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Simulating thermal energy community formation: Institutional enablers outplaying technological choice

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HIGHLIGHTS

- To study energy community formation agent-based modelling is proposed.
- Institutional conditions influence energy communities' formation greatly.
- Trained energy community boards facilitate energy community formation.
- Financial considerations alone are insufficient to form energy communities.
- Balancing between all relevant decision-making criteria is key to success.

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ABSTRACT

Energy communities are key elements for local energy transitions, collectively generating, distributing and consuming energy, using renewable energy technologies. Thermal energy communities, as one type of energy community, are focused on thermal energy applications, such as heating, cooling, bathing, showering and providing hot tap water. As thermal energy applications and systems receive increasing academic and policy attention, there is a need to better understand the formation processes they undergo. In this study, various technical and institutional conditions are explored that influence thermal energy community formation processes by using an agent-based modelling approach. The results show that technology selection is not the most crucial and determining factor for the success of thermal energy communities, yet the surrounding institutional conditions are. Key factors that influence these formation processes pertain to providing training, so that the thermal energy community leaders become more skilled, and allocating subsidies based on the projects' degree of environmental friendliness. For all stakeholders, finding the balance between all of the decision-making criteria is key to success. The results are useful for practitioners - and especially for policy makers - to develop more impactful policies and strategies to support the expansion of local thermal energy communities.

1. Introduction

Among the multiple approaches to greenhouse gas mitigation in energy transition, the deployment of renewable energy technologies (RETs) is considered to be the main strategy [1]. Energy transition has been discussed at different levels, namely, supranational, national, regional, and community level [2,3].

At community level, in particular, energy communities are considered to be a key element for the deployment of RETs, as they contribute to their own energy generation, distribution and consumption [2]. Since households are responsible for around 25–30% of total energy consumption [4,5], energy communities could potentially play a major role in energy transitions. There are different definitions for energy community in academic literature. This term can be defined, for instance, as, "people in a neighbourhood, who invest in renewable energy technologies jointly and generate the energy they consume" [6].

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Another definition works around an installation of one or more renewable energy technologies in or close to a rural community where community participation is a key factor [7,8]. Schram et al. define energy community as, "a group of consumers and/or prosumers, that together share energy generation units and electricity storage" [9]. While energy communities are usually built on norms and values such as trust, and the environmental and financial concerns of their participants [10], the more formal organisational-legal version of energy communities, i.e. energy cooperatives, are characterised as commercial organizations operating in a market environment [11,12]. Overall, we conclude that the concept of energy community in the academic literature encapsulates initiatives that focus on collective generation, distribution and consumption of renewable energy for all community members [13,14].

In the literature about energy communities, thermal energy applications are understudied [15], however, thermal energy covers no less than 75% of total non-transport related energy consumption among households [16,17]. Discussions mainly address either energy communities in the general sense of the concept (e.g. [2,8,18]) or, more particularly, electric energy communities (e.g. [19,20,21]). Within the scarce literature on thermal energy communities, studies are mainly focused on technological aspects (e.g. [17,22,23,24]), and in particular, on district heating technology (e.g. [25,26,27]). For example, in Sweden, [28] and [29], have studied heat load patterns and the technical design of district heating. Studies such as [30] and [31], also provide an overview about the status of Swedish district heating and its benefits and risks. In this context, [32] and [33], discuss the overview of technical developments in Danish district heating. However, these studies do not focus on the thermal energy community and its collective action nature, explicitly. Yet, according to [34] and [35], this is key in order to change the institutional context which is currently hindering the potential to overcome economic and technological challenges related to adopting local heat technology and the related infrastructure (e.g. high capital investment requirements and long installation time).

Overall, there is a lack of understanding about thermal energy community (TEC) initiatives, what their formation process entails and the institutional conditions needed for TEC initiatives to thrive. This hinders the deployment and implementation of TEC initiatives, which consequently hampers the energy transition as a whole. The goal of this study is therefore to explore and gain insights into the potential impact of various institutional and technological conditions on the formation process of thermal energy communities. The research question is formulated as: "What technical and institutional conditions hinder and enable thermal energy community formation?" In this regard, an Agent-Based Modelling (ABM) approach [36,37], is considered to be a suitable tool for studying the complex dynamics and interactions within (thermal) energy community initiatives. ABM allows the exploration of the complexities of decision-making processes of an energy community, and experimentation with alternative strategies within a virtual simulation environment. In fact, because of their usefulness in studying bottom-up social processes, several researchers have already used ABM for modelling community energy systems. For example, [38] uses ABM for studying zero energy communities. By using ABM and considering the leadership role, the emergence of local energy initiatives for solar and wind energy is explored in [39,40] use this approach for exploring the adoption of residential solar photovoltaic systems. [41] also developed an ABM for studying the conflict of values within local energy systems. In the context of thermal energy applications, [42] uses ABM for studying local heating systems in the built environment. Based on an ABM approach, [43] studies valued conflicts and social acceptance of sustainable heating systems and showed that an aligned value system across stakeholders can potentially lead to higher acceptance rates of new heating systems. Policy interventions and business models related to heat network development in UK cities are studied in [34]. Although all these studies explore specific aspects of energy communities, none have explored the technical and institutional conditions for the formation of thermal energy communities.

The ABM model that was developed in this study is about technical (thermal) energy innovation that goes hand in hand with social innovation (in the form of energy community formation). It is used to look at how certain combinations of technical and institutional conditions influence the formation of thermal energy communities. Furthermore, it proposes recommendations about the institutional changes required to foster the establishment of Dutch thermal energy communities. The model itself has the potential to serve as a simplified tool for stakeholders to explore how to foster thermal energy transitions in their local context. The results of this study exemplify how the model can be applied in the Dutch energy context, but this tool can be applied to other contexts as well by adjusting the data.

The structure of this paper is as follows: Section 2 provides insights about thermal energy communities. The theoretical background of the research is presented in Section 3. Research methods are introduced in Section 4. A model description, which entails the development and implementation of an agent-based model, is presented in Section 5. Section 6 then discusses model implementation and assumptions. Next, model results are presented in Section 7. Section 8 then presents the academic discussion. And finally, conclusions, implications and suggestions for further research are presented in Section 9.

2. Thermal energy communities (TEC)

In order to contextualise the modelling exercise of this study, the relevant literature on community energy systems in general, and TEC in particular, is presented in this section.

TEC, in particular, focus on providing sustainable energy for thermal applications, such as heating, cooling, bathing, showering and cooking [15]. As a sub-category of energy communities, TEC consist of three main components: (thermal) renewable energy technology, stakeholders involved and related institutions [15]. As elaborated in studies such as [44,45,46], these components interact with each other within the TEC system boundaries and with the environment outside the TEC system's boundaries.

2.1. The thermal technology component

TECs involve the implementation of common local RETs which are used for thermal energy applications. In the existing literature, the technological component of TEC has been studied relatively more than the other two components (i.e. stakeholders and institutions) [34]. Regarding the technology, topics such as energy system design (e.g. [47,48]), energy system integration (e.g. [49,50]), demand-side management (e.g. [51,52,53]), and thermal storage (e.g. [54]), have received academic attention. According to [24,55,56], the technology components of TEC can be decoupled into three main elements: (i) generation (input); (ii) distribution (transition); and (iii) consumption (output).

- Generation: This encompasses the heat source and the thermal energy generating technology [24]. In addition to the renewable thermal energy resources and technologies, such as biomass, biogas, geothermal, solar thermal, and waste heat [57,58], renewable electricity for thermal purposes (e.g. heat pumps) is also included in TEC initiatives [58].
- Distribution: This entails making the generated heat available for consumption through its transportation from the heat source to the end user [27,59]. It consists of connections, heat exchangers, and the network of pipelines [23,59].
- Consumption: This focuses on the thermal applications inside the households, such as space heating or cooling, and hot tap water [24]. Therefore, besides demand-side management, studies such as [60,61] explore the influence of energy saving measures for heat consumption. Energy labelling is another topic that is touched upon in the literature on thermal energy consumption (e.g. [62,63]).

2.2. The stakeholders component

The second component of energy communities comprises participants within any energy community, e.g. TEC initiatives, their roles and responsibilities [15]. The role of different stakeholders on the level of social acceptance of community energy systems [64], the influence of leadership [39,65], and vision building [65] on the establishment of energy communities are examples of topics explored in this regards. The division of financial responsibilities has also been studied as a key success factor in TEC initiatives [66,67].

Recent research, however, has focused on exploring the participation motives [68,69], willingness to invest [66], and trust [10,70]. In this context, [3,71,72], focus on stakeholder involvement and engagement, [3,73], discuss participants' norms and values, and [74], study participants' characteristics, such as willingness to participate. Approaches like co-creation [75] are also explored in the local thermal energy transition literature.

2.3. The institutional component

Institutions are human-constructed rules which shape social, political and economic interactions or, more loosely, rules that govern the system, in this case the local (thermal) energy system [76]. Institutions can be discerned into formal and informal rules [77,78].

Research into formal rules influencing community energies looks into topics such as energy policies (e.g. [66,79]), regulations (e.g. [80,81,82]), and incentive mechanisms (e.g. [11,83,84]). More particularly in the context of TEC initiatives, regulatory design [85,86,87,88], and market design and pricing strategies [89,25,26] have received considerable academic attention.

On the other hand, informal institutions include norms and values that influence the behaviour of stakeholders [64,90,91] and interaction structures between them [81,92]. In other studies, the role of values and behaviour in energy communities is addressed (e.g. [93,94,40,95]). Other issues that have to do with public values, but also tap into informal rules held by community members and stakeholders, include trust [70], psychological factors [96], environmental concerns [97,98,99], and local energy autonomy [100].

2.4. Social and governance settings

Following the meta categorisation developed by Warbroek et al. (2019) for solar energy communities on organisational and governance drivers that positively influence local energy initiatives, factors influencing community energy performance and their relative success can be divided into three different groups: (i) intra-organizational characteristics of an energy community; (ii) interaction with the local community; and (iii) governance setting and linkage to government [101].

(1) Intra-organizational characteristic of the TEC initiatives

Key factors influencing community energy performance include:

- The presence of actors who are specially committed to the project and effectively provide direction to the group (i.e., 'project champions') [101].
- Having the required knowledge and expertise to overcome impediments and take the required actions to establish the energy communities [101,102].
- Having access to funds [101], such as subsidies to cover (a fraction of) the required investment and increase the project's affordability [71,67].

(2) The interaction with the local community

Frequent interaction between project champions and the local community is essential to ensure a high level of local community involvement, which is then translated into high willingness to participate and invest in the project [101]. This can be achieved through the early direct involvement of the neighbourhood and open decision-making processes [103]. Active engagement of the local community could be ensured by aligning the needs, expectations and values of different stakeholders, including the local community and leaders [71]. The importance of other related factors, such as a high level of cohesion [104] and trust [10,70], are also addressed in academic literature.

(3) Governance and the involvement of external stakeholders

It is critical to connect the external stakeholders to the project champions and local community [101] in order to achieve external support and complete the overall set of skills, capacities, information, and expertise required for the establishment of an energy community [71,101]. Creating such a network facilitates information sharing, which is important for enhancing learning from the experience of other energy communities [102]. Developing supportive policy frameworks that ease the provision of planning permits and provide external funding is another example of external stakeholders' influence on establishing an energy community [3,82,101]. Nevertheless, all these interactions and networks will only be successful if the different discourses and visions held among stakeholders are shared and aligned [103].

2.5. The formation process of TEC initiatives

The development of viable local heating networks requires the main actors to navigate through a series of project stages which are elaborated as follows [34,105]:

- *The idea phase*: This phase focuses on the initial mobilization of TEC participants. The outcome of this phase is typically the shared approval of a vision and a first plan. Key issues in this phase concern: a vision, a new technology, a new partnership between the actors around the TEC project.
- *The feasibility phase:* This phase focuses on building consensus about the project's characteristics, with the condition that this is technically and financially feasible. A key requirement is that the project is linked to both the spatial characteristics of the region and the socio-economic features of the residents. Additionally, the financial and organisational arrangements need to be agreed upon with the TEC members during this phase.
- *The procurement and construction phase*: Once the consensus about the local heat network project has been reached, finance needs to be secured, customers contracts arranged, and the infrastructure built.
- *The expansion phase:* Lastly, this phase includes the daily operation of the local heat network once it is in place, and its expansion to involve a larger share of the community.

3. Theoretical background

In this section we introduce the theories that are used as the backbone of our modelling exercise. We also use these theories to analyse our simulation results as will be discussed in the following sections. While the four-layer model of Williamson [106] and the Institutional Analysis and Development framework [77] support the structuring of the elements of thermal energy communities, the Behavioural Reasoning Theory [107] supports the understanding of how these elements relate to each other.

3.1. The four-layer model of Williamson

The four-layer model of Williamson categorises institutions into four different layers [106], as presented in Fig. 1. These four layers interact, provide feedback to each other, and have a temporal aspect since each level operates at its own pace [106,108].

- **Level 1: Social embeddedness**: The highest layer includes the informal institutions of cultures and values, which operate at the lowest pace and require hundreds of years to change. However, they

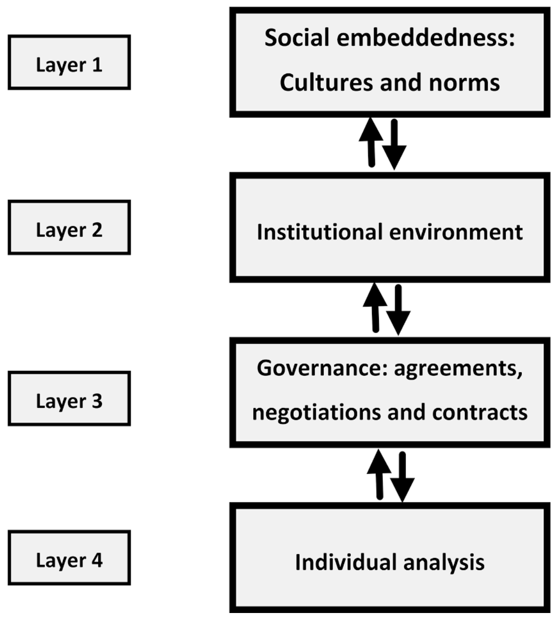

Fig. 1. The four-layer model of Williamson [106]

have a large influence on the other layers. These institutions mainly have a spontaneous origin and have a lasting grip on the way society behaves.

- **Level 2: Institutional environment:** This level comprises the political, legal and governmental, more formal arrangements that shape the activities in the other levels. Changes in this level occur when there are windows of opportunity, such as a hard economic crisis. These formal rules are in the form of laws and regulations which can come from a (supra)national, and regional level. The time horizon of change in these institutions is in the order of a decade to a hundred years.
- **Level 3: Governance:** This layer looks into the modes of organizations which are formalised with contracts and agreements that describe the division of roles and responsibilities across stakeholders. However, informal agreements based on trust and reciprocity can also be analysed on this level. The time horizon of change in these institutions is in the order of one year to a decade.
- **Level 4: Individual analysis:** This level accounts for the analysis of the operation and management of the system. It looks at what individuals take into consideration when making decisions and how they make these decisions. This is the fastest changing level and it is continuously developing [106,109].

The key element of Williamson's four-layer model concerns feedback loops [106,110], illustrating the interconnectedness of institutions within a specific system, using a system's perspective [109]. These loops show how developments and changes at a lower level are, on one hand, steered and restricted by the institutional arrangements at higher levels, and on the other, they open up paths for new arrangements at higher institutional levels [109].

The four-layer model of Williamson has traditionally been used to understand complex environmental issues. However, [111,112,113] argue that the four-layer model of Williamson also provides a useful platform to study and analyse energy systems.

In the present study, the four-layer model of Williamson is used to represent the stakeholders and their decision-making hierarchy in the ABM (See Section 5). The high-level meta-conceptualisation of the four-layer model of Williamson provides the structure to identify the key action situations within the decision-making processes of thermal energy communities' formation processes. Additionally, it supports the classification of these action situations into the different institutional layers. We leave the first layer out in the simulation, as we are looking at shorter time horizons.

3.2. *The institutional analysis and design (IAD) framework*

The IAD framework developed by Ostrom (2005) enables the dynamic analysis of decision-making processes in a system by breaking them down and organising them into simpler, more manageable parts [76,77] (see Fig. 2).

The action situation is the main component of the IAD framework [77,114] describes the action situation as: "a conceptual space in which actors inform themselves, consider alternative courses of action, make decisions, take action, and experience the consequences of these actions". What happens in the action situation is influenced by exogenous variables which are classified into three main components: biophysical conditions, community attributes and rules-in-use.

- The biophysical conditions include the physical and material resources and capabilities available within the system's boundaries. Resources include technology options, finance, population and available labour, for instance [76,114].
- The attributes of community include the cultural norms accepted by the community. In other words, the values, beliefs and preferences about the potential outcomes of the action situation [76,94].

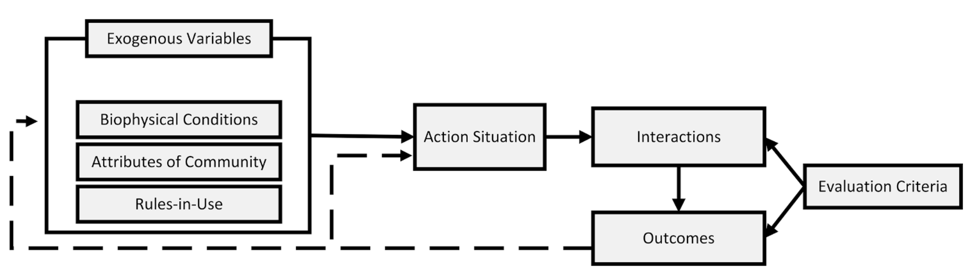

Fig. 2. The IAD framework [110]

- Lastly, there is the rule-in-use component, which is about the formal rules that govern the system. Ostrom categorises them into seven rules which influence the action situation: boundary, aggregation, scope, pay-off, position, information and choice [109,110].

These exogenous variables and action situation components lead to patterns of interaction that generate certain outcomes. These outcomes can be objectively assessed on the basis of evaluation criteria [77,110]. In the end, there is a feedback loop which connects the outcome to the action situation and the exogenous variables [109,110].

Even though the IAD framework has conventionally been applied to the study of traditional, common pool resource management, it has lately been extensively applied to energy systems (e.g. [115,116,117]) and the community energy system, in particular (e.g. [93,118,94]).

In our simulation, the IAD framework will be used to model the interactions and decision-making processes of stakeholders in each layer of the four-layer model of Williamson. Once the key actions for the formation of thermal energy communities have been identified, the IAD framework supports a more in-depth analysis of these actions through the identification of the components that shape them and the important external and internal conditions that influence them. This provides the required depth of understanding for the proper representation of the action within the ABM model presented in this paper.

3.3. Behavioural reasoning theory

The Behavioural Reasoning Theory (BRT) is used to analyse and guide how actors make decisions and behave [107,119]. BRT focuses on understanding the personal factors that influence sustainable behaviour [120,121].

As presented in Fig. 3, BRT postulates that intentions are strong predictors of behaviour and that attitudes are a key antecedent of the adoption of these intentions [107,122]. BRT then theorises that attitudes are a key antecedent of the adoption of behavioural intentions [107]. BRT includes the relevance of context-specific reasons for and against a decision as a key predictor of the attitudes, as well as of the final decision [107,123]. In addition, BRT proposes that, most importantly, resulting from a desire for simplified information processing, people's processing of value information directly affects the reasoning for their anticipated behaviour. In this line, BRT argues that project leaders, when searching to make the right decision, scan their values and belief systems and find the action that aligns best [124].

In the energy transition related literature, there are several studies, such as [120,122], that use BRT to analyse the deployment of RET. In our study we use BRT to capture the values, reasons and attitude of individuals concerning participation in TECs. BRT connects variables that are defined according to the two aforementioned frameworks: (i) how the community attributes within the IAD framework influence the action situation and, (ii) how the informal rules in first layer of the Williamson framework influence the decisions made by the individuals in the fourth layer.

By building our ABM model on the theoretical grounding provided in this section, we aim to, firstly, analyse the way in which a certain combination of technical and institutional conditions influences the formation of thermal energy communities, and secondly, provide recommendations on the institutional change required to foster the establishment of TECs.

4. Research methods

4.1. Agent-based modelling (ABM)

In ABM, agents are heterogeneous, autonomous and individual decision-making entities (e.g. any stakeholder, such as households, municipalities, companies and policy-makers), that are able to learn and interact with each other and their environment [125,126]. This allows the capture of individual behavioural choices while also allowing the understanding and analysis of the emergent behaviour of the system as a whole [36]. Moreover, institutional changes and policy interventions can be analysed in ABM by using different scenarios and comparing the emergent behaviours of agents that arise from them [34,37].

For these reasons, ABM is considered a suitable approach for studying the behaviour of stakeholders, their decision-making process, and dynamics within a TEC. In addition, ABM has the following key benefits:

- ABM creates a simplified representation of reality, easing the research while breaking free the constraints imposed by the need to obtain analytical solutions and mathematical formulations [36,37].
- ABM can be applied to situations where the study of macro-level complexities is required, looking at the interaction of simple system components, which prompts the emergence of complex behaviour(s), using a bottom-up approach [109,127].
- ABM provides the ability to add the time variable, allowing the examination of different scenarios so as to understand inputs, variables, and outputs with little effort, enhancing the investigative power [36,37].

Considering the complexity of the real world, an ABM cannot represent all of the details of a real-world decision-making process. However, ABM can facilitate decision-making processes by equipping decision makers with insights about crucial variables affecting such a process. In this research, ABM is used in order to approach and explore the technical and institutional conditions which influence the formation of TECs in urban districts.

4.2. Case study: The Netherlands

In order to parameterize the model, delineate reliable results and derive practical recommendations, we have used data from the Netherlands. A country level of analysis has been chosen for the following reasons: (i) the characteristics of energy systems differ per country, (ii) the availability of national statistical data at country level, and (iii) it allows the study of institutions (both formal and informal

Fig. 3. BRT [107]

rules) with a broad view. The Netherlands was selected as the country for the case study in this research because of the:

- Presence of a high number of energy communities as compared to other EU countries [67];
- Presence of a well-developed energy/heating infrastructure [87,128];
- Ambitious Dutch national CO_2 reduction targets which have influenced the heating sector [129];
- National norms for environmental concerns and sustainable development [130,131];
- Urge for (heat) energy transition due to gas quakes [132].

The Netherlands is used as a case study to populate the model, based on real-world data. The data was collected from the 'Stimuleringsregeling Duurzame Energie' (SDE++) (in English: the Sustainable Energy Incentive Scheme; translation by the authors), and the Netherlands Environmental Assessment Agency (PBL).

5. Model description

This section explains the agent-based model that is used to study institutional and technological factors that affect the formation of TEC initiatives.

5.1. Model conceptualization

The model represents a city with multiple neighbourhoods. It assumes each neighbourhood can implement one thermal energy community. In each community, there are individual households who make decisions on whether they are willing to collectively generate and consume renewable thermal energy together. The municipality, as a representative of government, has a limited budget per year (e.g. a subsidy), to facilitate the implementation of thermal energy communities in the city. The model conceptualization is based on the IAD framework as follows[1].

5.1.1. Participants: Agents

The agents included in the model are households, the board of energy communities and the municipality, each representing one of the four layers in Williamson's model (see Section 3.1.)

- **Social embeddedness.** Each agent has a particular value system that guides their decision-making processes and level of involvement in the formation of thermal energy communities.
- **Institutional environment: the municipality.** This layer comprises the political, legal and governmental, formal arrangements, the "rules of the game" that shape the activities in the lower layers. In the model, the municipality, which represents the government departments that are responsible for the energy transition, is responsible for defining the formal institutions that will be available to support the neighbourhoods' transition from gas. Their tasks include setting eligibility requirements for subsidies, and providing training for the energy community boards.
- **Governance: the TEC board.** This layer looks into the modes of organization which are formalised through contracts and agreements that describe the division of roles and responsibilities. In the model, it is assumed that, right from the start, there is already a group of people interested in leading the transition to a natural gas-free area in each neighbourhood that will take ownership of the project. The TEC board is responsible for gaining sufficient household support, organising the individuals who participate in TEC, the initial decision-making regarding collective technology, negotiating, and applying for subsidies as representatives of TEC. The TEC board also has a specific set of values, which define its vision, and it can participate in training courses in order to learn how to persuade more individuals to participate in the project.
- **Individual analysis: households.** These are the individual households forming the neighbourhood, that are initially using natural gas to cover the demand for thermal energy in the houses and hold a specific set of value preferences. At a later stage, they can adapt their value preferences when influenced by the preferences of their neighbours, and they can decide to participate in the TEC initiative by supporting the technology scenario, making the required investment and installing the technology.

5.1.2. Action situation and interactions: Model narrative

Agents, as representatives of participants, interact with each other and make decisions, which follow a narrative based on the establishment process of the TEC initiatives. There are action arenas in which agents interact with each other based on various exogenous variables.

5.1.2.1. Idea phase.

- Individual households decide whether they support the TEC board in their role of leading and owning the TEC, based on whether their visions align. Before the initiation of the community, the household agents use natural gas to cover their heating demand.

5.1.2.2. Feasibility phase.

- If training is available for the TEC boards and the TEC board has not yet had this training, the TEC board will take it in order to gain skills and learn how to better communicate and connect with the households within the neighbourhood.

- When the TEC board has sufficient household support, it goes through a value-based multi-criteria decision-making process (MCDM) to select the collective system that will be implemented in the neighbourhood. In MCDM, different criteria, such as financial gain and environmental concerns will be used to make the final decision. The MCDM results are reported to the TEC board supporters (first MCDM).

- When TEC board supporters receive the information about the TEC board's MCDM, they evaluate this option through an individual MCDM process. Individuals might value criteria such as financial gain and environmental concerns differently than the TEC board. If households have the same perception of the collective system, they will support it (second MCDM).

- Once there is sufficient support for the collective technology, households go through a second MCDM process to select their preferred individual technology option to complement the collective system (third MCDM).

The details of the three MCDMs are presented in Section 6 and the Appendix.

5.1.2.3. Procurement and building phase.

- The TEC board considers which scenario has the most support and conducts a technical and investment feasibility analysis for the collective and individual components of the selected scenario. For the technical feasibility, energy generation (input energy), CO_2 intensity technology, and average capacity and load hours are used. For the

[1] The model is available in CoMSES Net:https://www.comses.net/codebase-release/9a9cd2ec-0519-45ba-8b17-6534e0c4c19c/

investment feasibility, criteria such as life time, investment costs, operation costs and availability of subsidies are used.

- Based on the investment required and the total amount the technology supporters are willing to invest, the TEC board calculates how much subsidy they need to request in order to cover the full investment. If this amount does not exceed the maximum amount the government is willing to give to one neighbourhood, the TEC board sends the request.

- The municipality receives the subsidy requests and once a year considers the TECs that have applied for the subsidy. The municipality ranks the requests based on their own subsidy distribution strategy and provides the subsidy to those that meet their criteria until all the funding has been used.

- After receiving the subsidy, the thermal energy community goes into a construction phase for half a year and once the infrastructure is in place, the community is considered to be set up.

5.1.2.4. Expansion phase.

- After the initial set up of the community, "non-supporters" can re-evaluate their participation: check if they support the TEC board and the selected energy scenario. If their willingness to pay is equal to or lower than the investment required per person in the neighbourhood, they will be willing to make the changes and connect to the community.

- Depending on the participation policy of the TEC board, households will be able to make the required changes at any time (i.e. under individual participation policy), or they will have to wait until they have gathered enough neighbourhood support for the expansion of the TEC in order to connect to the district heating infrastructure (i.e. under a collective participation policy).

5.1.3. Biophysical conditions technology

As described in Section 3.2, biophysical conditions include natural surroundings and human-made infrastructure, which, in this study, has focussed on thermal energy technologies. There are several technology scenarios from which the households, TEC boards and the municipality can choose from. For simplification, although in reality the district heating (DH) infrastructure can be of low or medium heat, in this ABM it is assumed that only one alternative is possible. The Heat Expertise Centrum (ECW, 2020) has identified eight key sustainable heat sources for the Netherlands: aqua thermal energy storage, geothermal, residual heat from surface water, green gas, bioenergy, residual heat, hydrogen and solar heat. Among all of these sustainable heating technology alternatives, aqua thermal energy storage (ATES), residual heat from surface water (TEA), and bioenergy are the heat sources that have been included in this ABM modelling exercise of the present study. This was done for the following reasons:

- They are the alternatives that are currently more readily available and the ones that need to overcome the least barriers for implementation;
- In currently used top-down implemented district heating systems, these are the dominating sustainable thermal technologies; moreover, these technologies fit well with neighbourhood size heating systems, and are already used successfully or are tested in pilots with the aim to scale them on the short term;
- The scope and scale of our model (i.e. one community in one neighbourhood) does not allow for generation and consumption of green gas and hydrogen; hydrogen is technologically not ready yet for use in neighbourhoods; green gas is not feasible to deploy in most neighbourhoods (with a few exceptions) for logistic and financial-economic reasons.
- Residual heat is often troublesome because of dependence on residual heat suppliers that are privately owned, and for which the owners find it too risky to commit oneself to long term heat supplying contracts. Moreover, in practice residual heat is not a 100% renewable energy source.

For individual applications, solar thermal (ST) and individual heat pumps (HP) are considered. Therefore, among the eight sustainable heat sources, four of them are included in this modelling exercise. The information and data regarding these technologies are presented in Section 6.1. Limitations regarding these choices are also explained in details in Section 8.2. Besides the technology, another condition would be the size of the city, which is translated as the number of neighbourhoods in the model. According to Netherlands Environment Assessment Agency (PBL) [133,134], on average each neighbourhood has 660 households and the majority of Dutch municipalities have 7 neighbourhoods or less. Although this scale is relatively small (as it does not represent the metropolitan areas), it is insightful to explore the municipality's size in the context of TEC initiatives.

5.1.4. Attributes of community

It is assumed that the neighbourhoods are not connected to each other. As a result, each neighbourhood forms a network that is independent of each other. To simulate the social structure of each neighbourhood, the model uses a small-world network [135,136]. Within this approach, the nodes represent households, and the edges connect households that interact with each other.

Following the BRT, norms and values are at the core of the factors that influence the final intention and decision making of an actor. [70] concluded that the key values to consider when studying energy community systems are environmental concern, energy independence, and sense of community. To these, a fourth one has been included, which is financial concern [84,137]. As a result, all agents in the model have a perception of their own internal values and how they are ranked with respect to each other.

Regarding the dynamics within the neighbourhood, the ABM assumes that all households in one neighbourhood can interact with each other. It is assumed that households interact in monthly residents' meetings where it is assumed that 10% of the neighbourhood participate. The dynamics occur based on the following principle as argued in [39]: When two households interact, one will tend to slightly lean towards the opinion of the another, attempting to simulate peer pressure. Lastly, it is assumed that households with very extreme values (either high or low) will not be peer pressured and hence will not be influenced by the interaction. Table 5 in Section 6.2. presents the data related to the attributes of the communities that are used in the simulation.

5.1.5. Rules-in-use

The regulations and subsidies related to each technology are implemented in accordance with the 'Stimuleringsregeling Duurzame Energie' (SDE) and the Netherlands Environmental Assessment Agency (PBL).

As in studies already mentioned, such as [65], and [101], training leadership skills is considered to be a municipality's policy. If the municipality provides training finances for the TEC initiative's boards, then as skilled boards they will be able to persuade more households to join the TEC initiative. Also, it is important to find out the participation policy for individual households who will join the community after it has been created. The two options for participation policy are: (A) participating instantly after the household decides to join, (B) household will join a buffer (i.e. a waiting list), and when the buffer is full (i.e. enough households are willing to join), all of them will join the TEC initiative. These two options represent the individuals' joining processes for energy community initiatives, which are discussed in studies such as

[34,138,139].

As the municipality's budget is limited each year, one of the most important rules for decision making is how the municipality will decide to allocate the subsidy that is available. Further to studies such as [34,56,140], the model has four available policies for community initiatives: economy (least economic burden for the municipality), environment (most CO_2 reduction option), social (most participants) and trade-off (a balance between the three). Lastly, the amount of the municipality's budget is important. For PBL the limit is 4 million Euros per municipality.

5.1.6. Evaluation criteria and outcomes (KPI models)

In order to understand and measure the performance of the simulations, key performance indicators (KPIs) are defined. Table 1 presents the evaluative criteria that will be used as key performance indicators to analyse the outcomes of the different experiments.

Table 2 summarises the key characteristics of the agents in the model, as well as the key tools they have to influence the decision-making process simulated in the ABM. Fig. 4 also illustrates the model's narrative.

Table 1
Description of key performance indicators used to evaluate the model outcomes.

Key performance indicator	Unit	Description
Cumulative CO_2 emission reduction	%	Percentage reduction of the total CO_2 emissions after 10 years compared to the reference scenario where 100% of the neighbourhood uses natural gas for heating the houses
Final share of neighbourhood TEC board support	%	Percentage of the neighbourhood households that supports the thermal energy community after 10 years, irrespective of whether they are connected, or not
Final share of neighbourhood participation in TEC	%	Percentage of the neighbourhood households that is connected to the district heating infrastructure after 10 years
Duration of the formation process	months	Time that it takes from the moment the TEC board is established to when the thermal energy community starts generating
Collective technology selection	–	The collective technology that the neighbourhood has selected and installed in the neighbourhood (biogas, ATES, heat recovery from wastewater)
Individual technology selection	–	The individual technology that the neighbourhood has selected and installed in the neighbourhood (nothing, heat pump, solar thermal)
Average household investment	€	The average amount a household in the neighbourhood is willing to invest in the establishment of a thermal energy community.
Share of community investment	%	Share of total investments covered by the neighbourhood. The rest is assumed to be covered by the subsidy granted by the municipality.

6. Model parameters and input data

In this section, first the assumptions and data from the case study in the Netherlands are presented. Next, the sensitivity analysis results are explained. Finally, all the inputs for the simulation experiment are summarised.

6.1. Data for biophysical conditions - technology

In this section we provide data on the technological choices that are included in the model. As mentioned above, the technology is divided into two categories: (i) collective technologies: bio energy, aqua thermal energy storage (ATES) and residual heat from surface water (TEA), and (ii) individual technologies: Solar thermal and heat pump.

6.1.1. Collective heating technology

As discussed in the model conceptualization (Section 5.1.3.), for the collective thermal energy technology, stakeholders choose one of the three options according to their own values (see Appendix). Information about each of these technologies is summarised in Table 3. The information is provided based on the 'Stimuleringsregeling Duurzame Energie' (SDE++) (PBL, 2020). The SDE++ provides financial incentives to renewable energy projects, either community energy initiatives or via other organisations, improving the energy price for generating energy. Following studies such as [141,142], and [143], in this modelling exercise, the three collective thermal technologies are: bio wood pellet boilers, ATES and TEA technologies. Table 3 provides an overview of the data related to collective heating technologies.

According to [144], for all three collective technologies, the peak energy demand is considered to be 10% and the CO_2 intensity of electricity consumption is 0.429 kg/kWh. Furthermore, the lifetime of the technologies is 30 years. Further information on collective heating technologies see Appendix C.

6.1.2. Individual heating technology

As mentioned in Section 5.2., after choosing and agreeing on the collective technology, households have three options: (i) use the

Table 2
Agents, their roles and characteristics.

	Agents		
	Municipality	TEC board	Households
Role	CO_2 emissions monitoring and policy implementation	TEC project decisions and leadership	Level of project participation and investment
Biophysical conditions	Municipality size	Skills	Annual heat consumption and CO_2 emissions
Attributes of the community	Heat vision objective: cost minimisation, autonomy maximisation, participation maximisation, and emission minimisation	Values ranking: environmental concern, energy independence and financial concern	Values ranking: environmental concern, energy independence, and financial concern Social value orientation: Payback time and willingness to pay
Rules-in-use	Subsidy schemes Subsidy allocation strategy Provision of workshops CO_2 tax	Technology decision policy Minimum neighbourhood participation policy Process duration policy Expansion policy Household persuasion	Technology decision policy Investment decision strategy

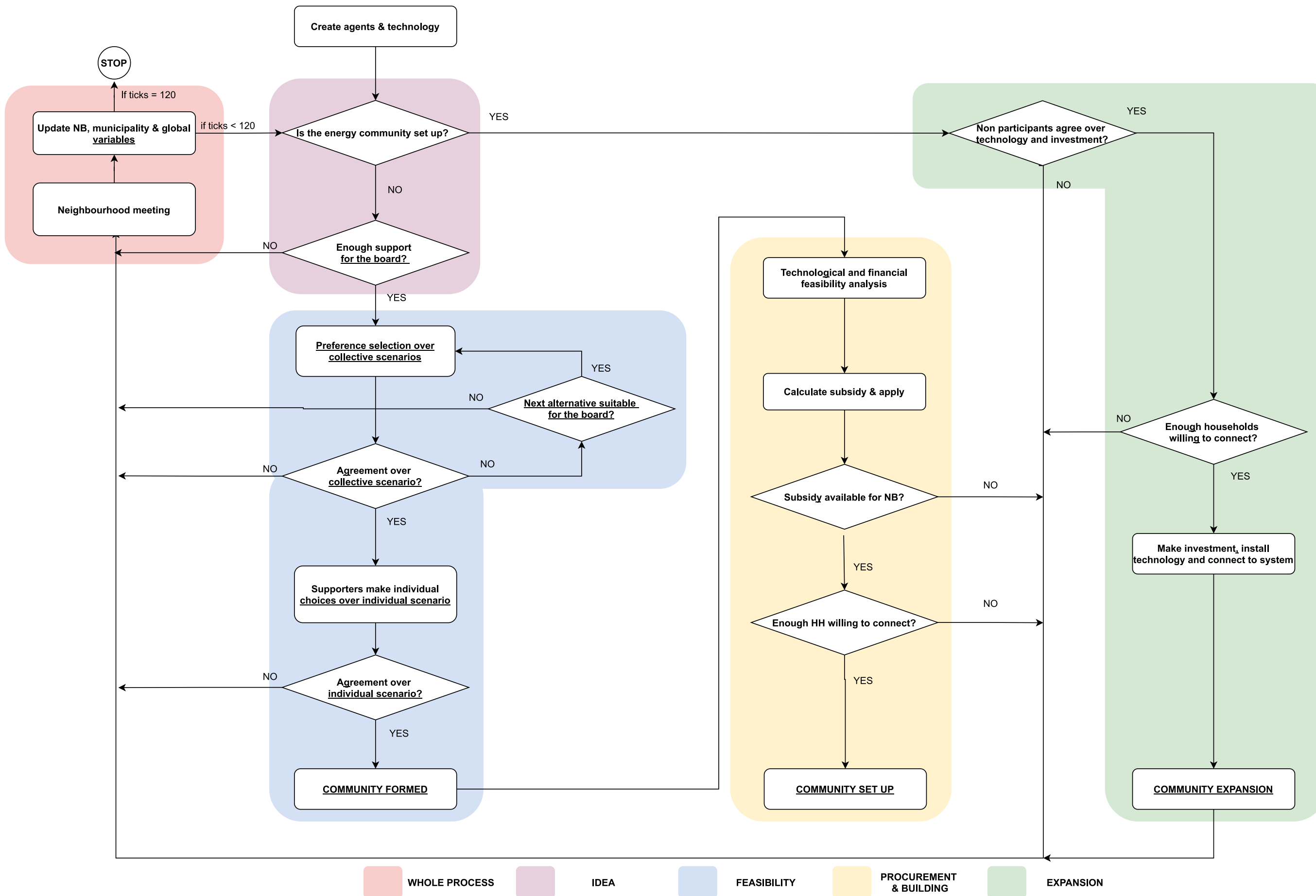

Fig. 4. Overview model structure.

Table 3
Data for collective technology.

	Investment costs €/kW	Operation costs €/kW/year	CO_2 intensity of technology kg/kWh	Average capacity kW	Electricity consumption kWh/year	Load hours hour/year
Bio pellet boiler	415	25	0.26	–	–	3000
ATES	2401	113	0.152	800	994,000	3500
TEA	2364	170	0.138	10,000	1,935,000	6000

collective technology to cover 100% of their consumption; (ii) combine the chosen collective technology with an individual ground-source heat pump (i.e. brine to water); and (iii) combine the chosen collective technology with individual solar thermal (i.e. flat plate solar collector). Information about each of these individual technologies is summarized in Table 4.

Considering the Dutch electricity grid characteristics, according to [147], CO_2 intensity is assumed to be 0.14 $kgCO_2$/ kWh for the heat pumps in the model. For the calculation of the CO_2 intensity of the solar thermal systems, it was assumed that a solar water heater would be used to supply hot water 80% of the time, and the remaining 20% would be supplied by an electric water heater (Patel et al., 2012). In other words, this 20% will be covered by the electricity grid. By calculating 20% of the CO_2 intensity of the grid we arrive at a CO_2 intensity for the water heater systems of 0.086 kg CO_2/kWh. For further information on individual heating technologies see Appendix D.

6.2. Data for the attributes of the community

In order to capture the community's attributes, as presented in Table 5, the following criteria is used in the model, based on the literature:

Table 4
Data on individual heating technology.

	Investment costs €/kW	Operation costs €/kW/year	Average capacity kW	Lifetime years	Load hours hour/year	Total cost €
Ground-source heat pump	1770	35.4	1	20	1500	4602
Sources	[145]		RVO, 2020b	[145]	[146]	
Flat plate solar collector	1666	22.5	2	30	700	4680
Sources	The Renewable Energy Hub, 2018	[38]	RVO,2020a	[145]	Solar Thermal World	

Table 5
Criteria for attributes of the community.

Criteria	Sub-criteria	Unit	Description	Reference
Financial criterial	CAPEX	€	Investment costs	[148]
	OPEX	€	Operational and maintenance costs during the lifetime of the system	[149]
	Payback time	Years	Years for the investment and maintenance cost to equal the accumulated energy savings from the change	[150]
	Subsidy coverage	%	Percentage of the capital costs covered by the subsidy (in the present study this would be the SDE++ subsidy)	[149]
Environmental criteria	CO_2 emissions	kg CO_2eq	CO_2 emission intensity of technology, based on capacity	[151]
	Land use	HA	Amount of land use required for technology, based on capacity	[148]
	Social acceptance	1 to 10	Degree to which that technology is accepted, recognized and implemented	[149]
Independence criteria	Energy input to the system	kWh	Amount of energy input required for the technology to produce the heat to cover the neighbourhood heat demand	[151]

Table 6
Data for Natural gas price and CO_2 price.

	Price €/kWh	Growth €/kWh/year	Sources
Gas	0.096	0.003	Eurostat, 2019 PBL, 2019
CO_2 tax (22 EUR + 2.5 EUR/yr)	0.106	0.004	PBL, 2019

These criteria are used in a MCDM process by stakeholders in order to make decisions about the TEC initiatives, as described in the model conceptualization section (i.e. Section 5.2.3.). For further information on MCDM see Appendix A and B.

6.3. Natural gas price and CO_2 price

As studies such as [129,152], and [153] explain, the price of natural gas is influential for the deployment of renewable thermal energy technologies and district heating systems. A policy that will have a great impact on the future gas price if it finally gets implemented is the application of a CO_2 tax. [154] states that a CO_2 tax set at 50 Euros will increase the gas price by 30%. Therefore, given the fact that such a CO_2 tax has already been announced as part of the climate plans, this should be taken into consideration in the model. For the model (pertaining to the Dutch context) the following prices have been chosen (See Table 6).

6.4. Model input parameters

Table 7 presents an overview of all parameters and the data used in the model.

6.5. Sensitivity analysis and experimentation analysis

A sensitivity analysis [155,156], was conducted for various model parameters to explore different experimental configurations. This was done by following the one-factor-at-a-time (OFAT) approach [156,157]. All the parameters were fixed at a certain value and only the value of the study was altered [157,158]. For each parameter the model was run 30 times. The sensitivity analysis is presented in Appendix B.

Table 7
Model's parameters and data.

Parameter	Type	Value
Months	Numeric	120
Number of neighbourhoods	Range	1–7
Minimum neighbourhood participation	%	10
Number of households per neighbourhood	Numeric	660
Household interactions	%	10
Environmental concern	Distribution	1–10
Cost concern	Distribution	1–10
Energy independence concern	Distribution	1–10
Sense of community	Distribution	1–10
Social Value Orientation	Range	1–4
Payback time	Range	5–20
Annual heat demand per household	Numeric	13,510
Insulation heat demand reduction	%	50
Hot water heat demand share	%	16.5
Municipality subsidy	Numeric	4000
Municipality subsidy policy	Options (Environment, social, economic, trade-off)	
Municipality subsidy dispatch frequency	Numeric	1
Gas price	Numeric	0.0965
CO_2 price	Numeric	22
Gas price increase	Numeric	0.003
CO_2 price increase	Numeric	2.5
TEC board value ranking: environment	Random	1–3
TEC board value ranking: social	Random	1–3
TEC board value ranking: economic	Random	1–3
Collective technology decision time limit	Numeric	12
Individual technology decision time limit	Numeric	6
Technology installation time	Numeric	6

6.6. Experimentation settings

The experiments include a total number of 96 different combinations of institutional conditions (3*2*2*2*4 = 96), as presented in Table 8.

Table 8
Experimentation settings.

Parameter	Value	Unit
Number of neighbourhoods per municipality	1, 4, 7	–
Participation policy	A/B	–
Training availability	No/Yes	–
Municipality subsidy amount per neighbourhood	3, 4	Million Euros
Municipality subsidy policy	Environment, social, economy, trade-off	–

Each combination was repeated 100 times, hence, the experimentation resulted in a total number of 9600 runs. Table 8 summarises the experimentation settings for the simulation. The duration of experiments is 10 years.

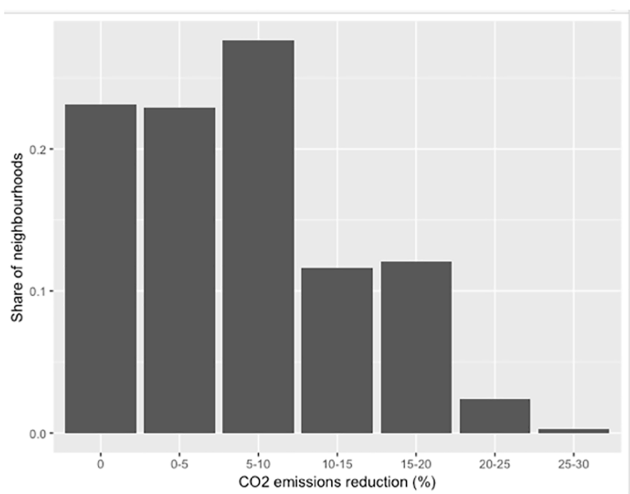

Fig. 5. Accumulated of CO_2 emission reduction.

7. Results

In this section, we present the results of the simulation analysis. These results are discussed at three levels: (i) KPIs, (ii) the impact of institutional conditions, (iii) successful and unsuccessful neighbourhoods.

7.1. *KPIs at neighbourhood level*

In the simulation, the size of a municipality is the number of neighborhoods per municipality (1, 4, 7). In this part, the results are discussed for all of the neighborhoods, regardless of the size of their municipality.

7.1.1. *CO_2 emission reduction*

Fig. 5 presents the CO_2 emission reduction in the neighbourhoods. The neighbourhoods with 0% are the ones that had not formed a thermal energy community by the end of the simulation time.

As Fig. 5 presents, although in the majority of simulation runs, the neighbourhoods reduced their CO_2 emissions, few of them (less than 5% of all simulation runs) achieve more than 20% CO_2 emission reduction.

7.1.2. *Formation process duration*

Fig. 6 presents the duration of TEC initiative formation, where the red line represents the average duration of establishment and the blue line the share of neighbourhoods (Y-axis) that successfully formed a TEC initiative before the month indicated in the X-axis.

The average duration for forming a TEC initiative is 37 months (roughly 3 years), and around 40% of all neighbourhoods have formed a TEC initiative within less than two years (See Fig. 6). These results show that it is possible for stakeholders to reach a consensus and establish thermal energy community projects in a short amount of time.

7.1.3. *Neighbourhood support and participation*

While neighbourhood support accounts for the share of households that *agree* with the project plans, neighbourhood participation only accounts for those households that finally invest and connect to the district

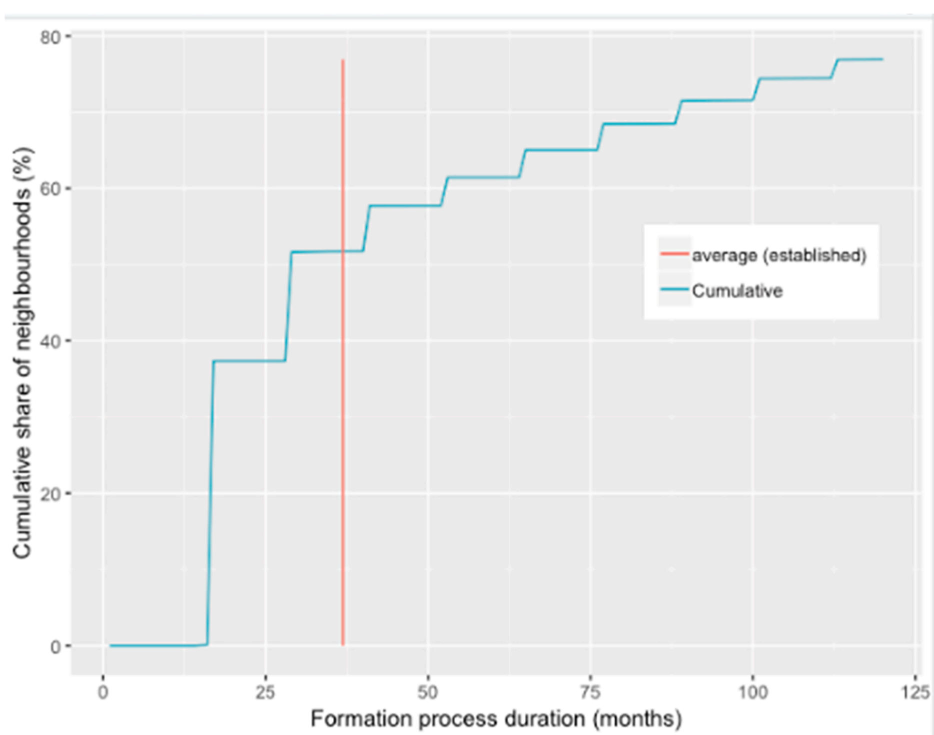

Fig. 6. The duration of forming TEC initiatives.

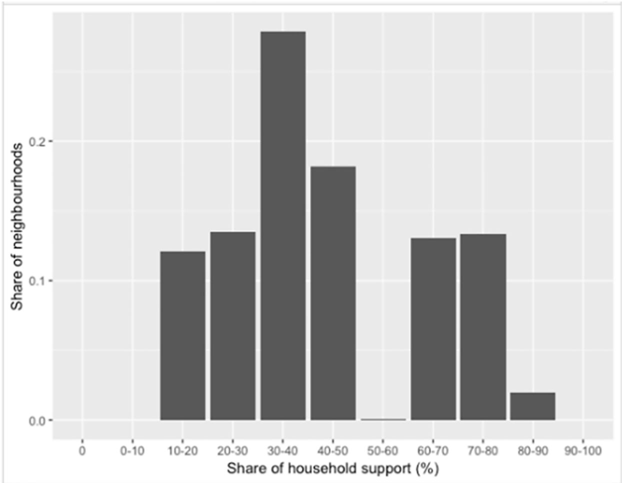

Fig. 7. Neighbourhood distribution for share of support from households.

heating system. Figs. 7 and 8 show the distribution of neighbourhoods, based on the level of neighbourhood support and participation, respectively.

The average level of neighbourhood support for established TEC initiatives is around 50%, and the maximum is 85%. With respect to neighbourhood participation (i.e. connection to the thermal energy community), the average level is 22%, the maximum level is 77%. The results for neighbourhood support are quite positive, yet for participation they can be considered to be low, since only 30% of the neighbourhoods achieve a participation of more than 25%. In other words, the gap between the number of supporters and participants is significant. This means that there is a large share of homeowners that are interested and supportive of the project but the project does not meet their financial expectations and they end up not participating in the TEC. The zero-value gaps in Figs. 7 and 8 are the model's assumptions. In the modelling exercise it is assumed that, for a community to be considered established, at least 10% of the households is required to participate. If the community is not formed, the participation is zero. Therefore, the runs with zero value in Fig. 8 present the communities that were not established.

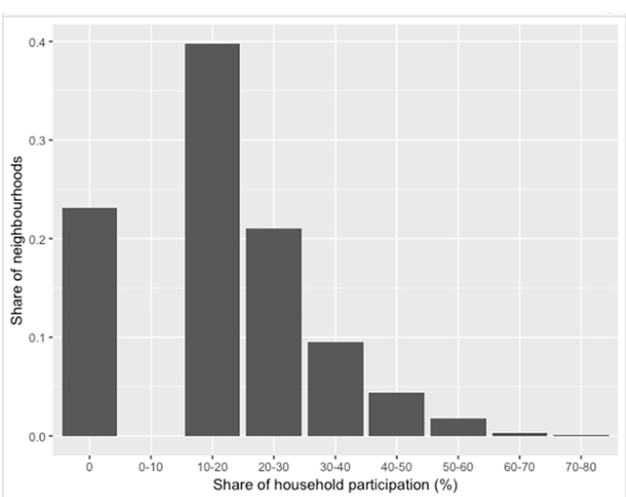

Fig. 8. Neighbourhood distribution for share of participating households.

7.1.4. Collective and individual technology selection

Fig. 9 presents the frequency distribution of each selected technology scenario. The bars indicate the collective heating technology and the colour the individual heating systems.

It can be observed that agreement over the technology scenario can be reached fairly easily since in almost every run a decision is reached. Regarding the collective generation technologies, residual heat from surface water (TEA) systems are preferred over the others (50% TEA, 30% aqua thermal energy storage (ATES), 20% biogas). In addition, regarding the combination of collective technologies with individual technologies, there is a clear preference for combining the ATES and TEA systems with solar thermal systems, and the biogas system with heat pumps. As combinations of ATES and TEA with solar thermal systems are the most environmentally-friendly options among the combinations of technologies, these are the options that are most targeted by environmentally-friendly neighbourhoods. However, the most environmentally-friendly options, which are the fully collective systems (e.g. fully collective ATES), were not very popular and were only selected around 5% of the time. This is mainly due to their higher initial investment requirements.

7.1.5. Share of community investment and average household investment

Fig. 10 presents how much households invest in the TEC as a proportion of the total required investment. Also, Table 9 shows how much households invested per chosen technology, for those thermal energy communities that are already established.

Fig. 10 shows that the range of the neighbourhoods' contribution to the total investment is quite large. On average, in the neighbourhoods, residents are willing to cover 55% of the total investment and only a few neighbourhoods were capable of fully covering the investment without external support. It can be concluded that it is unrealistic to request households to cover more than 70% of the costs, which means that for projects to succeed, municipalities will need to cover at least 30% of the project costs. Moreover, from Table 9 it can be observed that, overall, households are willing to invest, on average, around 20,000 Euros in a timeframe of 10 years. In other words, they are willing to invest around

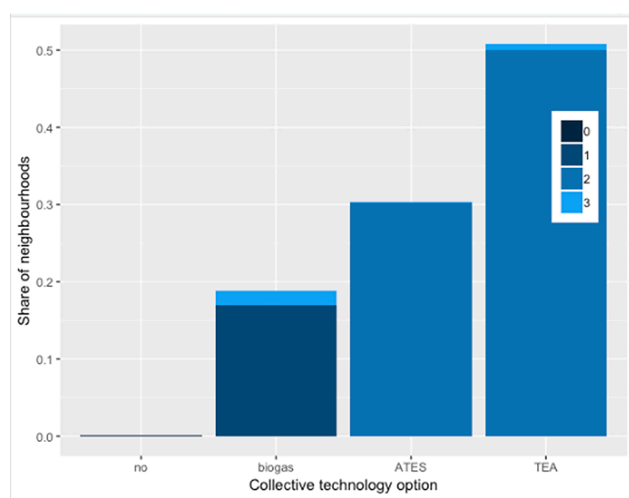

Fig. 9. Neighbourhood distribution for technologies.

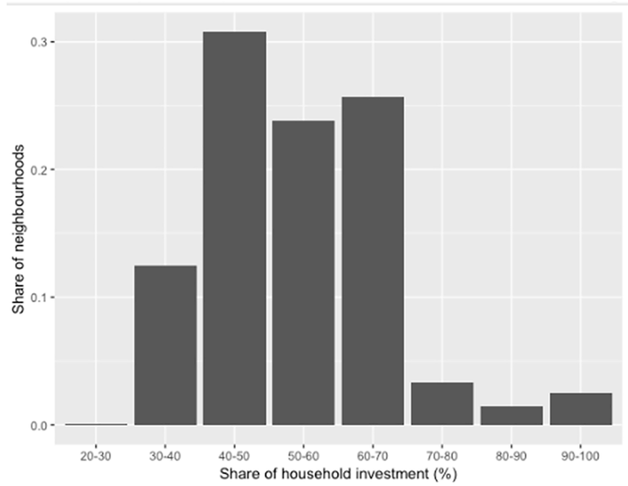

Fig. 10. Share of the households' contribution to the total investment.

Table 9
Households' investment per chosen technology (in Euros).

Tech scenario	Bio	ATES	TEA
Fully collective	14,000	23,000	20,000
Collective + individual	18,000	26,000	22,500

1,000 Euros per year on heating transition. However, it is higher for those scenarios with ATES systems, followed by TEA and then bioenergy wood pellets. Additionally, scenarios including individual generation technologies are costlier for households.

7.2. *Impact of technical and institutional conditions*

This section presents the results of the three most relevant institutions and factors modelled: (i) TEC boards' technology selection, (ii) training policy, and (iii) subsidy strategy policy.

7.2.1. *TEC boards' technology selection*

As mentioned in Sections 5 and 6, the TEC board has a certain value upon which decisions are made. Fig. 11 illustrates the leading value of TEC boards under each chosen technology. Table 10 presents the specific data on the average level of environmental, financial and

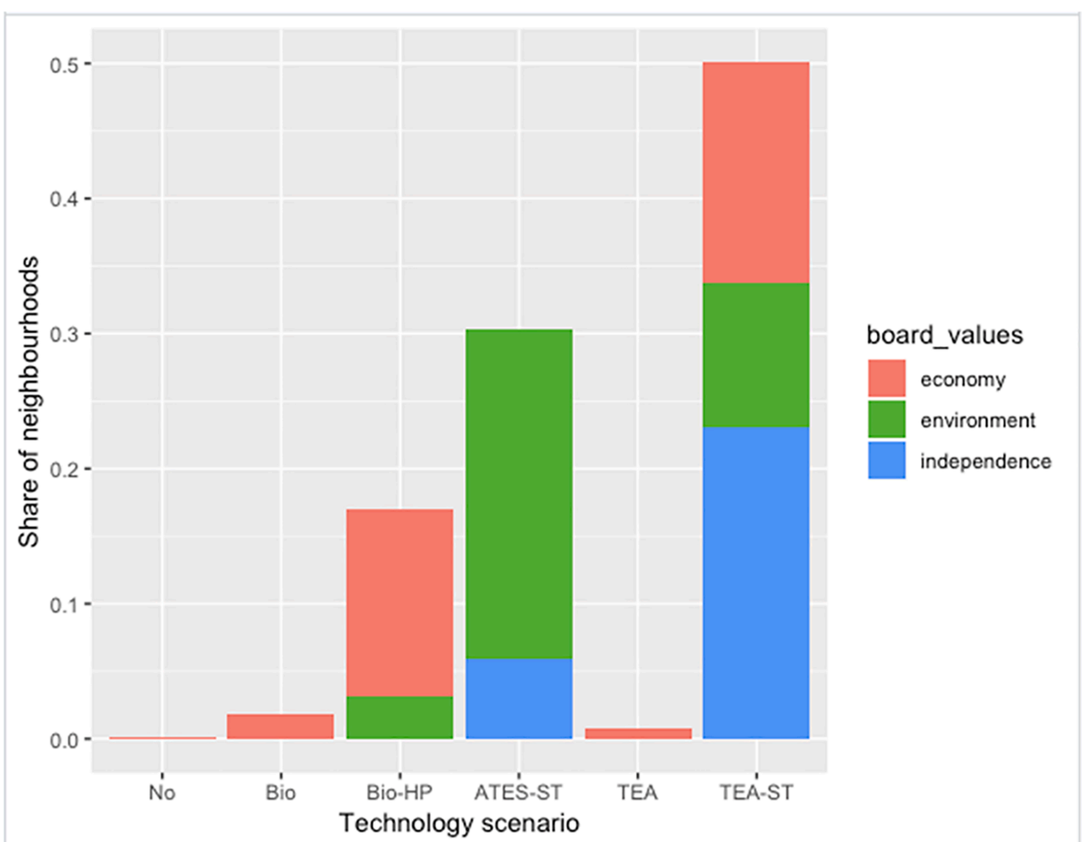

Fig. 11. Neighbourhood distribution per technology scenario based on board values.

Table 10
Average level for the TEC boards' value priority for the chosen technologies.

TEC board value priority	Technology scenario	Average environmental concern	Average economic concern	Average independence concern
Economy	No	4.0	8.0	1.0
	Bio-HP	3.7	8.1	2.5
	Bio	3.8	8.4	2.9
	TEA-HP	4.3	7.9	6.3
	TEA	3.9	7.6	5.9
Environment	Bio-HP	8.0	7.2	1.5
	ATES-ST	8.0	3.1	4.4
	TEA-ST	7.7	6.7	5.5
Independence	ATES-ST	7.0	1.9	8.3
	TEA-ST	3.6	4.6	8.0

independence concerns of the TEC boards per selected technology scenario, in more detail.

7.2.2. *Training policy*

Training policy is about the training that the municipality provides for TEC boards to have more fruitful, effective and appealing communication skills with the households. The graphs show the impact of the training policy on the level of CO_2 emission reduction and the level of household participation at the municipal level.

According to Figs. 12 and 13, it can be observed that providing training sessions to the TEC board members to improve their cooperation and communication with the neighbourhoods has a positive impact on the success of TECs regardless of the municipality size. In particular, the availability of training increases both the level of CO_2 emission reduction and of household participation by 5% in average.

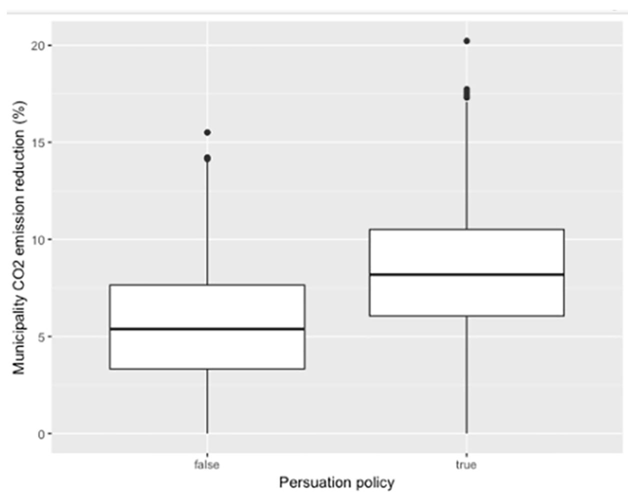

Fig. 12. Influence of training policy on municipality CO2 reduction.

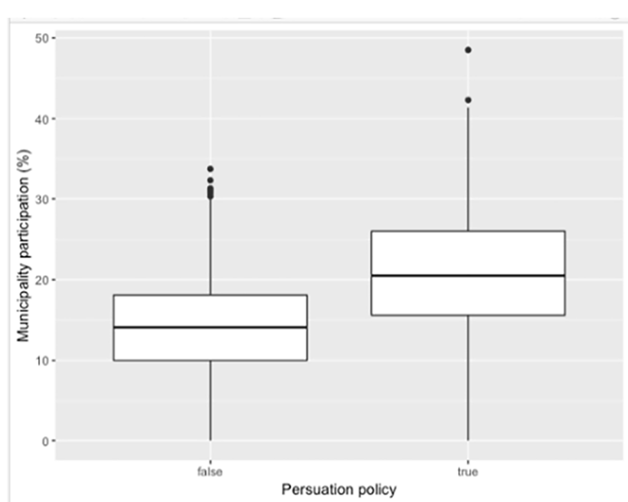

Fig. 13. Influence of training policy on municipality participation.

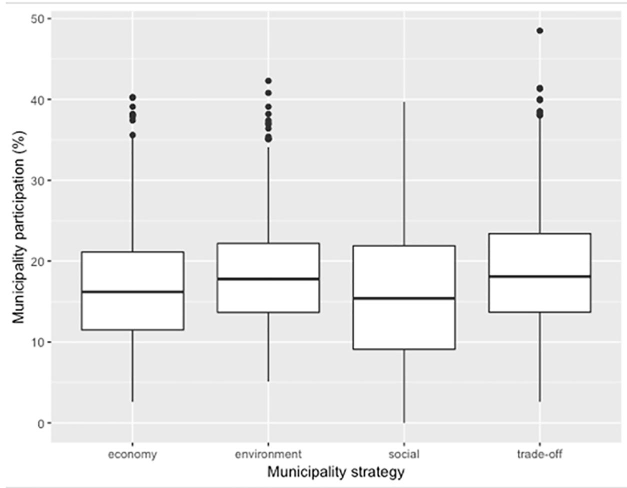

Fig. 14. Influence of municipality strategy on municipality participants.

7.2.3. Subsidy strategy policies

Subsidy policy is about how the municipality decides to allocate financial support, considering the limitation of the subsidies. There are four available policies: (i) economy (least economic burden for the municipality), (ii) environment (most CO_2 reduction option), (iii) social (most participants), and (iv) trade-off (a balance between the three), which are presented in Figs. 14 and 15.

The results show that the municipality's strategies that lead to a better outcome in terms of both CO_2 emission reduction and participation level are the environmental and the trade-off policies. The economic policy (only assessing the TECs based on their cost) is clearly the least effective one in smaller municipalities, as the reason might be that the

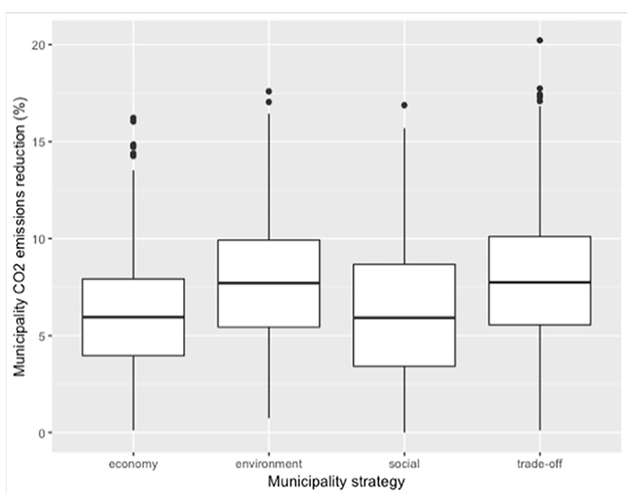

Fig. 15. Influence of municipality strategy on CO_2 emission reduction in the municipality.

neighbourhood overall has very high environmental and social concerns, so when the municipality implements an economic policy, this is misaligned with the value system of the neighbourhood. Therefore, it is less effective.

7.3. Successful and unsuccessful neighbourhoods

In order to go further and understand the influence of technical and institutional conditions on the formation of TEC initiatives, we focused on the most successful and unsuccessful TECs. For that, it is important to first define what a “successful neighbourhood” and “unsuccessful neighbourhood” is.

We define success in relation to the range of simulation outcomes, i.e., their performance using the three key performance indicators, namely cumulative reduction of CO_2 emissions, duration of the formation process, and share of neighbourhood connections. For each of these KPIs, thresholds were defined for the highest 10% of the neighbourhood for each KPI. For the reduction of CO_2 emission percentage, for the highest 10% of neighbourhoods this was set at a reduction of 17% or higher, the share of neighbourhood connections was 39%, and the duration process of TEC formation was 17 months or less. When combining these three criteria, the data set of the neighbourhoods that comply with it account for 5% of the total number of neighbourhoods. The unsuccessful neighbourhoods are defined as the ones which did not manage to form a TEC initiative within the timeline of the models’ run. Consequently, the parameters for the most successful and least successful neighbourhoods were more closely studied (See Table 11).

As Table 11 presents, the most successful communities are the ones in which their municipality has the trade-off or environmental subsidy policy, and provides training workshops. Also, the values of their TEC boards are balanced with the environmental concerns as their leading value. In contrast, for the unsuccessful communities, the emphasis is on economic conditions and concerns within the municipality and the board.

8. Discussion

As presented in the Introduction, this study and the results seen from the models, complement existing models that explore specific aspects within thermal energy systems, (e.g. value conflicts for social acceptance of sustainable heating systems [43], and policy interventions and business models for the emergence of district heating networks [34]). Our model adds to this literature by providing insights into technical and institutional conditions that are relevant to the formation of TEC initiatives as a collective action approach for thermal energy generation and consumption. The results from Section 7 are translated into detailed discussions and recommendations as following:

8.1. Key insights from the applied theoretical angles

8.1.1. Institutional layers

As presented in Section 7.3. (e.g. in Table 9), it can be concluded that technology selection itself is not the most crucial and determining factor for the success of thermal energy communities as much as the institutional conditions surrounding it are. These institutions can be located on the different layers of Williamson’s framework [106] which correspond with different stakeholder groups:

- Layer 1 – Cultures: The alignment of the values held by the municipality and TEC board with those of the neighbourhood is a key condition for success;
- Layer 2 – Institutional environment: It is very important to have fiscal policies, such as national subsidy and loan schemes, available that support the initial investment requirements of these communities;
- Layer 3 – Governance: Sharing responsibilities with the citizens themselves by ensuring active household participation is a key factor;
- Layer 4 – Individual: Gathering neighbourhood support is really important. It can be achieved by actively engaging with the neighbourhoods and integrating them in the design process by taking their preferences into account.

8.1.2. Technological vs institutional conditions

The IAD framework [110] is applied to the model’s outcome to study the effect of exogenous conditions on the successful establishment of TEC initiatives:

- Biophysical conditions: Considering the model’s simplification regarding the techno-economic aspects of the heating technologies, the results show that technology selection itself is not the most crucial and determining factor. Collective technologies are both economically and environmentally more feasible: Aqua thermal energy systems (ATES) and residual heat from surface water options are the most popular collective technological solutions, and the ones that lead to a higher level of household participation and larger CO_2 emissions reduction levels (see Sections 7.1. and 7.2.).
- Attributes of the community: Although the environmental concerns are the main driver for the successful establishment process, the model outcome shows that it is more effective to focus on visions built on a balance between economic, environmental and social considerations (see also Sections 7.2. and 7.3.);
- Rules-in-use: The model showed that the policy that led to the best outcome is the trade-off strategy; in addition, providing a platform to train the TEC board is considered important.

8.1.3. Behavioural reasoning

The Behavioural Reasoning Theory (BRT) [107] is used to explore the relevance of context-specific reasons for and against a decision as a key predictor of the attitudes, as well as of the final decision, of the agents in the model. When examining the extent to which the values held by the TEC board are able to explain the success of the TECs, the results show that understanding the general attitude of the TEC board (i.e. whether they prioritise environmental concerns, costs minimisation or becoming energy independent) does not provide much information. Nonetheless, when delving deeper into understanding how the TEC boards specifically value different concerns (i.e. the context specific reasons), a better explanation on how internal values lead to a specific scenario preference can be provided.

8.2. Limitations

Although this study brought interesting insights to light about the formation of TEC initiatives, it has certain limitations that can be developed further. The first limitation concerns the application and conceptualisation of TEC initiatives using the theoretical concepts used in this study. The decision to use Ostrom's IAD framework together with the four-layer model of Williamson has provided a specific lens through which TECs have been researched. Despite the benefits this offers, it is important to keep in mind that there are also other theoretical frameworks such as the Socio-Ecological System framework by Ostrom [78], that when applied to the same issue, system and processes, could potentially provide different insights. For example, using Ostrom's Collective Action theory [77] or Theory of Planned Behaviour [159] could have derived different insights regarding the importance of building inter-actor trust in thermal energy community projects.

The second limitation is the selection of the case study. Although the Netherlands provides an opportunity to explore the TEC initiatives (See Section 4.2.), due to the nature of the domestic heating sector, the choice of the Netherlands is a limitation. This has influence on data collection, the chosen technical and institutional conditions to conceptualize in the model and then investigate (e.g. input data on heat pumps and solar thermal energy systems). Even though the model relies on the input data from the Netherlands, the results and recommendations are to some extent generalizable as they are seen in relative rather than in absolute terms. More importantly the results and findings of this study are in line with findings from empirical and theoretical studies from other European countries, like [66,80,81]. It would be still insightful to adapt the inputs of the model to fit the context of another country (e.g. Sweden, Denmark or Germany) and to compare the differences in the outcomes of the model and its relation with the differences in the initial conditions of multiple countries.

Furthermore, a previous study showed that for modelling heating transitions at the local level a lot of information is missing in the heating transition data ecosystem [160]. This mostly pertains to empirical data on collective heat generation and distribution. However, more general empirical data on the thermal energy community is scarce. Therefore, more empirical research, both explorative and descriptive, is needed; for instance, case study research about ongoing TEC initiatives in a number of (Dutch) cities can be beneficial. In this study we used national statistical data, while empirical data from actual local initiatives would have led to more practical and applicable insights. Moreover, the modelling approach itself has limitations. Models are representations of a selected aspect of the world. Therefore, by definition, models cannot include all the details of the objects that they represent and they have their own specific limitations [161]. As such, our model's assumptions and structure can be improved. More specifically, technological aspects are simplified in this study's modelling exercise. The reason for this was to focus on institutional design insights rather than to explore the techno-economic feasibility of TEC initiatives and to provide insights on technical design. Therefore, as long as these simplifications and limitations are considered, they do not jeopardize the results and outcome. In order to overcome these limitations, the model could be coupled with a technical optimization model for the technical outcome to be completer and more conclusive. The model presented in this study explores the fully renewable thermal energy system, however, it is also meaningful to explore thermal energy communities that are based on using both renewable and natural gas as energy sources. Finally, further research on the stakeholders' roles could improve the model's insight. For example, the model has extensively studied the role of the municipality as a resource supporter, while in reality, their function is much more complex than this.

9. Conclusion

The number of community energy projects in Europe is rapidly growing and is expected to have a major impact within the energy sector on this continent. Energy communities are key elements of the energy transition at the local level as they aim to generate and distribute energy based on renewable energy technologies. This research aimed to investigate the technical and institutional conditions that influence the formation process of energy communities with thermal applications (TECs); in particular, in order to speed up the transition to a sustainable heating sector. The focus was on understanding which conditions enhance (i) the fastest formation process, (ii) the higher degrees of community participation, and (iii) the higher CO_2 emission reduction levels, as three indicators for analysing the formation of TECs. In order to do so, an agent-based model was built, using the Netherlands as a case study to populate the model, based on real-world data.

TEC initiatives consist of three main components: (thermal) renewable energy technology, the stakeholders involved, and related institutions. Regarding the technological conditions, TECs can include either collective and individual heating components, or both, simultaneously. The results of the analysis show that households prefer scenarios combining collective and individual technologies. Aqua thermal energy systems (ATES) and residual heat from surface water options are the most popular collective technological solutions, and the ones that lead to a higher level of household participation and a larger reduction of CO_2 emissions. However, the model also showed that technology selection itself is not the most crucial and determining factor for the success of the establishment of TEC projects. Instead, it is the institutional conditions surrounding TECs. Considering the modelling simplifications and limitations of this study (see Sections 5 and 8), the overall results indicated that TECs could potentially be formed on average within three years with a high level of support from the households (e.g. approximately 50% on average). Although there are few runs that are fully covered, financially, by households, municipalities would be required to invest at least 30% of the project costs, in reality.

Regarding the institutional context, the model demonstrates that projects are likely to be successful when stakeholders share a common vision that highly and equally values: (i) developing energy independent communities; (ii) using environmentally-friendly heating generation technologies; and (iii) providing heat at an affordable price for the consumers. Lastly, the results demonstrate that it is crucial to have supportive institutional conditions that are responsive to the local context and local needs. In order to develop such an enabling institutional environment in the Dutch context, based on the results of this study we recommend: (i) sharing decision making and financial responsibility among all actors involved in the design and implementation of municipal heat plans; (ii) designing fiscal structures that focus on supporting those TEC projects that are able to balance out project costs with their potential environmental impact; and (iii) developing

Table 11
Comparison of successful and unsuccessful neighbourhoods.

		Successful neighbourhood		Unsuccessful neighbourhood
Municipalities	Subsidy policy strategy	Trade-off	Environment	Economy
	Training	Providing workshops for TEC board members		No workshop for TEC board members
TEC Boards	Technology scenario	TEA + ST		ATES + ST
	Values	Balanced values with environmental concerns as highest		Focus only on value (mostly economy and social)
	Subsidy	Yes		No
Households	Support	75%		less than50%
	Investment	25,000		15,000

programmes that improve the marketing capabilities of TEC boards to increase residents' knowledge about the heating transition and their participation in TECs. These actions and policies have been widely used in the Netherlands to facilitate renewable energy communities. However, we suggest this is also needed to help TECs build capacities. In the Dutch context, platforms such as 'Buurtwarmte' [162] (in English: Neighbourhood heat; translation by the authors), set up by the Dutch community energy branch association 'Energie Samen', are helpful initiatives as they seek to help individuals who want to form their own TEC initiatives and facilitate the formation process.

These results provide new insights for stakeholders, especially policy-makers, municipalities and households, with technical and institutional conditions to focus on for enhancing the development of TEC initiatives that contribute towards local energy transition. The model and results presented in this research are based on certain assumptions and theoretical background (see Sections 3, 5 and 6) for exploring TECs within a Dutch context. As presented in Section 8.2., for further research it would be insightful to use other theories and countries as a case study to further generalise the insights provided by this research. Furthermore, a more detailed consideration of housing insulation in the model, instead of a modelling parameter, can also provide extra insights into how households at a community level can achieve more sustainability. All these would further support the exploration of the most supportive technical and institutional conditions for TEC initiatives with different starting conditions. Also, more reliable empirical data is needed in order to have more insightful outcomes. Conducting surveys and expert interviews would be helpful for this. Finally, other computer modelling approaches, such as optimization and equilibrium modelling, would be useful for studying other topics related to TEC initiatives.

Declaration of Competing Interest

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

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Appendix A. Households attributes

The calculations for the households' decision to join TEC initiatives are presented as follows:

Drivers to Join

The four key values that influence a person's degree of participation in a community energy system, which are included in the model, are: environmental concern, financial concern, energy independence concern, and sense of community. The survey conducted for Koirala et al., (2018) asked respondents to rate the environmental and socio-economic-institutional drivers using Likert-type scales with 7 points. The results for four of the drivers included in this survey was used as input for the values held by the households in the model (see Table 12).

Since the survey was done on a scale of 7 points, the information was first calibrated for a 10-point scale to fit the data input for the model. Then, the information on the mean and standard deviation were inputted in an online tool to produce a normal distribution dataset (Socscistatistics, 2020). The tool produced a dataset of 100 values ranging from 1 to 10 which was then visualised as a histogram. The histogram presented the results by frequency of responses for each point in the scale. Finally, the information on the histogram was used to create Table 13. The information on this table was used to assign a value to each household for each value type.

Table 12
Mean and standard deviation values for drivers used to model the values system of households in the model.

	Drivers	Mean	SD	Scale
Environmental	Good for the environment	5.45	1.55	7-point
Socio-economic-institutional	Economic benefits	5.19	1.54	7-point
	Sense of community	3.80	1.72	7-point
	Independence of national grid	3.62	1.87	7-point

Table 13
Percentage of the neighbourhood population that is initially related to each point in the scale for each value type.

Scale	1	2	3	4	5	6	7	8	9	10	Total
Environmental concern	–	1	2	3	10	13	11	10	13	37	100
Economic concern	1	1	4	8	10	15	20	10	16	15	100
Independence concern	9	9	10	13	13	16	14	7	5	4	100
Sense of community	6	6	10	16	17	15	14	8	4	4	100

Household SVO

Once every household in the neighbourhood has been assigned a value for each value type, the social value orientation (SVO) of the household is calculated. The two-stage classification method developed by Nascimiento (2019) was used to classify the households into one of the four social value orientation groups (altruistic, cooperative, individualistic, competitive).

The overall drive to join the community is calculated using the following expression in Equation (1):

$$\Delta drive = S_{environment} + S_{community} - \left(S_{financial} + S_{independence}\right) \tag{1}$$

The first stage was to identify the households that fall under the altruistic and the individualistic social value orientation. For that, it is assumed that the altruistic households are those who place a higher value to the environmental concern and sense of community ($\Delta drive > 1$). As opposed to the more individualist households that score higher in the financial and energy independence concern ($\Delta drive < -1$).

However, those individuals whose final score ($\Delta drive$) is close to 0 ($-1 > \Delta drive < 1$), move onto the second stage of the classification method. For these, the focus is how high they score in the sense of community driver. Those with a score lower than 5 will be classified under the competitive SVO and those that score higher than 5 under the cooperative SVO.

The results shown in Table 14 indicate that most of the households have a more pro-social orientation (62%) and most of the households fall under the altruistic and individualist group (92%).

Table 14
Example of initial SVO distribution for an average Dutch neighbourhood, given the model output.

	SVO 1 Altruistic	SVO 2 Cooperative	SVO 3 Individualistic	SVO 4 Competitive
Neighbourhood share (%)	58	4	34	4

Pay-back time (PBT) & willingness to pay (WTP)

Based on the SVO group each household falls into, the household is assigned a specific expected payback time period. Following Kastner and Matthies' (2016) line of reasoning, which is that the more an individual has a pro-social value orientation, the higher they will be willing to invest. Additionally, the results from Koirala et al. (2018) survey that Nascimiento (2019) prepared, substantiated this assumption. Table 15 shows the range of PBT period linked to each SVO category. For instance, a household that falls under the SVO 1 will be assigned an expected PBT of between 15 and 20 years.

Table 15
Range of PBT period assigned to each social value orientation category.

	SVO 1 - Altruistic	SVO 2 - Cooperative	SVO 3 - Individualistic	SVO 4 - Competitive
Expected PBT	15–20	10–15	5–10	1–5

Based on this expected PBT, assigned to each household, a limit to how much the household is willing to invest (WTP) in the thermal energy community is then calculated. The following equations explain how this attribute is calculated. The willingness to invest is calculated based on the accumulated savings the household will make during the time period of their PBT (Equation (2)). The accumulated savings are calculated by the sum of the difference between what the household would pay in the reference scenario and what they expect to pay in the new technology scenario, based on the expected annual gas and heat price. In the model, the household has the information on the current gas price and the expected gas price increase for the 10-year period. The heat price is assumed not to vary throughout time.

$$\mathrm{Willingnesstoinvest(WTP)} = \Sigma_1^{PBT}\left(\mathrm{gascosts}_{r,i} - \mathrm{heatcosts}_i\right) \tag{2}$$

$$\mathrm{gascosts}_{r,i} = heatdemand_r \times gasprice_i$$

$$\mathrm{heatcosts}_i = heatdemand_i \times heatprice_i$$

CO_2 emissions

Another important attribute of each household is the amount of CO_2 emissions related to the heat consumption emitted per year. Equation (1) shows the way in which this is calculated. The calculation of the CO_2 intensity, as explained in the technology section, is presented in Equation 3:

$$CO2emissions_{HH} = heatdemand_{collect} \times CO2_{int,collect} + heatdemand_{ind} \times CO2_{int,ind}(Eq.3)$$

Other parameters

Table 16 shows other important attributes that are assigned to the households.

Table 16
Other variables assigned to households in the model.

Parameter	Value	Unit	Source
Heat demand	13,500	kWh/year	CBS
Insulation heat demand reduction	50	%	Nava Guerrero et al., 2019
Space heating share	0.835		Eurostat
Hot water share	0.165		Eurostat

Appendix B. Arrangement of the neighbourhoods

Number of neighbourhoods & number of households

When developing the parameter of how many neighbourhoods should be included in what the model is representing as one municipality in the Netherlands, the focus was on estimating the average number of neighbourhoods per municipality that are expected to be disconnected from the gas grid by 2030.

The Netherlands Environment Assessment Agency (PBL) concluded that the measures proposed in the Climate Accord published on 13 March 2019 would result in some 250,000 to 1,070,000 buildings being made 'gas-free'. However, the target is for 1.5 million buildings. With the information of the number of municipalities in the Netherlands (277) and assuming there is an average of 1440 inhabitants per neighbourhood [133], and 2.17 inhabitants per household (CBS), the number of neighbourhoods per municipality that should make the transmission from gas can be estimated (Equation (4)). The calculation results in an average of 664 households per neighbourhood and a range of between 1.19 and 5.08 neighbourhoods, using the proposed measures, with 7.11 neighbourhoods being the target.

$$\frac{Numberneighbourhoodsoffgas}{municipality} = \frac{householdsoffgas}{municipality} \tilde{A}\cdot \frac{households}{neighbourhood} \tag{4}$$

$$\frac{householdsoffgas}{municipality} = \frac{gasfreebuildings}{municipality} \times shareresidentialstock$$

$$\frac{households}{neighbourhood} = \frac{inhabitants}{neighbourhood} \tilde{A}\cdot \frac{inhabitants}{household}$$

As a result, the decision was made to model one neighbourhood as 660 households and run the model for a number of neighbourhoods per municipality, ranging from 1 to 7, to consider the scenarios with the current policies and the target for 2030, and to be able to analyse whether the most suitable institutional conditions vary across municipality sizes. Therefore, three municipality sizes will be included in the experimentation: 1, 3 and 7 neighbourhoods.

Neighbourhood structure and dynamics

The structure for the small world network of the neighbourhoods and the interactions between the households has been modelled by replicating and adapting the network generated by the "small worlds" model found in Netlogo library. This model is an adaptation of a model proposed by Watts and Strogatz (1998). It begins with a network where each household (node) is connected to its two neighbours on either side. Then, with every time step, which corresponds to one month, 10% of the nodes rewire one of their edges to connect with a different node. After rewiring, the households involved in the interactions will update their value systems leaning towards that of the neighbour's opinion. Since the household's SVO depends on its value systems, this might also be altered as a result of these neighbourhood interactions.

Share of neighbourhood

This attribute relates to the minimum share of the neighbourhood that needs to find consensus over each decision in the model before being able to move to the next stage. The PAW subsidy website states that the feasibility studies, presented as part of the subsidy application, should take into consideration the participation of all the households in the neighbourhood. However, from conversations with experts, it was concluded that it is improbable that this will be achieved and that in practice, municipalities are having conversations with any neighbourhood willing to start a TEC project regardless of the initial neighbourhood participation levels. Since there is not a clear understanding of where to draw the line in this attribute, a sensitivity analysis was conducted to give this attribute a specific value.

The sensitivity analysis was conducted following the OFAT (one-factor-at-a-time) approach (Ten Broeke et al., 2016). All the parameters were fixed at a certain value and only the value of the study was altered. For each parameter the model was run 30 times. The amount of CO_2 emissions avoided per neighbourhood and the share of households connected at a municipality level were gathered as the output to determine the attribute's value. These were considered to be the most important KPIs out of the nine KPIs developed since they account for both the sustainability and acceptability of the thermal energy project.

A first sensitivity analysis was conducted for a range between 0 and 1 in steps of 0.2. However, it was observed that after 0.4, the average share was 0. As a result, a second sensitivity analysis for a range between 0 and 0.5 in steps of 0.1 was done. Figs. 16 and 17 show the outcome of the sensitivity analysis for the indicators of CO_2 emissions avoided per neighbourhood and the share of households in the municipality connected to the district

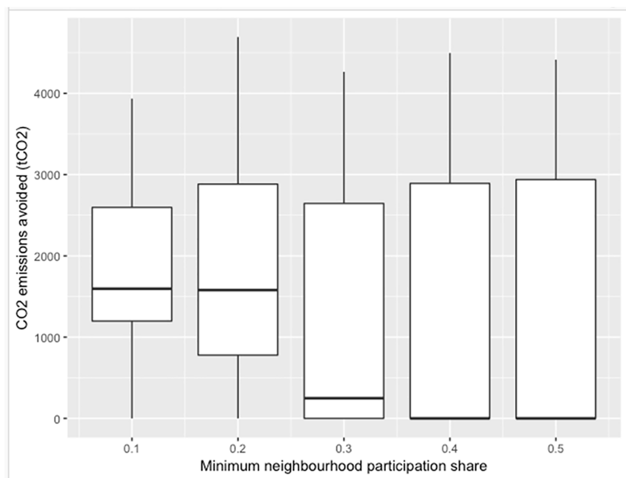

Fig. 16. Sensitivity analysis outcome for the share of the neighbourhood ($C0_2$ emission reduction).

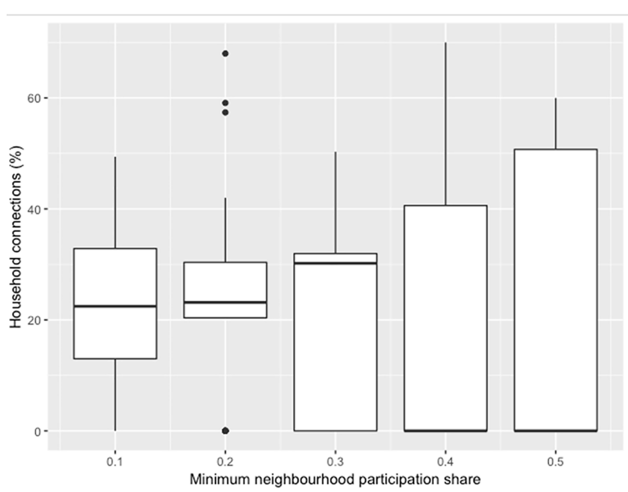

Fig. 17. Sensitivity analysis outcome for the share of the neighbourhood (household participation).

heating network. On the x-axis the Figures show the parameter ranges (0–0.5) and on the y axis the two outcomes of the sensitivity analysis. Each box represents the range in the results and the black line the mean for each parameter value.

The results show that when the minimum neighbourhood share is set higher than 0.3, few neighbourhoods reach the set-up phase. However, between the other two values, 0.1 and 0.2, the conclusion is not as straightforward. On the one hand, the average and maximum CO_2 emissions avoided is higher when the minimum share is set at 0.1, yet, on the other hand, the average share of connections is higher when the share is set at 0.2. In the end, it was decided to leave the share at the minimum possible value (10% of the neighbourhood), since it's the one closer to the reality in the Netherlands.

Household interactions in neighbourhood

Research has previously been conducted which qualitatively studies the degree of involvement and participation of Dutch neighbours in their neighbourhood. However, when gathering quantitative information on the matter, little information was found. A survey conducted by Kamer (2020) in the Netherlands with 2108 respondents asked participants to describe their level of household participation (see Fig. 18).

The results, which are presented below, show that at least 4% of the neighbourhood is very active and involved in the neighbourhood and 24% are sometimes involved. Provided with this information, a sensitivity analysis was conducted to fix the parameter somewhere in the range of between 4% and 30%.

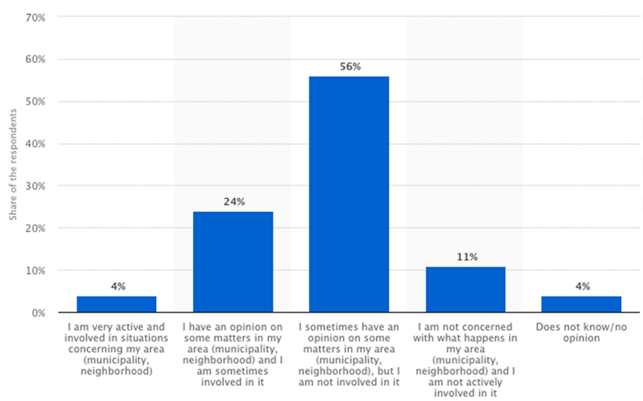

Fig. 18. Neighbourhood participation in the Netherlands (Kamer, 2019).

Fig. 19 and Fig. 20, displaying the output from the sensitivity analysis, show that the projects are more successful when the interaction rate is 10% or higher. However, between 10% and 30%, the change in the indicators is not significant enough. Going back to the statistics gathered in Koirala et al. (2018), 10% of the neighbourhood seemed like a reasonable assumption for the model since it would include the 4% of highly involved neighbours and 25% of the ones that sometimes get involved.

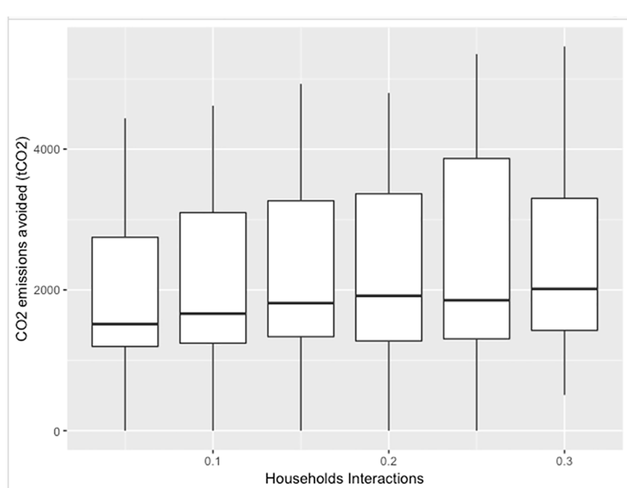

Fig. 19. Sensitivity analysis outcome for household interactions (CO_2 emissions reduction).

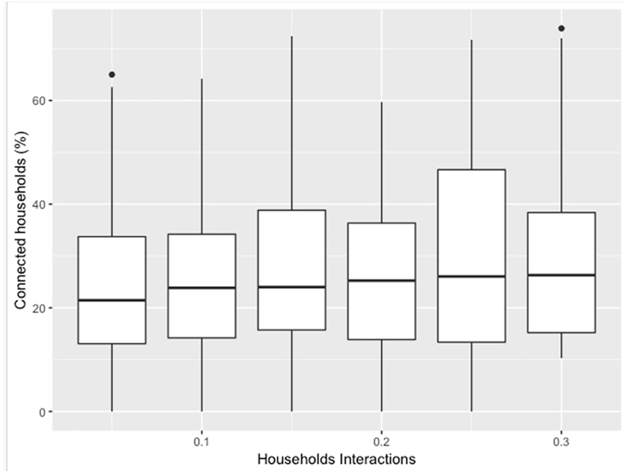

Fig. 20. Sensitivity analysis outcome for household interactions (Household participation).

Appendix C

Collective heating technology Tables 17-20.

Table 17
Collective bio-energy data:

Variable	Units	Bio-boiler (wood pellets)
Average capacity	kW	950
CAPEX	€/kW	415
OPEX fixed	€/kW	25
OPEX variable	€/kWh	0.003
Load hours	hour/year	3000
Electricity consumption	kWh/year	–
CO_2 emissions	kg/kWh	0.26
Lifetime	years	20
SDE++ subsidy	€/kWh	0.03
Subsidy time	year	12
Peak demand	%	10
Min required household	number	50
Land use	km^2/kWh	59,5
Efficiency	%	0,85

Table 18
Collective aqua-thermal energy storage (ATES) data.

Variable	Units	ATES
Average capacity	kW	800
CAPEX	€/kW	2401
OPEX fixed	€/kW	113
OPEX variable	€/kWh	0.0019
Load hours	hour/year	3500
Electricity consumption	kWh/year	994,000
CO_2 emissions	kg/kWh	0.152
Lifetime	years	30
SDE++ subsidy	€/kWh	0.08
Subsidy time	year	15
Peak demand	%	10
Min required household	number	50
Land use	km^2/kWh	2.68

Table 19
Collective residual heat from surface water (TEA) data.

Variable	Units	TEA
Average capacity	kW	1000
CAPEX	€/kW	2369
OPEX fixed	€/kW	170
OPEX variable	€/kWh	0.0019
Load hours	hour/year	6000
Electricity consumption	kWh/year	1,935,000
CO_2 emissions	kg/kWh	0.138
Lifetime	years	30
SDE++ subsidy	€/kWh	0.042
Subsidy time	year	15
Peak demand	%	10
Min required household	number	50
Land use	km^2/kWh	3

Table 20
Collective heat pump data.

Variable	Units	Collective heat pump
Average capacity	kW	45
CAPEX	€/kW	848
OPEX fixed	€/kW	21
OPEX variable	€/kWh	0.015
Load hours	hour/year	8000
Electricity consumption	kWh/year	–
CO_2 emissions	kg/kWh	0.000
Lifetime	years	20
SDE++ subsidy	€/kWh	0.017
Subsidy time	year	15
COP		3.5
Peak demand	%	10
Min required household	number	50

Appendix D

Individual heating technology Table 21 and Table 22.

Table 21
Information on individual heat pump systems.

Type	What	Value	Unit
Individual HP	Min capacity (brine-water)	0	kW
	Max capacity (brine-water)	70	kW
	Average capacity	1	kW
	CAPEX	1770	€/kW
	OPEX	35.4	€/kW
	CO_2 emissions	0.14	kg/kWh
	Lifetime	20	years
	COP	3	
	Subsidy (SDE++)	500	€
	Load hours	1500	hour/year

Table 22
Information on individual solar thermal systems.

Type	What	Value	Unit
Solar thermal	Average capacity	2	m^2
	Generation	540	kWh/m^2
	CAPEX	1666	€/kW
	OPEX	22,491	€/kW
	Load hours	700	hour/year
	CO_2 emissions	0.086	kg/kWh
	Lifetime	30	years
	Subsidy (SDE++)	0.678	€/kWh
	Subsidy (SDE++)	732.24	€
	Electric water supply	20	%

Appendix E

District heating technology Table 23.

Table 23
Data on district heating systems.

Type	What	Value	Unit
MH/LH/VLH	Connection fee	4500	€/connection
	OPEX	524	€/year
	Lifetime	40	years
Insulation	Investment costs to achieve B-grade energy label	10,000	€

Appendix F

Environmental attributes Table 24.

Table 24
Data on environmental attributes.

What	Value	Unit
Gas price	0.097	€/kWh
Gas price increase	0.003	€/kWh/year
Heat price	0.096	€/kWh
Electricity price	0.136	€/kWh
Electricity price increase	0.0014	€/kWh/year
CO_2 price (ETS)	22	€/t CO_2
CO_2 price growth	2.5	€/year
CO_2 price of 22 Euros: effect on natural gas price	0.009	€/kWh
Gas price increase with initial tax at 22 Euros	0.001022727	€/kWh/year
Ticks	1	month
Total duration of model	10	year
CO_2 emissions (gas)	0.2	kg/kWh
CO_2 emissions (elect)	0.429	kg/kWh
CO_2 emissions (biomass)	0.225	kg/kWh
Conversion factor (gas to kWh)	10	kWh/m^3 gas

Appendix G. Value-based multi-criteria decision-making procedure

The calculation regarding the criteria presented in Table 5 (Section 6.2.) is presented as follows:

Financial criteria

The investment and maintenance costs were calculated by multiplying the capacity per household by the investment costs. The operating costs were calculated in the following way (Equation (5)):

$$Costs_{main} = Cap_{tech} \times Operatingcosts_{fixed} + heatdemand \times Operatingcosts_{var} \tag{5}$$

The payback time period of the technology was calculated by dividing the total costs for a period of 30 years by the savings (Equation (6)): Table 25

$$PBT_{tech} = \frac{totalcosts}{Annualenergycostsavings} = \frac{invest_{cost} + operating_{costs} \times 30}{heatdemandreduction_{annual} \times price_{gas}} \tag{6}$$

For the percentage of subsidy coverage, the following information on the SDE++ subsidy amount per technology, found in the reports published by PBL, were used:

The share was calculated by dividing the total subsidy amount dispatched through the SDE++ subsidy scheme by the total cost of the technology throughout its lifetime, presented in Equation (7).

$$Subsidy_{coverage} = \frac{totalsubsidy}{totalcosts} = \frac{heatdemand + subsidy_{SDE++} \times subsidytime}{investment_{costs} + operating_{costs} \times lifetime} \tag{7}$$

Table 25
Data input for subsidy coverage sub-criteria for each collective technology alternative.

	Units	Bio-boiler	ATES	TEA
Subsidy amount	€/kWh	0.030	0.080	0.042
Subsidy time	year	12	15	15

Environmental criteria

The annual CO_2 emissions per household were calculated by multiplying the intensity of the $C0_2$ emissions of the technologies by the annual household heat demand.

The data for the second environmental sub-criteria - land use - was taken from the study conducted on the sustainability assessment of renewable power and heat generation technologies [163]. They describe land use as the “amount of technological demand on land used for agricultural, forestry or nature conservation purposes”. Information for the land demand of a district heating system connected to a wastewater treatment plant was not found and it was then assumed to be similar to that of the ATES system (see Table 26).

Table 26
Data input for land use sub-criteria for collective technology alternatives.

	Bio-boiler	ATES	TEA
Land demand(km^2 /kWh)	59.5	2.68	No info

For the third environmental criteria - awareness of the technology - a more qualitative assessment was done. As discussed in Sections 1 and 2, there are studies that focus on the social aspects and the interactions of stakeholders of energy communities. In the model it is assumed that: the more a heating technology has been used in a sustainable heating project, the more easily accepted it will be by an actor, and the higher it will score in the awareness sub-criteria. The technologies are given a score from 1 to 10 on how aware Dutch households are about each technology. Table 27

Table 27
Score given for level of social awareness to each heating technology.

Heating technology	Bio-boiler	ATES	TEA	Heat pump	Solar thermal system
Awareness score	7	5	2.5	8	3

To develop the awareness sub-criteria for the collective technology, a score from 1 to 10 was given to each technology by normalising the number of district heating projects that use each technology and multiplying the final value by 10. The data set on the current testing grounds of the PAW programme - the 25 neighbourhoods that received the subsidy - was used to count the number of projects that were planning to install each collective technology. Out of the 25 projects, a total number of 14 projects were planning on installing one of the technologies incorporated in the model. In particular, there were 8 biomass projects, 4 ATES projects and 2 aqua thermal projects. Taking current literature into account, that argues for a high awareness of heat pumps, and due to Dutch weather, which has an influence on the adaptation and awareness of solar thermal energy, a score of 3 and of 8, respectively, were given to the solar thermal systems and heat pumps for the level of awareness in the Netherlands:

Independence criteria

The third criteria used for the multi-criteria decision-making process is the energy dependence criteria. In this thesis, these criteria are defined as the amount of energy that is imported into the thermal energy community of study. With respect to the bio-boiler technology, this refers to the amount of energy stored in the wood pellets that are imported to the thermal energy community for the generation of heat. Regarding the ATES and TEA systems, since most of the heat is considered to be located within the boundaries of the thermal energy community, this energy refers to the amount of electricity consumed by the systems for the generation of heat.

For the bio-boiler, the energy import is calculated by dividing the annual household heat demand by the efficiency of a wood pellet bio-boiler (85%). For the ATES and the TEA system, the energy input to the system was derived by dividing the annual electricity consumption of the technology by the average installed capacity of the technology.

Criteria calculation

Table 28 shows the calculation in absolute terms of each sub-criterion for each collective technology alternative. For the results of the individual technology, refer to the Appendix A.

Table 28
Results for the calculation of data input on each sub-criteria for multi-criteria decision-making processes for the selection of a collective-technology alternative.

Nr Criteria	Criteria	Sub-criteria	Goal	Unit	Alternative rankings		
					A1	**A2**	**A3**
C1	Financial	Investment costs	Min	€/household	1402	4635	2668
		Maintenance costs	Min	€/year	77	231	204
		PBT tech	Min	year	4	13	10
		Subsidy coverage	Max	Fraction	0.99	0.70	0.48
C2	Environmental	CO_2 emissions	Min	t/household/year	1757	1029	935
		Land use	Min	km^2/kWh	60	3	3
		Awareness	Max	number	7.0	5.0	2.5
C3	Energy	Energy independence	Min	kWh/year	7949	2399	2179
		Tech capacity	Min	kW/household	2.25	1.93	1.13

Criteria rating

Once the parameters for each alternative have been calculated, the rating of each alternative on each criterion is calculated by normalising the absolute values on the basis of whether the goal is to maximise or minimise such criteria.

When the goal is minimisation, a value of 0 is given to the alternative with the highest score in the sub-criteria and a value of 1 to the alternative with the lowest score. For the third alternative whose sub-criteria falls between the other two, the following expression is used to arrive at a value between 0 and 1, as presented in Equation (8):

$$value_{norm,AX} = \frac{value_{abs,AX} - value_{abs,Amax}}{value_{abs,Amin} - value_{abs,Amax}} \tag{8}$$

When the goal is maximisation, a value of 0 is given to the alternative with the lowest score in the sub-criteria and a value of 1 to the alternative with the highest score. For the third alternative whose sub-criteria falls between the other two, the following expression is used (Equation (9)):

$$value_{norm,AX} = \frac{value_{abs,AX} - value_{abs,Amin}}{value_{abs,Amax} - value_{abs,Amin}} \tag{9}$$

Table 29 shows the results for the normalisation of the criteria for the collective technology alternatives.

Table 29
Results for normalisation of sub-criteria information for each collective technology alternative.

Nr Criteria	Criteria	Sub-criteria	Goal	Unit	Alternative rankings		
					A1	**A2**	**A3**
C1	Financial	Investment costs	Min	€/household	1.000	0.000	0.608
		Maintenance costs	Min	€/year	1.000	0.000	0.173
		PBT tech	Min	year	1.000	0.000	0.352
		Subsidy coverage	Max	Fraction	1.000	0.432	0.000
C2	Environmental	CO_2 emissions	Min	t/household/year	0.000	0.885	1.000
		Land use	Min	HA/kWh	0.000	1.000	0994
		Awareness	Max	number	1.000	0.556	0.000
C3	Energy	Energy independence	Min	kWh/year	0.000	0.962	1.000

Criteria weighting

First, the value system of the agent is normalised. Then, this normalised value is used for determining the preference weight for each criterion in the MCDM process. Then, the weight for each sub-criterion is calculated by dividing the weight for each criterion by the number of sub-criteria (see example in Table 30).

Table 30
Example of final weight per sub-criteria in MCDM for technology alternative selection.

Criteria	Values	Normalised value	Number of sub-criteria	Sub-criteria	Weight
Financial criteria	6	0.3	4	CAPEX	0.075
				OPEX	0.075
				Payback time	0.075
				Subsidy coverage	0.075
Environmental criteria	9	0.5	3	CO_2 emissions	0.16
				Land use	0.16
				Social acceptance	0.16
Independence criteria	4	0.2	1	Energy input to the system	0.2

Alternative scoring

Once the rating of each alternative on each sub-criterion has been calculated and each sub-criterion has a weight assigned, the score for each alternative is calculated by multiplying all sub-criteria ratings for an alternative with their respective weights. The outcome provides a number from 0 to 1 and the alternative with the highest score is considered to be the preferred option (Equation 10).

$$Alternative1(A1) = (1+1+1+1) \times 0.075 + (0+1+0) \times 0.16 + 0 \times 0.2 = 0.46(Eq.10)$$

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