Energy security in community energy systems
An agent-based modelling approach

Fouladvand, Javanshir; Ghorbani, Amineh; Sarı, Yasin; Hoppe, Thomas; Kunneke, Rolf; Herder, Paulien

DOI
10.1016/j.jclepro.2022.132765

Publication date
2022

Document Version
Final published version

Published in
Journal of Cleaner Production

Journal of Cleaner Production 366 (2022) 132765

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Energy security in community energy systems: An agent-based modelling approach

Javanshir Fouladvand [a,*], Amineh Ghorbani [a], Yasin Sarı [a], Thomas Hoppe [b], Rolf Kunneke [c], Paulien Herder [d]

[a] Energy and Industry Section, Engineering Systems and Services Department, Technology, Policy and Management Faculty, Delft University of Technology, TU Delft, the Netherlands

[b] Organization and Governance Section, Multi-Actor Systems Department, Technology, Policy and Management Faculty, Delft University of Technology, TU Delft, the Netherlands

[c] Economics of Technology and Innovation Section, Values, Technology and Innovation Department, Technology, Policy and Management Faculty, Delft University of Technology, TU Delft, the Netherlands

[d] Applied Sciences Faculty, Delft University of Technology, TU Delft, the Netherlands

A R T I C L E I N F O

Handling Editor: Zhifu Mi

Keywords:
Energy security
Energy community
Thermal energy system
Collective action
Institutional analysis and development
Agent-based modelling

A B S T R A C T

In community energy systems, the energy demand of a group of households is met by collectively generated electricity and heat from renewable energy sources. What makes these systems unique is their collective and collaborative form of organization and their distributed energy generation. While these features are crucial to the resilience of these systems and are beneficial for the sustainable energy transition in general, they may at the same time undermine the security of energy within these systems. This paper takes a comprehensive view of the energy security of community energy systems by considering dimensions such as energy price, environment and availability, which are all impacted by decentralized and collective means of energy generation and distribution. The study analyses community energy systems' technical and institutional characteristics that influence their energy security. An agent-based modelling approach is used for the first time to study energy security, focusing on thermal energy communities given the considerable share of thermal energy applications such as heating, cooling, and hot tap water. The simulation results articulate that energy communities are capable of contributing to the energy security of individual households. Results demonstrated the substantial potential of energy communities in CO_2 emissions reduction (60% on average) while being affordable in the long run. In addition, the results show the importance of project leadership (particularly regarding the municipality) concerning energy security performances. Finally, the results reveal that the amount of available subsidy and natural gas prices are relatively more effective for ensuring high energy security levels than CO_2 taxes.

1. Introduction

The energy sector has the most considerable potential to reduce greenhouse gasses (GHG) emissions (Masson-Delmotte et al., 2018), mainly by deploying renewable energy technologies (RETs) (Young and Brans, 2017). One of the possible approaches to enlarging the share of renewable energy in this sector is local community initiatives, commonly referred to as community energy systems (Oteman et al., 2014). Community energy systems (CESs) promote local collective citizen action, which addresses various aspects of the sustainable energy transition to low carbon energy systems, including generation, distribution and consumption of energy for their community members (Gregg et al., 2020).

CESs have received considerable attention in the academic literature over the past years. These systems have been studied from several disciplinary angles: technological (e.g. (Y. Li, Jin, and Li, 2017)), behavioural (e.g. (Wirth et al., 2017)), organizational (e.g. (Boon and Dieperink, 2014)) and institutional (e.g. (Heldeweg and Saintier., 2020)), among others. In this relatively mature literature, however, little attention has been given to the energy security of CESs (Ilieva and Hernandez, 2018).

As one of the focal points in the energy-related literature, energy

* Corresponding author. Delft University of Technology, Faculty of Technology, Policy and Management, Jaffalaan 5, 2628 BX Delft, PO, Netherlands Box 5015, 2600 GA Delft, the Netherlands.

E-mail address: j.fouladvand@tudelft.nl (J. Fouladvand).

https://doi.org/10.1016/j.jclepro.2022.132765
Received 21 October 2021; Received in revised form 24 May 2022; Accepted 17 June 2022
Available online 28 June 2022

security is a complicated concept (Sovacool, 2010). Traditionally energy security was defined in terms of security of supply (Sovacool, 2010). However, in the academic literature, attention has shifted to a more comprehensive approach, with several other dimensions (e.g. affordability, environment and efficiency). Among many definitions (as presented by (Sovacool, 2010)), the Asia Pacific Energy Research Center (APERC) defines energy security as: "The ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy" (Sovacool, 2010). Along with this definition, APERC suggests the "4 A's concept" to measure energy security, i.e. in terms of availability, affordability, accessibility and acceptability.

Besides the diversity in definitions, the energy security literature mainly focuses on conventional, centralized, fossil-fuel-based, and (inter)national energy systems (Sovacool, 2010). There are only a limited number of papers address the security of decentralized energy systems. In contrast to the broader energy security literature, they mainly consider the narrower and traditional notion of security of supply of these energy systems. Given the collective and decentralized nature of CESs, other security dimensions (besides the security of supply) also seem to play a crucial role. More specifically, energy may not be available at all times, especially when the system is not connected to the national grid (Poggi et al., 2020), and energy may not be *accessible* at all times, given the distributed infrastructure and the intermittent nature of renewable energy sources (A. Mittal et al., 2019). Community energy may not be *affordable* for everyone, given the upfront investment costs, among other factors (Bauwens, 2019). Increasing energy efficiency levels and reducing environmental impacts of (local) energy systems such as CESs also offer significant challenges in this context (Morris, 2013). Thus, considering the collective and decentralized nature of CES, various energy security concerns exist (Ilieva and Hernandez, 2018). This knowledge gap, namely lack of attention to the multi-dimensional and distinguished nature of energy security in CESs, hampers the adoption of such collective energy systems to become mainstream on a larger scale. As CESs could drastically contribute to achieving sustainable energy transition goals, such as the GHG emissions reduction targets (Fouladvand et al., 2021), there is a need for an improved conceptualization of security for these decentralized systems.

Therefore, the present study aims to contribute to a more comprehensive understanding of energy security in CESs by looking at energy security in an integral fashion, going beyond the mere security of supply in these systems. Given these systems' bottom-up, decentralized nature, we take a collective action perspective (Ostrom, 2014a) that looks at CESs from behavioural and institutional perspectives and pays attention to how members arrange and manage such collective systems. To accommodate this, we use agent-based modelling and simulation (ABMS), adopting a bottom-up simulation approach (Wilensky and Rand, 2015), to measure and assess the energy security of CESs. ABMS allows to explore the complexities of decision-making processes in CESs and provides the opportunity to experiment with alternative strategies (e.g. policies) within a virtual simulation environment. Agent-based modelling is becoming a prominent tool for studying energy systems, particularly CESs (Hansen et al., 2019); however, no research to date has used this approach to study the energy security of CESs.

To accurately explore energy security with a simulation approach, we focus on thermal applications of CESs, including heating, cooling, bathing, showering and cooking (Fouladvand et al., 2020). Thermal energy communities have received little attention in the literature despite the substantial share of thermal energy in energy systems (Busch et al., 2017). Thermal energy applications in buildings and communities considerably impact CO_2 emissions (Sun et al., 2022); therefore, studying thermal energy would potentially bring further merit to sustainability discussions. The present study can also be seen as a further investigation into thermal energy communities with a particular focus on their energy security. To summarize, the scientific contributions of this research are as follows:

1 To study and investigate different dimensions of energy security that could play a role in the energy security of CESs.
2 To demonstrate the applicability and usefulness of computer simulations, namely ABMS, in the domain of energy security. This research is the first to use ABMS to study the collective energy security of CESs.
3 To focus on the characteristics of thermal community energy systems instead of the mainstream electricity-based communities.

The study also aims to provide concrete insights and recommendations to relevant stakeholders in decision-making processes along with these scientific contributions. In addition to local stakeholders (e.g. municipalities, local policy makers and community-boards), such insights and recommendations could also potentially contribute to energy, environmental and sustainability agendas at a higher level. More specifically, the study can be seen as a response to concerns in relation to the sustainability, societal impact and energy security of CESs.

The structure of the paper is as follows: Section 2 elaborates the research approach and positions our research in the literature on community energy systems. Section 3 explains the theoretical background of this research. Section 4 describes the context of this research. Section 5 is dedicated to model conceptualization. Section 6 presents the model results. Finally, Section 7 concludes the main findings, presents an academic discussion, and provides recommendations and suggestions for further research.

2. Using agent-based modelling to study energy systems

Community energy systems (CESs) can roughly be defined as a group of actors in a neighbourhood, who jointly invest in energy-saving measures (Schram et al., 2019), and renewable energy technologies and generate the electricity and heat they consume (Dóci et al., 2015). However, in the academic literature, other definitions are used as well (e.g. (Magnusson and Palm, 2019)).

Complementary to qualitative approaches, simulations can enhance our analytical power to study social systems such as CESs by relying on computational power to study multiple variables over time simultaneously. Like other modelling practices, ABMS represents a simplified version of reality (Wilensky and Rand, 2015). In an agent-based model, agents are heterogeneous, autonomous and individual decision-making entities (such as households) that are able to learn and interact with each other and their environment (Railsback and Grimm, 2012). In addition to capturing individuals' behavioural choices, using ABMS also allows for studying emerging system behaviour(s) (Bonabeau, 2002). ABMS provides the ability to add the time variable, which allows to examine different scenarios and understand inputs, variables, and outputs (Wilensky and Rand, 2015).

Given the bottom-up nature of CESs and the importance of individual characteristics, decision-making, and interactions for measuring energy security, we use ABMS instead of other simulation approaches such as System Dynamics (Ouyang, 2014) and discrete event simulations (Bagrodia and WenLiao., 1994) that focus on system processes and outcomes.

The use of ABMS is becoming more prominent in the community energy literature. Among modelling research in this area (T E De Wildt et al., 2020), study value conflict for accepting these decentralized energy systems. (Ghorbani et al., 2020a), also simulate behavioural attitudes and explore leadership in energy communities (Fouladvand et al., 2020). take a broader perspective and explore factors that influence the formation of thermal energy communities (Busch et al., 2017), also study local heating systems (Fouladvand et al., 2021), also examined the role of institutional conditions on the formation and functioning of energy communities. Social acceptance of sustainable heating systems is explored in (Tristan E De Wildt et al., 2021), and collective decision-making in local heat transition is investigated in (Nikolic and Ghorbani, 2011). Modelling and simulating zero energy communities, including the new and old buildings based on solar energy, is presented (Anuj Mittal et al., 2019) and exploring the renewable energy technology adoption (Rai and Robinson, 2015) are examples of studies using ABMS in community energy research (Bellekom et al., 2016). also developed a model that explores energy exchange between prosumers and consumers to observe how the presumption affects the self-consumption of a neighbourhood (Fichera et al., 2020). focuses on prosumers behaviour, including technological and spatial constraints for small-scale solar energy systems.

Besides models focusing specifically on CESs, ABMS is often used to study behaviour in energy systems. For example, the influence of the regulatory framework on the adoption of renewable technology is explored in (Rai and Robinson, 2015). This study examines how additional rebates (i.e. partial refund of an item's cost) for low-income households and changes in the rebate amount affect the adoption of solar photovoltaic (solar PV) in Texas (Lee and Hong, 2019). explores factors that are influencing solar PV adoption (Mahmood et al., 2020). presents an ABMS to simulate and forecast wind power plants in Pakistan (Alasinrin et al., 2021). explores the influence of different energy policies such as natural gas subsidy on CO_2 emission reduction in Malaysia's energy sector. The impact of distribution tariff structures and peer effects on adopting distributed energy resources is presented (Moncada et al., 2021). Flexible market design and voluntarily bidding strategies for the electricity market are explored (Vries, 2021). (Burli et al., 2021) presents an ABMS where the decision-making processes and characteristics of different stakeholders, particularly the farmers, are modelled for bioenergy crop adoption.

Along with these modelling exercises, several review studies provide an overview of different topics, variables and applications of ABMS in the energy domain. For instance (Berger and Mahdavi, 2020), reviews ABMS with a focus on buildings demand and the indoor environment, while (Castro et al., 2020) analyse ABMS with a focus on climate-energy policy (Hesselink and Chappin, 2019). provides an overview of ABMS that modelled energy technology adoption, and ABMS with a focus on socio-technical sustainable energy transition is studied (Hansen et al., 2019). Nevertheless, none of these studies and models has explored the energy security of CESs.

3. Theoretical background

This section introduces the key concepts and theoretical approaches used as the backbone of our modelling exercise: energy security, the collective action perspective, and the social value orientation theory. We also use these theories to analyse our simulation results, as discussed in the coming sections.

3.1. Conceptualizing energy security for community energy systems

Energy security is crucial for energy communities (Fulhu et al., 2019), (Sokolnikova et al., 2020), like any other energy system. As presented in (Ang et al., 2015), energy security consists of seven dimensions that contribute to its concept and measurement, including energy availability, infrastructure, energy price, environment, societal effects, governance, and energy efficiency. Table 1 gives an overview of these dimensions.

Table 1
Dimensions and indicators of energy security, adapted from (Ang et al., 2015).

Dimension in (Ang et al., 2015)	Short definition	Indicators
Energy availability	Availability of energy supply	Diversification, geopolitical factors influencing the supply of energy streams, supply disruptions
Infrastructure	Infrastructure is integral in providing a stable and uninterrupted energy supply, including all relevant energy technologies	Adequate and robust infrastructure with spare capacity, reliability
Energy prices	Energy prices determine the affordability of energy supplies	Absolute price level, price volatility, market competitions
Social effects	Social concerns and effects of the energy system	Societal welfare, energy poverty, social equity, distributional fairness
Environment	Sustainability and environmental issues	Environmental pollution and risks
Governance	Sound government policies help to hedge against and mitigate short-term energy disruptions	Diplomacy, information gathering, policies (e.g. tax/subsidies)
Energy efficiency	Developments in energy technologies, systems, and practices help to reduce energy needs and improve energy security	Technological developments, energy intensity and consumption

Although the energy security concept presented in (Ang et al., 2015) (Table 1) is not explicitly developed for the energy security of energy communities, it is still the most suitable concept for measuring the energy security of CESs, among other definitions (examples are presented in (Sovacool, 2010)) for the following reasons:

- ❖ This concept is one of the most recent concepts, which is well adapted to recent developments in the energy security literature;
- ❖ It is a multidisciplinary concept that addresses the multi-dimensional nature of energy security. Furthermore, Besides the environment, two other dimensions of societal effects and governance, which are influential to energy communities, are also present in this concept.

3.2. Community energy system as a collective action problem

Theoretically, CESs can be seen as a form of collective action where actors join efforts to achieve shared goals on a common-pool resource dilemma (Ostrom, 2014a), namely renewable energy generation and consumption. In this regard, the Institutional Analysis and Development (IAD) framework of Ostrom (2014b) is specifically designed to analyse collective action problems from an institutional perspective. Institutions are political, social and legal rules, more loosely rules of the game, that form the basis of activities of actors (Gagliardi, 2008). The IAD framework enables the analysis of a collective system by breaking it into a number of building blocks (McGinnis, 2011). Fig. 1 presents the IAD framework.

The action situation is the main component of the IAD framework (A Ghorbani et al., 2010), which pertains to a conceptual space (Ostrom, 2014b), where actors consider alternative courses of action, make decisions, take actions, and experience the consequences of their actions (McGinnis, 2011). Exogenous variables influence action situation:

- ❖ The biophysical conditions include the physical and material resources and capabilities available within the system's boundaries (McGinnis, 2011). Resources include, for instance, available RETs and collective investment in them for collective energy generation (Ostrom, 2014a).
- ❖ The attributes of the community include the cultural norms accepted by the community (McGinnis, 2011). In other words, the shared values, beliefs and preferences about the potential outcomes of the action situation (Milchram et al., 2019).
- ❖ Lastly, the rule-in-use component concerns the formal rules that govern the system (Ostrom, 2011). Such formal rules include regulations and policies for the system's governance.

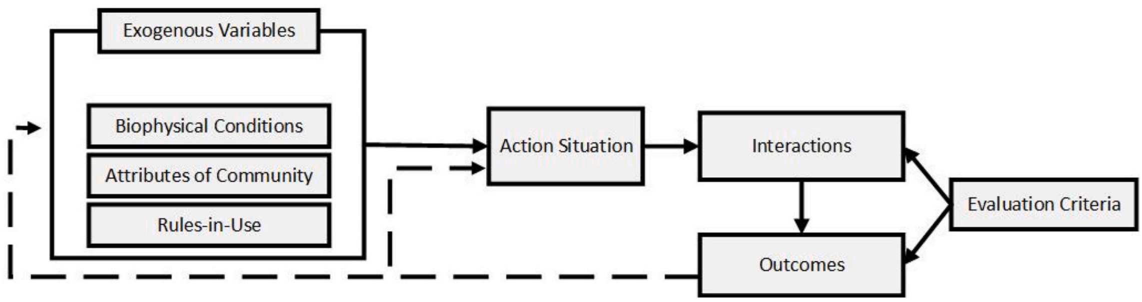


Fig. 1. *IAD framework, adapted from* (Ostrom, 2011).

The interaction between exogenous variables and inter-actor agency in action situations results in patterns of interaction that generate certain outcomes (Ostrom, 2011). Based on evaluation criteria, these outcomes can be objectively assessed (Ostrom, 2014b). In the end, there is a feedback loop that connects the outcome to the action situation and the exogenous variables (A Ghorbani et al., 2010).

Even though the IAD framework has conventionally been applied for the study of traditional common pool resource management, such as irrigation and fishery, it has recently also been extensively applied to energy systems (e.g. (Lammers and Heldeweg, 2019), (Lammers and Hoppe, 2019)). The IAD framework has also proven to be highly instrumental in the CESs domain (Lammers and Hoppe, 2018) because it explicitly addresses the formal and informal institutional challenges for such collective initiatives (Milchram et al., 2019). Besides its analytical power for studying CESs from a collective action perspective, the IAD has proven useful for building agent-based models (Nikolic and Ghorbani, 2011). Different studies in the energy-related literature used the IAD framework in developing ABMS (e.g. (Verhoog et al., 2016) and (Iychettira et al., 2017)). In these studies, the IAD framework is used to conceptualise the model and analyse the simulation results. The IAD framework is used in a similar way in the present study.

3.3. Modelling individual behaviour: the social value orientation (SVO) theory

Fulfilling specific concerns (e.g. environmental and energy security concerns) and achieving certain goals (e.g. financial benefits) are the main motivations of individual people for joining CESs (Bauwens, 2016), (Dóci and Vasileiadou, 2015). In this regard, the Social Value Orientation (SVO) theory explains the motivations and concerns of people when they make decisions. In the SVO theory, it is assumed that people vary in their motivations or goals when evaluating different resource allocations between themselves and another person (Murphy et al., 2011). SVO theory classifies individuals' personalities based on four groups considering pro-self-versus pro-social orientations (Murphy et al., 2011):

- ❖ Altruistic: these individuals are selfless, focusing on maximising joint benefits regardless of the impact on their own payoff; the opportunity of helping others is their motivation;
- ❖ Cooperative: these individuals aim to maximise others' outcomes in addition to their own;
- ❖ Individualistic: these individuals are mainly concerned with their own outcomes, focusing on their own payoff without having a specific need to minimising other's benefits;
- ❖ Competitive: these individuals aim for maximum results and strive to minimise other individuals' benefits.

The SVO theory helps capture and simulate real-life decision-making situations more closely by considering various decision-making motivations (Murphy and Ackermann, 2014). The SVO theory has been used across a range of interpersonal decision-making contexts, specifically in the domains of negotiation settings (Dreu and Boles, 1998) and environmental attitudes (e.g. (Pahl et al., 2005)), including resource dilemmas (Roch et al., 2000). This theory has also been used in the energy domain (e.g. (Kastner and Matthies, 2016)).

To sum up, this section explained the theoretical underpinning for building an agent-based model to study the energy security of thermal energy communities. The energy community in this model is viewed as a collective action and therefore conceptualized using the IAD framework. To have a more concrete conceptualization of the institutional and technical structure of community energy systems, we focus on systems with thermal applications. In this setting, behaviour and decision-making are conceptualized using the SVO theory to categorize individuals based on their motivations. Finally, implementing energy security in the model builds on the concept defined by (Ang et al., 2015) and is summarized in Table 2.

4. Modelling context

4.1. Thermal applications in community energy systems

Depending on the type of generation and its application, the CESs literature is divided into two mainstreams: either energy communities in the general sense of the concept (e.g. (Walker and Devine-Wright, 2008) (Koirala et al., 2016)) or, more particularly, electrical energy communities (e.g. (Vuichard et al., 2019), (Rees et al., 2011)). However, thermal energy communities-focused on collective generation, distribution and consumption of thermal energy for applications such as heating, cooling, bathing, showering and cooking-have received little scholarly attention thus far (Fouladvand et al., 2022). The literature is mainly focused on top-down approaches as governments' solutions for providing heat (e.g. (Abokersh et al., 2020) (Jensen et al., 2020)) rather than the collective action of individual households within CESs to generate and distribute some sort of heat together.

Thermal energy communities consist of three main components: (thermal) energy technology, affiliated institutions, and involved actors, including their behaviour (Fouladvand et al., 2020). Thermal energy technology consists of renewable heating generation technologies (such as biogas, geothermal valves and solar thermal collectors) (Mavromatidis et al., 2018), distribution systems (mainly district heating) (Rezaie

Table 2
Indicators of energy security in the model.

Dimension	Implemented indicators in the model
Energy availability	Average voluntary shortage per household
Infrastructure	Diversity of technologies (which have their own robustness)
Energy prices	Average renewable thermal heating costs of households
Social effects	Average community benefit per household
Environment	Average CO_2 emission per household
Governance	Duration of establishment for households
Energy efficiency	Average thermal insulation per household based on the housing energy label

and Rosen, 2012), and final consumption (e.g. space heating and showering) (D. Majcen, Itard, and Visscher, 2013).

As rules of the game, the affiliated institutions are the second component of thermal energy communities, which refer to the human-constructed agreements and regulations for the generation, distribution and consumption of thermal energy within CESs (Fouladvand et al., 2021). In the literature on thermal applications in CES, formal rules such as regulation design (e.g. (Vitéz and Lavrijssen, 2020)), pricing strategies and market design (e.g. (Hoekstra et al., 2020), (Liu et al., 2019)) have received considerable scholarly attention. Informal rules such as norms and values (e.g. (Reyes et al., 2015), (Mujuru et al., 2020)) have also received attention.

Involved actors, their behaviour: roles and responsibilities represent the third component of thermal energy communities (Fouladvand et al., 2020). Topics such as actors involvement (Dvarioniene et al., 2015)), financial responsibilities (Bauwens et al., 2016), and leadership (Ghorbani et al., 2020b) are related to this component.

4.2. The Netherlands as a case study

This research builds an agent-based model focusing on thermal applications in CESs and uses data from the Netherlands. The Netherlands was selected as the country to study CESs with thermal applications because of the following reasons:

- Presence of a high number of CESs as compared to other EU countries (Bauwens et al., 2016);
- Presence of well-developed energy and specifically heating infrastructure (F. Hooimeijer and Tummers, 2017);
- Dutch national ambitious CO_2 reduction targets which influenced the heating sector (Van den Broek et al., 2011);
- National norms for environmental concerns and sustainable development (Ligtvoet et al., 2016);
- The urge for the sustainable heat energy transition is due to a recently increasing number of gas-quakes (Perlaviciute et al., 2017).

Energy security is also important in the Dutch energy policy debates (Matsumoto et al., 2018). Historically, the Netherlands has a strong performance in the security of supply due to natural gas fields in the province of Groningen (Radovanović et al., 2017). However, as energy security has adopted more diverse dimensions, various studies have evaluated the energy security of the Netherlands in different ways (e.g. (Matsumoto et al., 2018), (Radovanović et al., 2017)). Furthermore, particularly in the thermal energy context, topics such as gas quakes (Kester, 2017), the geopolitics of natural gas imports/exports (Correljé and Coby van der Linde, 2006), and energy pricing (Liu et al., 2019) contribute to the importance of energy security within the Dutch thermal energy context.

The data used in the model include supportive policies (e.g. renewable energy subsidies) and prohibiting policies (e.g. taxes) from the "Stimuleringsregeling Duurzame Energie" (SDE++), Netherlands Environmental Assessment Agency (PBL), and built environment and energy efficiency regulations (e.g. retrofitting policies based on 'Energiesprong' and building energy labels).

5. Model conceptualization

In this section, we explain the conceptual model using the IAD framework. First, the agents in the model and their motivations are introduced. Next, the exogenous variables, biophysical conditions, attributes of community and rules-in-use are elaborated. To explain the action situations and interactions, the decision-making processes of agents and the model narrative are presented. Lastly, evaluation criteria and outcomes are introduced as the model's key performance indicators (KPIs).

5.1. Agents in the model

The model represents a city with multiple neighbourhoods, where each neighbourhood can only have one CES. The model has two types of agents: (i) individual households and (ii) the municipality.

- Individual households initially use natural gas to cover their thermal energy demand, and they also hold a specific set of internal motivations to participate in a thermal energy community. Following (Dóci and Vasileiadou, 2015) (Koirala et al., 2018), the primary motivations taken into account to conceptualise the motivations of the individual households in a CES are energy independence, a sense of community, environmental concern and economic benefits. Independently from each other, the motivations have a value between 0 and 10 (i.e., 0 is the weakest and 10 is the strongest). Preferences of neighbours can influence the internal motivations of households (see Section 5.3.). The community-board consists of the five most environmentally-friendly households in the neighbourhood. The other motivations of members of the community board (energy independence, sense of community and economic benefit) are also higher than the median value (≥ 5) following (Fouladvand et al., 2021). The individual households make decisions based on their four internal motivations. The SVO theory is used to capture these internal motivations and categorize the decision-making processes based on the agents' personality types following (Von Wirth et al., 2017), (Koirala et al., 2018). The SVO-type of the individual households is calculated as follows:

$$\textit{Level of motivation} = (\textit{environmental concern} + \textit{sene of community}) - (\textit{financial concerns} + \textit{energy independence}) \quad (1)$$

- If Level of motivation >1: SVO-type 1,
- If Level of motivation < -1: SVO-type 3,
- If Level of motivation ≥ -1 and ≤ 1, and, sense of community <5: SVO-type 4,
- If Level of motivation ≥ -1 and ≤ 1, and, sense of community ≥ 5: SVO-type 2.
- The municipality represents the department(s) of the local government responsible for sustainable energy transition (particularly sustainable heat transition). The municipality is responsible for defining the formal institutions to support the neighbourhoods' transition off-gas, including the availability of subsidies, eligibility requirements of subsidies, and any other formal regulations and arrangements in the model. Following (Magnusson, 2016) (Fouladvand et al., 2021) (Ceglia et al., 2020), municipalities have four strategies for supporting energy communities and, specifically, thermal energy communities, namely: environmentally driven (i.e. most CO_2 reduction option), economically driven (least economic burden for the municipality itself), socially driven (most involved participants in a neighbourhood) and a trade-off between the three. These strategies influence and determine the municipalities' decisions over their actions, such as subsidy allocation. Individual households are aware of the municipality's strategy from the beginning of the simulation.

5.2. Biophysical conditions

5.2.1. Technological scenarios

The agents can choose from several technological options (particularly for the Netherlands). Following (Mavromatidis et al., 2018) (Magnusson, 2016), technological options are presented in three categories:

- **Renewable thermal energy generation technology:** The collective renewable thermal energy generation technology options included in the model are biogas heaters, aquifer thermal energy systems (ATES), and electric boilers. The individual renewable thermal energy generation options are heat pumps, small bio-energy heaters (i.e. wood pallet based) and photovoltaic thermal hybrid solar collectors (i.e., Solar PVT).

- ❖ **Heat distribution:** The technological option for distribution is district heating. Although, in reality, the district heating infrastructure can be outfitted for low or medium temperature heat, for simplification, it is assumed that only medium temperature heat transportation is possible in this model.
- ❖ **Heat consumption:** The average households' heating demand and the housing insulation label are considered.

5.2.2. Average ambient surrounding temperature

The ambient temperature is essential in determining (thermal) energy consumption. When the outdoor environment is colder, demand increases as the energy system generates more thermal energy. Therefore, the ambient temperature is modelled as a biophysical condition, influencing the agents' actions. Due to climate change, the ambient temperature changes over time in the coming decades (Masson-Delmotte et al., 2018), (Pacesila et al., 2016), translating to changes in energy demand. The model's standard distribution of households' demand is based on the PBL data. To capture the impact of ambient temperature changes based on climate change scenarios, the model assumes that climate change leads to hotter outdoor temperatures and, therefore, reduces the households' energy demand in European countries, including the Netherlands.

5.3. Attributes of community

It is assumed that each neighbourhood has only one CES, implying that each individual household can only participate in one CES. The model assumes that households in one neighbourhood can interact with each other in monthly resident meetings (i.e. each tick in the model represents a month) but not with other neighbourhoods. In order to capture and simulate the interactions within each neighbourhood, the model uses a small-world network (Watts and Strogatz, 1998). 'Small world' is a common approach for representing the social networks of individuals within local renewable energy systems (e.g. (Fouladvand et al., 2020), (Amineh Ghorbani, Nascimento, and Filatova, 2020a)). The dynamics occur based on the following principle as argued in (Amineh Ghorbani, Nascimento, and Filatova, 2020b): when two households interact, if the value of each motivation is between 2 and 8, the value will slightly lean towards the opinion of another agent attempting to simulate peer pressure. This means that the value will be updated by 1 towards the other agent's motivation's value. It is also assumed that households with very extreme values (either higher than 8 or lower than 2) will not be peer pressured and hence will not be influenced by the interaction.

5.4. Related institutions

In our modelling exercise, two types of formal institutions are considered (i) supportive policies (e.g. renewable energy subsidies): and (ii) and punishing policies (e.g. CO_2 taxes). The data for these institutions are based on the SDE++ and built environment and energy efficiency regulations (e.g. retrofitting policies based on 'Energiesprong' and building energy labels). Furthermore, according to the PBL, the available subsidy is 2–5 million euros per municipality per year (Fouladvand et al., 2021). As the municipality's budget is limited, one of the crucial rules for decision-making is how the municipality should rank the communities and decide on the subsidy allocation.

5.5. Action situation and interactions

The processes during the lifetime of a CES can be modelled in four stages or action situations following (Busch et al., 2017), (F. L. Hooimeijer, Puts, and Geerdink, 2016):

5.5.1. Initiation phase

The initiation phase aims to select the project leader (municipality or community board) and the collective renewable heating technology source (biogas heaters, ATES or electric boilers) for the CESs.

5.5.1.1. Decision on the project leader. First, the households have a period to exchange information to know each others' motivations and align them. These interactions are based on the description in Section 5.3. The duration of the information exchange period is considered to be 7 months (see Table 4). After a period of information exchange among households, individual households decide on the type of project leadership, with two options: (i) community-board and (ii) municipality. The project leader is responsible for organizing and taking the initiative within a CES. In order to make such a decision, each household first checks the municipality's strategy. If the municipality's strategy is environmental, each household compares their own environmental friendliness value with the municipality's (which is assumed to be 6 or higher to favour the environment over other values). If the household also has a value greater than or equal to 6 and belongs to the first (i.e., altruistic) or second (i.e., cooperative) SVO types, it votes for the community-board. In case the household is SVO-3 (i.e., individualistic) or SVO-4 (i.e., competitive), it checks its "sense of community" value. If it's greater than or equal to 5, it goes for the community-board. If the municipality's strategy is societal capacity, the procedure works the same way as described above for the municipality with the environmental friendliness strategy. The only difference is that instead of environmental friendliness, agents compare their sense of community values with the value of the municipality in the first place.

When agents observe an alignment of high economic values with a municipality that prioritizes economic benefit as its strategy, they vote for the municipality, unlike in the two other cases. Finally, if the municipality's strategy is the trade-off between the three, the agents randomly go through one of the above mentioned processes with an equal chance.

5.5.1.2. Decision on collective renewable heating technology source. **If the municipality takes the lead**, specific collective heating technology is selected and communicated to individual households based on its strategy (environmental, economic, social and trade-off). To select the heating system, the municipality calculates three variables concerning each technology (i.e., CO_2 emission, costs, minimum needed participants).

$$\begin{aligned}&\textit{Total demand per year} = \\&\textit{number of households} \times \textit{average demand per household per year}\end{aligned} \tag{2}$$

$$\textit{Annual CO2 emission} = [\textit{total demand per year} \times \textit{CO2.intensity}] \tag{3}$$

$$\begin{aligned}&\textit{Costs (investment)} = \textit{Technology capacity} \times \textit{Capex}+ \\&\textit{heat demand} \times \textit{Operating costs} \times \textit{lifetime}\end{aligned} \tag{4}$$

Minimum needed participants to make a CES economically feasible:

$$\textit{Min. needed participants} = < \frac{\textit{Costs}}{\textit{natural gas prices} \times \textit{current consumption}} \tag{5}$$

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

If the community-board takes the lead, the procedure of choosing a collective heating technology will be more participatory. The community-board goes through a multi-criteria decision-making process (MCDM) to select a collective thermal technology. The initial preference of the community-board over the type of collective technology is determined based on the majority vote of the individual preferences of the *board* members. The individual preference of a board-member is calculated as a weighted sum of each criterion where the weights are the set of motivations (i.e. environmental friendliness, financial drive, sense of community and energy independence). The board suggests the technology with the highest MCDM score as the thermal technology for the community as the alternative.

Once the community-board suggests a collective thermal technology, households within the neighbourhood (excluding the board members) calculate their score per collective thermal technology alternative in the way described above (i.e., MCDM). Based on this calculation, the following two conditions must hold at the same time for the technology to be accepted: i) the suggested technology by the community-board is not the technology that is rated as the lowest by more than one-third of the neighbourhood; ii) the suggested technology is the one that is rated as the highest by more than half of the neighbourhood. This step is necessary, as individuals might value motivations such as environmental concerns differently than the community-board. If the municipality is the project leader, this step is skipped.

Through both types of project leadership, the community as a whole reaches a consensus on collective renewable thermal energy technology. As part of this technology selection (i.e. investment), individual households commit to improving their home's energy efficiency level in this stage by 1 step (e.g., from energy label E to energy label D).

5.5.2. Technical settings and meeting energy demand (i.e. feasibility phase)

Once the project leader and the collective renewable thermal energy technology are finalized, individual households have to decide how much of their individual energy demand would be covered by collective energy technology and how much would be covered by other sources (i.e. national-gas grid or individual renewable generation).

5.5.2.1. Decision on the amount of collective generation. Individual households decide how much energy they want to generate collectively through the selected collective thermal technology. Following (Kaundinya et al., 2009), individual households select a fraction between 0 and 100% of the demand to be generated collectively. The capacity of collective thermal energy generation is calculated in terms of the percentage of total thermal demand of the members, and it is determined as the average percentage value favoured by individual households in a neighbourhood and applied to all the members. Therefore, a generation capacity is allocated to cover the corresponding percentage share of the thermal demand of each community member. A household's preference over how much collective thermal energy to generate is influenced by its budget and the SVO category it belongs to. The upper limit for this percentage is determined by the collective technology budget of the household, i.e., how much at most the household can afford with its budget. If the household belongs to the altruistic SVO-type, it prefers to meet all its demand (i.e. 100%) from the collective system. For the other SVO-types, the preferences to cover their energy demand collectively is as follows: Households with SVO-2 (i.e., cooperative) 90%, households with SVO-3 (i.e. individualistic) 80%, and households with SVO-4 (i.e. competitive) 70%. Suppose the collective energy system cannot fully cover the entire community's energy demand. In that case, the individuals depending on their internal motivations, have to choose individual heating systems or use the national natural gas grid.

5.5.2.2. Decision on individual heating technology source. For individual heating systems, first, individual households decide on alternative energy scenarios based on their internal motivations: (i) if their financial concern is greater than environmental friendliness, they use natural gas as the energy source for the remaining demand that is not covered by the selected collective heating energy system, (ii) if an individual has higher environmental concerns than economic motivation hence does not choose natural-gas, there are going to be two options:

- ❖ If an environmental-friendly household's budget is allowed, it will further increase housing insulation and install an individual renewable thermal energy system.
- ❖ If the financial means of an environmentally friendly household is not sufficient for such an investment at a particular moment, it will choose to save up to install the technology in the future. This means that the individual household will use less heat and may voluntarily face thermal energy discomfort due to its unmet demand. In reality, this can be translated in different ways, such as: (i) turning off/down the thermal energy system inside the homes in the absence of individuals, (ii) shifting the thermal demand from peak hours, (iii) reducing hot tap-water consumption. Members make this decision by comparing their budget with the needed investment for individual selected RETs. The money saved due to the voluntary discomfort will be accumulated over time and invested in individual renewable thermal energy systems when the financial situation allows.

When the household equally values environmental concerns and financial drives, the sense of community value serves as a tie-breaker. If its value is smaller than 5 (on a scale of 0–10), the household decides to leave the CES.

5.5.3. Financial feasibility and supporting phase

After choosing the technologies, there is a need to check the financial feasibility of the system for the second time, which entitles technical and financial calculations in order to apply for subsidies. The output of the financial feasibility and supporting phase is granting the subsidy and final checking the number of participants to distribute the costs.

The project leader (either the community-board or the municipality) considers the technical scenario with the most supporters and conducts a second technical and investment feasibility analysis for the collective and individual thermal energy systems of the selected scenario. This calculation is related to subsidy allocation processes. For the technical feasibility, renewable generation (including collective and individual technologies), CO_2 emission per kW heat generation (i.e. CO_2 intensity technology), and average heat generation capacity and load hours are used. For investment feasibility, criteria such as lifetime, investment costs, operation costs and availability of subsidies are used (to cover unreliable costs in business cases); see Appendix A and B.

Based on the total requested demand for energy as calculated in phase 2 (i.e. technical settings and meeting energy demand), the project leader calculates how much subsidy they need to request in order to cover the entire investment. If this amount does not exceed the maximum amount, the government gives it to the neighbourhood. If the amount is more, the project leader requests the highest possible subsidy option the government is willing to give to one neighbourhood.

Once a year (every 12 ticks), the municipality considers all the CESs that have applied for the subsidy. The municipality ranks the requests based on its subsidy distribution strategy (i.e. environmental friendliness, financial drive, societal drive and trade-off) and provides the subsidy to those that meet their criteria until all the funding has been used. If a CES does not receive the subsidy (as it might not meet the municipality's criteria for receiving the subsidy or as it might be low in the ranking of the municipality), it waits for the next year and applies again.

5.5.4. Installation, generation and expansion phase

Once the technology investment has taken place and the community energy system is installed, energy is generated (thermal energy generation is calculated monthly). New participants can be potentially added to the community initiative over time.

After receiving the subsidy and collective investment of individuals, the CES goes into a construction state for a year (i.e. twelve ticks in the simulation). Once the infrastructure is in place, the community is considered to be set up.

After setting up, every year (i.e. twelve ticks in the simulation), the individuals and community board check whether they have reached the end of their project time horizon (i.e. 20 years in the simulation). When the technologies reach their lifetime, the community will start another information exchange round, including new community members and choosing new technologies (i.e. starting from phase 1).

After the initial setup of the community, "non-members" can re-evaluate their participation, i.e., check if they are willing to participate. As "non-supporters" can interact with other agents in the neighbourhood (as presented in 5.3.), their opinions might grow towards their neighbours' opinions who are members of CES. If these potential members agree with the installed energy technology, they will invest in thermal insulation as part of the agreement. Suppose their willingness to pay equals or is lower than the investment required per person in the neighbourhood. In that case, they will increase their energy efficiency (i.e. housing label insulation) and participate in the community system. When individuals disagree with the board's decisions, they will no longer participate and will leave the energy community.

Fig. 2 presents the four steps explained in Section 5.5. as a conceptual model flowchart.

5.6. Evaluation criteria and outcomes: key performance indicators

By using seven energy security dimensions presented in (Ang et al., 2015) (see Table 2), seven key performance indicators (model's KPIs) are defined for measuring the energy security of (thermal) energy communities. Calculations related to these KPIs are presented in Appendix B.

5.6.1. Energy Availability: average voluntarily discomfort per household

Energy availability can be measured by calculating the average percentage of the energy demand per year, which is not met. Not meeting the demand could be because of the behavioural attributes and technical and institutional choices of the individuals and the community as a whole. In the real world, this can be translated as discomfort for households which means the generation is insufficient to provide enough thermal energy to heat the cold water and accommodations to the desired temperature.

5.6.2. Energy prices: Average costs per household

The average cost per year for each household participating in a CES is calculated based on four primary sources of costs: collective renewable thermal energy system, individual renewable thermal energy system, natural-gas consumption and insulations.

5.6.3. Environmental: Average CO_2 emission per household

This indicator is about the average CO_2 emission per year of a household participating in a CES. Although households reduce their CO_2 emission by adopting renewable thermal energy, there is still a possibility that they emit CO_2 as they might choose bioenergy and natural gas as their resources.

5.6.4. Infrastructure: Average diversity of infrastructure per household

Diversification of energy systems involves having a range of energy infrastructures (including generation and distribution) (Ang et al., 2015) that would provide various energy sources for involved stakeholders. In the community context, the diversity of infrastructure is reflected by the number of distinct energy sources households have access to. There are three main energy setups in the model, in which individuals choose from collective renewable thermal energy (including the selection of one of the following technologies: biogas heaters, ATES, and electric boilers), individual thermal energy (including a choice of one of the following technologies: heat pumps, wood pallet and Solar PVT), and natural gas. The modelling exercise uses the Shannon index (Ranjan and Hughes, 2014) to calculate diversification.

5.6.5. Energy efficiency: Average thermal insulation per household

Individual households improve the efficiency of their accommodations represented by their home energy label, which is considered a KPI to measure the overall energy efficiency of households. There are two moments that individuals can improve their housing energy label. First, the moment they decide on collective renewable generation, they are required to improve their energy label by one step (e.g. from energy label D to energy label C). Second, suppose they want to choose an individual thermal energy system. In that case, they also have the opportunity to choose to invest in improving their housing energy label one step further (e.g. from energy label C to energy label B). These steps have different investment sizes and effects on energy consumption reduction. We used data from (Filippidou and Nico Nieboer.), (Daša Majcen and Itard, 1947), (Filippidou et al., 2017) for calculations related to insulation. At the end of the model, the average insulation of the whole community is calculated (see Appendix A-4 and B-5).

5.6.6. Governance: establishment duration of energy communities

The duration of the process in which the community goes through the establishment is used as an indicator for the governance dimension. This duration is influenced by various decisions, such as choosing the type of project leadership, technological choices, municipality subsidy allocation strategy and dynamics in individuals' motivations.

5.6.7. Societal effects: Average community benefit per household

Participating in a CES has direct and indirect benefits for a community. Direct benefits are the financial benefits related to energy savings over the years. Indirect benefits are a community's economic (and social) benefits associated with CO_2 emission reduction (e.g., fewer health issues).

In addition to these seven specific energy security KPIs, other criteria will be used to evaluate energy-secure TEC initiatives' establishment and functioning processes, presented in Table 3.

5.7. Sensitivity analysis and experimentation

A sensitivity analysis was conducted to explore the model's robustness in different experimental configurations for various model parameters following the one-factor-at-a-time (OFAT) approach (Frey and SumeetPatil, 2002). For each parameter presented in Table 4, the model was run 30 times where all parameters were fixed at a certain value, and only the parameter under study was altered to test the model's sensitivity to that parameter (Frey and SumeetPatil, 2002). The values for the parameters presented in Table 4 are set based on the sensitivity analysis. These values align with the current body of literature, such as neighbourhood size (Sleutjes et al., 2018), the number of connections each household has, and the number of neighbourhoods in a municipality (Fouladvand et al., 2021).

5.8. Parameters and experimentation settings

To study the energy security of thermal energy communities, four parameters are selected from the literature that are potentially influential for the energy security of such systems:

- ❖ Natural-gas prices: the price of natural gas is influential for both (i) the deployment of renewable thermal energy technologies and district heating systems (Van den Broek et al., 2011) (Osman, 2017), and (ii) energy security (Van den Broek et al., 2011), (Keppler, 2016).

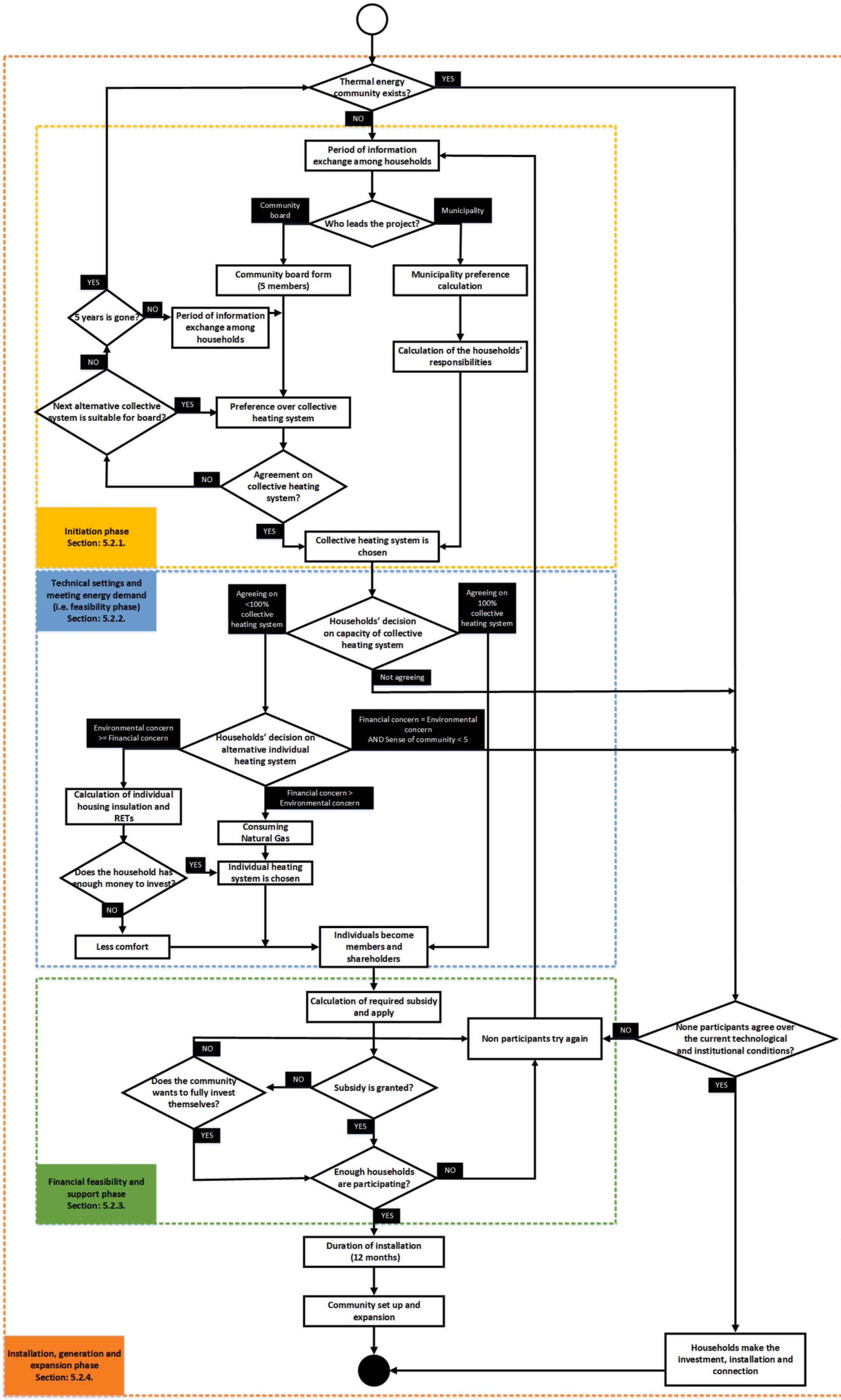


Fig. 2. Model flowchart Individual Model conceptual framework.

Table 3
General key performance indicators.

Key performance indicator	Unit	Description
Final share of neighbourhood participation in CES	%	Percentage of the neighbourhood households that are connected to the district heating infrastructure after 20 years
Collective technology selection	-	The collective technology that the neighbourhood has selected and installed in the neighbourhood (biogas, ATES, electric boiler)
Individual technology selection	-	The individual technology that the neighbourhood has selected and installed in the neighbourhood (nothing, wood pallet, heat pump, solar thermal)
Percentage of collective renewable thermal energy generation	%	Percentage of collective renewable thermal energy generation based on the decision-making of individuals
Percentage of natural-gas consumption	%	Percentage of natural-gas consumption in a CES
Project leadership selection	-	The project leader that the neighbourhood has selected to lead the CES (either community board or municipality)

Table 4
Parameter configuration based on sensitivity analysis.

Parameter	Value	Unit
Duration of information exchange	7	Months
Neighbourhood size	600	households
Steps of percentage preference reduction per SVO type	20	%
Number of connections each household has	3	Number
Number of neighbourhoods in a municipality	3	Neighbourhood
Steps of yearly gas price increase	0.01	(€/kWh)
Steps of yearly CO_2 tax increase	0.002	(€/kg)

❖ CO_2 tax: A policy that could significantly impact the RETs deployment and fossil fuel prices is the application of a CO_2 tax. CO_2 emission tax also influences energy security.
❖ Ambient temperature: Changes in ambient temperature has a considerable influence on energy security and RETs deployment, as it can potentially influence the (thermal) energy demand (Francés and GonzaloMarín-Quemada, 2013), (Turton and Barreto, 2006).
❖ Amount of subsidy and municipality subsidy allocation strategy: The amount and allocation strategy of subsidy influences affordability of the energy system, and therefore it impacts the RETs deployment and energy security.

We use these four parameters as input in our modelling exercise. The experimentation included a total number of 108 different combinations of the four-parameter values (3*3*3*4 = 324) in Table 5. Each combination was repeated 50 times; hence, the experimentation resulted in a total number of 16200 runs. As the number of neighbourhoods (i.e. CES) in each run is set at 3, the total number of CESs in this modelling exercise is 3*16200 = 48600. The influence of these parameters on the modelling's KPIs is elaborated in Appendix C.

6. Results

In this section, we present the results of the experiments on two levels: (i) an overview of KPIs individually, which provides an overall view of energy security; and (ii) High and low energy security performances by combining the seven energy security KPIs.

6.1. General security performance

6.1.1. Overview of technical and institutional factors

Among all the 48,600 simulated CESs (i.e. neighbourhoods in the model), around 60% of them chose aquifer thermal energy system (ATES) as their collective thermal energy system (see Fig. 3). The explanation for this is (i) the relatively better environmentally performance (i.e. less CO_2 emission) of ATES systems in comparison with other technologies and (ii) the relatively long projects' time horizon (i.e. 20 years), which makes ATES more economically feasible. Furthermore, thermal energy communities also always include individual renewable energy sources, usually in the form of heat pumps (blue in Fig. 3). Natural gas is the second choice for the individual systems (red in Fig. 3). Less than 500 CESs chose wood pallets and solar PVT as their individual renewable thermal energy systems. These results confirm the relatively high willingness to adopt different RETs, particularly individual RETs (e.g. heat pump and Solar PVT), while the natural-gas option is available as an individual technology choice. Fig. 3 presents the distribution of the technological choices among all 48,600 CESs.

The results show that thermal energy communities could dramatically reduce natural gas consumption and, therefore, contribute significantly to the CO_2 emission reduction in the Netherlands. However, as presented in Fig. 4, almost no community became completely natural-gas free. As illustrated in the model's narrative in Section 5.2., considering that individual households and communities as a whole could potentially not choose natural-gas consumption at all, this emphasizes the importance of natural gas for the (i) Dutch heat energy transition; and (ii) the energy security of (thermal) energy communities.

The results show that community-boards took the leadership of 67% of CESs. Considering the Dutch context (i.e. attributes of community and rules-in-use particularly), this can be translated to communities being

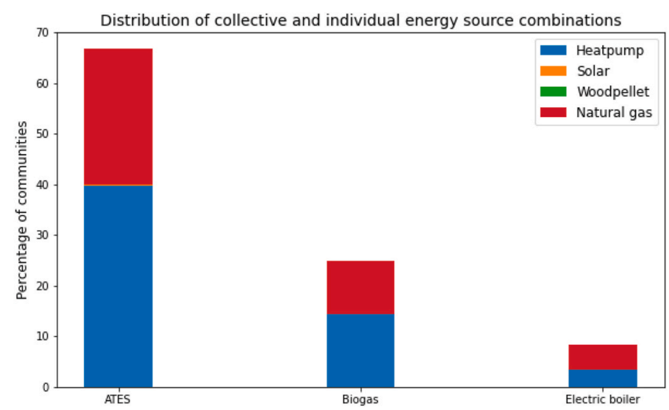


Fig. 3. Distribution of collective and individual energy sources combinations in all runs.

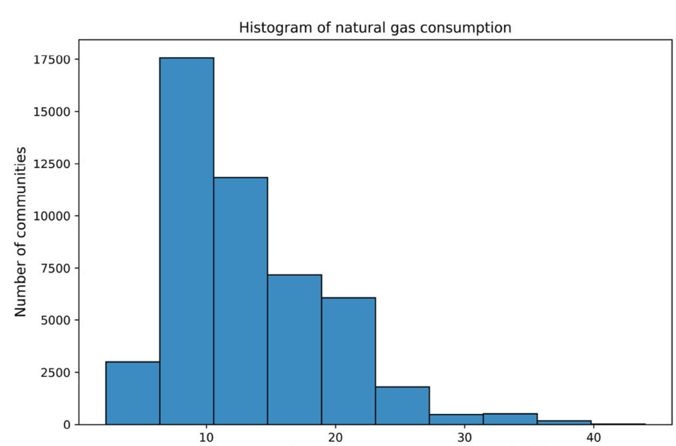


Fig. 4. Natural-gas consumption of all 48600 communities.

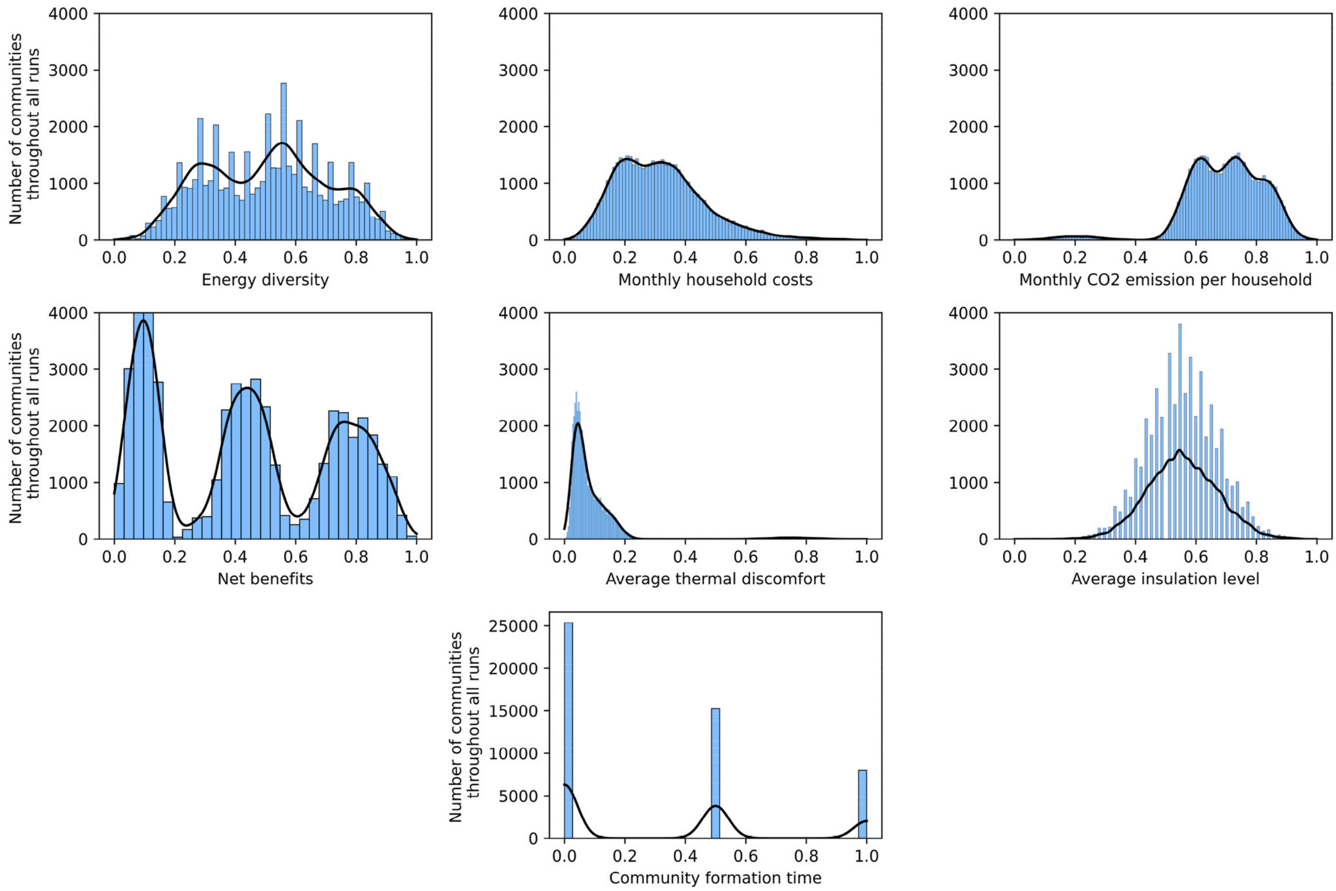


Fig. 5. Overview of normalized KPIs vs number of thermal energy communities overall runs.

more likely to be led by their own community-boards. Such leadership does not necessarily lead to higher energy security performances, as elaborated in Sections 6.2 and 7.

6.1.2. *Overview of energy security key performance indicators*

In order to compare the energy security KPIs with each other (see Table 2), the normalized distribution of each energy security KPI is presented. For instance, the modelling results for CO_2 emission per household as one of the energy security KPIs are between 95 and 150 kg/month, which as a normalized distribution, is translated into values between 0 and 1. In Fig. 5, the X-axis presents values between 0 and 1 as a normalized distribution of results for each energy security KPI in the model. The Y-axis presents the density of the number of runs.

As Fig. 5 shows, the results for thermal discomfort are mostly less than 0.2 on a normalized scale (9% discomfort), which shows the potential for high energy availability (i.e. security of supply) within CESs. Also, the results show that 53% of CESs' formation time is less than three years for formation time.

KPIs such as energy costs, thermal insulation, and the energy diversity index are distributed among normalized values depending on technical and institutional settings. There is no distinctive peak for these specific KPIs except for energy insulation. This can be translated into (i) depending on different parameter settings (e.g., CO_2 taxes and natural-gas prices), such KPIs can perform well, (ii) such KPIs do not have a significant influence on determining the energy security of thermal energy communities. Other KPIs, such as community benefit, community formation time and thermal discomfort, have distinctive peaks. The peak is nearly zero for discomfort KPI, meaning the individual households face little thermal discomfort (less than 4% of their yearly thermal demand). Particularly, there are three peaks for community benefit, with most performance lower than 0.5 in normalized presentation. Community formation time also has three discrete peaks due to decisions over subsidy allocation time at a certain time every year. The majority of the communities form relatively quickly (i.e. less than 3 years). This indicates that these KPIs could potentially play a significant role in determining the energy security of thermal energy communities as they show a lot of variability and sensitivity towards the parameter settings of the model. In the next section, we dive into the reasons behind these differences.

6.2. *Technical and institutional factors of high energy security performance*

This section analyses the technical and institutional factors for TEC initiatives with high and low energy security performances. To provide such analysis, first, we labelled the thermal energy communities as high or low energy security performance through the following procedure:

- ❖ High performance: For each KPI, the top 60% of all 48,600 communities across all runs are selected, leading to 29160 communities performing better than the rest. The communities that fall within the top-performing group of *all* KPIs are chosen as the highest performing ones in terms of security in general. This selection led to 472 communities in total.
- ❖ Low performance: The worst-performing communities are selected across all KPIs through the same process, leading to 587 thermal energy communities.[1]

[1] This process was first conducted with 50% highest and lowest performance, however, the sample was very small (i.e. 47 and 132 communities respectively) therefore the percentage was changed to 60%.

Table 5
Experimentation settings.

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

Table 6
General technical and institutional factors of high and low energy security performances.

	Low energy security performances (587 CES)	High energy security performances (472 CES)
The leadership of the Community-board	89%	15%
The leadership of the Municipality	11%	85%
Collective technology choice	90% ATES, 10% Bio-energy	15% ATES, 85% Bio-energy
Collective generation	83%	80%
Individual technology choices	56% Heat pump, 43% natural-gas, 1% Solar PVT	64% Heat pump, 35% natural-gas, 1% Solar PVT
Natural-gas consumption reduction	56%	64%
Participation of households	91%	84%

Table 6 shows the KPIs of communities the low and high-performance categories per KPI.

As Table 6 shows, there is a meaningful relationship between project leadership and energy security performances. 89% of CES with low energy security performances (523 runs out of 587) are led by the community-board. On the other hand, project leadership by the municipality can potentially lead to a higher energy security performance. ATES and bio-energy are the two collective technologies for both high and low performances. Although collective choices for technology differ substantially in high performing and low performing communities (ATES more popular in low performing communities and Bio-energy more popular in high performing ones), individual technology choices are quite similar.

To understand the influence of the five input parameters, namely natural-gas prices, CO_2 taxes, ambient temperature (i.e. the influence of climate change), amount of subsidy and municipality subsidy allocation strategy (Table 5) on high and low energy security performance, we studied them more closely. Among the five parameters, municipality strategy, amount of subsidy and ambient temperature (i.e. climate change influence) showed a clear and meaningful influence on energy security performances. The economic-drive strategy of the municipality is considered the dominating strategy for high energy security performance communities. The lowest subsidy amount dominates the low-performance communities. Natural-gas prices for low and high energy security performances are dominated by the median value (i.e. 0.002 €/kWh). The CO_2 taxes showed no meaningful division between the high and low energy security performances. Fig. 6 illustrates the parameters for high and low energy security performance.

Furthermore, to bring more meaningful insights, the seven energy security indicators of the high energy secure communities are also

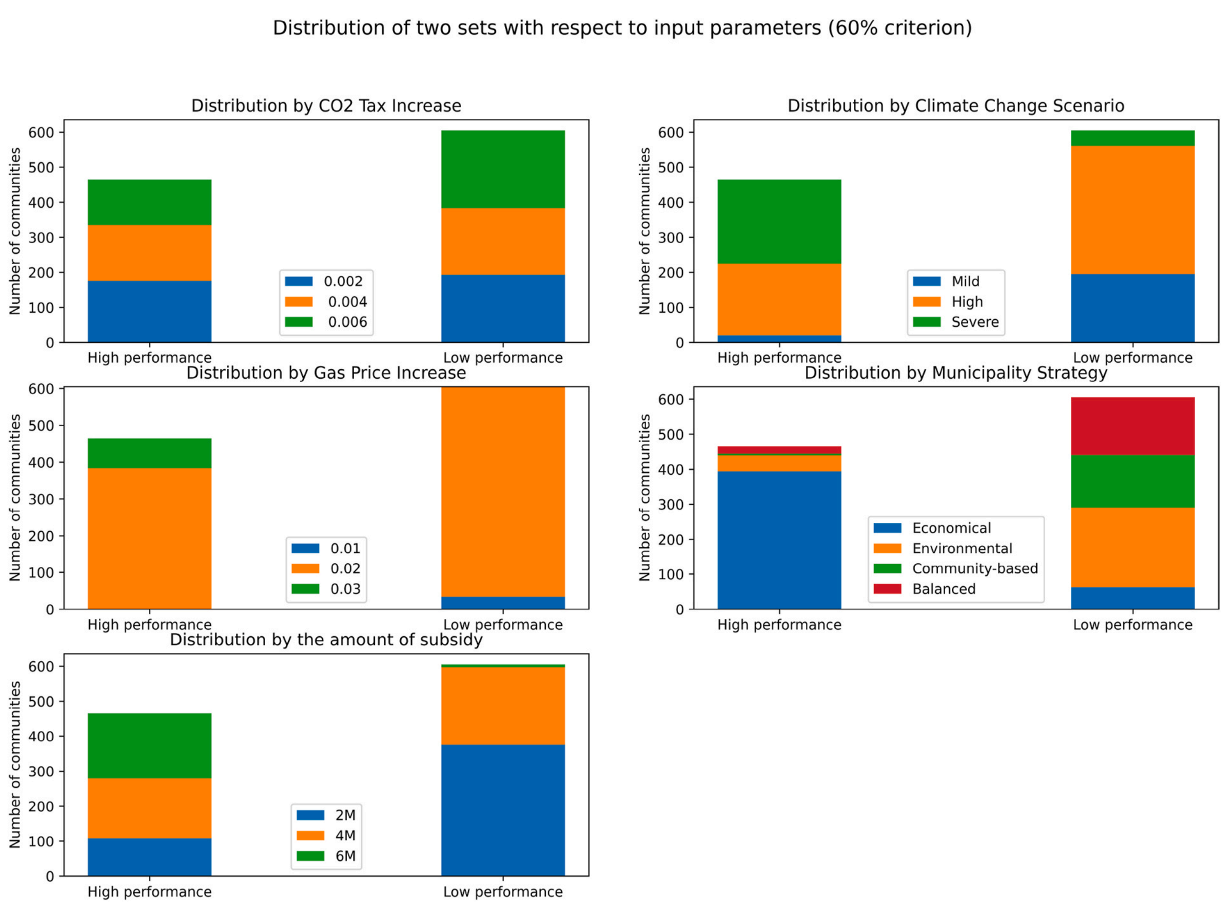


Fig. 6. Parameters for 60% high and low energy security performance.

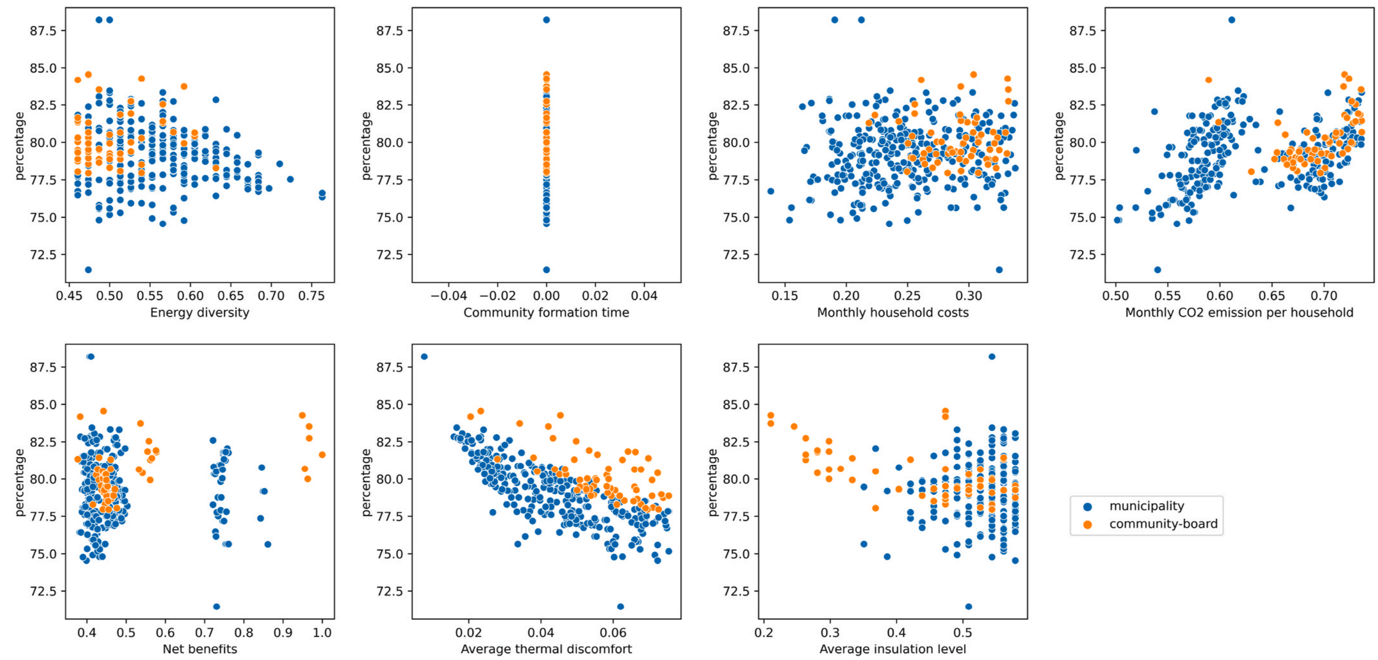


Fig. 7. Type of leadership and percentage of collective energy generation in the high energy secure communities.

analysed in relation to the two most essential characteristics, namely type of leadership and percentage of collective energy generated (see Fig. 7).

Considering that all the communities in Fig. 7 are highly energy secure, 87.5% is the highest collective energy generation. The leadership type has considerably influenced the performance of these high energy secure communities. For instance, community-board project leadership potentially leads to higher community benefit, while municipality project leadership leads to better performance of energy diversity and improves thermal insulation. As illustrated in Table 6, community-board leadership is more likely to lead to a lower energy security performance. All seven energy security KPIs show that community-board project leadership leads to higher collective generation in highly energy secure communities.

7. Discussion and conclusions

7.1. Energy security of community energy systems

The present study analysed the energy security of CESs, particularly CESs for thermal applications. It explored the technological and institutional factors that could potentially influence the energy security of such energy initiatives. By focusing on thermal energy communities, we also aimed to shed light on the unique characteristics and processes of these types of communities (e.g. thermal energy implementation and building insulation). An agent-based model (ABM) was built and parameterised using Dutch data. The developed model is the first ABM in the broader energy security literature, introducing the applicability and usefulness of this modelling approach to the field.

The energy security concept presented in (Ang et al., 2015), which goes beyond the security of supply by considering various dimensions (e.g. environment, governance and energy efficiency), was used to conceptualise energy security in our modelling exercise. The results demonstrated the substantial potential of CESs to reduce CO_2 emissions while being affordable in a long-time horizon (i.e. 20 years in this modelling simulation). In detail, among all 48600 CESs in the modelling exercise, members of most CESs (i.e. around 28200, 58% in total) reduced their CO_2 emission by 60%, while their monthly payment was less than 80 Euros and only faced discomfort for 4% of their demand on a yearly basis. At the same time, 53% of all CESs were established within three years after the start of the simulation, demonstrating the relatively short duration of establishing such collective entities. With an increasing number of CESs in the future, these results highlight the importance of energy security dimensions other than only security of supply (i.e. availability). More specifically, in addition to availability, environment, governance and energy price dimensions need to be rigorously taken under consideration for a comprehensive energy security assessment with further uptake of these decentralized energy systems.

The study showed the importance of different technological configurations for the energy security of (thermal) energy communities. Although different energy source options were available for individual households in the model (e.g. fully collective renewable energy systems, individual renewable energy systems and fully natural-gas consumption (see Section 5.2.)), CESs have always decided to adopt natural gas as part of their energy mix. This highlights the importance of a connection to a natural gas grid (i.e. often a national grid) for maintaining (thermal) energy communities' energy security. However, it is important to note that our research only took the national gas grid into account, given its thermal application focus. To study whether the electricity grid plays an equally important role, the model needs to be further extended with other specific configurations (e.g. national electricity grid, micro grid and electric vehicle).

At the same time, the results also confirmed that collective energy generation could contribute to the energy security of individual households (e.g. see Fig. 7). Among the RETs options, ATES and heat pumps, respectively, are the collective and individual renewable thermal energy technologies mostly used. The results showed that such a combination of technologies also reduces environmental impact, as highlighted in other studies (e.g. (Rostampour, 2019)). However, CESs with high energy security performances turn out to have mostly bio-energy as their collective energy source, mainly due to its lower price and faster establishment process than ATES.

Further analysis (Section 6.2) revealed that CES's leadership has also significantly impacted the CESs' energy security performances. In more detail, municipality leadership could potentially lead to a higher energy security performance of CESs. In contrast, community-board project leadership is advantageous for the communities themselves and the local government, resulting in a higher share of the collective heat generation and community economic benefit in the long run.

Finally, among the five input parameters (see Section 5.8.), the present study found that available renewable energy subsidies are far more impactful on the energy security of (thermal) energy communities than natural-gas prices and CO_2 taxes. The ambient temperature (i.e. demand reduction) also showed a relatively positive influence on CESs' energy security performances but requires further investigation.

Considering all these points, we conclude that the following technical and institutional factors are critical for the energy security of (thermal) energy communities: (i) maintaining a connection to the national grid, (ii) enabling and promoting collective energy generation (e.g. in the form of ATES), (iii) municipality leadership, (iv) subsidy availability for community energy, and (v) more extended vision (e.g. 20 years) on return on investment.

7.2. Limitations and suggestions for future research

Although this study brought new insights into the energy security of (thermal) energy communities, it has certain limitations. A first limitation is the conceptualization of energy security using the concept developed in (Ang et al., 2015) (i.e. energy availability, infrastructure, energy price, environment, societal effects, governance, and energy efficiency). Despite the benefits this concept offers, it is crucial to keep in mind that other energy security concepts and indicators (such as the 4As energy security concept and WEC indicators as presented in (Sovacool, 2010) (Bartos and Robertson, 2014)) could also be used in security-focused models.

A second limitation concerns the selection of theories used in the present study to structure our modelling exercise and approach the energy security of CES. The decision to use Ostrom's IAD framework and the SVO theory has provided a specific lens through which CES have been researched. Nevertheless, there are other frameworks and theories, such as Ostrom's Collective Action theory (Ostrom, 2014b) and Theory of Planned Behaviour (Ajzen, 1991), that, when applied to the same issue, systems and processes could provide potentially different insights. Using such frameworks and theories could complement current findings on the energy security of thermal energy communities.

A third limitation is regarding ABMS as a method to explore the energy security of CES. As argued in Section 4, ABM is considered a suitable approach for this study; however, it has limitations. ABMS presents a simplified version of real-world phenomena or systems like any other modelling approach. ABMS is mainly used to explore bottom-up approaches, decision-making processes, and system behaviour emergence. At the same time, the real world is somewhat more complicated, and top-down structures are also present. Therefore, other research methods such as equilibrium modelling and serious gaming could be beneficial in addition to the presented ABMS. More specifically, equilibrium modelling could address issues related to energy supply-demand, while serious gaming could provide insights into stakeholders' decision-making processes.

Finally, the case study selection (i.e., the Netherlands) is the fourth limitation. Although due to its unique characteristics, the Netherlands provides an opportunity to explore the energy security of CES (see Section 4.3.), it is still a limitation, as it has its own energy system's specifications. The selected case influences data collection reflecting the national technical and institutional factors, influencing the conceptualization of the model (e.g. input data on energy demand, building energy labels, heat pumps, solar thermal energy systems). Although technological choices, data, and the model's parameters are based on real-world realities, they still limit the study. For instance, other RETs such as deep geothermal energy systems and high-temperature district heating can be explored. An important consideration for further work is adding more details on thermal energy applications within buildings. The present study contributes to studies such as those (K. Li et al., 2022) and (Zhang et al., 2022), where CO_2 emissions of buildings are explored. Another assumption of the model is that climate change impact is only limited to energy demand. Although the model provides meaningful results, it would be insightful to adapt the model's inputs in such a way that it can also fit the context of other countries such as Denmark, Belgium, Germany and the United Kingdom. Lastly, more reliable empirical data is needed to have more insightful outcomes. Conducting surveys and expert interviews would be helpful for this.

7.3. Recommendations

Considering the modelling simplifications and limitations of the present study, the overall results indicate that thermal energy communities can, on average, be established within three years if a high degree of support is experienced by households (e.g., approximately 50%). The modelling results and analysis show that scenarios combining a high degree of renewable energy generation (including both collective and individual technologies) with a connection to the national natural gas grid are preferred among households. Results also show that the majority of CESs considerably reduce their CO_2 emissions. Based on the present study, the following societal and policy recommendations are made:

- ❖ Policy-makers are suggested to consider the importance of maintaining natural gas as an option to sustain the energy security of thermal energy communities in the coming 20 years (as per the simulation timeline).
- ❖ Policy-makers are encouraged to focus more on developing supportive policies (e.g., renewable energy subsidies), which allocate the available resources based on economic considerations, rather than punishing policies (e.g. CO_2 taxes and increasing energy prices).
- ❖ Policy-makers are recommended to support community-boards leadership when possible. If a CES and its board are not in place, initiate the CESs through municipal leadership as it could lead to households' energy security.
- ❖ Policy-makers and households are recommended not to aim for completely independent energy systems. It appears that self-sufficient (i.e. off-grid) thermal energy communities could potentially not be established and face lower energy security if established.
- ❖ Regarding renewable energy technology, ATES (with a combination of heat pumps) appears to be the dominant technology that significantly contributes to thermal energy communities' energy security. Therefore, all stakeholders (particularly policy-makers) are encouraged to consider this technology in their decision-making.
- ❖ Households are recommended to overlook the size of investments and economic considerations in the initiation phase of CESs (and focus on the total cost of ownership) if possible, as in the long run, higher investment in (thermal) energy community systems leads to higher community benefits, less environmental impact and even more individual economic benefits.

Funding

This work was financially supported by the Netherlands Organization for Scientific Research [NWO Responsible Innovation grant – 313-99-324]. Also, the work received substantial support from the Energy Transition Lab of Technology, Policy and Management faculty.

CRediT authorship contribution statement

Javanshir Fouladvand: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Visualization. **Amineh Ghorbani:** Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Supervision, Project administration. **Yasin Sarı:** Software, Formal analysis, Investigation, Visualization. **Thomas Hoppe:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing, Supervision. **Rolf Kunneke:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing, Supervision. **Paulien Herder:** Methodology, Validation, Writing – review & editing, Supervision, Project administration.

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.

Acknowledgements

The authors would like to thank the Netherlands Organization for Scientific Research and Energy Transition Lab of Technology, Policy and Management faculty for their financial support.

Appendix

A. Input data

1. *Collective heating technology*

As discussed in model conceptualization (Section 5.1.3.), actors choose one of the three collective thermal energy technology options according to their values. Information about each of these technologies is summarized in Table 3. According to (Airaksinen and Vuolle, 2013), the peak demand is considered 10% for all three collective technologies, and the CO_2 intensity of electricity consumption is 0.429 kg/kWh. The information is provided based on the "Stimuleringsregeling Duurzame Energie" scheme (SDE++). Furthermore, for each collective technology, the following information is used:

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

2. *Individual heating technology*

As mentioned in Section 5.2. after choosing and agreeing on the collective technology, households have four options: (i) using the collective technology to cover 100% of their consumption; (ii) combining the chosen collective technology with an individual heat pump; (iii) combining the chosen collective technology with the individual photovoltaic thermal hybrid solar collector (Solar PVT); and (iv) combining the chosen collective technology with individual small bioenergy (i.e. wood pallet).

Considering the Dutch electricity grid characteristics, CO_2 intensity is assumed to be 0.14 kgCO_2/Kwh for the heat pumps in the model. For calculating the CO_2 intensity of the solar thermal systems, it was assumed that the solar water heater is used to supply hot water 80% of the time, and the electric water heater will supply the rest 20%. In other words, this 20% will be covered by the electricity grid. By calculating 20% of the grid's CO2 intensity, we arrive at a CO_2 intensity for the water heater systems of 0.086 kg CO_2/kWh. Information about each of these individual technologies is summarized in Table 4 below.

Variable	Units	Heatpump
Capex	euros/kW	1770
Opex	euros/kW/yr	35.4
Load hours	h/yr	1500
CO_2 emission	kg/kWh	0.14

(*continued on next page*)

(*continued*)

Variable	Units	Heatpump
Lifetime	yr	15
Variable	**Units**	**Solar PVT**
Capex	euros/kW	1450
Opex	euros/kW/yr	11
Load hours	h/yr	700
CO_2 emission	kg/kWh	0.086
Lifetime	yr	20
Variable	**Units**	**Woodpellet**
Capex	euros/kW	415
Opex	euros/kW/yr	140
Load hours	h/yr	2000
CO_2 emission	kg/kWh	0.35
Lifetime	Yr	20

3. *Data for attributes of the community*

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

Criteria	Sub-criteria	Unit	Description	Reference
Financial criteria	CAPEX	€	Investment costs	Dénarié et al. (2018)
	OPEX	€	Operational and maintenance costs during the lifetime of the system	Tsoutsos et al. (2009)
	Payback time	Years	Years for the investment and maintenance cost to equal the accumulated energy savings from the change	Sadiq et al. (2019)
	Subsidy coverage	%	Percentage of the capital costs covered by the subsidy (in the present study, this would be the SDE++ subsidy)	Tsoutsos et al. (2009)
Environmental criteria	CO_2 emissions	kg CO_2eq	The CO_2 emission intensity of technology based on capacity	Mckenna et al. (2018)
	Land use	HA	Amount of land use required for technology based on capacity	Dénarié et al. (2018)
	Social acceptance	1 to 10	The degree to which that technology is accepted, recognized and implemented	Tsoutsos et al. (2009)
Independence criteria	The energy input to the system	kWh	Amount of energy input required for the technology to produce the heat to cover the neighbourhood heat demand	Mckenna et al. (2018)

4. *Distribution of energy labels in the Dutch context*

Insulation label distribution	
Label	**Percentage**
A	5.3
B	18
C	32.5
D	24.4
E	11.6
F	6
G	2.2

5. *Other data*

Variable	Units	Electric boiler
Average thermal energy demand per year	kWh	12000
Gas price	euros/kWh	0.1
CO_2 tax	euros/kg CO_2	0.025
CO_2 emission of natural gas	kg/kWh	0.2

B. *Calculations of seven energy security KIPs*

1. *Energy Availability: average voluntarily discomfort per household*

In the model, discomfort is calculated based on Equations (6) and (7):

$$\text{Voluntarily discomfort for a household} = \frac{\sum_{1}^{lifetime}\left(100\%demand - \%collective\ generation - \%individual\ generation - \%natural\ gas\ consumption\right)}{lifetime} \tag{6}$$

$$\text{Average percentage of voluntarily discomfort per household in the community} = \frac{\sum_{1}^{number\ of\ households}(percentage\ of\ voluntarily\ discomfort\ for\ a\ household)}{number\ of\ households} \tag{7}$$

Equation (6) is based on each possible energy resource percentage, and Equation (7) calculates the average percentage of discomfort each household faces.

2. *Energy prices: average cost per household*

This KPI is calculated using equations (8) and (9):

$$\text{Costs for a household} = \frac{\begin{array}{l}[(investment\ for\ collective\ system) + (collective\ system\ yearly\ costs) \times (lifetime)] + \\ [(investment\ for\ individual\ system) + (individual\ system\ yearly\ costs) \times (lifetime)] + \\ [(natural\ gas\ consumption\ per\ year) \times (lifetime)] + \\ [insulation\ investments]\end{array}}{lifetime} \tag{8}$$

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

Equations (8) and (9) calculate the costs of households based on different energy technologies and lifetime (i.e. duration of the project and simulation).

3. *Environmental: Average CO2 emission per household*

The CO_2 emission per household is calculated in Equations (10) and (11):

$$CO_2\ \text{emission for the whole community} = \frac{\begin{array}{l}\sum_{1}^{lifetime}(collective\ system\ emission) + \\ \sum_{1}^{lifetime}\sum_{1}^{number\ of\ households}(individual\ system\ emission) + \\ \sum_{1}^{lifetime}\sum_{1}^{number\ of\ households}(natural\ gas\ emission)\end{array}}{lifetime} \tag{10}$$

$$\text{Average } CO_2 \text{ emission per household in a community} = \frac{CO_2\ emission\ for\ the\ whole\ community}{number\ of\ households} \tag{11}$$

Information regarding the CO_2 emissions of each technology is presented in Appendix A.

4. *Infrastructure: average diversity of infrastructure*

The diversity of infrastructure is calculated as follows in equation (12).

$$\begin{array}{c}Diversity\ index = \\ -1 * ((collective\ thermal\ energy \times \ln collective\ thermal\ energy) + (natural\ gas\ consumption \times \ln natural\ gas\ consumption) \\ + (individual\ thermal\ energy \times \ln individual\ thermal\ energy))\end{array} \tag{12}$$

5. *Energy efficiency: average thermal insulation per household*

Thermal insulation is calculated in Equation (13). Note that insulation labels are mapped into numbers ascendingly, i.e., A: 1, B: 2, C: 3 etc. So the lower the average score, the better the insulation efficiency:

$$\text{Average insulation per households in a community} = \frac{\sum_{1}^{number\ of\ households} insulation\ of\ a\ household}{number\ of\ households} \tag{13}$$

6. *Governance*

The time is calculated to count the months until the community generates collective renewable energy.

7. *Societal effect: average community benefit*
In the model, the benefit is calculated as follows:

$$\text{Average social benefit per household} = \left[\frac{\text{Direct benefits} + \text{Indirect benefits}}{\text{lifetime}}\right] \tag{14}$$

$$\text{Direct benefits} = \frac{\sum_{1}^{\text{number of households}} \sum_{1}^{\text{lifetime}} \text{Cost savings on bills}}{\text{number of households}} \tag{15}$$

$$\text{Indirect benefits} = \frac{\sum_{1}^{\text{lifetime}} \frac{(CO_2 \text{ emission reduction})}{\text{Inderct costs of } CO_2 \text{ emission}}}{\text{number of households}} \tag{16}$$

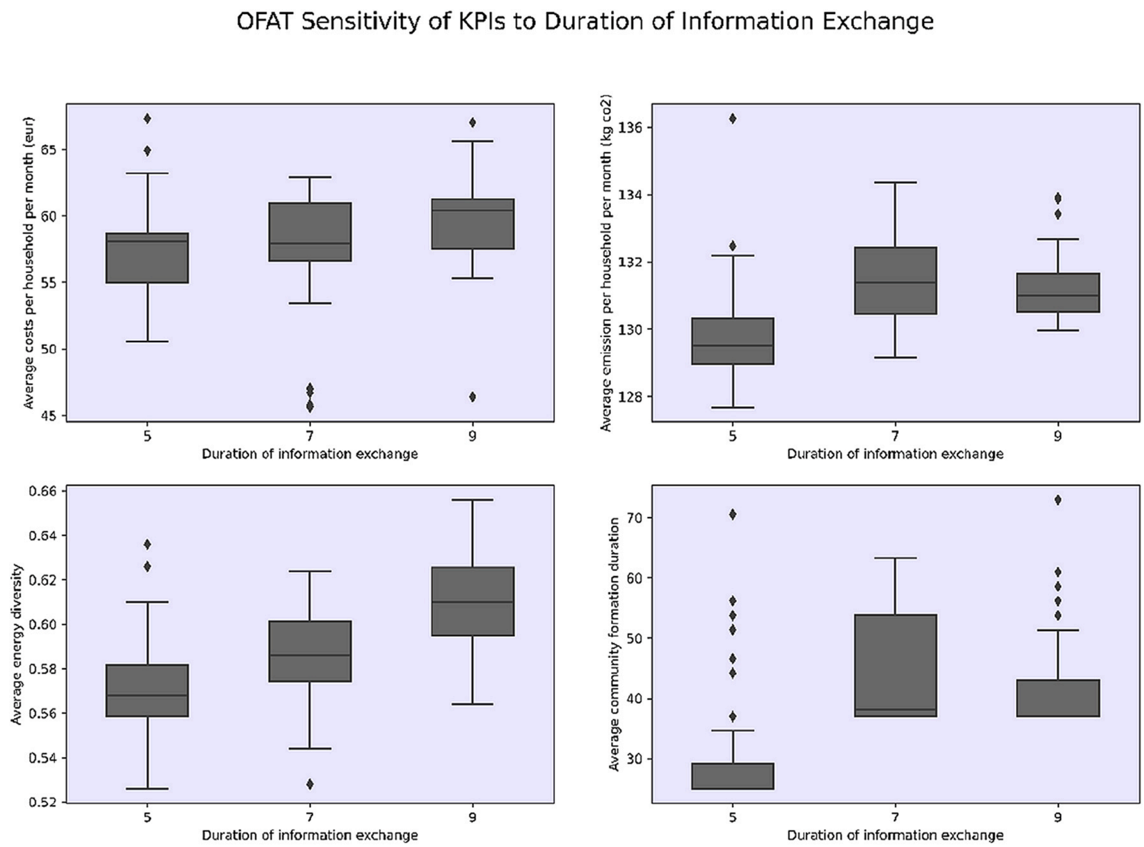
C. Sensitivity analysis

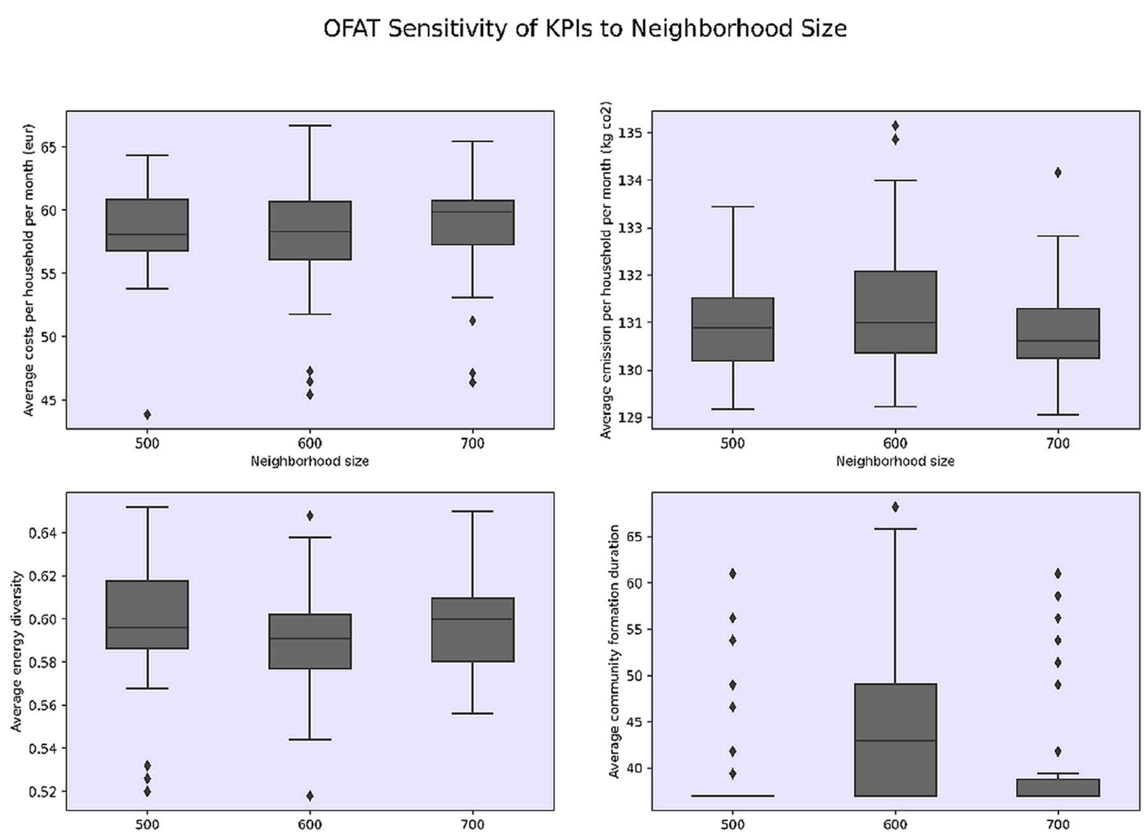
There are often some uncertainty in the parametrisation of most, if not all, model variables. Where this uncertainty is considerable, the parametrisation can be systematically explored by experimenting with the input value of the variable by doing a sensitivity analysis (Frey and SumeetPatil, 2002). A sensitivity analysis will reveal whether some values given to the parameters will lead to specific effects on the model outcomes (Schouten et al., 2014).

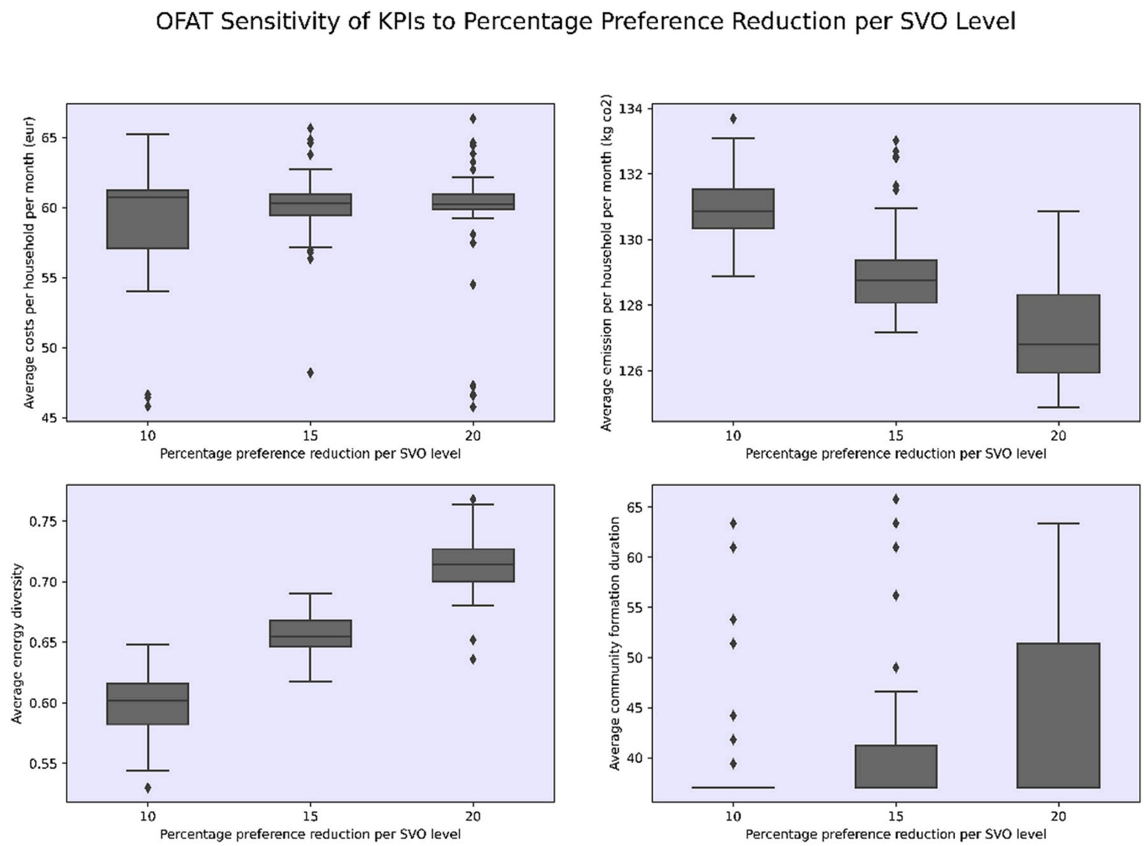
One-factor-at-a-time (OFAT) was used (Frey and SumeetPatil, 2002), which essentially consists of selecting a base parameter setting (nominal set) and varying one parameter at a time while keeping all the other parameters fixed. This reveals the relationship between the varied parameter and the output, given that all parameters have their nominal values. Table 6 presents the parameters and their ranges that have been explored through this sensitivity analysis.

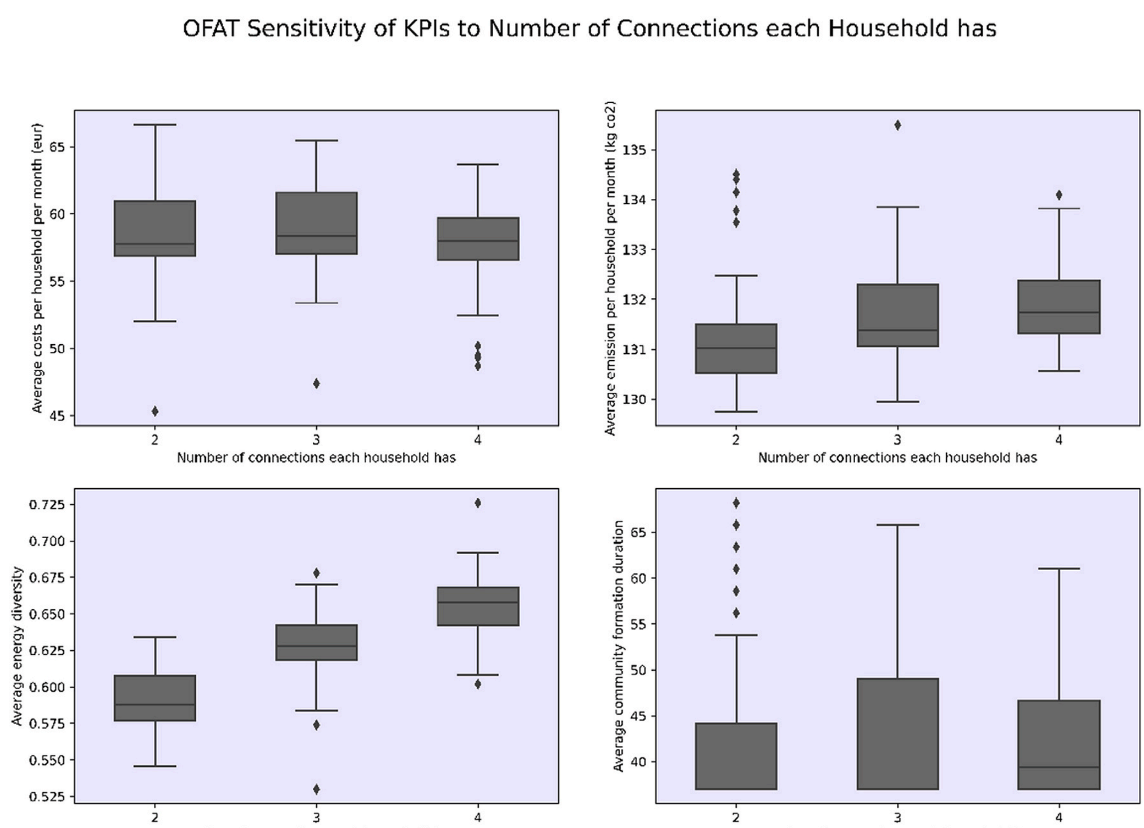
Parameter	Range	Unit
Duration of information exchange	5, 7, 9	Months
Neighbourhood size	500, 600, 700	households
Steps of percentage preference reduction per SVO type	10, 15, 20	%
Number of connections each household has	2, 3, 4	
Number of neighbourhoods in a municipality	3, 4, 5, 6	Neighbourhood
Steps of yearly gas price increase	0.005, 0.01, 0.015, 0.02	(€/kWh)
Steps of yearly CO_2 tax increase	0.01, 0.02, 0.03	(€/kg)

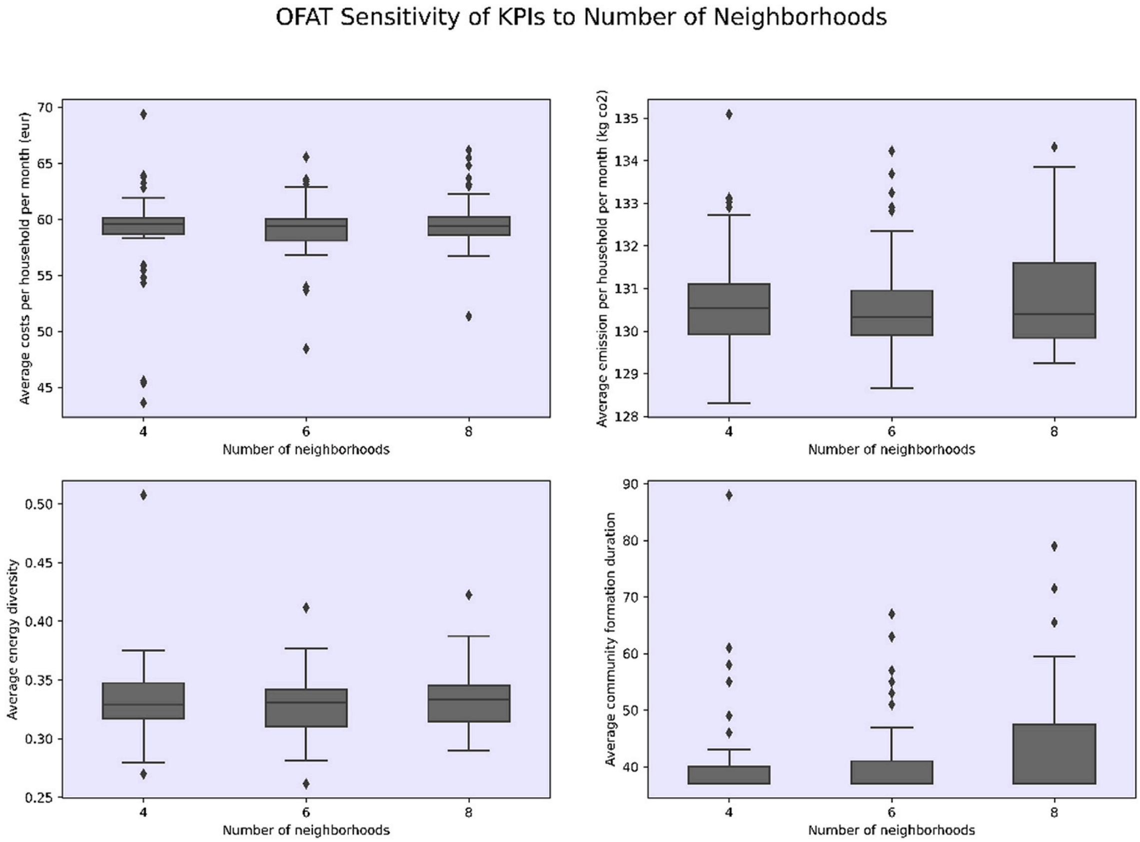
After 50 times simulation, boxplots were generated for each parameter for four chosen KPIs. The reason for selecting these four KPIs, the average cost per household per month, average emission per household per month, average energy diversity and average community formation duration, is to reduce computation time in this step while using four well known KPIs for assessing energy community performance. Fig. 8 presents OFAT sensitivity analysis results for the information exchange parameter.

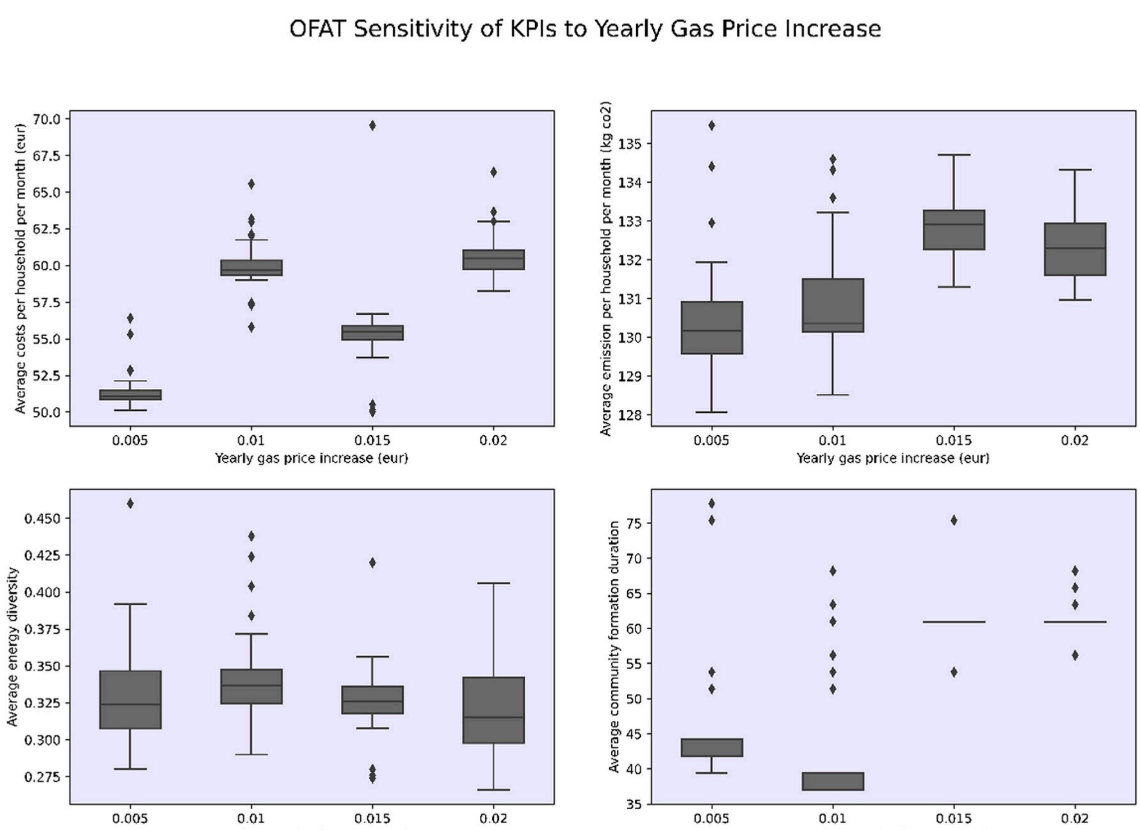

OFAT Sensitivity of KPIs to Duration of Information Exchange
Average costs per household per month (eur)
Average emission per household per month (kg co2)
Average energy diversity
Average community formation duration
Duration of information exchange

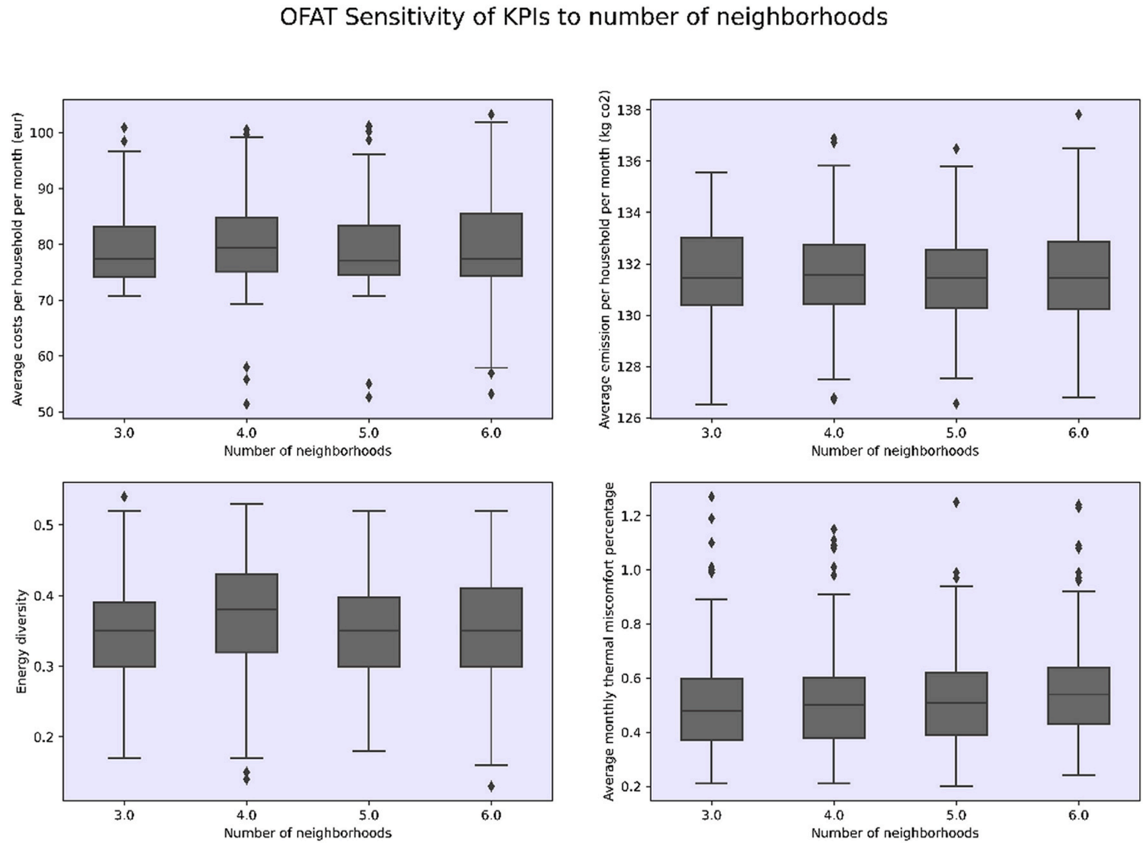

OFAT Sensitivity of KPIs to Neighborhood Size
Average costs per household per month (eur)
Average emission per household per month (kg co2)
Average energy diversity
Average community formation duration
Neighborhood size


OFAT Sensitivity of KPIs to Percentage Preference Reduction per SVO Level
Average costs per household per month (eur)
65
60
55
50
45
10
15
20
Percentage preference reduction per SVO level
Average emission per household per month (kg co2)
134
132
130
128
126
10
15
20
Percentage preference reduction per SVO level
Average energy diversity
0.75
0.70
0.65
0.60
0.55
10
15
20
Percentage preference reduction per SVO level
Average community formation duration
65
60
55
50
45
40
10
15
20
Percentage preference reduction per SVO level


OFAT Sensitivity of KPIs to Number of Connections each Household has
Average costs per household per month (eur)
65
60
55
50
45
2
3
4
Number of connections each household has
Average emission per household per month (kg co2)
135
134
133
132
131
130
2
3
4
Number of connections each household has
Average energy diversity
0.725
0.700
0.675
0.650
0.625
0.600
0.575
0.550
0.525
2
3
4
Number of connections each household has
Average community formation duration
65
60
55
50
45
40
2
3
4
Number of connections each household has


OFAT Sensitivity of KPIs to Number of Neighborhoods
Average costs per household per month (eur)
Average emission per household per month (kg co2)
Average energy diversity
Average community formation duration
Number of neighborhoods


OFAT Sensitivity of KPIs to Yearly Gas Price Increase
Average costs per household per month (eur)
Average emission per household per month (kg co2)
Average energy diversity
Average community formation duration
Yearly gas price increase (eur)



References

Abokersh, Mohamed Hany, Vallès, Manel, Cabeza, Luisa F., Boer, Dieter, 2020. A framework for the optimal integration of solar assisted district heating in different urban sized communities: a robust machine learning approach incorporating global sensitivity analysis. Appl. Energy 267, 114903. https://doi.org/10.1016/j.apenergy.2020.114903. November 2019.

Airaksinen, Miimu, Vuolle, Mika, 2013. Heating energy and peak-power demand in a standard and low energy building, 235–50. https://doi.org/10.3390/en6010235.

Ajzen, Icek, 1991. The theory of planned behavior. Organ. Behav. Hum. Decis. Process. 50 (2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T.

Alasinrin, Kazeem, Faizah, Fathin, Ghani, Nor, Ara, Rawshan, Mahmoud, Moamin A., 2021. Coherent or con fl icting ? assessing natural gas subsidy and energy ef fi ciency policy interactions amid CO 2 emissions reduction in Malaysia electricity sector. J. Clean. Prod. 279, 123374 https://doi.org/10.1016/j.jclepro.2020.123374.

Ang, B.W., Choong, W.L., Ng, T.S., 2015. Energy security: definitions, dimensions and indexes. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2014.10.064.

Bagrodia, Rajive L., Wen, Toh, Liao, 1994. Maisie: a language for the design of efficient discrete-event simulations. IEEE Trans. Software Eng. 20 (4), 225–238. https://doi.org/10.1109/32.277572.

Bartos, Jan, Robertson, Andrews, 2014. Energy Supply Security: Emergency Response of IEA Countries, vol. 606. International Energy Agency. https://www.iea.org/publications/freepublications/publication/energy-supply-security-the-emergency-response-of-iea-countries-2014.html%5Cnhttps://www.iea.org/publications/freepublications/publication/ENERGYSUPPLYSECURITY2014.pdf.

Bauwens, Thomas, 2016. Explaining the diversity of motivations behind community renewable energy. Energy Pol. 93, 278–290. https://doi.org/10.1016/j.enpol.2016.03.017.

Bauwens, Thomas, 2019. Analyzing the determinants of the size of investments by community renewable energy members: findings and policy implications from flanders. Energy Pol. 129 (March), 841–852. https://doi.org/10.1016/j.enpol.2019.02.067.

Bauwens, Thomas, Gotchev, Boris, Holstenkamp, Lars, 2016. What drives the development of community energy in europe? The case of wind power cooperatives. Energy Res. Social Sci. https://doi.org/10.1016/j.erss.2015.12.016.

Bellekom, Sandra, Arentsen, Maarten, Van Gorkum, Kirsten, 2016. Prosumption and the distribution and supply of electricity. Energy, Sustainability and Society 1–17. https://doi.org/10.1186/s13705-016-0087-7.

Berger, Christiane, Mahdavi, Ardeshir, 2020. Review of current trends in agent-based modeling of building occupants for energy and indoor-environmental performance analysis. Build. Environ. 173 (February), 106726 https://doi.org/10.1016/j.buildenv.2020.106726.

Bonabeau, Eric, 2002. Agent-based modeling: methods and techniques for simulating human systems. Proc. Natl. Acad. Sci. U. S. A 99, 7280–7287. https://doi.org/10.1073/pnas.082080899. SUPPL. 3.

Boon, Frank Pieter, Dieperink, Carel, 2014. Local civil society based renewable energy organisations in The Netherlands: exploring the factors that stimulate their emergence and development. Energy Pol. 69, 297–307. https://doi.org/10.1016/j.enpol.2014.01.046.

Broek, Machteld Van den, Paul, Veenendaal, Paul, Koutstaal, Turkenburg, Wim, Faaij, André, 2011. Impact of international climate policies on CO2 capture and storage deployment. Illustrated in the Dutch energy system. Energy Pol. https://doi.org/10.1016/j.enpol.2011.01.036.

Burli, Pralhad H., Nguyen, Ruby T., Hartley, Damon S., Griffel, L Michael, Vazhnik, Veronika, Lin, Yingqian, 2021. Farmer characteristics and decision-making : a model for bioenergy crop adoption. Energy 234, 121235. https://doi.org/10.1016/j.energy.2021.121235.

Busch, Jonathan, Roelich, Katy, Bale, Catherine S.E., Knoeri, Christof, 2017. Scaling up local energy infrastructure; an agent-based model of the emergence of district heating networks. Energy Pol. 100, 170–180. https://doi.org/10.1016/j.enpol.2016.10.011. October 2016.

Castro, Juana, Drews, Stefan, Exadaktylos, Filippos, Foramitti, Joël, 2020. A Review of Agent-Based Modeling of Climate-Energy Policy," No. https://doi.org/10.1002/wcc.647. March: 1–26.

Ceglia, F., Esposito, P., Marrasso, E., Sasso, M., 2020. From smart energy community to smart energy municipalities: literature review, agendas and pathways. J. Clean. Prod. 254, 120118 https://doi.org/10.1016/j.jclepro.2020.120118.

Correljé, Aad, Coby van der Linde, 2006. Energy supply security and geopolitics: a European perspective. Energy Pol. 34 (5), 532–543. https://doi.org/10.1016/j.enpol.2005.11.008.

Dénarié, A., Calderoni, M., Aprile, M., 2018. Multicriteria Approach for a Multisource District Heating. Green Energy and Technology, pp. 21–33 no. 9783319757735. https://doi.org/10.1007/978-3-319-75774-2_2.

Dóci, Gabriella, Vasileiadou, Eleftheria, 2015. 'Let's do it ourselves' individual motivations for investing in renewables at community level. Renew. Sustain. Energy Rev. 49, 41–50. https://doi.org/10.1016/j.rser.2015.04.051.

Dóci, Gabriella, Vasileiadou, Eleftheria, Petersen, Arthur C., 2015. Exploring the transition potential of renewable energy communities. Futures 66, 85–95. https://doi.org/10.1016/j.futures.2015.01.002.
Dreu, Carsten K W De, Boles, Terry L., 1998. Share and share alike or winner take all. The Influence of Social Value Orientation upon Choice and Recall of Negotiation Heuristics 76 (3), 253–276.
Dvarioniene, Jolanta, Gurauskiene, Inga, Gecevicius, Giedrius, Ruth Trummer, Dora, Selada, Catarina, Marques, Isabel, Cosmi, Carmelina, 2015. Stakeholders involvement for energy conscious communities: the energy labs experience in 10 European communities. Renew. Energy 75, 512–518. https://doi.org/10.1016/j.renene.2014.10.017, 2015.
Francés, Escribano, Gonzalo, José María, Marín-Quemada, Enrique San Martín González, 2013. RES and risk: renewable energy's contribution to energy security. A portfolio-based approach. Renew. Sustain. Energy Rev. 26, 549–559. https://doi.org/10.1016/j.rser.2013.06.015.
Fichera, Alberto, Pluchino, Alessandro, Volpe, Rosaria, 2020. From self-consumption to decentralized distribution among prosumers : a model including technological , operational and spatial issues. Energy Convers. Manag. 217 (May), 112932 https://doi.org/10.1016/j.enconman.2020.112932.
Filippidou, Faidra, and Nico Nieboer n.d. "Energy Efficiency Measures Implemented in the Dutch Non-profit Housing Sector.".
Filippidou, Faidra, Nieboer, Nico, Visscher, Henk, 2017. Are we moving fast enough ? the energy renovation rate of the Dutch non- pro fi t housing using the national energy labelling database. Energy Pol. 109 (December 2016), 488–498. https://doi.org/10.1016/j.enpol.2017.07.025.
Fouladvand, Javanshir, Aranguren, Maria, Hoppe, Thomas, Ghorbani, Amineh, 2021. Simulating thermal energy community formation : institutional enablers outplaying technological choice. Appl. Energy. https://doi.org/10.1016/j.apenergy.2021.117897. , no. xxxx: 117897.
Fouladvand, Javanshir, Ghorbani, Amineh, Mouter, Niek, Herder, Paulien, 2022. Analysing community-based initiatives for heating and cooling: a systematic and critical review. Energy Res. Social Sci. 88, 102507 https://doi.org/10.1016/j.erss.2022.102507.
Fouladvand, Javanshir, Mouter, Niek, Ghorbani, Amineh, Herder, Paulien, 2020. Community Systems : an Explorative Agent-Based.
Frey, H Christopher, Sumeet, R., Patil, 2002. Identification and Review of Sensitivity Analysis Methods" 22 (3).
Fulhu, Miraz, Mohamed, Muaviyath, Krumdieck, Susan, 2019. Voluntary demand participation (VDP) for security of essential energy activities in remote communities with case study in Maldives. Energy for Sustainable Development 49, 27–38. https://doi.org/10.1016/j.esd.2019.01.002.
Gagliardi, Francesca, 2008. Institutions and Economic Change : A Critical Survey of the New Institutional Approaches and Empirical Evidence" 37: 416–43. https://doi.org/10.1016/j.socec.2007.03.001.
Ghorbani, A., Ligtvoet, A., Nikolic, I., Dijkema, G., 2010. Using institutional frameworks to conceptualize agent-based models of socio-technical systems. In: Proceeding of the 2010 Workshop on Complex System Modeling and Simulation, vol. 3.
Ghorbani, Amineh, Nascimento, Leonardo, Filatova, Tatiana, 2020a. Energy research & social science growing community energy initiatives from the bottom up : simulating the role of behavioural attitudes and leadership in The Netherlands. Energy Res. Social Sci. 70, 101782 https://doi.org/10.1016/j.erss.2020.101782. March.
Ghorbani, Amineh, Nascimento, Leonardo, Filatova, Tatiana, 2020b. Growing community energy initiatives from the bottom up: simulating the role of behavioural attitudes and leadership in The Netherlands. Energy Res. Social Sci. 70, 101782 https://doi.org/10.1016/j.erss.2020.101782. March.
Gregg, Sterling, Jay, Nyborg, Sophie, Hansen, Meiken, Jana Schwanitz, Valeria, August, Wierling, Zeiss, Jan Pedro, Delvaux, Sarah, et al., 2020. Collective action and social innovation in the energy sector: a mobilization model perspective. Energies 13 (3). https://doi.org/10.3390/en13030651.
Hansen, Paula, Liu, Xin, Morrison, Gregory M., 2019. Energy research & social science agent-based modelling and socio-technical energy transitions : a systematic literature review. Energy Res. Social Sci. 49, 41–52. https://doi.org/10.1016/j.erss.2018.10.021. June 2018.
Heldeweg, Michiel A., Saintier, Séverine, 2020. Renewable energy communities as 'socio-legal institutions': a normative frame for energy decentralization? Renew. Sustain. Energy Rev. 119 https://doi.org/10.1016/j.rser.2019.109518. November 2019.
Hesselink, Laurens X.W., Chappin, Emile J.L., 2019. Adoption of energy efficient technologies by households – barriers , policies and agent-based modelling studies. Renew. Sustain. Energy Rev. 99 (September 2018), 29–41. https://doi.org/10.1016/j.rser.2018.09.031.
Hoekstra, N., Pellegrini, M., Bloemendal, M., Spaak, G., Andreu Gallego, A., Rodriguez Comins, J., Grotenhuis, T., et al., 2020. Increasing market opportunities for renewable energy technologies with innovations in aquifer thermal energy storage. Sci. Total Environ. 709, 136142 https://doi.org/10.1016/j.scitotenv.2019.136142. December 2019.
Hooimeijer, Fransje L., Puts, Hanneke, Geerdink, Tara, 2016. Successful Development of Decentralised District Heating Application of a Theoretical Framework Successful Development of Decentralised District Heating : Application of a Theoretical Framework. https://doi.org/10.19188/03JSSPSI052016.
Hooimeijer, Fransje, Tummers, Lidewij, 2017. Integrating subsurface management into spatial planning in The Netherlands, Sweden and flanders. Proc. Inst. Civ. Eng.: Urban Design and Planning 170 (4), 161–172. https://doi.org/10.1680/jurdp.16.00033.
Ilieva, Rositsa, Hernandez, Andreas, 2018. Scaling-up sustainable development initiatives: a comparative case study of agri-food system innovations in Brazil, New York, and Senegal. Sustainability 10 (11), 4057. https://doi.org/10.3390/su10114057.
Iychettira, Kaveri K., Hakvoort, Rudi A., Linares, Pedro, 2017. Towards a comprehensive policy for electricity from renewable energy : an approach for policy design. Energy Pol. 106, 169–182. https://doi.org/10.1016/j.enpol.2017.03.051. August 2016.
Jensen, Ida Græsted, Wiese, Frauke, Bramstoft, Rasmus, Münster, Marie, 2020. Potential role of renewable gas in the transition of electricity and district heating systems. Energy Strategy Rev. 27 (November 2019), 100446 https://doi.org/10.1016/j.esr.2019.100446.
Kastner, Ingo, Matthies, Ellen, 2016. Energy research & social science investments in renewable energies by German households : a matter of economics , social influences and ecological concern. Chem. Phys. Lett. 17, 1–9. https://doi.org/10.1016/j.erss.2016.03.006.
Kaundinya, Deepak Paramashivan, Balachandra, P., Ravindranath, N.H., 2009. Grid-connected versus stand-alone energy systems for decentralized power-A review of literature. Renew. Sustain. Energy Rev. 13 (8), 2041–2050. https://doi.org/10.1016/j.rser.2009.02.002.
Keppler, J.H., 2016. Climate change, security of supply and competitiveness: does europe have the means to implement its ambitious energy vision. The New Energy Crisis: Climate, Economics and Geopolitics 192–216.
Kester, Johannes, 2017. Energy security and human security in a Dutch gasquake context: a case of localized performative politics. Energy Res. Social Sci. https://doi.org/10.1016/j.erss.2016.12.019.
Koirala, Binod Prasad, Araghi, Yashar, Kroesen, Maarten, Ghorbani, Amineh, Hakvoort, Rudi A., Herder, Paulien M., 2018. Trust, awareness, and independence: insights from a socio-psychological factor Analysis of citizen knowledge and participation in community energy systems. Energy Res. Social Sci. 38 (January), 33–40. https://doi.org/10.1016/j.erss.2018.01.009.
Koirala, Binod Prasad, Koliou, Elta, Jonas, Friege, Hakvoort, Rudi A., Herder, Paulien M., 2016. Energetic communities for community energy: a review of key issues and trends shaping integrated community energy systems. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2015.11.080.
Lammers, Imke, Heldeweg, Michiel A., 2019. An empirico-legal analytical and design model for local microgrids: applying the 'iltiad' model, combining the iad-framework with institutional legal theory. Int. J. Commons 13 (1), 479–506. https://doi.org/10.18352/ijc.885.
Lammers, Imke, Hoppe, Thomas, 2018. Analysing the institutional setting of local renewable energy planning and implementation in the EU: a systematic literature review. Sustainability 10 (9). https://doi.org/10.3390/su10093212.
Lammers, Imke, Hoppe, Thomas, 2019. Watt rules? Assessing decision-making practices on smart energy systems in Dutch city districts. Energy Res. Social Sci. 47, 233–246. https://doi.org/10.1016/j.erss.2018.10.003. October 2018.
Lee, M., Hong, T., 2019. Hybrid agent-based modeling of rooftop solar photovoltaic adoption by integrating the geographic information system and data mining technique. Energy Convers. Manag. 183, 266–279.
Li, Kai, Ma, Minda, Xiang, Xiwang, Feng, Wei, Ma, Zhili, Cai, Weiguang, Ma, Xin, 2022. Carbon reduction in commercial building operations : a provincial retrospection in China. Appl. Energy 306, 118098. https://doi.org/10.1016/j.apenergy.2021.118098. PB.
Li, Yuan, Jin, Ming, Li, Yutong, 2017. Community energy system planning: a case study on technology selection and operation optimization. Procedia Eng. 205, 2076–2083. https://doi.org/10.1016/j.proeng.2017.10.100.
Ligtvoet, Andreas, Cuppen, Eefje, Di Ruggero, Olga, Hemmes, Kas, Pesch, Udo, Quist, Jaco, Mehos, Donna, 2016. New future perspectives through constructive conflict: exploring the future of gas in The Netherlands. Futures. https://doi.org/10.1016/j.futures.2016.03.008.
Liu, Wen, Klip, Diederik, Zappa, William, Jelles, Sytse, Kramer, Gert Jan, van den Broek, Machteld, 2019. The marginal-cost pricing for a competitive wholesale district heating market: a case study in The Netherlands. Energy 189, 116367. https://doi.org/10.1016/j.energy.2019.116367.
Magnusson, Dick, 2016. Who brings the heat? – from municipal to diversified ownership in the Swedish district heating market post-liberalization. Energy Res. Social Sci. 22, 198–209. https://doi.org/10.1016/j.erss.2016.10.004.
Magnusson, Dick, Palm, Jenny, 2019. Come together-the development of Swedish energy communities. Sustainability 11 (4), 1–19. https://doi.org/10.3390/su11041056.
Mahmood, Imran, Mobeen, Mahe, Anis Ur, Younis, Shahzad, 2020. Modeling , simulation and forecasting of wind power plants using agent-based approach. J. Clean. Prod. 276, 124172 https://doi.org/10.1016/j.jclepro.2020.124172.
Majcen, D., Itard, L.C.M., Visscher, H., 2013. Theoretical vs. Actual energy consumption of labelled dwellings in The Netherlands: discrepancies and policy implications. Energy Pol. 54, 125–136. https://doi.org/10.1016/j.enpol.2012.11.008.
Majcen, Daša, Itard, Laure, 1947. Energy Labels in Dutch Dwellings – Their Actual Energy Consumption and Implications for Reduction Targets, pp. 1947–1952.
Masson-Delmotte, V., Portner, H.O., Roberts, D., 2018. IPCC Global Warming of 1.5 C. Ipcc. https://doi.org/10.1017/CBO9781107415324.004.
Matsumoto, Ken'ichi, Doumpos, Michalis, Andriosopoulos, Kostas, 2018. Historical energy security performance in EU countries. Renew. Sustain. Energy Rev. 82, 1737–1748. https://doi.org/10.1016/j.rser.2017.06.058. December 2016.
Mavromatidis, Georgios, Orehounig, Kristina, Jan, Carmeliet, 2018. A review of uncertainty characterisation approaches for the optimal design of distributed energy systems. Renew. Sustain. Energy Rev. 88 (February), 258–277. https://doi.org/10.1016/j.rser.2018.02.021.
McGinnis, Michael D., 2011. An introduction to IAD and the language of the Ostrom workshop: a simple guide to a complex framework. Pol. Stud. J. https://doi.org/10.1111/j.1541-0072.2010.00401.x.

Mckenna, R., Bertsch, V., Mainzer, K., Fichtner, W., 2018. Combining local preferences with multi-criteria decision analysis and linear optimization to develop feasible energy concepts in small communities. Eur. J. Oper. Res. 268 (3), 1092–1110. https://doi.org/10.1016/j.ejor.2018.01.036.

Milchram, Christine, Märker, Carolin, Friedrich Hake, Jürgen, 2019. The role of values in analyzing energy systems: insights from moral philosophy, institutional economics, and sociology. Energy Proc. 158, 3741–3747. https://doi.org/10.1016/j.egypro.2019.01.882.

Mittal, A., Krejci, C.C., Dorneich, M.C., Fickes, D., 2019. An agent-based approach to modeling zero energy communities. Sol. Energy 191, 193–204. https://doi.org/10.1016/j.solener.2019.08.040.

Mittal, Anuj, Krejci, Caroline C., Dorneich, Michael C., Fickes, David, 2019. An agent-based approach to modeling zero energy communities. Sol. Energy 191, 193–204. https://doi.org/10.1016/j.solener.2019.08.040 (December 2018.

Moncada, J.A., Tao, Z., Valkering, P., Meinke-hubeny, F., Delarue, E., 2021. Influence of distribution tariff structures and peer effects on the adoption of distributed energy resources. Appl. Energy 298, 117086. https://doi.org/10.1016/j.apenergy.2021.117086. June.

Morris, Jason, 2013. The evolving localism (and neoliberalism) of urban renewable energy projects. Culture, Agriculture, Food and Environment 35 (1), 16–29. https://doi.org/10.1111/cuag.12002.

Mujuru, Munyaradzi, Dube, Timothy, Mabizela, Hlengiwe, Ntuli, Ntombifuthi, 2020. Evaluating greenhouse gas emission reductions by using solar water heaters: a case of low income households in ekurhuleni, South Africa. Phys. Chem. Earth. https://doi.org/10.1016/j.pce.2020.102843. March 2019: 102843.

Murphy, Ryan O., Ackermann, Kurt A., 2014. Social Value Orientation : Theoretical and Measurement Issues in the Study of Social Preferences. https://doi.org/10.1177/1088868313501745.

Murphy, Ryan O., Ackermann, Kurt A., Handgraaf, Michel J.J., 2011. Measuring Social Value Orientation" 6, pp. 771–781 (8).

Nikolic, Igor, Ghorbani, Amineh, 2011. A Method for Developing Agent-Based Models of Socio-Technical Systems A Method for Developing Agent-Based Models of Socio-Technical. https://doi.org/10.1109/ICNSC.2011.5874914. May 2014.

Osman, N., 2017. Barriers to district heating development in The Netherlands. A Business Model Perspective 1–108.

Ostrom, Elinor, 2011. Background on the institutional analysis and development framework. Pol. Stud. J. 39 (1), 7–27. https://doi.org/10.1111/j.1541-0072.2010.00394.x.

Ostrom, Elinor, 2014a. Collective action and the evolution of social norms. J. Nat. Resour. Pol. Res. 6 (4), 235–252. https://doi.org/10.1080/19390459.2014.935173.

Ostrom, Elinor, 2014b. Do institutions for collective action evolve? J. Bioecon. 16 (1), 3–30. https://doi.org/10.1007/s10818-013-9154-8.

Oteman, Marieke, Wiering, Mark, Kees Helderman, Jan, 2014. The institutional space of community initiatives for renewable energy: a comparative case study of The Netherlands, Germany and Denmark. Energy, Sustainability and Society 4 (1). https://doi.org/10.1186/2192-0567-4-11.

Ouyang, Min, 2014. Review on modeling and simulation of interdependent critical infrastructure systems. Reliab. Eng. Syst. Saf. 121, 43–60. https://doi.org/10.1016/j.ress.2013.06.040.

Pacesila, Mihaela, Gabriel Burcea, Stefan, Elena Colesca, Sofia, 2016. Analysis of renewable energies in European union. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2015.10.152.

Pahl, Sabine, Harris, P.R., Todd, Helen A., Rutter, D.R., 2005. Comparative Optimism for Environmental Risks" 25: 1–11. https://doi.org/10.1016/j.jenvp.2004.12.004.

Perlaviciute, Goda, Steg, Linda, Hoekstra, Elisabeth J., Vrieling, Leonie, 2017. Perceived Risks, Emotions, and Policy Preferences: A Longitudinal Survey Among the Local Population on Gas Quakes in the Netherlands. Energy Research and Social Science. https://doi.org/10.1016/j.erss.2017.04.012.

Poggi, Francesca, Firmino, Ana, Amado, Miguel, 2020. Shaping energy transition at municipal scale: a net-zero energy scenario-based approach. Land Use Pol. 99, 104955 https://doi.org/10.1016/j.landusepol.2020.104955. April 2019.

Radovanović, Mirjana, Filipović, Sanja, Pavlović, Dejan, 2017. Energy security measurement – a sustainable approach. Renew. Sustain. Energy Rev. 68, 1020–1032. https://doi.org/10.1016/j.rser.2016.02.010.

Rai, Varun, Robinson, Scott A., 2015. Agent-based modeling of energy technology adoption: empirical integration of social, behavioral, economic, and environmental factors. Environ. Model. Software 70, 163–177. https://doi.org/10.1016/j.envsoft.2015.04.014.

Railsback, Steven F., Grimm, Volker, 2012. Agent-Based and Individual-Based Modeling: A Practical Introduction. Princeton University Press, Princeton.

Ranjan, Ashish, Hughes, Larry, 2014. Energy security and the diversity of energy flows in an energy system. Energy 73, 137–144. https://doi.org/10.1016/j.energy.2014.05.108.

Rees, Marc T., Wu, Jianzhong, Awad, Bieshoy, Ekanayake, Janaka, Jenkins, Nick, 2011. A Total Energy Approach to Integrated Community Infrastructure Design. IEEE Power and Energy Society General Meeting. https://doi.org/10.1109/PES.2011.6038976.

Reyes, René, Nelson, Harry, Navarro, Fabian, Retes, Constantino, 2015. The firewood dilemma: human health in a broader context of well-being in Chile. Energy for Sustainable Development 28, 75–87. https://doi.org/10.1016/j.esd.2015.07.005.

Rezaie, Behnaz, Rosen, Marc A., 2012. District heating and cooling: review of technology and potential enhancements. Appl. Energy 93, 2–10. https://doi.org/10.1016/j.apenergy.2011.04.020.

Roch, Sylvia G., John A, S Lane, Charles, D Samuelson, Scott, T Allison, Jennifer, L Dent, 2000. Cognitive load and the equality heuristic : a two-stage model of resource overconsumption in small groups" 83. https://doi.org/10.1006/obhd.2000.2915, 2,185-212.

Rostampour, Vahab, 2019. Aquifer thermal energy storage (ATES) smart grids : large-scale seasonal energy storage as a distributed energy management solution. Appl. Energy 242 (March), 624–639. https://doi.org/10.1016/j.apenergy.2019.03.110.

Sadiq, Rehan, Karunathilake, Hirushie, Hewage, Kasun, 2019. Renewable Energy Selection for Net-Zero Energy Communities : Life Cycle Based Decision Making under Uncertainty" 130: 558–73. https://doi.org/10.1016/j.renene.2018.06.086.

Schouten, Marleen, Tim Verwaart, Heijman, Wim, 2014. Environmental modelling & software comparing two sensitivity analysis approaches for two scenarios with a spatially explicit rural agent-based model. Environ. Model. Software 54, 196–210. https://doi.org/10.1016/j.envsoft.2014.01.003.

Schram, Wouter, Louwen, Atse, Lampropoulos, Ioannis, Van Sark, Wilfried, 2019. Comparison of the greenhouse gas emission reduction potential of energy communities. Energies 12 (23), 1–23. https://doi.org/10.3390/en12234440.

Sleutjes, B., Valk, H.A.G. De, Ooijevaar, J., 2018. The measurement of ethnic segregation in the Netherlands: differences between administrative and individualized neighbourhoods. Eur. J. Popul. 34 (2), 195–224. https://link.springer.com/article/10.1007/s10680-018-9479-z.

Sokolnikova, P., Lombardi, P., Arendarski, B., Suslov, K., Pantaleo, A.M., Kranhold, M., Komarnicki, P., 2020. Net-zero multi-energy systems for siberian rural communities: a methodology to size thermal and electric storage units. Renew. Energy 155, 979–989. https://doi.org/10.1016/j.renene.2020.03.011.

Sovacool, Benjamin K., 2010. Introduction: defining, measuring, and exploring energy security. In: The Routledge Handbook of Energy Security, pp. 19–60. Routledge.

Sun, Zhaohui, Ma, Zhili, Ma, Minda, Cai, Weiguang, Xiang, Xiwang, Zhang, Shufan, Chen, Minxia, Chen, Liming, 2022. Carbon Peak and Carbon Neutrality in the Building Sector : A Bibliometric Review.

Tsoutsos, Theocharis, Drandaki, Maria, Frantzeskaki, Niki, Iosifidis, Eleftherios, Kiosses, Ioannis, 2009. Sustainable Energy Planning by Using Multi-Criteria Analysis Application in the Island of Crete" 37: 1587–1600. https://doi.org/10.1016/j.enpol.2008.12.011.

Turton, Hal, Barreto, Leonardo, 2006. Long-term security of energy supply and climate change. Energy Pol. 34 (15), 2232–2250. https://doi.org/10.1016/j.enpol.2005.03.016.

Verhoog, Reinier, Ghorbani, Amineh, Gerard, P., Dijkema, J., 2016. Modelling socio-ecological systems with maia: a biogas infrastructure simulation. Environ. Model. Software 81, 72–85. https://doi.org/10.1016/j.envsoft.2016.03.011.

Vitéz, Blanka, Lavrijssen, Saskia, 2020. The energy transition: democracy, justice and good regulation of the heat market. Energies 13 (5). https://doi.org/10.3390/en13051088.

Vries, Laurens De, 2021. Making the Most of Short-Term Flexibility in the Balancing Market : Opportunities and Challenges of Voluntary Bids in the New Balancing Market Design" 158. https://doi.org/10.1016/j.enpol.2021.112522.

Vuichard, P., Stauch, A., Dällenbach, N., 2019. Individual or collective? Community investment, local taxes, and the social acceptance of wind energy in Switzerland. Energy Res. Social Sci. 58 (January), 101275 https://doi.org/10.1016/j.erss.2019.101275.

Walker, Gordon, Devine-Wright, Patrick, 2008. Community renewable energy: what should it mean? Energy Pol. 36 (2), 497–500. https://doi.org/10.1016/j.enpol.2007.10.019.

Watts, Duncan J., Strogatz, Steven H., 1998. Collective dynamics of small-WorldNetworks. Nature 393, 440–442.

Wildt, T E De, Chappin, E J L, Van De Kaa, G, Herder, P.M., Van De Poel, I.R., 2020. Energy research & social science conflicted by decarbonisation : five types of conflict at the nexus of capabilities and decentralised energy systems identified with an agent-based model. Energy Res. Social Sci. 64, 101451 https://doi.org/10.1016/j.erss.2020.101451. January.

Wildt, Tristan E., Boijmans, AnneR., Chappin, Emile J.L., Herder, PaulienM., 2021. An ex ante assessment of value conflicts and social acceptance of sustainable heating systems an agent-based modelling approach. Energy Pol. 153, 112265 https://doi.org/10.1016/j.enpol.2021.112265. March.

Wilensky, Uri, Rand, William, 2015. An Introduction to Agent-Based Modeling. The MIT Press. https://doi.org/10.2307/j.ctt17kk851.

Wirth, Timo Von, Gislason, Linda, Seidl, Roman, 2017. Distributed Energy Systems on a Neighborhood Scale: Reviewing Drivers of and Barriers to Social Acceptance. https://doi.org/10.1016/j.rser.2017.09.086.

Young, Jasminka, Brans, Marleen, 2017. Analysis of factors affecting a shift in a local energy system towards 100% renewable energy community. J. Clean. Prod. 169, 117–124. https://doi.org/10.1016/j.jclepro.2017.08.023.

Zhang, Shufan, Ma, Minda, Li, Kai, Ma, Zhili, Feng, Wei, Cai, Weiguang, 2022. Historical carbon abatement in the commercial building operation : China versus the US. Energy Econ. 105 (November 2021), 105712 https://doi.org/10.1016/j.eneco.2021.105712.