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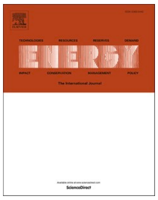

Behavioural attributes towards collective energy security in thermal energy communities: Environmental-friendly behaviour matters

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ABSTRACT

Community energy systems as decentralized and collective renewable energy systems, where the energy is jointly generated and distributed among a community of households, are gaining momentum. The collective action of individual households as a core characteristic of such energy systems influences the energy availability, energy costs, and eventually, their energy security. This study investigates the influence of individual households' behavioural attributes on the energy security of such collective energy systems. An agent-based model was built based on the following energy security dimensions: availability, affordability, accessibility and acceptability, referred to as the 4A's concept. The research focused on thermal energy communities given the considerable share of thermal energy applications, such as heating, cooling, and hot tap water. The simulation results demonstrated that such communities could cost around 1250 €/year while reducing their CO_2 emissions by 50% on average. Environmentally friendly behaviour leads to higher energy security performances. Such behaviours considerably influence the technical configurations while contributing positively to affordability and acceptability dimensions of collective energy security of thermal energy systems. Furthermore, the investment size of individual households was found to be the most influential parameter for energy security performances, while natural gas prices were identified as the least impactful parameter.

1. Introduction

Community energy systems (CESs) (also referred to as energy communities) are considered key elements of the energy transition at the local level [1]. Although there are different definitions of CESs in literature (as presented in [2,3]), as an overarching term, all definitions define a CES based on the collective action of participants (i.e. individual households) to generate, distribute and consume renewable energy resources (RECs) [4,5].

As collective action is one of the main CESs characteristics, various studies explore behavioural attributes, motivations and the decision-making process of participants (e.g. [6–8]). For instance [9], studies the influence of values on assessments and evaluations of different renewable energy technologies (RETs). In a broader energy transition context, behavioural economics is used to understand consumer decision-making and behaviour for energy consumption [10]. Behavioural patterns and user profiles related to energy consumption for heating are explored in [11]. The influence of behavioural and socio-economic factors on households' energy consumption is investigated in [12]. Other studies, such as [13,14], study the behaviour and values of households concerning energy consumption. Notably, the influence of households' environmentally friendly behaviour on greenhouse gas emissions and climate change mitigation in the residential sector is also investigated (e.g. [15,16]).

Few studies employ agent-based modelling and simulation (ABMS) to explore individuals' behavioural attributes and collective action towards establishing and functioning CESs within this branch of literature. Studies such as [17] explore different factors, including behavioural attitudes for adopting RETs, particularly solar photovoltaic (Solar PV). A multi-agent model to analyse the energy-saving behaviour of urban residents in China is presented in [18]. Particularly, Ghorbani and her colleagues in [19] explore the role of behaviour and leadership in CESs' emergence in the Netherlands. Along with technical and institutional conditions, participants' behaviour in successfully establishing thermal

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Abbreviations: CESs, Community energy systems; TECs, Thermal energy communities; RECs, Renewable energy resources; RETs, Renewable energy technologies; ATES, Aquathermal energy storage; ABMS, Agent-based modelling and simulation; SVO, Social value orientation; BRT, Behavioural reasoning theory.

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energy communities is explored in [4]. Consumers' behaviour and the demand side of the energy system are discussed in [20]. The model presented in [21] focuses on prosumers' behaviour, including technological and spatial constraints. A model for analysing urban energy networks is also studied in [22]. [23] explores energy exchange between prosumers and consumers to observe how the presumption affects the self-consumption of a neighbourhood. Although various models and studies are available, none of them modelled the collective energy security of CESs, except [24], which presents a conceptual ABMS.

Energy security is a crucial consideration for any energy system [25]. Among many definitions (as presented in [26]), 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" [27]. With this definition, APERC suggests the "4A's concept" to measure energy security, i.e. availability, affordability, accessibility and acceptability. Within energy security literature, few studies, such as [28,29], investigated CESs' energy security. The security of supply of a CES based on solar photovoltaic (solar PV) and battery storage is explored [30]. A framework was developed and tested in [31] for analysing distributed energy systems, including their supply security. Different dimensions of energy security, particularly within distributed biofuel-based energy systems, are studied in [32]. The notion of voluntary demand participation (including voluntary shortage) for the energy security of off-grid communities is the focus of [33]. Topics such as supply security in assessing distributed energy systems under uncertainties are included [34]. The scheduling and integration of energy systems within CESs by employing optimisation approaches are also investigated in this literature (e.g. [35,36]).

In this line, studies such as [37,38] argued that energy security concerns become more crucial in the context of CESs, as CESs are based on RECs and individuals' collective action. Particularly, energy may not always be available and accessible at all times due to the collective generation, distributed energy infrastructure and RETs' intermittent nature [37,39]. The affordability of such collective energy systems may also be undermined given the factors such as large upfront investment costs [40]. Therefore, in this context, the behavioural attributes of participants are a crucial consideration, as CESs could potentially reduce the vulnerabilities of individual households [41,42]. However, no study investigates the influence of behavioural attributes and their related trade-offs on the multi-dimensional energy security of such collective energy systems.

To address this research gap, this study aims to explore how the behavioural attributes of CESs participants influence collective energy security by employing ABMS. Given the collective action nature of CESs and the importance of individual characteristics, behavioural attributes and decision-making processes, the research uses ABMS instead of other simulation approaches such as Equilibrium Modelling [43], System Dynamics [44], and Discrete Event Simulations [45] that focus on system processes and outcomes. Building the model based on the 4A's energy security concept [27] allows exploring different dimensions of energy security within such a collective energy system. To address the research objective concretely, the focus of this study is narrowed to a particular type of CESs, namely thermal energy communities (TECs). TEC initiatives focus on providing collective renewable energy for thermal applications, such as heating, cooling, bathing, showering and cooking [4]. As TEC initiatives have received little attention within CESs literature [46], the current study could potentially provide an opportunity to investigate such systems further. The study particularly includes different thermal renewable energy technologies to address the thermal energy supply within CESs. Therefore, this study would also foster the local thermal energy transition and ultimately contribute to establishing and functioning real-world energy-secure (thermal) energy communities. To summarize, the study adds to the energy literature by investigating the impact of behavioural attributes of participants on collective energy security of particular collective energy systems, namely TEC initiatives.

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

2. Theoretical background

This section introduces the theories used as the backbone of our modelling exercise. The 4A's energy security concept [47] is used for conceptualising and investigating energy security. While the Social Value Orientation (SVO) theory [48] for structuring the behavioural attributes and motivations of individuals, the Behavioural Reasoning Theory [49] supports the understanding of how these behavioural attributes and motivations relate to each other.

2.1. 4A's energy security concept

The 4A's concept includes availability, affordability, accessibility and acceptability as dimensions of energy security [50].

- ❖ **Availability** is about the physical existence of the energy resources to be used for the energy system [25]. Various indicators in the literature measure the availability dimension, such as domestic energy generation per capita of an energy system [50] and shortage percentage, which occurs when there is a mismatch in demand-supply and individuals are disconnected from energy supplies [51].
- ❖ **Affordability** is related to the costs of an energy system and whether it is affordable or not for its stakeholders [50]. Energy price is the most common indicator for measuring the affordability of an energy system [25]. However, other indicators, including the size of investments made to improve energy security and willingness to pay [25], are other affordability indicators.
- ❖ **Accessibility** can be defined as having sufficient access to available and useable energy sources to promote an equal society [50]. Among various accessibility indicators, diversity is the most commonly used indicator in the literature [25]. Diversity quantifies the variety of energy sources to eliminate supply risks and make energy accessible [25]. Multiple integrated diversity indicators are presented in the literature, such as the Shannon index [25].
- ❖ **Acceptability** refers to the public perception and support towards energy sources [25], which is often linked to societal elements such as social welfare and environmental issues [52]. In this context, indicators such as the CO_2 emission of an energy system [25] and investments for switching away from fossil fuels are presented to measure an energy system's acceptability [50].

There are various energy security concepts (as presented in [26,52]), and studies such as [53,54] used an energy security concept other than 4A's concept to assess the energy security of an energy system. However, 4A's energy security concept is the most well-known and frequently used concept [47] and is a starting point of contemporary energy security studies [55]. Furthermore, it provides room to capture the collective nature and decentralized characteristics of CESs [24]. Therefore, 4A's energy security is selected as the core definition of energy security for this modelling exercise to be the starting point of the studies around collective energy security. Further reflection on this choice is presented in Section 6.1.

2.2. Social Value Orientation (SVO) theory

Social Value Orientation (SVO) theory particularly investigates the motivations and concerns of individuals when they make decisions [48]. "Within the SVO theory, it is assumed that people vary in their motivations or goals when evaluating different resource allocations between themselves and another person" [56]. SVO theory explores motivations and provides measurement tools for studying them [56], which is done by grouping individuals based on their internal values and hypothesising the relationship between these groups and their motivations with specific behaviours under study [57]. Thus, SVO theory classifies individuals' personalities based on four groups considering pro-self versus pro-social orientations [56]:

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

Such classification is highly instrumental in understanding and investigating individuals' motivations and concerns in decision-making. Even though SVO theory has traditionally been applied in the domain of negotiation settings and resource dilemmas (e.g. [58,59]), it has been lately used in the environmental behaviour domain (e.g. [60,61]) and behaviour studies in energy domain (e.g. [19,62,63]). The calculations related to SVO types are presented in Equation (1), in Section 4.2.

2.3. Behavioural Reasoning Theory (BRT)

The Behavioural Reasoning Theory (BRT) is used to structure and study how actors make decisions and behave [49,64] by theorising that attitudes are a vital antecedent of the adoption of behavioural intentions [49]. BRT postulates that intentions are strong predictors of behaviour [7], as presented in Fig. 1. In addition to addressing values and beliefs, BRT also includes context-specific reasons (for and against) as a critical predictor of particular attitudes and, therefore, of the final decision [49,65].

Such an approach allows incorporating the fact that although values are a significant predictor of behaviour, individuals also rationally evaluate reasons for and against adoption, which may influence their final attitude towards a decision [49]. This is especially relevant for expensive and high-involvement products such as renewable energy technologies [66]. Therefore, there are several studies in the context of the energy transition that employ BRT to analyse the deployment of RET (e.g. [7,67,68]). Additionally [4], investigates the technical and institutional conditions for establishing TEC initiatives using BRT.

In the present study, three elaborated theoretical approaches are used as a backbone of the modelling conceptualisation. 4A's energy security concept is employed to conceptualise and study the collective energy security of TEC initiatives. SVO theory is used to capture individual households' strategic behaviours, and BRT is employed to capture the values, reasons and attitudes of individuals participating in energy-secure TEC initiatives. By building the ABM model on the theoretical grounding provided in this section, the research aims to study and analyse how behavioural attributes influence collective energy security. Secondly, the research provides further insights into the establishment processes of the TEC initiatives. Thirdly, it provides recommendations on the behavioural attributes required to foster the establishment of energy-secure TEC initiatives.

3. Research approach

This section briefly introduces the main functions of agent-based modelling and simulation (ABMS) and presents the experimental settings and the Netherlands as our modelling exercise's contextual setup.

3.1. Agent-based modelling and simulation (ABMS)

Like other modelling practices, ABMS represents a simplified version of reality, easing the research while breaking free of the constraints imposed by the need to obtain analytical solutions and mathematical formulations [69,70]. In an ABMS, "An agent is the software representation of some entity that completes an action or takes a decision, by which it effectively interacts with its environment" [71]. Agents are heterogeneous, autonomous and individual decision-making entities (such as individual households) that can learn and interact with each other and their environment [72,73]. In addition, to studying and capturing behavioural attributes and choices of individuals, using ABMS also provides the opportunity to explore the emergent behaviour of the system [69]. Therefore, ABMS would help study different complexity levels (e.g. macro-level and meso-level). Moreover, ABMS allows adding the time variable, which allows examining different energy security scenarios under different input settings [69,70]. Therefore, ABMS is considered a suitable approach for studying the behavioural attributes, dynamics and interactions within energy-secure TEC initiatives.

3.2. Experimental setting and contextual data

To parameterize the ABMS, delineate reliable results and derive practical recommendations, the model was populated based on real-world data. In particular, the Netherlands was selected as the country to study the collective energy security of TEC initiatives because of the following reasons:

- Presence of a high number of energy communities as compared to other EU countries [74];
- Presence of well-developed energy and specifically heating infrastructure [75];
- Dutch national ambitious CO_2 reduction targets which influenced the heating sector [76];
- National norms for environmental concerns and sustainable development [77,78];

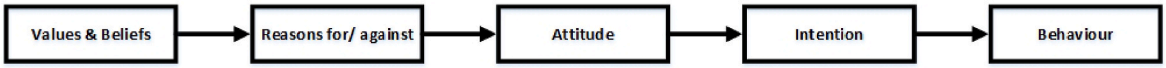


Fig. 1. BRT [49].

- ❖ Historically strong energy security performance of the Netherlands [79], and the importance of energy security in the Dutch energy policy debates [80,81];

Furthermore, topics such as gas quakes [82] and energy geopolitics [83], and energy prices [84,85] contribute to the importance of energy security within the Dutch thermal energy context. Therefore, the Netherlands provides a unique context to study the energy security of TEC initiatives. The data from Netherlands Environmental Assessment Agency (PBL), “Stimuleringsregeling Duurzame Energie” (SDE++), and Statistics Netherlands (CBS) are used to parameterize the model, including information on available renewable technologies, policy mechanisms and energy demand (e.g. [86]).

In order to investigate the impact of behavioural attributes and institutional conditions on the collective energy security of TEC initiatives by using SVO types (see Sections 2.2. and 4.2.), the experiment settings are designed in two experimental batches as follows:

- ❖ **First batch: more environmental-friendly batch:** In the first batch, the model was populated based on the Dutch data on households’ internal motivations (i.e. energy independence, trust, environmental concern and economic benefits). This was done using data from a survey among 599 Dutch citizens about their motivations for joining an energy community [8]. Therefore, the SVO types (see Sections 2.2. and 4.2.), interactions and decision-making processes (see Section 4.4.) are calculated based on Dutch behavioural attributes.
- ❖ **Second batch: less environmental-friendly batch:** The model was populated based on random households’ internal motivations as a second batch. Therefore, the SVO types, interactions and decision-making processes are based on the random input data, different from the first batch.

4. Model conceptualisation

This section describes the model conceptualisation and implementation using the ODD protocol [87].

4.1. Modelling purpose

The purpose of the model is to explore individuals’ behavioural attributes on collective energy security of TEC initiatives. This is done by investigating the impact of behavioural attributes and various parameters (see Section 4.7.) on the energy security of TEC initiatives.

4.2. Entities and state variables

Households are the only agents in the model. Following studies such as [4,8,88], and [89], the households’ internal motivations taken into account are energy independence, trust, environmental concern and economic benefits. These four internal motivations have a value between 0 and 10 (0 weakest, 10 strongest). Preferences of their neighbours can influence these internal motivations of households (see Section 4.3.). In order to capture the households’ internal motivations and categorise the decision-making processes based on their personality type, following [8,90], SVO theory (see Section 2.2.) is used. The SVO-type of the individual households is calculated as follows in Equation (1):

- ❖ If level of motivation >1: SVO-type 1 (i.e. Altruistic),
- ❖ If level of motivation < -1: SVO-type 3 (i.e. Individualistic),
- ❖ If level of motivation ≥ -1 and ≤ 1, and, sense of community <5: SVO-type 4 (i.e. Competitive),
- ❖ If level of motivation ≥ -1 and ≤ 1, and, sense of community ≥ 5: SVO-type 2 (i.e. Cooperative).

It is assumed that these agents are in one neighbourhood and have already decided to join a TEC initiative at the start of the simulation. Being a member of the TEC initiative means the households have three energy choices, namely:

- ❖ **Natural gas grid:** The assumption is that households use natural gas before joining a TEC initiative. If their selected collective renewable thermal energy does not fully cover their energy demand, they can potentially continue to consume natural gas.
- ❖ **Collective renewable thermal energy:** The collective renewable thermal energy generation technology options included in the model are biogas heaters and aquifer thermal energy systems (ATES).
- ❖ **Individual renewable thermal energy generation:** The individual renewable thermal energy generation options are heat pumps and small bioenergy heaters (i.e. wood pallet based).

The reasons for including these energy choices in this study are: (i) as mentioned in [4], they are among the key sustainable heat sources for the Netherlands that Heat Expertise Centrum (ECW) has identified, (ii) they are alternatives that are currently more readily available and dominating sustainable thermal technologies, and (iii) they fit well with the scope and scale of the model, community energy systems in a neighbourhood size thermal systems, and they are already used or tested successfully.

Lastly, the attributes of the households are energy demand, budget and internal motivations that change during the simulation based on their network (see Sections 4.3. and 4.4.). The technological option for distribution is medium-temperature district heating.

4.3. Interactions, network and adaptation

In the model, it is assumed that individual households are connected by a small-world network [91], commonly used in the context of CESs (e.g. [4,19,92]). In each tick (representing a month), a random household interacts and influences other households in its social network. If the household’s internal motivations (i.e. energy independence, trust, environmental concern and economic benefits) are between 2 and 8 (i.e., the values are not extreme and hard to change [4,19]), they will be updated, leaning one value towards the interacting neighbour’s opinion, for better or worse. This form of social interaction is used at the beginning of each simulation step to update the internal motivations of each agent. If the internal motivations are lower than 2 or higher than 8 (i.e., the values are extreme), the individual households will not change their own values during the interactions.

4.4. Model initialisation and narrative

Before joining a TEC initiative, it is assumed that the households (i.e. agents) use natural gas to cover their heating demand. After joining a TEC initiative, the households first go through a period of information

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

exchange, which means connected individual households learn more about their neighbours' internal motivations and possibly grow more towards each other. The period of information exchange is based on social interactions presented in Section 4.3. After the period of information exchange, households have four decisions to make, namely: (i) Selecting the collective thermal renewable energy (i.e. biogas heaters or ATES), (ii) the percentage that they want to generate collectively together (0%–100% of the whole CES′ demand), (iii) Selecting the additional individual thermal energy (i.e. natural gas grid, heat pump, wood pallet), in case the collective renewable generation does not fully cover the demand, and (iv) after the technology reaches its lifetime, involving new participants and deciding on continuing participating and new a TEC initiative. The processes of these four decisions are as follows:

- Based on their internal motivations and SVO-type, households first select collective thermal renewable energy (i.e. biogas heaters or ATES). More environmental friendly households select ATES, while biogas heater is the choice of more economically driven households.
- Then households select the percentage that they want to generate collectively together. The households select a fraction between 0%–100% of the whole community demand to be covered by collective renewable thermal energy generation. In this selection, more environmental-friendly households (i.e. SVO 1 and 2) select higher collective renewable energy generation. The constraint, however, is in the initial investment, as higher collective renewable energy generation needs higher investment. Each household will make an individual decision about its preferred percentage of collective renewable energy. The percentage selected the most among the households is for the whole community.
- When the selected percentage of collective renewable thermal energy generation does not fully cover all the community demand, the households depending on their motivations, have three options: (i) import energy from the grid (i.e. continue to consume natural gas, (ii) selecting an individual renewable thermal energy (i.e. heat pump or wood pallet), and (iii) compensate their energy demand (i.e. lowering the demand and facing discomfort). The decision-making about this choice is as follows: If an agent's economic benefits value is more significant than its environmental concerns, it selects to use natural gas for the remaining demand that is not covered by the selected collective renewable thermal energy generation. If an individual agent has higher environmental concerns than economic benefits, hence does not select natural gas, there are going to be two options:
    - If the agents have a sufficient budget, they select individual renewable energy generation, depending on their internal motivations and SVO, either heat pump or wood pallet.
    - Suppose the budget is insufficient to select and invest in individual renewable energy generation at a particular tick. In that case, the agent selects to compensate for their energy demand and save money to invest in individual renewable energy generation in the future. This means the individual household will face voluntary energy discomfort/shortage due to 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 absents of individuals, (ii) shifting the thermal demand from peak hours, and (iii) reducing hot tap-water consumption. 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.
- Lastly, every year (12 ticks in the simulation), the community checks (i) whether they have reached the end of their project time horizon and (ii) whether the technologies in place have reached their lifetime. If the technologies reach their lifetime, the community will start another information exchange period, including new members (i.e. new households who moved to the neighbourhood) and decide on a new energy configuration (i.e. 0%–100% collective renewable thermal energy generation). The new households have their own motivations, energy demand, and investment, so that the new collective renewable thermal energy generation might differ. When the community selects the new collective renewable thermal energy generation, households with a different preference over the new percentage leave the TEC initiative, which means they are disconnected from the TEC initiative (i.e. they connect fully to the natural gas grid or get their energy demand elsewhere). Fig. 2 presents the model conceptual flowchart.

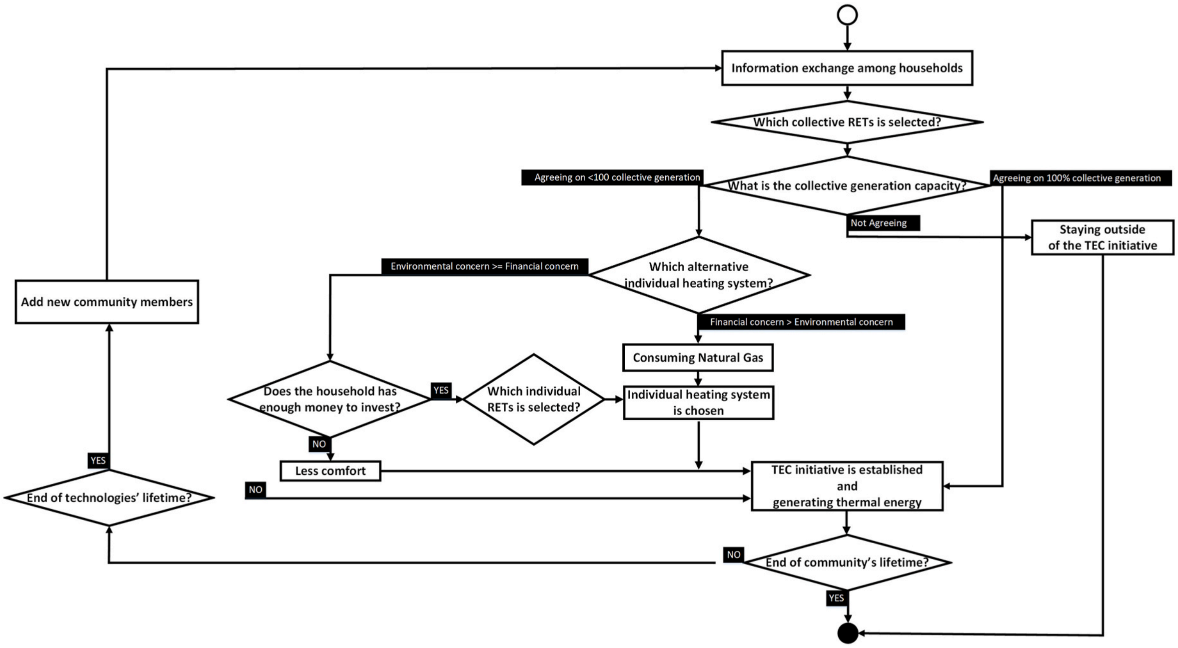


Fig. 2. Modelling flowchart.

Table 1
Model's KPIS.

	Key Performance Indicator	Unit	Description
Indicators of 4A's energy security concept	The average percentage of voluntary blackout/discomfort	%	To what extent is the energy available to meet each agent's demand, considering all possible options, including natural gas consumption, collective and individual renewable thermal energy generation.
	Average costs	€	Each agent's average cost per year, which is based on three main sources: collective renewable thermal energy system, individual renewable thermal energy system, and natural gas consumption.
	Diversity	–	Diversification of energy flow is based on the inclusion of three energy choices (i.e. natural gas, collective and individual renewable thermal energy generation). This is calculated based on the Shannon index.
	CO_2 emission reduction	kg CO_2	Amount of CO_2 emission reduction by the TEC initiative during the project time horizon.
Technical configurations	Collective technology selection		The collective thermal technology (i.e. biogas heater, ATES) is selected by the neighbourhood.
	Individual technology selection	–	The individual thermal technology (i.e. nothing, heat pump, wood pallet) is selected by the neighbourhood.
	Percentage of collective energy generation	%	How much of the total TEC initiative's energy demand is covered by collective energy generation
	Percentage of natural gas consumption	%	How much of the total TEC initiative's energy demand is covered by natural gas consumption

4.5. Key performance indicators (KPIs)

In order to understand and measure the performance of simulations, key performance indicators (KPIs) are defined, where four are based on 4A's energy security concept. Table 1 presents the model's KPIs to analyse the outcomes of the different experiments. Further information on the calculation of KPIs is presented in Appendix C.

4.6. Assumptions and input data

4.6.1. Available technical energy options

As presented in Sections 4.2. and 4.4., there are three categories of available energy options: (i) natural gas grid, (ii) collective RETs (i.e. ATES or bio-energy boiler), (iii) individual RETs (i.e. nothing, ground-source heat pump (i.e. brine to water), and wood pallet). Following [4], information on each of these technologies is based on information provided by 'Stimuleringsregeling Duurzame Energie' (SDE++), which provides financial incentives for renewable energy projects in the Netherlands [93]. To confirm and complete SDE++ information, additional data is extracted from studies such as [94,95], summarised in Table 2. Appendix A presents further data and assumptions on technological configurations.

4.6.2. Sensitivity analysis

There is often some uncertainty in the parametrisation of model variables and assumptions. Sensitivity analysis was conducted to explore such uncertainty and limit their influence [96]. Sensitivity analysis was done by following the one-factor-at-a-time (OFAT) approach [97]. For each parameter presented in Table 3, the model was run 30 times, all the parameters were fixed at a specific value, and only the value of the study was altered [97]. The sensitivity analysis is presented in Appendix B, summarising its results in Table 3.

Table 3
Sensitivity analysis results.

Parameter	Value	Unit
Information exchange	7	Months
Number of connections per household	14	Numbers
Size of the neighbourhood	750	Households
Baseline energy	15	%
New households that join the community yearly	10	%

4.7. Model parameters

To investigate the collective energy security of TEC initiatives, four behavioural and institutional parameters are selected, which the literature argues to comply with the two following criteria: (A) have proven impact on energy security, and (B) have proven impact on motivations and concerns of individual households and therefore on their decision-making processes for joining (thermal) energy communities. These four parameters and the literature supporting them are presented in Table 4.

Following the experimental settings explained in Section 3.2., for each batch (i.e. Dutch SVO-type and Random SVO-type batches), the experimentation includes a total number of 108 different combinations of settings for the four parameters (4*3*3*3 = 108), as shown in Table 4. Each combination was repeated 100 times; hence, the experimentation

Table 2
Data on available energy options.

		Investment costs	Operation costs	CO_2 intensity of technology	Average capacity	Load hours
		€/kW	€/kW/year	kg/kWh	kW	hour/year
Collective technologies	Bio pellet boiler	825	55	0.26	950	3000
	ATES	1600	113	0.152	800	3500
Individual technologies	Heat pump	1770	35.4	0.14	15	1500
	Wood pellet	415	140	0.35	20	2000

Table 4
Model parameters.

Model parameter	Rang of values	Unit	(A)	(B)
The demand of the households (Total household demand)	8185, 15161, 22622, 30084	(kWh/year)	[52,98]	[3]
Natural gas price	0.09, 0.12, 0.15	(€/kWh)	[52,98]	[99]
Willingness to compensate	10, 20, 30	(%)	[79]	[79]
Budgets/Investment-size	2500, 5000, 7500	(€)	[25]	[89]

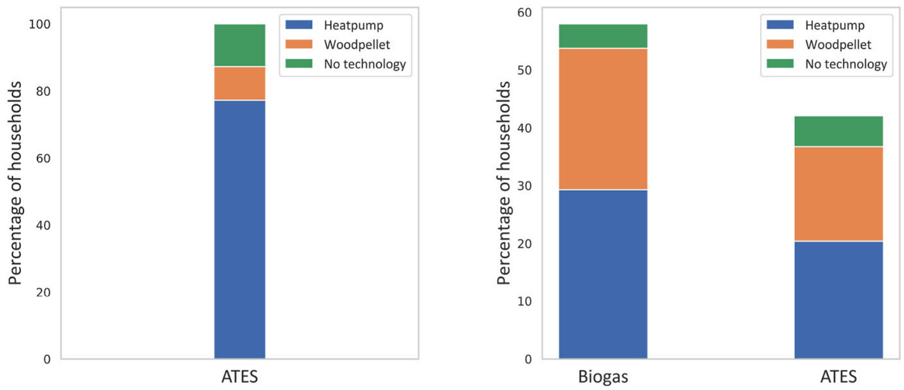
resulted in a total number of 10800 runs for each batch and 2*10800 = 21600 runs in total. The model was run for 10 years (i.e. the KPIs are calculated at the end of 10 years).

5. Results and discussion

In this section, the results of the simulation analysis are presented. These results are discussed in three main steps for both batches: (i) Results of the Dutch SVO-type batch as a more environmental-friendly batch, and (ii) results of the Random SVO-type batch as a less environmental-friendly batch.

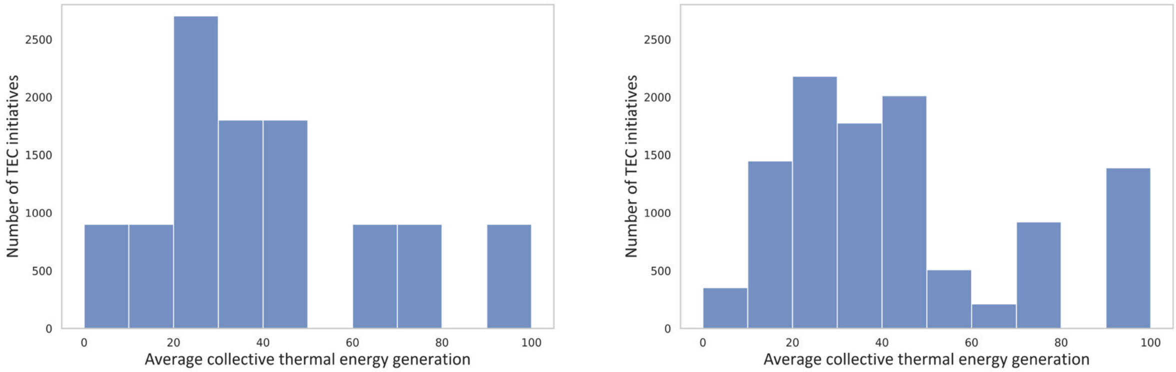
5.1. Overview of technical configurations

The selected thermal technology configurations showed clear differences between the two batches. TEC initiatives in the Dutch SVO-type batch only selected ATES as their collective technology, while Random SVO-type selected both biogas (58%) and ATES (42%). Furthermore, the Dutch SVO-type batch is dominated by heat pumps (about 75%) as their individual renewable technology, while the Random SVO-type batch has both heat pumps (about 50%) and wood-pellet (about 45%). This shows a considerable influence of households' motivations and attributes on technology selection, mainly due to the less CO_2 emission of ATES and heat pumps, compared to biogas and wood pellet. Fig. 3 shows this clear difference, where the bars indicate



A. Dutch SVO-type batch B. Random SVO-type batch

Fig. 3. Distribution of thermal technology selection.



A. Dutch SVO-type batch B. Random SVO-type batch

Fig. 4. Distribution of collective thermal energy generation.

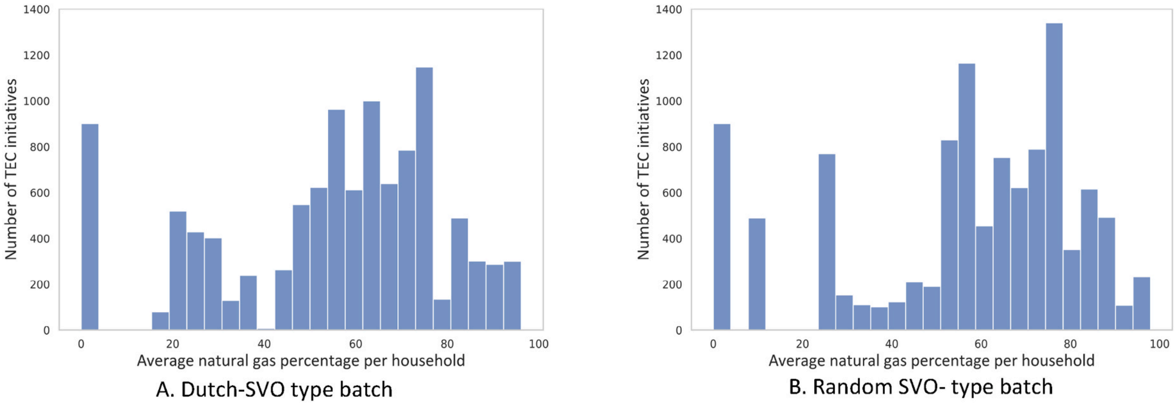


Fig. 5. Distribution of natural gas consumption.

the collective thermal technology, and the colours present the individual thermal technology.

The collective thermal energy generation and natural gas consumption percentages differ for both batches, as presented in Figs. 4 and 5. In more detail, on average, the Dutch SVO-type batch's collective thermal energy generation is 37%, and the Random SVO-type batch is 38%. On the other hand, on average, the TEC initiatives in the Dutch SVO-type batch consume 52% natural gas, while the Random SVO-type batch's average natural gas consumption is 58%. This considerable difference between the natural gas consumption of the two batches is mainly due to their differences in motivations and attributes, whereas in Random SVO-type, the individual households and TEC initiatives decide to consume natural gas more often to avoid the shortage and blackout.

5.2. Overview of energy security KPIs

Each energy security KPI, as a representative of the energy security dimension (see Section 2.1. and Table 1), are analysed separately in this section. The KPIs showed almost the same pattern for both batches, which can be seen in Appendix D. However, the absolute values for minimum, average and maximum values for each energy security KPI are different, as elaborated in Table 5.

Table 5 shows that the Random SVO-type batch performs better in the average percentage of voluntary blackout KPI. This result is mainly due to the selection of natural gas by TEC initiatives in this batch. On the other hand, TEC initiatives within the Dutch SVO-type batch spent 1135 €/year, while TEC initiatives within the Random SVO-type batch spent 1362 €/year. Considering that the Dutch SVO-type batch always chose the more expensive technologies (i.e. ATES and heat pumps in comparison with biogas and wood pellets), this shows a considerable difference between the two batches. Although the results show maximum CO_2 emission reduction of TEC initiatives within the Random SVO-type batch is higher (i.e. 3579 kg CO_2), on average values, both batches have almost the same CO_2 emission reduction rates. The Dutch SVO-type batch also performed better on average and maximum values for the diversity KPI. The normalised values for each energy security KPIs of both batches are presented in Appendix D.

Table 5
Energy security KPIS.

	Dutch SVO-type batch			Random SVO-type batch		
	Min	Avg	Max	Min	Avg	Max
Voluntarily blackout (%)	0	8	20	0	4	11
Average cost per year (€)	401	1135	3323	425	1362	3355
Diversity	0	0.72	1	0	0.66	0.95
CO_2 emission reduction (kg)	0	1046	3254	0	1073	3579

5.3. High and low energy security performances

As energy security is an integrated and multi-dimensional concept, the TEC initiatives with high and low energy security performances were analysed. To provide such analysis, first, the TEC initiatives with high and low energy security performances are identified for each of the batches through the following procedure:

- **High energy security performances:** In each batch, from the 10800 model runs (i.e. TEC initiatives), for each KPI, the 50% best performances are extracted separately. Therefore, for each KPI, 5400 runs are considered to have performed the best. Within these four sets of 5400 runs, the overlapping runs are selected. For the Dutch SVO-type batch, 184 model runs are identified as high energy security performances, while for the Random SVO-type batch, 160 model runs are identified.
- **Low energy security performances:** Through the same process, 50% of the worst performances are selected separately for each KPI, and then the overlaps are extracted. This led to 459 model runs as low energy security performances for Dutch SVO-type, and 527 model runs for Random SVO-type.

The Dutch SVO-type batch had a higher number of TEC initiatives with high energy security performances (i.e. 1.15 = 184/160) and fewer TEC initiatives with low energy security performances (i.e. 0.87 = 459/527) in comparison with the Random SVO-type batch. Therefore, overall, the Dutch SVO-type batch performed better in the integrated energy security assessment. This can be translated as TEC initiatives with more environmentally friendly behaviour (i.e. Dutch SVO-type) have a more significant chance to perform better in the energy security context.

Consequently, the values of the four model parameters, namely households' budget, willingness to compensate, natural gas prices and household demands (see Table 4) of these high and low energy security performances within both batches, are studied closely.

As Fig. 6 presents, for budget, demand and willingness to

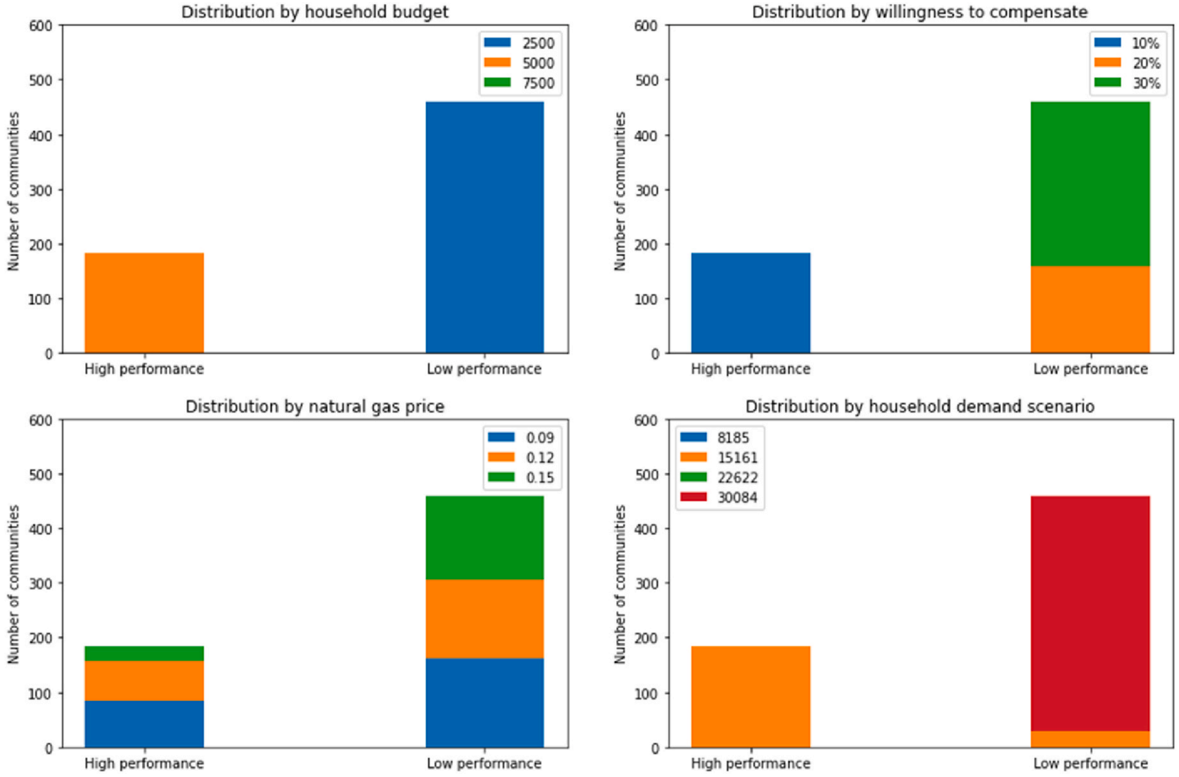


Fig. 6. High and low energy security performances of Dutch SVO-type batch.

compensate, a clear division was identified between TEC initiatives' high and low energy security performances in the Dutch SVO-type batch. In this batch, the low energy security performances are dominated by the lowest budget (i.e. €2500), highest demand (30084 kWh/year), and high willingness to compensate (i.e. 30% or 20%). Natural gas prices are distributed between high and low energy security performances, which can be translated as not influential for energy security performances within this batch.

The results for analysing the Random SVO-type batch's high and low energy security performances showed some differences, as Fig. 7

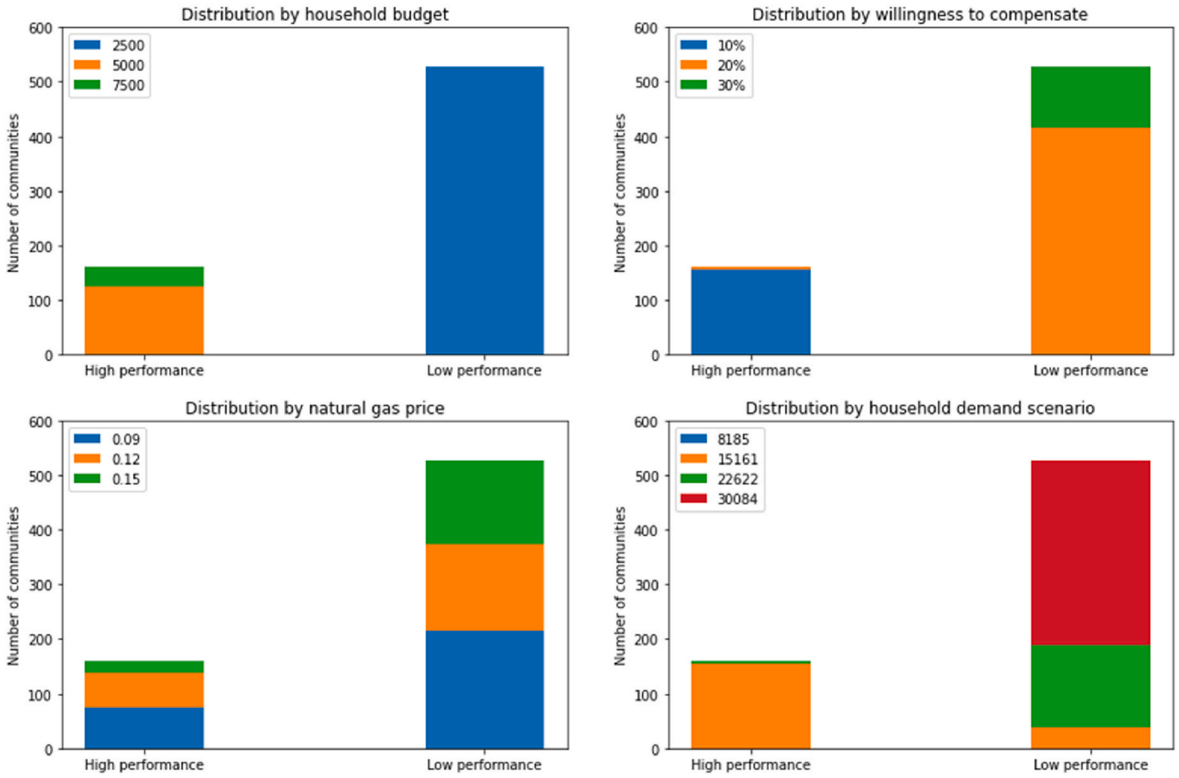


Fig. 7. High and low energy security performances of random SVO-type batch.

presents. Remarkably, the low energy security performances within this batch are also dominated by the lowest budget (€2500); however, in addition to €5000, €7500 are also among the budget of high energy security performances. This can be interpreted as the importance of larger budgets for high energy security performances within the less environmental-friendly batch. Furthermore, the low energy security performances have different types of demand, which can be translated as not influential for energy security performances within this batch.

Furthermore, comparing Figs. 6 and 7 highlights the importance of the households' budget for both batches, while natural gas prices do not influence energy security performances.

5.4. Discussions

The study showed that TEC initiatives could considerably contribute to the energy transition as a specific kind of community energy system. TEC initiatives (i.e. model runs within both batches, 21600 runs) significantly reduced their natural gas consumption (i.e. 50% on average for all runs approximately) and reduced their CO_2 emissions dramatically, which confirms the finding of studies such as [4,16,100]. Such TEC initiatives are established and functioned for ten years with a reasonable cost range across the 21600 runs (i.e. on average, 1250 €/year, in a range between 401 and 3355 €/year). Depending on technical, institutional and behavioural conditions, this can be translated to a range of 33 €/month to 280 €/month (i.e. 104 €/month on average) for individual participants of TEC initiatives. Although the collective energy generation was almost the same for both batches, the more environmentally friendly batch significantly reduced their natural gas consumption and CO_2 emission. Furthermore, more environmental-friendly technologies (i.e. ATES and heat pumps) dominated these communities' choices. Therefore, TEC initiatives performed well in the CO_2 emission reduction (as an indicator of acceptability) and the yearly cost (as an indicator of affordability).

Among the four energy security KPIs (i.e. voluntarily blackout, average cost, diversity and CO_2 emission reduction), the environmental friendly batch (i.e. Dutch SVO-type batch) showed better energy security performances. The less environmental friendly batch (i.e. Random SVO-type batch) only had considerably better performance regarding voluntarily blackout KPI. The batch with more environmentally friendly behaviour (i.e. Dutch SVO-type batch) showed more significant chances to perform higher in energy security.

Analysing the four modelling' s parameters (i.e. budget, willingness to compensate, natural gas prices and demand) showed that budget and willingness to compensate have a meaningful impact on the high and low energy security performances within both experimental batches. Households' demands also impacted energy security performances; however, less environmentally friendly batches (i.e. Random SVO-type batches) showed more sensitivity to this parameter. Natural gas prices did not significantly influence high and low energy security performances in any batches. These insights added to studies such as [24] which investigated the energy security of energy communities as a whole, and not particularly TEC initiatives.

6. Conclusions

This research aimed to study and investigate the influence of individuals' behavioural attributes on collective energy security within thermal energy communities (TEC) as a particular type of collective energy system. The study included thermal energy systems within a collective energy system and explored different parameters that could potentially influence the collective energy security of thermal energy systems from a behavioural and institutional standpoint. An agent-based model (ABM) was built by using 4A's energy security concept [47], Social Value Orientation (SVO) theory [48], and Behavioural Reasoning Theory (BRT) [49]. The experimental setting was designed based on two experimental batches: the Dutch SVO-type batch as more environmentally friendly and the Random SVO-type batch as less environmentally friendly.

From the energy security point of view, the study delineated the substantial potential of TEC initiatives for high energy security performances. The results demonstrated a positive influence of environmentally friendly behaviour on collective energy security performances. Particularly collective and environmentally friendly behaviour could increase the chances for higher energy security performances without no significant negative influence on households' costs. Furthermore, such behaviour could potentially be more robust to economic constraints (e.g. available budget of households). Lastly, results confirmed that TEC initiatives could considerably contribute to a CO_2 emissions reduction in individual households without jeopardizing their energy availability.

6.1. Limitations and future work

Although the current study sheds light on the influence of behavioural attributes on the collective energy security of TEC initiatives, it has certain limitations, which highlight avenues for further research. The first limitation is the conceptualisation of energy security within this modelling exercise. 4As' energy security concept and its representative indicators were useful for studying the energy security of TEC initiatives (as elaborated in Section 2); however, it is crucial to keep in mind that there are other energy security concepts and dimensions as discussed in [26,52]. For instance, considering dimensions such as societal effects [52], adaptability [53], and applicability [101] could bring further insights into collective energy security. Also, the research used four KPIs in total (i.e. voluntary blackout, average costs, diversity and CO_2 emission reduction) for the energy security dimensions (i.e. availability, affordability, accessibility and acceptability). However, the modelling exercise could include more energy security indicators (for instance, two indicators per dimension and, therefore, eight energy security indicators in total). Using several indicators for the same energy security dimension can be translated to approaching that dimension from different angles. Such an approach could potentially lead to a more comprehensive understanding of the energy security dimensions.

Secondly, by using SVO theory and BRT theory, the study provided insights into the behaviour of individuals within a TEC initiative; however, applying theories such as Ostrom's Collective Action theory [102], the Institutional Analysis and Development (IAD) framework [103], and Theory of Planned Behaviour [104] could have led to more detailed insights regarding the decision-making processes.

The third limitation is the selection of the case study. Although the Netherlands provides an opportunity to explore the TEC initiatives (See Section 3.2.), due to the nature of the domestic heating sector, the choice of the Netherlands is a limitation. The case study influences data collection and the model's chosen technical and institutional conditions. Thus, it is insightful for future research to populate the model based on data from other countries (e.g. Sweden, Denmark, United Kingdom and Germany) to provide more insights for stakeholders, particularly policymakers. This could also potentially lead to expansion and development of the current version of the model further to capture other related technologies (e.g. deep geothermal valves, high-temperature district heating and fully electric heating), other related actors (e.g. municipalities and community-boards), and other related policies (e.g. electricity prices and CO_2 tax), as the model has its simplifications.

Fourthly, although the study contributed to the local energy transition literature by focusing on TEC initiatives, the choice of TEC initiatives is a limitation, which influenced the model's chosen technical and institutional conditions. Therefore, it is crucial to keep in mind that the current study did not address other types of energy carriers (e.g. electricity) and CESs, such as electricity-generating communities and off-grid CESs, which have different social and technical considerations [46]. Studying different kinds of energy carriers and CESs and comparing the results would lead to more detailed insights related to the influence of behavioural attributes on collective energy security.

Furthermore, the study did not include the geopolitical developments and crises, which could potentially influence the model's variables and inputs (e.g. natural gas prices).

Finally, a fifth limitation concerns the research approach of this study, ABMS, as a method to explore the influence of behavioural attributes on the collective energy security of TEC initiatives. ABMS represents a simplified version of real-world phenomena or systems like any other modelling approach. It is mainly used to explore the collective action of heterogeneous agents, their decision-making processes and the emergence of system behaviour. However, the real world is more complicated, and various other factors potentially influence the outcomes. To capture these complexities, different research methods such as optimisation modelling, system dynamics modelling and equilibrium modelling could be beneficial in addition to the presented ABMS. More specifically, optimisation modelling could explore the technical design, while equilibrium modelling could address issues related to energy supply-demand, and system dynamics modelling could contribute to the whole energy system from a top-down and global perspective.

6.2. Recommendations

The results from previous sections are translated into detailed recommendations as follows for policy-makers and individual households:

- Individual households are encouraged to take the initiative to establish their own energy-secure TEC initiatives. The policy-makers are also recommended to support such initiatives, as they contribute considerably to the local energy-secure transition.
- Individual households are also encouraged to adopt environmental-friendly behaviour and act collectively, as such behaviour could potentially lead to a higher energy security performance.
- The investment size (i.e. budget) of households can be considered the most decisive parameter for the higher collective energy security performances of TEC initiatives. Therefore, providing more support (e.g. subsidies and loans) is effective and essential for establishing such entities.
- The households' demand is also influential for the energy security of TEC initiatives, as less demand leads to better energy security performances. As this parameter showed the most sensitivity to individual households' environmentally friendly behaviour, it should receive explicit attention in establishing and functioning energy-secure TEC initiatives.
- Natural gas prices do not play a significant role in TEC initiatives' high or low energy security performances, while the connection to the natural gas grid seems essential, as most TEC initiatives consume natural gas. Therefore, the current PBL energy price scenario (0.12 €/kWh) is considered successful.

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Credit author statement

Javanshir Fouladvand: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Visualization

Declaration of competing interest

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

Data availability

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

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Appendix A. Technological assumptions and data

This section presents the assumptions and input data related to three energy options.

Collective renewable thermal energy

Table 6
Data on collective bioenergy boiler

Variable	Units	Bioenergy
Average capacity	kW	950
Capex	€/kW	825
Opex fixed	€/kW/yr	55
Opex variable	€/kWh	0.003
Load hours	h/yr	3000
CO2 emission	kg/kWh	0.26
Lifetime	yr	20

Individual renewable thermal technologies

TABLE 7
Data on ATES

Variable	Units	ATES
Average capacity	kW	800
Capex	€/kW	1600
Opex fixed	€/kW/yr	113
Opex variable	€/kWh	0.0019
Load hours	h/yr	3500
CO2 emission	kg/kWh	0.152
Lifetime	yr	30

TABLE 8
DATA on ground-source heat pump (i.e. brine to water)

Variable	Units	Heatpump
Capex	€/kW	1770
Opex	€/kW/yr	35.4
Load hours	h/yr	1500
CO2 emission	kg/kWh	0.14
Lifetime	yr	15

Other technical assumptions

TABLE 9
Data on wood pellet

Variable	Units	Wood pellet
Capex	€/kW	415
Opex	€/kW/yr	140
Load hours	h/yr	2000
CO2 emission	kg/kWh	0.35
Lifetime	yr	20

Following [105]., for both collective renewable thermal technologies, the peak demand is considered to be 10%, and the CO_2 intensity of electricity consumption is 0.429 kg/kWh.

TABLE 10
Other relevant data

Variable	Units	
Average thermal energy demand per year per household	kWh	12000
Natural gas price	€/kWh	0.1
CO_2 tax	€/kg CO_2	0.025
CO_2 emission of natural gas	kg/kWh	0.2

Appendix B. Sensitivity analysis

As explained in Section 4.6.2. a one-factor-at-a-time (OFAT) sensitivity analysis was conducted on different model variables to explore the uncertainties systematically. Table 11 presents the parameters and their ranges that have been explored through this sensitivity analysis.

TABLE 11
Sensitivity analysis parameters

Parameter	Range	Unit
Information exchange	1, 4, 7, 10, 13,	Months
Number of connections per household	5, 8, 11, 14, 17	Numbers
Size of the neighbourhood	500, 750, 1000, 1250, 1500	Households
Baseline energy	5, 10, 15	%
New households that join the community yearly	10, 15, 20, 25, 30	%

After 50 times simulations, boxplots were generated for each parameter for four KPIs representing 4A's energy security concept. Fig. 9 presents OFAT sensitivity analysis results for the information exchange parameter.

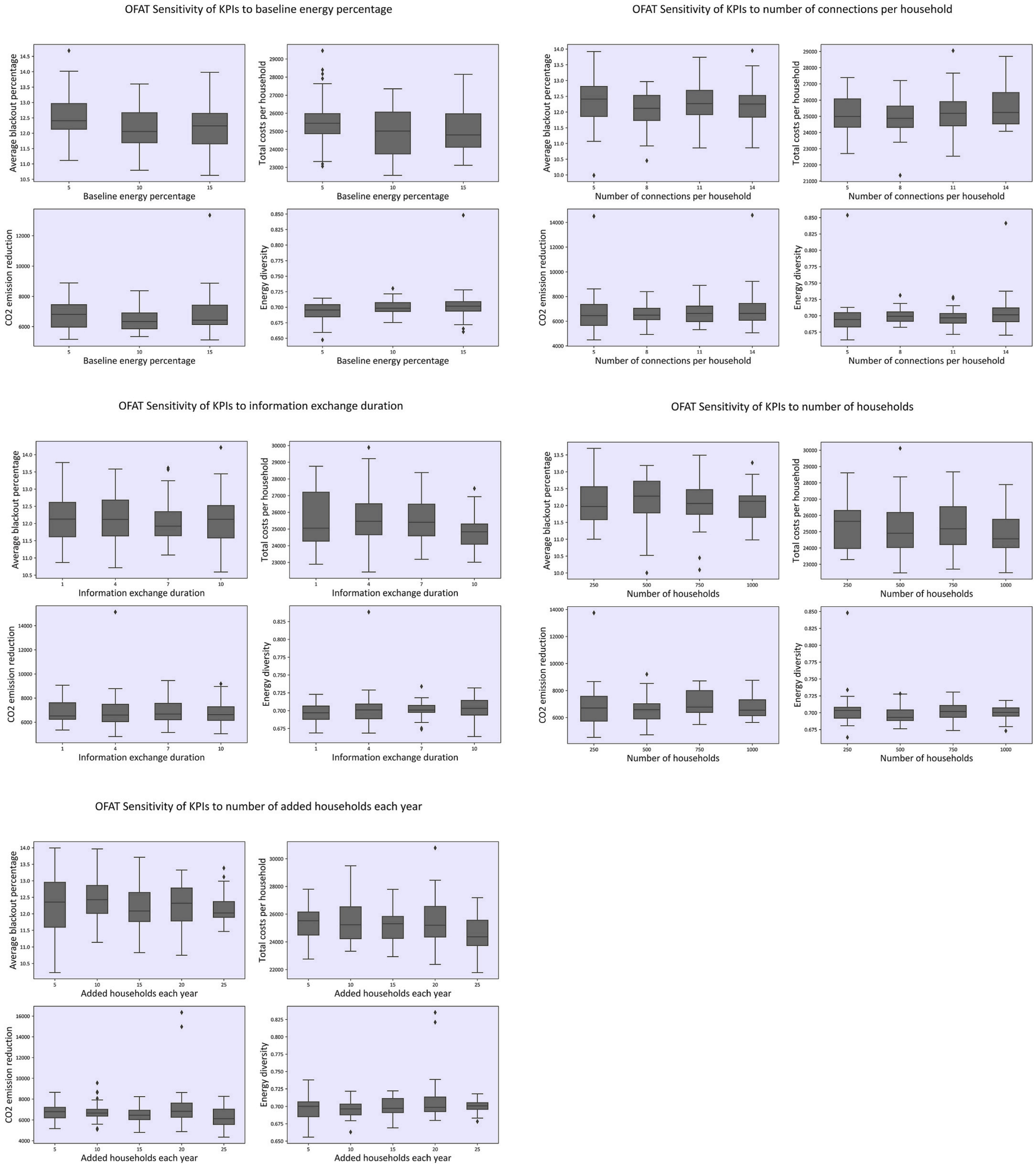


Fig. 8. Sensitivity analysis results

Appendix C. Model's KPIs

Availability: The average percentage of voluntary blackout/discomfort

$$\boldsymbol{\mathit{Average\ voluntary\ shoratge\ percentage}}\ (\%) = (100\% - \mathit{total\ RE}\ (\%) - \mathit{baseline\ energy}\ (\%) - \mathit{average\ williwgness\ to\ compensate}\ (\%))$$

Affordability: Average cost

$$\textit{\textbf{Average costs}}\ (€) = \frac{Investment\ costs\ scenario\ (€) + costs\ energy\ import\ (€) +\ investment\ new\ community\ members\ (€)}{Participating\ households}$$

Accessibility: Diversity index

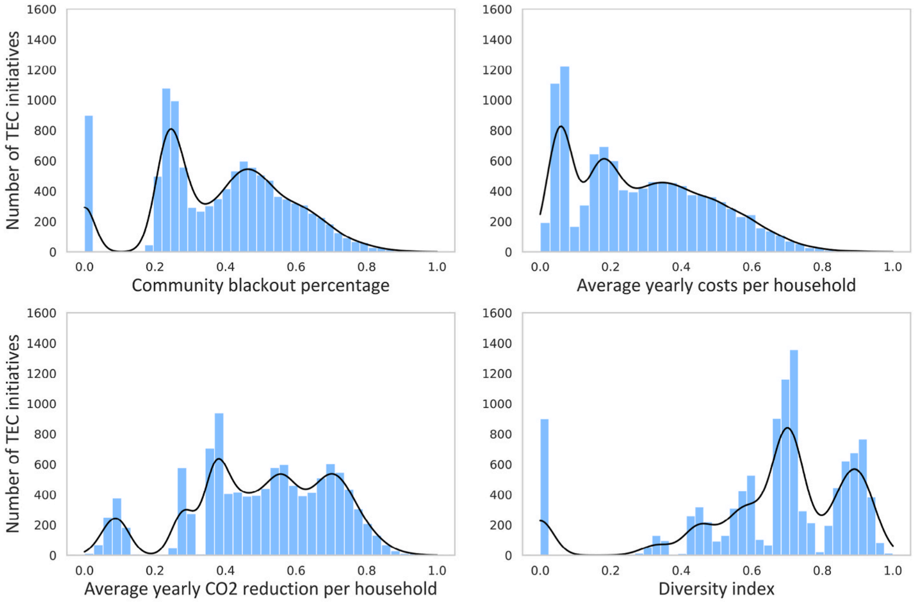
$$\textit{\textbf{Diversity index}} = -1 * ((\%\ selected\ collective.\ RE * \ \ln\%selected\ collective.\ RE) + (\%\ selected\ individual.RE * \ \ln\%\ selected\ individual.RE) + (\%\ selected\ national\ grid * \ \ln\%\ selected\ national\ grid))$$

Acceptability: CO_2 emission reduction

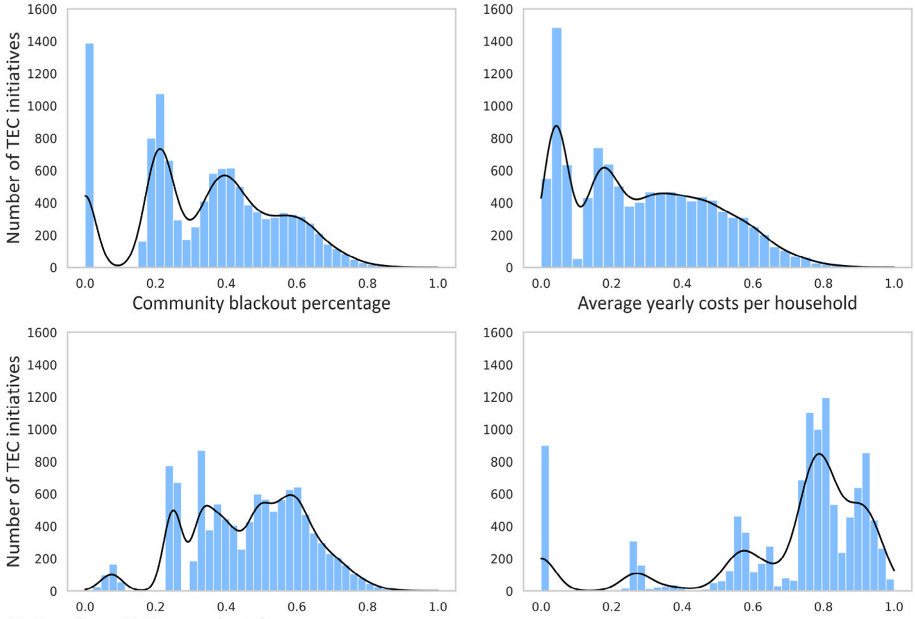
$$\textit{\textbf{Carbon reduction}}\ (kg\ CO2) = \frac{Emission\ of\ fully\ using\ national\ grid\ (kg\ CO2) - Emission\ of\ CES\ (kg\ CO2)}{Participating\ households}$$

Appendix D. Energy security KPIs for each batch

To compare the energy security KPIs with each other, the normalised distribution of each energy security KPI is presented, as presented in Fig. 9. For instance, the modelling results for average yearly costs per household in the Dutch SVO-type batch are between 401 and 1521 €/year, which in a normalised distribution, is translated into values between 0 and 1.



A. Dutch-SVO types batch



B. Random SVO-type batch

Fig. 9. Overview of normaliSed energy security kpis vc. number of tec initiatives within both batches

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