TEC initiatives in the energy transition and reducing CO_2 emissions.

In the same line, as Fig. 4 presents, considering all the 48,600 simulated TEC initiatives, the average generation for collective thermal energy system is 83%, which is also higher than previous studies. This indicates that the simulated individual households prefer to get their thermal energy from collective renewable thermal energy systems rather than a foreign country that does not align with their internal motivations.

Fig. 5 demonstrates the alternative energy choices in more detail,

$$[3\times3\times3\times3\times4](\textit{permutation of paremeters' combination})\times[50](\textit{reputation of each combination})\\ \times[3](\textit{number of neighbourhoods in each simulation})=48600\ (\textit{simulated TEC initatives in total}) \tag{2}$$

$$48600\ (\textit{simulated TEC initiatives in total})\times600\ (\textit{individual households in each of TEC initiatives})=29\,160\,000\ (\textit{simulated individual households in total}) \tag{3}$$

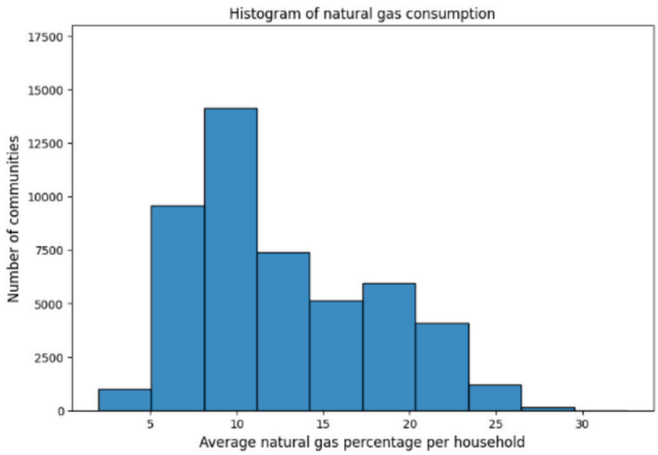

Fig. 3. Average natural gas consumption.

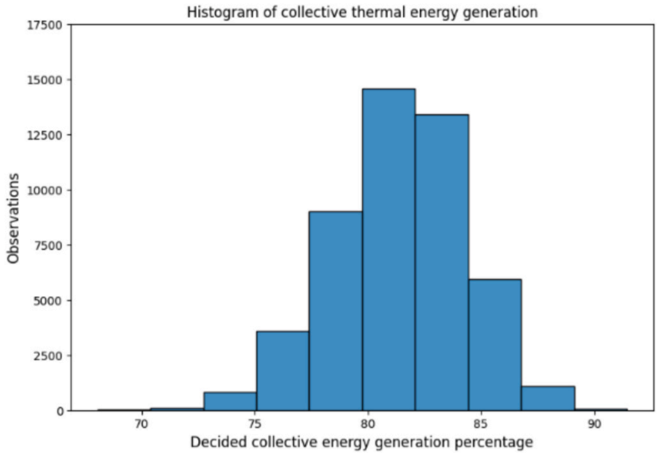

Fig. 4. Percentages of collective thermal energy generation.

Table 3
Details of alternative energy choices in percentage.

		Collective thermal energy systems			Total (%)
		ATES	Biogas	Electric boiler	
Individual energy choices	Heat pump	40.7	14.9	5.0	60.6
	Ally gas	5.2	2.2	0.7	8.1
	Other gas	4.7	2.0	0.7	7.4
	Solar	0.2	0.0	0.0	0.2
	Wood pellet	0.0	0.0	0.0	0.0
	Solar waiting	0.1	0.0	0.0	0.1
	Wood pellet waiting	0.0	0.0	0.0	0.0
	Heat pump waiting	15.7	5.8	2.1	23.6
Total (%)		66.6	24.9	8.5	100%

divided by collective and individual thermal energy systems and natural gas consumption (from allies and other countries). As the technical and institutional settings for collective thermal energy systems in this study are similar to those in the previous study, as elaborated in Sections 1 and 4.7, the distribution of the collective thermal energy systems stays mostly the same in comparison with [35]. ATES and heat pumps are the most chosen thermal energy systems as they have relatively better environmentally friendly and economical performances. However, as presented previously, the capacity of such collective technologies has increased (as presented in Fig. 4).

Compared with previous studies such as [25], Fig. 5 clearly shows that households (i.e., agents in the simulation) replace their natural gas consumption with individual heat pumps. The details of the percentages are presented in Table 3.

As Fig. 5 and Table 3 illustrate, heat pumps dominate individual renewable energy choices. Most communities (approximately 60% of 29,160,000 simulated individual households in 48,600 TEC initiatives) choose heat pumps as their individual renewable thermal energy system. On top of that, approximately 23% of individual households choose temporary blackouts to install heat pumps in the near future. These households are either (i) the ones who are environmentally friendly but do not have enough money for the heat pump immediately or (ii) the ones who have a high value for the energy independence of their country but do not have the money to invest in heat pump immediately. On the other hand, the wood pellet and solar were not adopted by households and in TEC initiatives (only 0.3% solar in total), which could be potentially related to their economic and environmental performances. As Fig. 5 and Table 3 show, natural gas from allies (e.g., Norway and the UK) has almost the same share as natural gas from other sources (e.g.,

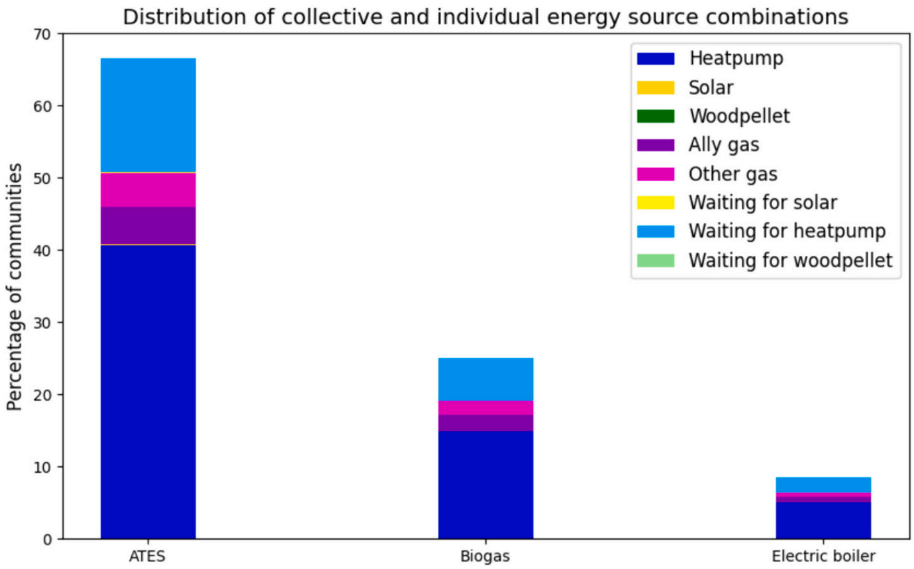

Fig. 5. Distribution of energy alternative choices in all runs.

Table 4
Overview of KPIs.

	Minimum	Average	Maximum
Voluntary blackout/ discomfort (%)	0,3	2,7	8,4
Average costs per month (€/month)	90,89	128,41	230,85
Average CO_2 emission per year ($KgCO_2$/ month)	131,9	151,1	173,8

Qatar). All these could be translated as the availability of more alternative energy choices, potentially leading to a more sustainable choice, in this case, collective and individual renewable thermal energy systems.

5.2. Overview of other KPIs

As mentioned in Section 4.6., along with analysing the alternative energy choices and technical configurations, three other KPIs are also measured in the simulation presented in Table 4.

As Table 4 presents, considering all 48,600 simulated TEC initiatives, the average voluntary blackout/ discomfort is 2.7%, which is considerably lower than the previous studies (e.g., [29,30,35]). Although there are various possibilities that individual households could face blackout/ discomfort (as explained in Section 4 and Fig. 2), as households have alternative energy choices, they could still manage better avoiding it. However, this resulted in increasing the costs for individual households, as could be expected. Compared to studies such as [18,20], the average costs are approximately 20–25% higher. Increasing the share of (collective and individual) thermal energy systems and reducing natural gas consumption also significantly reduce CO_2 emissions.

6. Discussion and limitations

By capturing and simulating the Dutch thermal energy transition, with its unique characteristics and factors, the study illustrated the importance of the availability of alternative energy choices for the (local) energy transition. In the modelling exercise, the individual households (i.e., agents in the simulation) had three layers of alternative energy choices: (i) natural gas (i.e., the current mixture of the grid, ally and other countries), (ii) collective renewable thermal energy systems (i.e., ATES, biogas and electrification), and (iii) individual renewable thermal energy systems (i.e., heat pump, wood pellet, solar PVT).

6.1. Discussion

The main difference between this study and similar ones in the field (e.g., [28,30,35]), and eventually one of its contributions, is related to adding the decision-making loop on the natural gas source. In other words, the previous studies included only the two lower levels of multi-level governance (MLG) (e.g., individual and municipal decision-making levels), and the possibility of choosing a natural gas source was not investigated. Although the real-world application of such findings is challenging (i.e., each household chooses its own sources of natural gas), this could be translated into policies on a higher level (e.g., including public opinion on the sources of natural gas). The study showed that the availability of alternative energy choices (i.e., including the choice of the source of natural gas) could amplify the contribution of individual households and thermal energy communities (i.e., TEC initiatives) to the local energy transition. By employing multi-level governance (MLG), the study explored and explained the need to include public opinion in all three mentioned levels of decision-making in governmental institutions. These insights are in line with the findings of previous empirical studies such as [20,26,98], which emphasise the importance of institutional settings (such as including public opinion and developing supportive policies) for the local (heat) transition.

The simulated TEC Initiatives drastically reduced their natural gas consumption, on average, by approximately 20%. In order to cover the thermal energy demand without natural gas consumption, the TEC initiatives mainly increased the capacity of their collective renewable thermal energy systems (25%–30% increase compared to previous studies, where the possibility of choosing natural gas sources is not included) or adopted more individual heat pumps (15%–20% increase compared to previous studies). Such choices and configurations led to a significant decrease in individual households' CO_2 emissions (decreased by 90% approximately compared to using fully natural gas for thermal energy demand) and reduced the voluntary blackouts/ discomfort that individual households face (on average 2.7% compared to previous studies it 5%–10% decreased).

Such improvements are reflected in individual households' average costs, which resulted in an average of 128,41 (€/month) over 20 years of simulation. This is almost two times higher than using a thermal energy system based on fully natural gas, in comparison with energy prices from 2020. It is approximately 30%–35% more expensive than previous studies that studied TEC initiatives (e.g., [28,35]). Financial feasibility is one of the most important factors that influence the deployment of innovative systems (as extensively discussed in [98]), and therefore, to make such multi-level collective action complex systems feasible, it needs to be addressed. Shifting the available subsidies from fossil fuels to RETs, new business strategies (examples are presented in [99,100]) and the CO_2 emissions tax (as it is currently implemented for Dutch companies and as presented in policy reports), are the examples of economic solutions for making the suggested systems more financially attractive and feasible.

The study showed the importance of public opinion on the higher level of governance (e.g., natural gas imports) and the performance of TEC initiatives. These insights contribute to studies such as [21,22,25,26], which empirically investigated the different factors influencing the local heat transition and natural gas consumption reduction. The findings could also contribute to establishing and functioning other types of energy communities, such as solar-based energy communities, as there are some similarities between the challenges, as presented in [101]. Considering all these points, it is concluded that the availability of alternative energy choices on different levels (e.g., national, municipal and individual levels) could potentially lead to more desirable (i.e., environmentally friendly and sustainable) outcomes, in this case, by amplifying the contribution of TEC initiatives to the energy transition.

6.2. Limitations and future research

Although this study brought new insights into the sustainable (energy) transition, energy policy and institutional design, it has certain limitations.

Firstly, ABMS as a method has certain limitations. Although the modelling practice and its results provided new insights, ABMS represents a simplified version of reality like other computational modelling practices. The real world is more complicated, and other factors, such as fluctuations in natural gas prices and introducing of new energy policies, could potentially influence the outcomes. Therefore, considering new research questions and aims, the future models could potentially include such factors to understand and explore them within the context of thermal energy transition and TEC initiatives. Furthermore, to address and capture such complexities, different research methods such as optimisation modelling (to explore the techno-economic trade-offs), system dynamics modelling (to explore the energy system from a top-down perspective), and equilibrium modelling (to explore the supply-demand dynamics in a CESs) could be beneficial.

Secondly, like any other modelling exercise, the study and the model have specific assumptions that are simplified for their purpose. For instance, public opinion towards natural gas only had three choices: a mixture of the grid, ally countries, or other countries, which does not make a distinguish between the countries in the same category (the ally countries are used as an overarching category, and do not get to the details of each country in this category). Or the model did not include all the possible energy sources (e.g., hydrogen). Although such assumptions serve the aim of the study and provide insights related to the importance of public opinion and the need for the availability of alternative energy choices, they could be modelled in more detail in the follow-up studies (e.g., collecting data and including specific countries as natural gas sources).

Thirdly, to provide meaningful and concrete insights, the study focused on the Dutch thermal energy transition as its case study and heavily relied on comparing its results with previously published models (as the earlier versions of the described model). The choice of the case study (and all related assumptions) is justified; however, in future research, populating the current models with data from other countries (e.g., Germany and Denmark) could be beneficial in verifying the current findings further and bringing new insights. Exploring a new case study could also potentially lead to the expansion and development of the current version of the model further to capture new technical and institutional settings (e.g., renewable energy technologies and subsidy schemes) and actors (e.g., business owners).

Lastly, although the theoretical backbone of the model, the SVO theory, the IAD framework and the multi-level governance (MLG) were instrumental and novel in achieving the study's aim, they have certain limitations, as they frame the thermal energy transition in a certain way. However, applying theories such as the Theory of Planned Behaviour (TPB) [102] and The Behavioural Reasoning Theory (BRT) [103] could have led to more detailed insights regarding the individuals' concerns, motivations and values in the decision-making processes. The four-layer model of Williamson [104] could also be used to understand the feedback loops and dynamics of the development of institutional arrangements. Using the multi-level perspective (MLP) [63] could also lead to conceptualising TEC initiatives as niche innovations and understanding the dynamics of the deployment, making TEC initiatives become the dominating energy systems (i.e., socio-technical landscape) for providing thermal energy for households.

7. Conclusions and recommendations

As one of the main sources of greenhouse gas (GHG) emissions, the energy sector is going through a fundamental transformation called the energy transition. In this context, special attention is being placed on the local level, as well as on household roles and contributions to the energy transition. This research aimed to explain and describe the influence of the availability of alternative energy choices for facilitating the households' (thermal) energy transition. Thermal energy communities (TEC initiatives), as local and collective energy systems for generating, distributing and consuming renewable thermal energy for individual households, are chosen to be the underlying complex energy system that this study investigated. In this context, agent-based modelling and simulation (ABMS) with the SVO theory, the institutional analysis and development (IAD) framework and the multi-level governance (MLG) as its theoretical backbone are employed and populated based on the available data from the Netherlands. Within this modelling exercise, the agents (i.e., households) had three layers of alternative energy choices: (i) national level: natural gas sources (i.e., the mixture of the grid, ally and other countries), (ii) municipality level: collective renewable thermal energy systems (i.e., ATES, biogas and electrification), and (iii) individual level: individual renewable thermal energy systems (i.e., heat pump, wood pellet, solar PVT).

The results demonstrate the significant importance and influence of the availability of different alternative energy choices on the performance of TEC initiatives, such as reducing the natural gas consumption to 12.6% on average for all 48,600 total simulated TEC initiatives. Individual households increased the share of collective renewable energy generation (on average 83% for all TEC initiatives) and adopted more heat pumps (84% of all households in TEC initiatives) to meet their thermal energy demand. Such collective action, with vast choices on different levels, led to smaller voluntary blackouts/ discomfort (2.7% on average) while significantly contributing to reducing the CO_2 emissions of TEC initiatives (by 85%). On the other hand, it increased the costs of establishing and functioning TEC initiatives. Considering that including the choice of natural gas sources is the main difference of this study with the previous ones (e.g., [28–30,35,75,76]), results demonstrate the positive impact of availability of such choices on environmentally friendly outcomes (e.g., reducing natural gas consumption and reducing CO_2 emissions) for the local (thermal) energy transition. The availability of such choices can be translated into public opinion on natural gas resources; therefore, the study constructively delineated the influence of and the need to include public opinion in such high-level energy governance and policy-making processes.

7.1. Recommendations

The results from previous sections are translated into detailed recommendations as follows:

- Policy-makers are advised to ask for and include public opinion on high-level energy governance (e.g., sources of natural gas imports), as it could considerably contribute to reducing natural gas consumption and CO_2 emissions.
- Municipalities and policy-makers are urged to provide alternative energy choices for individual households and empower them in the related decision-making processes to accelerate the (thermal) energy transition.
- Individual households are encouraged to discuss and share their opinion towards alternative energy choices and the energy transition as a whole to provide input into the decision-making processes at the higher levels.
- All stakeholders are recommended to support and facilitate the establishment and functioning of (thermal) energy communities, as their contribution to the reduction of natural gas consumption and thermal energy transition is significant.

In addition to the concrete energy-related insights on the technical, institutional, and behavioural settings, the study also contributes to the computer modelling and simulation field, particularly computational social simulation, by (i) using multi-level governance as its backbone for the first time, and (ii) concretely demonstrating an example of comparing with (and expanding) existing models to explore a new question and provide new insights. Therefore, the study could be used by energy system modellers as an example of expanding their computational models to address new questions.

CRediT authorship contribution statement

Javanshir Fouladvand: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Emre Ateş:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis. **Yasin Sarı:** Writing – review & editing, Validation, Software, Formal analysis, Conceptualization. **Özge Okur:** Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

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Appendix A. Input data

Table 5
Data on collective thermal energy systems (the peak demand is considered 10% for all of them).

Variable	Units	Bioenergy	ATES	Electric boiler
Average capacity	kW	950	800	400
Capex	euros/kW	825	1600	800
Opex fixed	euros/kW/yr	55	113	120
Opex variable	euros/kWh	0.003	0.0019	0.025
Load hours	h/yr	3000	3500	2000
CO_2 emission	kg/kWh	0.26	0.152	0.14
Lifetime	yr	20	30	30

Table 6
Data on individual thermal energy systems.

Variable	Units	Heatpump	Solar PVT	Wood pellet
Capex	euros/kW	1770	1450	415
Opex	euros/kW/yr	35.4	11	140
Load hours	h/yr	1500	700	2000
CO_2 emission	kg/kWh	0.14	0.086	0.35
Lifetime	yr	15	20	20

Table 7
Other data (for the Netherlands).

Variable	Units	
CO_2 intensity of electricity consumption for electric boiler	kgCO_2/ KWh	0.43
CO_2 intensity of electricity consumption for heat pump	kgCO_2/ KWh	0.14
CO_2 intensity of electricity consumption for solar PVT	kgCO_2/ KWh	0.09
Average thermal energy demand per year	kWh	12,000
Gas price	euros/kWh	0.1
CO_2 tax	euros/kg CO_2	0.025
CO_2 emission of natural gas	kg/kWh	0.2

Appendix B. Overall calculations of the leader

The leadership (either municipality or community board) calculations for choosing a collective renewable thermal energy system:

$$Total\ demand\ per\ year = number\ of\ households \times average\ demand\ per\ household\ per\ year \tag{4}$$

$$Annual\ CO2\ emission = [total\ demand\ per\ year \times CO2.intensity] \tag{5}$$

$$Costs\ (investment) = Technology\ capacity \times Capex + heat\ demand \times Operating\ costs \times lifetime \tag{6}$$

$$Min.needed\ participants = < \frac{Costs}{natural\ gas\ prices \times current\ consumption} \tag{7}$$

These values are then normalised on a scale between 0 and 1, where 0 represents the worst-performing alternative (i.e., highest emission, highest costs, or least number of needed participants) and 1 stands for the best-performing one. Then, the municipality ranks the technologies according to their normalised values and strategy (lowest emission first for environmental, lowest cost first for the economic and lowest number of participants for social).

Appendix C. KPIs calculations

C.1. Average voluntary blackout/ discomfort per household

$$\text{Voluntarily discomfort for a household} = \frac{\sum_{1}^{\text{lifetime}} \begin{pmatrix}100\%\text{demand} - \%\text{collective generation} - \\ \%\text{individual generation} - \%\text{natural gas consumption}\end{pmatrix}}{\text{lifetime}}$$

$$\text{Average percentage of voluntarily discomfort per household in the community} = \frac{\sum_{1}^{\text{number of households}} (\text{percentage of voluntarily discomfort for a household})}{\text{number of households}} \tag{9}$$

C.2. Average cost per household

$$\text{Costs for a household} = \frac{\begin{matrix}[(\text{investment for collective system}) + (\text{collective system yearly costs}) \times (\text{lifetime})] + \\ [(\text{investment for individual system}) + (\text{individual system yearly costs}) \times (\text{lifetime})] + \\ [(\text{natural gas consumption per year}) \times (\text{lifetime})]\end{matrix}}{\text{lifetime}} \tag{10}$$

$$\text{Average costs per household per month in the community} = \frac{\sum_{1}^{\text{number of households}} (\text{costs for a household})}{\text{number of households}} \tag{11}$$

Average CO_2 emission per household

$$CO_2 \text{ emission for the whole community} = \frac{\begin{matrix}\sum_{1}^{\text{lifetime}} (\text{collective system emission}) + \\ \sum_{1}^{\text{lifetime}} \sum_{1}^{\text{number of households}} (\text{individual system emission}) + \\ \sum_{1}^{\text{lifetime}} \sum_{1}^{\text{number of households}} (\text{natural gas emission})\end{matrix}}{\text{lifetime}} \tag{12}$$

$$\text{Average } CO_2 \text{ emission per household in a community} = \frac{CO_2 \text{ emission for the whole community}}{\text{number of households}} \tag{13}$$

Appendix D. Data for attributes of community

Table 8
MCDM inputs.

Criteria	Sub-criteria	Unit	Description	Reference
Financial criteria	CAPEX	€	Investment costs	[105]
	OPEX	€	Operational and maintenance costs during the lifetime of the system	[106]
	Payback time	Years	Years for the investment and maintenance cost to equal the accumulated energy savings from the change	[107]
	Subsidy coverage	%	Percentage of the capital costs covered by the subsidy (in the present study, this would be the SDE++ subsidy)	[106]
Environmental criteria	CO_2 emissions	Kg CO_2eq	The CO_2 emission intensity of technology based on capacity	[108]
	Land use	HA	Amount of land use required for technology based on capacity	[105]
	Social acceptance	1 to 10	The degree to which that technology is accepted, recognised and implemented	[106]
Independence criteria	The energy input to the system	kWh	Amount of energy input required for the technology to produce the heat to cover the neighbourhood heat demand	[108]

Appendix E. Data on energy independence and awareness/ care

Adopted from [21]	Likert scale 1 to 5, 1 meaning least agreeing with the statement, 5 strongly agreeing with the statement.				
Statements	Minimum	Maximum	Mean	Std Division	Variance
It is important for me to know the country's source of natural gas that I consume to heat my house.	1.00	5.00	3.49	1.10	1.21
It is important for me to consume natural gas extracted from my country of residence.	1.00	5.00	2.69	1.04	1.08

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