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Original research article

Infrastructure and governance: Prioritising energy security dimensions for community energy systems

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ABSTRACT

Energy security is one of the most important topics in energy-related literature. As such, various concepts and dimensions are introduced to contribute to energy security assessments. However, the literature lacks an approach to prioritise these dimensions, as they cannot always be addressed simultaneously. This study is the first step in investigating the importance and prioritisation of energy security dimensions by focusing on the context of community energy systems. Such collective and decentralised energy systems are gaining momentum in the energy transition context; however, they have received minimal attention on their energy security aspects. First, a literature review is conducted to gain an overview of the studied energy security dimensions, highlighting dimensions such as energy availability and infrastructure that are studied the most. In contrast, environment and societal effect dimensions have received minimal attention. Next, an existing agent-based model is used to assess the importance of energy security dimensions and their priority in community energy systems. The results revealed that infrastructure and governance are the most impactful dimensions for the energy security assessment of community energy systems. Energy prices were one of the least influential dimensions in energy security assessments. The study also explored various existing energy security concepts and proposed the most suitable one in the energy communities' context. A research agenda emphasising the need to study governance, societal effects and environmental dimensions is also presented. Lastly, infrastructure, governance, environment and societal effects are concluded to be the most crucial energy security dimensions for community energy systems.

1. Introduction

Energy security is one of the topics studied the most in energy-related literature [1]. As an overarching term, energy security is a dynamic [2] and context-dependent concept [3] in which various disciplines such as public policy, economics, and engineering contribute to its conceptualisation [4,5]. Therefore, depending on the context and energy systems, different energy security definitions and concepts are developed over time, including the ones from the International Energy Agency (IEA) [6], the World Bank [7], the Association of Southeast Asian Nations (ASEAN) [8], the World Energy Council (WEC) [9], and Asia Pacific Energy Research Centre (APERC) [10]. Consequently, for assessing energy security, each definition has its own unique set of energy security dimensions, such as security of supply (i.e. availability), affordability, accessibility and efficiency and their representative indicators (e.g., energy import rate and overall energy cost) [1].

As there are different energy security dimensions (in each energy security definition and overall), there are always trade-offs between such dimensions [10,11]. Particularly, social, technical and economic considerations (e.g., available financial resources such as subsidies, available space, energy independence and environmental concerns) put constraints on improving all energy security dimensions together [14], making prioritising the dimensions unavoidable. However, in the vast literature on energy security, no study investigates the prioritisation, importance and contribution of these dimensions in measuring and assessing energy security. Such lack of knowledge could potentially lead to undesirable resource allocation (e.g. investing in increasing availability rather than acceptability of an energy system), which could lead to undermining energy security in energy systems in the long term. This challenge becomes more vivid in the energy transition era, where

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conventional energy systems undergo a drastic change [12], especially considering the emergence of alternative energy systems, such as community energy systems (interchangeably energy communities also, CESs), with different characteristics (e.g. bottom-up, collective action and decentralised renewable energy systems) [13].

CES is a term employed to encompass initiatives focused on collectively generating, distributing, and consuming renewable energy for all participants involved locally [14]. Although there are various definitions for CESs in the literature (e.g. as presented in [15]), CESs can be conceptually defined as individual households within a community that engage and jointly invest in Renewable Energy Technologies (RETs), collectively generating the energy they consume while incorporating measures for energy saving and conservation [16,17]. Such collective energy systems are highly feasible [17], and they are gaining momentum in the real world [18] as the number of established energy communities is increasing [19,20]. Therefore, it is essential to include energy security considerations and constraints for related decision-making, especially as the resources are limited and the trade-offs are unavoidable [21,22]. Although few studies, such as [12,23], investigated different energy security dimensions in the CESs context, none of them studies the importance and prioritisation of these dimensions.

This study aims to investigate and illustrate the contribution and importance of energy security dimensions in measuring and assessing energy security and how these dimensions can be prioritised. To address the study's aim constructively and accurately, the focus is on CESs in particular. This would also help provide further insights on such alternative and collective energy systems that are gaining momentum, which could potentially facilitate the energy transition at the local level to become more energy secure. Furthermore, the study can also be seen as a response to the energy security concerns for local energy transition, as highlighted in [24,25]. The study consists of two main steps to achieve its aim. First, the literature on CESs' energy security is reviewed and analysed to identify the security dimensions already addressed in the current literature. This is done using the energy security concept presented in [1] to analyse and structure the literature. Second, an existing agent-based model (ABM), presented in [12], is used to complement the literature review in identifying and prioritising various CESs' energy security dimensions. The model presented in [12] is the most detailed and comprehensive ABM exploring the largest number of energy security dimensions. Such an approach also provides an opportunity to investigate different combinations of energy security dimensions to explore different energy security concepts. To summarise, the contributions of this study are:

- ❖ To investigate and illustrate the prioritisation of the energy security dimensions,
- ❖ To propose a combination of dimensions as a tailored energy security concept for CESs to potentially reduce the complexities and time of the decision-making process for energy security assessments and measurements;
- ❖ To demonstrate the applicability and usefulness of employing existing models for developing new insights in addition to their original purpose.

The structure of the paper is as follows. Section 2 elaborates on the research methods. Section 3 provides an overview of CESs' energy security literature. Section 4 presents the results of the ABM statistical analysis. Section 5 demonstrates the discussions, conclusions and recommendations.

2. Research methods

2.1. Systematic literature review on energy security of community energy systems

To accomplish the goal of this research, first, the literature on the energy security of energy communities was studied. This literature review was based on material from scholarly databases published until April 1st 2022. www.webofknowledge.com and www.scopus.com were searched for documents with a combination of keywords as presented in Table 1, which led to 247 documents.

Following studies such as [26–28], the choice of keywords is to cover the studies on the collective, small-scale and bottom-up RETs (e.g. "energy community", "energy cooperative", "energy initiative", "local energy system", "distributed energy system", and "decentralised energy system"). Such an approach would contribute to drawing the whole picture rather than analysing a specific case study or technology and resource (e.g. solar energy, geothermal, and district heating). The collected documents only covered articles and conference proceedings (e.g., [23]) written in English, leading to 247 documents. This setting provided an opportunity to conduct a critical review and propose a research agenda for studying CESs' energy security.

Although all 247 documents included the keywords, not all of them referred to the energy community as a local-scale energy system and addressed the energy security of such energy systems. For instance, in some of those documents, "energy initiative" referred to an official part of the government (energy initiative office/ plan), not local-scale community energy systems (e.g. [29–32]). The EU energy community, international energy community, atomic energy community, and East Asia energy community are other examples of using the keywords differently. Also, the security of information networks (e.g. [33]) and privacy and security (e.g. [34,35]) are examples of using the energy security keyword for topics not intended for this research. Since the goal of this study is to provide a critical overview and suggest prioritisation of energy security dimensions in the CESs context, the study deliberately left out research that does not address the bottom-up and collective nature of these systems or does not focus on energy security. Excluding such studies, only 95 documents discussed local-scale energy communities' energy security. In the next step, not-peer-reviewed documents and three studies which employed ABMs (i.e., [12,13,23]) were excluded, leading to 29 documents. To study and structure the literature on CES's energy security, all these 29 peer-reviewed documents (i.e. peer-reviewed articles) were carefully studied and further analysed. All the topics and energy security dimensions discussed in this literature review align with the seven energy security dimensions of Ang. et al.: energy availability, energy prices, energy efficiency, infrastructure, environment, societal effects and governance [1], which is one of the most recent and well-known concepts. This concept is a multidisciplinary concept that addresses the multidimensional nature of energy security [1]. For instance, as mentioned in studies such as [26,36], it includes influential dimensions for CESs, including the environment, societal effects and governance. The results of this analysis are presented in Section 3. Fig. 1 elaborates on the processes and outcomes of including and selecting documents.

Such an approach contributes to the literature reviews on energy security (e.g., [1,3]), as none of them focuses on CES's energy security (i.e., collective energy security). In the CES literature, there are various review studies. For instance, a review of the notions, activities and objectives of CESs is presented in [15], while a critical review of key issues and factors shaping integrated CESs is demonstrated in [37]. The literature on thermal applications in the CES context from the collective

Table 1
Keywords in literature search.

Keywords	Number of studies
energy security AND "energy community"	89
energy security AND "energy cooperative"	3
energy security AND "energy initiative"	74
energy security AND "local energy system"	16
energy security AND "distributed energy system"	52
energy security AND "decentralised energy system"	19

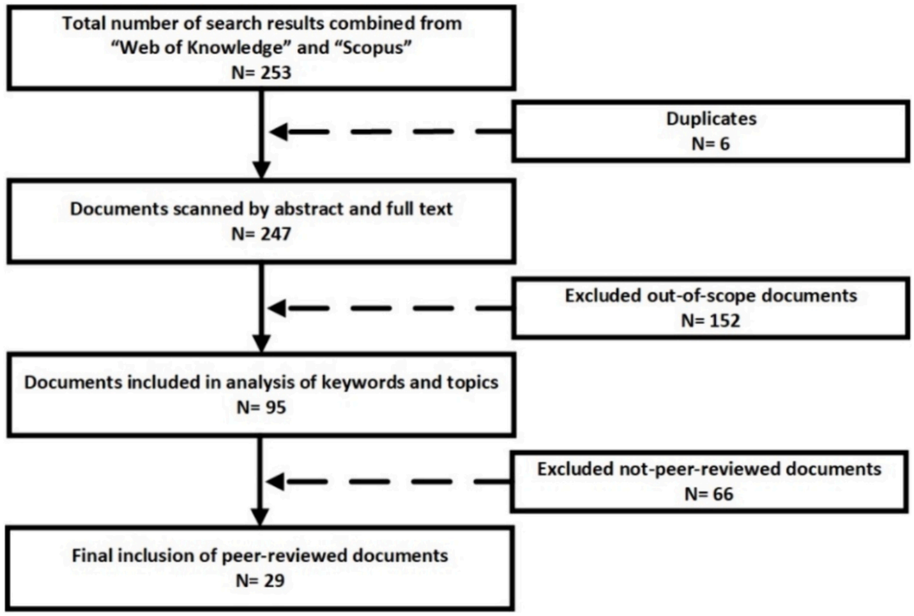

Fig. 1. Prisma Flow diagram literature search.

action perspective is structured and analysed in [26]. Looking through the transition lens, the factors for the emergence and establishment of CESs are identified in [38]. Also, several studies, such as [27], focused on a specific technology (e.g., solar energy in CESs). However, none of these studies focuses on the energy security of such collective energy systems.

2.2. An agent-based model for studying the energy security of energy communities

Agent-based modelling and simulation (ABMS) is a computational social simulation approach that represents a simplified version of reality, easing the research while providing the opportunity to analytically and systematically study a phenomenon or a system [39,40]. In an agent-based model (ABM), "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" [41]. Therefore, agents are heterogeneous, autonomous and individual decision-making entities (such as individual households) that can learn and interact with each other and their environment [42,43]. In addition to studying and capturing the behavioural choices of individuals, using ABMS provides the opportunity to study the emergent behaviour of the system [39]. Emergence relates to the idea of "the behaviour of the system", which results from individual actors' behaviour on lower levels and their interactions [39]. Moreover, ABMS allows for adding a time variable, which enables the exploration of different scenarios over time [39,40].

As the use of ABMS is becoming more prominent in the CESs literature [28], it is also considered a suitable approach for studying CESs' energy security. As the current study focuses on prioritising energy security dimensions and not developing a computational model, the study uses an existing model. The ABM presented in [12] was chosen as among the other few available ABMs with a focus on CESs' energy security, such as [13,23]; it is the most detailed one. Furthermore, the ABM presented in [12] is the only ABM that adopted the energy security concept presented in [1] to study CESs' energy security (it also has the largest number of dimensions and indicators), which is in line with the first part of the study, the literature review. The model's conceptual flowchart is presented in Fig. 2. The description and implementation are summarised in Table 2, adapting the Overview, Design Concepts and Details (ODD) protocol [44]. The ODD protocol is a well-known protocol for standardising the ABMs' descriptions to ensure clarity, transparency, and reproducibility in ABM research [28,44]. The energy security dimensions and their representative indicators (i.e. key performance indicators, KPIs) in the ABM are presented in Table 3.

Following Fig. 2 and Table 3, the detailed description of the main five decision-making points is as follows:

- ❖ **Joining CESs:** If there is an available CES, individual households consider joining it. If there are no CESs available, individual households consider establishing one.
- ❖ **Choosing the leader:** the individual households have two options for the project leader: (i) community board and (ii) municipality. The project leader is responsible for organising and taking the initiative within a CES.
- ❖ **Type and capacity of collective generation:** The project leader (i.e., community board or municipality) has three options for the collective renewable thermal energy generation technology options: biogas heaters, aquifer thermal energy systems (ATES), and electric boilers. Depending on the project leadership and individual households' motives and values, this type and capacity of collective generation is chosen.
- ❖ **Type and capacity of individual generation:** The individual households choose their individual renewable thermal energy generation separately among the following options: heat pumps, small bio-energy heaters (i.e. wood pallet based) and photovoltaic thermal hybrid solar collectors (i.e., Solar PVT).
- ❖ **Financing the CESs' establishment and functioning:** After choosing collective and individual renewable energy generation, the project leader takes the final techno-economic feasibility. Any available subsidy and willingness to pay would be considered at this stage.

To capture the motivations and behavioural aspects realistically, the ABM is populated with data from [48], which studies the factors influencing the participation of Dutch households in CESs. The simulated data explores four input parameters, namely, natural gas prices, CO_2 taxes, ambient temperature, and the amount of available subsidy and allocation strategy. The modelling exercise led to a total of 48,600 simulated CESs used for the statistical analysis presented in Section 4. Further information on the model, the decision-making processes, its KPIs, and the experimentation settings are presented in [12].

In this step, a statistical analysis was performed on the results of this

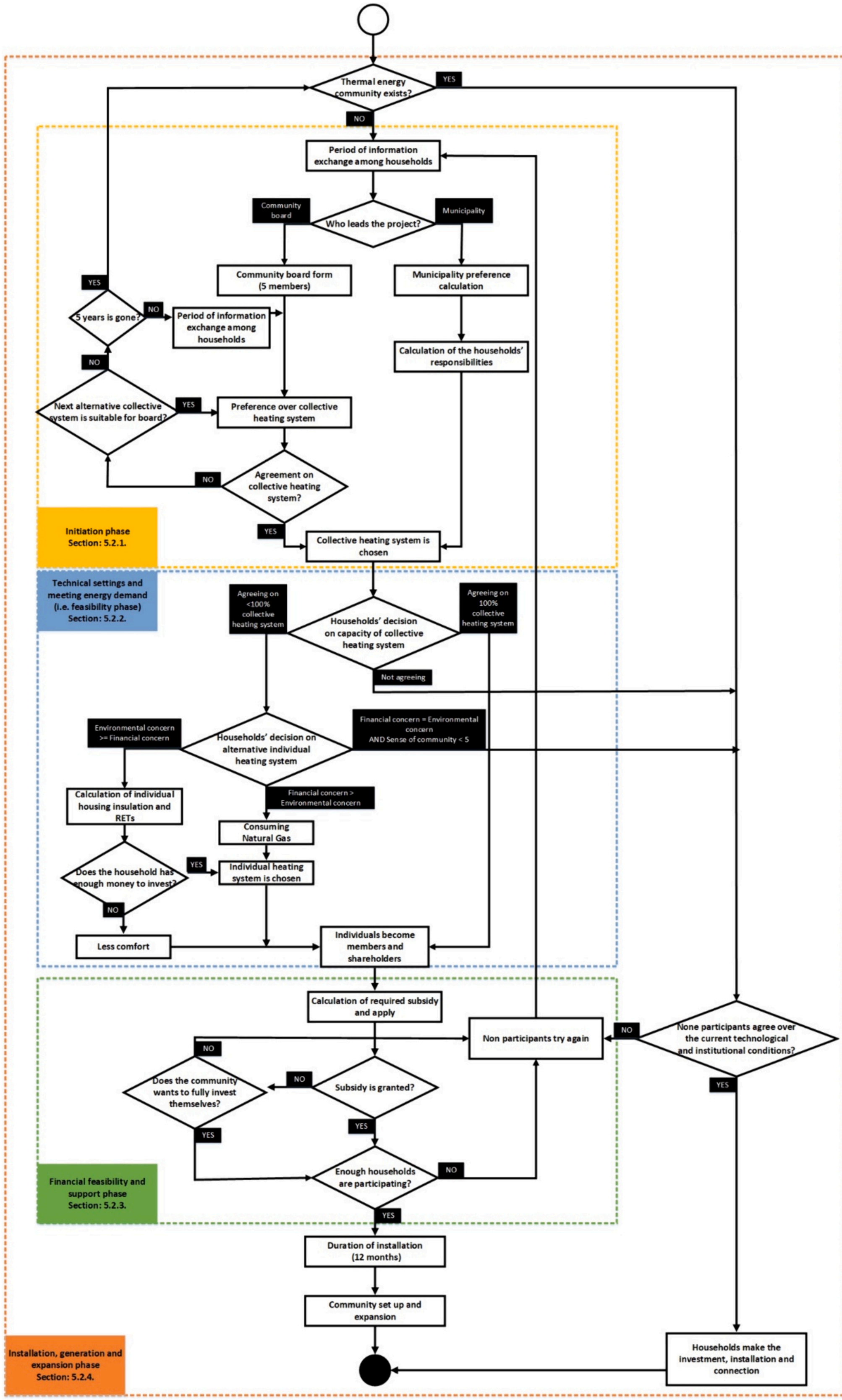

Fig. 2. The model flowchart, from [12].

Table 2
Model's description and implementation.

Purpose	To provide a comprehensive exploration of the energy security of CESs by including different technical, institutional and behavioural settings
Entities	There are two types of agents: individual households and municipalities.
Variables	Internal motivations, strategies for subsidy allocation, technical configurations, energy demand (influenced by ambient temperature)
Theoretical background and concepts	The energy security concept by Ang et al. [1], The Institutional Analysis and Development (IAD) framework [45], The Social Value Orientation (SVO) theory [46]
Interactions, network and adaptation	The small-world network [47] is used for the interactions. Depending on the strength of their motivations, households (i.e., agents) can learn and adapt their motivations based on interactions with each other.
Model initialisation and narrative	In chronological order, there are five main decision-making points in the model: (i) Joining the CESs, (ii) Choosing the leader, (iii) Type and capacity of collective generation, (iv) Type and capacity of individual generation, (v) Financing CESs through available subsidies or investment.
Key performance indicators (KPIs)	Energy security indicators, see Table 3

Table 3
Dimensions and indicators of energy security, adapted from [1].

Dimension	Short definition	KPIs in [12]
Energy availability	Referring to the security of supply.	Average voluntary discomfort per household
Infrastructure	Integral in providing a stable and uninterrupted energy supply, including all relevant energy technologies.	Average diversity of infrastructure per household
Energy prices	Determining the affordability of energy supplies.	Average costs per household
Societal effects	Including social concerns and the effects of the energy system.	Average community benefit per household
Environment	Integrating topics related to sustainability and environmental issues.	Average CO_2 emission per household
Governance	Policies, regulations and planning for energy systems.	Establishment duration of energy communities
Energy efficiency	Relates to developments in energy technologies, systems, and practices.	Average thermal insulation per household

modelling exercise. This statistical analysis leads to identifying the correlations, contribution, and importance of each energy security dimension in the energy security assessments, which eventually illustrates the prioritisation of such dimensions. The method that is used to quantify the variable importance of energy security dimensions in explaining the highest- and lowest-performing communities presented by [12] is "Extremely Randomised Trees" (Extra Trees) [49]. The extra trees method was advantageous, particularly regarding computational efficiency and its ability to make accurate predictions [49]. Furthermore, it was found to be successful in estimating the importance of predictor interactions in the context of global sensitivity analysis [50]. Two different classification problems are defined, considering the labels of highest and lowest-performing communities as the categorical response. The extreme observations are predicted in both problems using the whole set of 7 energy security dimensions. After fitting the extra tree models, feature importance was quantified as the mean decrease in the impurity to each predictor variable contributed. The resulting figures are normalised such that the contribution of all indicators adds up to 1. The Python implementation was used, as presented in [51]. For each classification problem, 10,000 trees are fitted to ensure the results are robust against the stochasticity inherent in the technique.

3. Overview of the CESs' energy security literature

This section provides a detailed and structured analysis of the documents (i.e. 29 peer-reviewed articles) that have already discussed the CESs' energy security. The energy security concept presented in [1] and its seven dimensions are used to structure this analysis. Fig. 3 provides an overview of the number of studies that studied each of the seven energy security dimensions.

As Fig. 3 presents, energy availability and infrastructure are the most studied dimensions in the CESs' energy security literature (within the 29 peer-reviewed articles). None of these documents explored energy efficiency or the environment as dimensions of energy security. Details of these documents and their exploration of energy security dimensions are presented in the following sections.

3.1. Energy availability

Energy availability (i.e. security of supply) is the most studied dimension in the CESs' literature. As explained in [1], this dimension concerns the security of supply, including indicators such as self-sufficiency (and energy imports) and supply disruptions. Studies such as [52] explored the general and traditional notion of security of supply in the CESs' literature. Robust optimisation of distributed electricity systems with supply considerations is presented in [52]. Several studies discuss the security of supply through network approaches such as n-1 security (i.e., mathematical approach). For instance, a model for designing robust energy internet by approaching energy security through n-1 robust security is presented in [53]. The security of supply of a Greek island, Sifnos, is explored in [54]. The role of (collective) distributed energy systems in increasing the security of supply for a city and its neighbourhoods, where the peak shaving method was employed, is explored in [55]. In this line, the energy planning and strategies for the energy security of distributed energy systems for energy availability (and security of supply) are investigated in [56]. Furthermore, the ways in which the local smart distributed power systems could achieve security of supply and reliability by utilising information-sharing technologies are investigated in [57]. The influence of such collective energy systems' energy autonomy on energy security (including energy availability) is discussed in [58]. The flexibility and reliability of energy resources for energy supply security of distributed energy systems are explored in [59]. Lastly, few studies focused on self-sufficiency as an energy security indicator. For instance, through analysing territorial resilience, [60] investigated the self-sufficiency and self-consumption of CESs and related them to the security of supply (i.e. availability) for CESs' energy security.

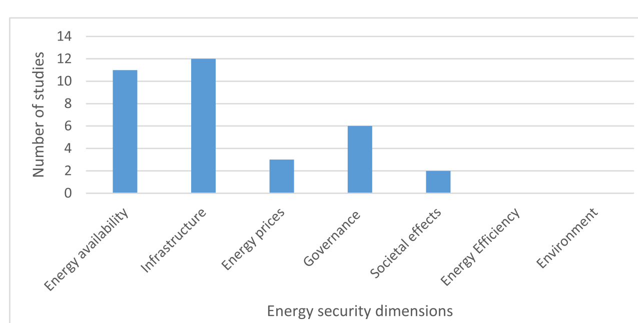

Fig. 3. Number of studies that studied each of the seven energy security dimensions.

3.2. Infrastructure

The infrastructure dimension of energy security is focused on adequate and reliable infrastructure with spare capacity for delivering energy and infrastructure integration as indicators [1]. This dimension has also been studied extensively in the CESs' literature.

CESs' literature investigates the influence of various novel infrastructures and technologies on the security of supply within such systems. For instance, the application and influence of blockchain on the establishment and functioning of CESs are explored in [61]. On the other hand, the application of blockchain as an alternative technology for increasing supply security of decentralised electricity systems in Sub-Saharan African countries is demonstrated in [62]. Different smart and automated infrastructures for improving the performance of local energy systems, including their energy security, are investigated in [35].

The influence of a particular infrastructure (i.e. monitoring systems) on achieving energy security within rural off-grid communities is studied in [63]. The role of different technologies (e.g. energy interconnections, energy control systems and energy savings) in the security and stability of distributed energy systems is studied in [64]. It also investigates the strategies and planning for such systems to increase their energy security and stability. The microgrid's ability to provide flexible services for household energy supply security is analysed in [65].

Other studies explored the diversification indicator in the context of CESs. For instance, studies such as [58] conclude that by diversifying energy supply sources, the energy security of CESs can be ensured. As explained in [66], energy diversification is assumed to promote the building of organic energy networks within urban districts and, therefore, can contribute to the energy security of CESs. Different possible diversification strategies (e.g. diversifying energy generation technologies) for the security of supply of decentralised solar energy in India are presented in [67]. The importance of diversity of energy resources and energy fuels for increasing CESs' energy security is mentioned in [62].

From the infrastructure integration point of view, studies such as [66,68] argue that integrating decentralised energy systems at the local level increases energy security at higher levels, such as the national level. These studies show that infrastructure integration is essential for achieving energy security. Lastly, in terms of reliability and interruptions of local infrastructure, different threats to the security of supply in rural decentralised energy systems and how to overcome them with a monitoring system are explored in [69].

3.3. Energy price

From an energy security standpoint, the energy price dimension is related to the absolute price level, price volatility, and market competition, which contribute to an energy system's affordability [1]. Although such a topic (and its indicators) receives substantial attention in the main body of literature on energy security, particularly from the affordability lens (as presented in studies such as [70–72]), it has received minimal attention in this branch of literature (i.e., energy security of CESs).

Few studies explicitly investigate the energy price dimension of CESs' energy security. For instance, [73] applied a specific energy security framework to local communities in Australia and Indonesia based on availability, affordability, technology development and efficiency, environmental and social sustainability, and regulation and governance (developed in [74]). Furthermore, along with increasing supply security, [62] investigated blockchain as an alternative solution for increasing the affordability of decentralised electricity systems in African countries.

3.4. Governance

The governance dimension of energy security is related to indicators such as democracy, information gathering, policies and strategies (e.g. available subsidies and taxes) [1]. This is the third most-studied energy security dimension in the literature on energy security of CESs.

In this branch of literature, the energy planning and strategies for the energy security of distributed energy systems availability and security of supply are investigated in [56]. The role of energy control and saving systems in increasing the security of distributed energy systems is studied in [64]. The strategies, policies, and potentials for decentralised solar energy in India and the conclusion that the diversification of energy sources contributes to the security of supply are explored in [67].

The importance of supportive policies for energy security in CES is discussed in [62]. The influence of governance structures on energy communities (and their influence on energy security) is presented in [75]. The impact of different types of (smart) contracts on energy security and the vulnerability of local energy systems is discussed in [76].

3.5. Societal effects

The societal effects of an energy system as one of the seven essential energy security dimensions is discussed in [1]. Topics and indicators such as societal welfare, energy poverty, social equity, and distributional fairness are related to the societal effects dimension.

In the literature on CESs' energy security, [77] studied the social acceptance of decentralised solar PV systems in rural areas of Ethiopia. The study concluded that the societal effects of such systems (e.g. safety of households) positively increase households' security levels. The health and gender issues associated with biomass as an energy source for CESs and their influence on the energy security of individual households and the whole community are explored in [78].

3.6. Energy efficiency and environment

Energy efficiency refers to technological developments promoting efficiency in energy generation, distribution, and consumption [1]. The environmental dimension is associated with indicators such as CO_2 emission (reduction) and the environmental footprint of energy systems, which plays a significant role in energy security [1]. Although these two dimensions exist in different energy security concepts (e.g. [1,79]), none of the 29 documents studies these two dimensions of CESs' energy security.

Reviewing the collected literature highlights the little attention CESs energy security (i.e., local collective energy security) has received. Specifically, along with no attention to energy efficiency and environment dimensions, governance and societal effects received minimal attention. Such minimal attention to these four dimensions is in contrast with both bodies of literature, energy security (as elaborated in [1,3,71]) and CESs (as elaborated in [26,80,81]). In detail, as [37] demonstrated, energy efficiency and the environment are crucial considerations for further CESs' development, while [26] also emphasises the importance of social consideration and its impact on CESs. Without studying these dimensions, understanding their contribution to local collective energy security and the potential trade-offs between all dimensions is not possible. Therefore, to address this gap in the literature and provide input for the trade-offs between energy security dimensions in the CESs context, as explained in Section 2, an existing ABM is employed, and the results are presented in Section 4.

4. ABM statistical analysis

This section presents the results of an agent-based model (ABM) used as a virtual experimental lab to analyse energy security dimensions. First, the correlation between the energy security dimensions (i.e. KPIs in the modelling experience as presented in Table 3) is presented. Next, as explained in Section 2.2., the simulated data is categorised into high and low energy security performances, and the contribution of each dimension to this categorisation is studied. Lastly, five well-known energy security concepts and their representative dimensions are analysed to provide more practical context and insights.

4.1. Correlation between the seven energy security dimensions

This section presents the Pearson correlation coefficient to explore the relationship between energy security dimensions (i.e., whether they conflict or harmonise) in order to understand the positive or negative trade-offs between different dimensions. The following categories have been created based on an equal scale to categorise the correlation factors:

- ❖ 0 = no correlation
- ❖ 0 – |0.20| = very weak correlation
- ❖ |0.20| – |0.40| = weak correlation
- ❖ |0.40| – |0.60| = moderate correlation
- ❖ |0.60| – |0.80| = strong correlation
- ❖ |0.80| – 1 = very strong correlation
- ❖ 1 = perfect correlation

Fig. 4 presents the bivariate correlation coefficient between the seven energy security dimensions. The colours represent the calculated correlations (i.e. darker blue represents a more positive correlation, while darker red represents a more negative correlation).

As Fig. 4 shows, no perfect or very strong correlation (i.e. above 0.8) was found between any two energy security dimensions. Therefore, from a practical point of view, no specific approach could simultaneously lead to an increase in all energy security dimensions. This is in line with the current energy security literature that argues there are always trade-offs between energy security dimensions (e.g. [1,3,71]). There is only one strong correlation: the positive correlation between societal effect (i.e., community benefit) and energy prices (i.e., household costs). In practical terms, this shows the relationship between larger investments/higher costs and higher societal benefits in the long term, which can be translated as higher costs potentially leading to higher benefits in the long term. There are also four moderate correlations: (i) negative correlation between energy availability (i.e. voluntary discomfort per household) and environment (i.e. CO_2 emissions); (ii) positive correlation between energy efficiency (i.e. final thermal insulation) and infrastructure (i.e. energy diversity), (iii) positive correlation between energy prices (i.e. households' costs) and environment (i.e. CO_2 emissions), (iv) negative correlation between energy availability (i.e. voluntary discomfort per household) and societal effects (i.e. community benefit). The negative correlations of energy availability with the environment and societal effects dimensions are due to fossil fuel consumption (i.e., natural gas), which positively impacts the availability and societal effects but negatively impacts the environment dimension.

Among all seven energy security dimensions, the environment dimension (i.e. CO_2 emissions as a representative indicator) is the only one that always has a positive correlation with the other dimensions, except energy availability. This can be translated as a generally positive impact of prioritising the environment dimension in energy security performance, as it also positively contributes to improving the other dimensions. The governance (i.e. community formation time as a representative indicator) is the only dimension that does not show any strong or moderate correlation with other energy security dimensions. It is important to note that this does not imply that it is not an important dimension, as explained in the next section and as emphasised in studies such as [1,71].

4.2. Contribution of each dimension to the energy security performance

To be able to prioritise energy security dimensions and explore their importance, the contribution of each dimension to high and low energy security performances is explored. To provide such analysis, the communities are labelled as having high or low energy security performance through the following procedure, as suggested in [12]:

- ❖ High performance: Across all simulated CESs (as presented in Section 2.2., 48,600 CESs in total), the ones that fall within the top 60 % performing of all seven energy security dimensions are selected as the highest-performing ones. This selection led to 498 CESs in total.
- ❖ Low performance: The worst-performing communities are selected across all dimensions through the same process (the CESs that fall within the low 60 % of all 48,600 CESs across all the runs), leading to 605 CESs.

In the next step, the contribution of each dimension separately for these high and low energy security performances is calculated based on the Extra Trees process, as explained in Section 2. Fig. 5 presents the prioritisation of each dimension on high and low energy security performances as an output of the Extra Trees process, where the colours represent the strength of the contributions (i.e., darker red represents larger contributions, while darker blue represents smaller contributions).

Infrastructure is the dimension that contributes most to identifying CESs with high energy security performance, while governance is the most impactful dimension for determining low energy security performance. This can be translated as prioritising a proper and reliable infrastructure (in this case, diversity in energy resources) over other dimensions, potentially leading to higher energy security performance. On the other hand, not having a proper and functional governance system would potentially lead to lower energy security performance

Fig. 4. Bivariate correlation between energy security dimensions using Pearson correlation coefficient.

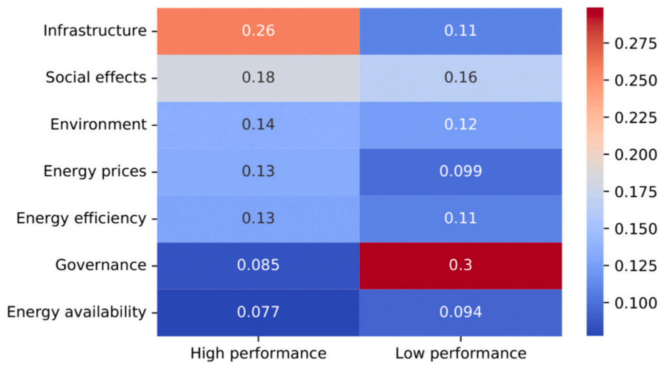

Fig. 5. Extra Trees results for seven energy security dimensions.

among all the dimensions. In other words, if a specific CES has low performance in governance and struggles with it (in this case, with a longer time to establish), it will face energy security issues later on. Therefore, the governance dimension (i.e., community formation time as a representative indicator) needs to be prioritised to avoid low energy security performance. In addition to these two dimensions, societal effects, environment, and energy efficiency also showed approximately the same contribution in identifying high and low energy security performances.

4.3. Influence of dimensions' integration on energy security assessments

This section explores five well-known energy security concepts (with their respective unique set of dimensions) and their influence on energy security assessments. This step provides further insights and examples on how the prioritisation and set of energy security dimensions could influence energy security assessments.

In this analysis, for each of the energy security concepts, through the same process explained in Section 4.2. (60 % of CESs with high and low performance in all seven dimensions), the CESs with high and low energy security performances are identified. Table 4 shows the number of CESs with high and low energy security performances for each energy security concept.

The observations and insights from Table 4 can be categorised into three main points. Firstly, using different energy security concepts considerably influences the number of identified high and low energy security performances. This was expected, as the dimensions' set is different; however, the differences between using different energy security concepts are considerable. For instance, using the energy security concept presented in [82] led to identifying 7873 CESs as having high energy security performance, which is almost 16 times higher than using the energy security concept presented in [1] (7873/ 498 = 15.81). This emphasises the considerable influence of the concepts on energy security assessments and, therefore, highlights the need for well-structured and transparent reasoning and explanation on using a concept in an energy security assessment study.

Table 4
Influence of energy security dimensions on high and low energy security performances.

Energy security concepts		[1]	[74]	[72]	[82]	[83]
Dimensions	Energy availability	X	X	X	X	X
	Infrastructure	X		X		X
	Energy prices	X	X	X	X	X
	Societal effects	X				
	Environment	X	X	X	X	
	Governance	X	X			
	Energy efficiency	X	X		X	
Number of CESs	High energy security performance	498	5046	2907	7873	4551
	Low energy security performance	605	1552	3792	8777	4743
	The ratio of high to low performances	0.82	3.25	0.77	0.90	0.96

Another observation is related to the influence of the number of dimensions in each concept on the results. For instance, results (i.e., the number of CESs of high and low energy security performances) from the energy security concept in [83], with the lowest number of dimensions (3 dimensions), are less than concepts such as [74,82] with 5 and 4 dimensions. Furthermore, two energy security concepts with four dimensions, [72,82], differ considerably in the number of CESs with high and low energy security performances. Therefore, a lower number of dimensions (which can be translated as fewer constraints for identifying high and low energy security performances) does not necessarily lead to larger numbers or ratios. This also emphasises that not all the dimensions have an equal influence.

Lastly, Table 4 also presents the ratio of high to low energy security performances. In practical terms, this ratio shows the probability of categorising an energy system as having a high energy security performance or a low energy security performance in the energy security assessments. This ratio stays almost the same and is always lower than 1 (between 0.77 and 0.96), which shows for most of the concepts (4 out of 5) that there is a larger portion of CESs with low energy security performance. The energy security presented in [74] is the only concept in which the number of CESs with high energy security performance is larger than the CESs with low energy security performance (ratio = 3.25). Considering that all these five energy security concepts analysed the same results (i.e., the data set of 48,600 CESs, see Section 2), [74] seems to be the most suitable existing concept for performing energy security assessments of community energy systems. However, it is important to keep in mind that this concept does not include the most important dimension of energy security, namely infrastructure.

5. Discussion and conclusions

Energy security is one of the most studied topics in energy-related literature. In this literature, various dimensions are suggested for conceptualising and assessing energy security; however, the importance and prioritisation of these dimensions have not been investigated. This is a vital consideration, as socio-technical-economic considerations and available resources (e.g. public funding and subsidies, space limitation, energy independence concerns and environmental conservation) make it infeasible to improve all these dimensions simultaneously. Therefore, this study investigated the contribution and prioritisation of different dimensions in measuring and assessing energy security, particularly in the context of community energy systems (CESs) as alternative and emerging energy systems.

First, the literature review revealed limited literature on CESs energy security, with only 29 peer-reviewed English articles. The analysis demonstrated that two dimensions, namely energy availability and infrastructure, are the most studied dimensions in this branch of literature. Such emphasis on these dimensions aligns with the mainstream energy security literature, where the security of supply and technological configurations are studied extensively. In contrast, the energy efficiency and environment dimensions have not received any attention in the CES's energy security literature. Societal effects also received minimal attention. Therefore, the current study highlights the knowledge gap and the need for studying these dimensions in the context of CESs' energy security.

Second, an existing ABM was used to demonstrate the importance of dimensions for energy security assessments and prioritisation. This analysis showed that infrastructure and governance are the most important dimensions for identifying CESs with high and low energy security performances. As infrastructure and governance do not have a considerable correlation with each other, they both need to be prioritised in developing and implementing such collective energy systems. Particularly, as governance is important for avoiding low energy security performances and does not correlate with any other dimensions, it requires special attention.

Furthermore, the societal effects (i.e. average community benefit per household as its indicator) and environment (i.e. average CO_2 emission per household as its indicator) also showed considerable contributions to identifying high and low energy security performances. At the same time, they correlate more with other energy security dimensions (e.g. the strong positive correlation between societal effects and energy prices), which means prioritising them could positively contribute to overall energy security performance assessments. Therefore, the study concludes that infrastructure, governance, environment and societal effects are the most influential dimensions for assessing CESs' energy security, and they need to be prioritised. This conclusion highlights the importance of these four dimensions rather than excluding other dimensions (i.e. energy availability, energy prices and energy efficiency).

Lastly, as presented in Section 4.3., five well-known energy security concepts (with their unique set of dimensions) were explored to study the impact of the theoretical conceptualisation of energy security on its assessment. The results demonstrated a high sensitivity to the chosen concept. The energy security concept presented in [74] (composed of energy availability, energy prices, energy efficiency, governance, and environment dimensions) is the most suitable existing energy security concept for assessing and measuring CESs' energy security.

By investigating the correlations, importance and trade-offs between energy security dimensions, the study contributed to the body of literature on energy security and CESs. By its structured approach and concrete insights, the findings would draw a broader picture of (CESs') energy security to help the stakeholders (particularly the policy-makers) in their decision-making processes, as there are various energy security dimensions and concepts. As trade-offs always exist in CESs' establishing and functioning, prioritising energy security dimensions would contribute to easing such decision-making processes.

5.1. Limitations

This research had a structured approach to studying the importance and prioritisation of energy security dimensions; however, it has certain limitations that must be kept in mind. Such limitations could also be seen as avenues for future research.

First, the research focused on community energy systems as collective and decentralised energy systems. Although this choice was deliberate (to bring more insights into such alternative energy systems, which are gaining momentum), the findings are useful for any other energy system. The finding also needs to be investigated in the context of other energy systems, such as national and integrated energy systems. As other energy systems might have different characteristics, such an investigation could widen the horizon of the current findings.

Second, the literature review has its own limitations. It should also be noted that the selection of keywords plays a crucial role in the investigated literature. As explained in Section 2.1., the keywords are deliberately chosen to focus on peer-reviewed literature on CESs' energy security. However, if the scope is to be extended beyond CESs, other keywords such as “energy systems”, “energy supply”, “renewable energy”, “national grid”, and “complex energy systems” could potentially help focus on a broader picture. Also, future research could focus on a specific technology and resource (e.g. solar, geothermal and natural gas) and, therefore, use the representative keywords. The literature used in this study included only peer-reviewed articles; however, there could be possibly valuable materials in conference papers, graduate theses, and reports published by academic and non-academic organisations. For future research, including such grey literature could further develop the current work.

Third, choosing ABMS as a research approach has limitations. Like any other modelling approach, ABMS presents a simplified version of real-world systems. As the real world is somewhat more complicated, other research methods, including optimisation, equilibrium modelling and serious gaming, could be beneficial in addition to the presented ABMS. Also, collecting empirical data through case studies, questionnaires, and interviews could broaden the picture of prioritising energy security dimensions (in the context of CESs).

Lastly, the specific agent-based model used in this study has its own assumptions, artefacts and limitations. For instance, in this model, instead of having one energy security indicator for each of the seven energy security dimensions (seven indicators in total), the modelling exercise could include two indicators per dimension and, therefore, fourteen energy security indicators in total. Using two or several indicators for the same energy security dimension can be translated to approaching that dimension from different angles, potentially leading to a more comprehensive/ extensive understanding of the energy security dimensions and energy security as a whole. Therefore, it could contribute to capturing more realistic trade-offs. Furthermore, when a household decides to invest in an individual thermal heating system, it increases its own costs while increasing its energy diversity (by adding a new renewable thermal energy system) and its insulation (by increasing its insulation one step further). Therefore, while it influences energy security performance as a whole, it negatively impacts cost and positively impacts diversity and thermal insulation. The detailed elaboration on these artefacts, assumptions and the model are presented in [12].

5.2. Research agenda and recommendations

Following the literature review's results presented in Section 3 and the ABM statistical analysis results presented in Section 4, the following research agenda is suggested:

- ❖ Overall, the CESs' energy security is a limited literature that needs further exploration. As energy security is an important consideration for any energy system, there is a need for an urgent and constructive approach to this knowledge gap.
- ❖ In particular, four dimensions, namely, energy efficiency, governance, environment, and societal effects, need to be explored in more detail as they received the least attention in the literature, in contrast with their relatively high contribution in identifying high and low energy security performances.
- ❖ Different energy security indicators need to be explored in the context of CESs. The starting point could be indicators of the well-studied dimensions such as energy availability and infrastructure (e.g., self-sufficiency, energy consumption rates and energy diversity; however, it needs to be expanded to the other dimensions and their indicators.
- ❖ There is a need to explore the prioritisation of energy security dimensions in other contexts (e.g. national energy systems) or by using different energy modelling approaches (e.g. optimisation and equilibrium modelling).

Based on the results and the findings (and considering the limitations discussed in Section 5.1.), the following recommendations are formulated:

- ❖ Among all energy security dimensions, the infrastructure dimension is recommended to be prioritised, as it is the most influential dimension for high energy security performance,
- ❖ The environment dimension also needs to be prioritised, as it is the only dimension that positively correlates with most of the dimensions and, therefore, could contribute to improving energy security performance.
- ❖ CESs' actors should pay considerable attention to their governance structure to prevent low energy security performance.
- ❖ It is also encouraged to prioritise the societal effects dimension in the energy security assessments as it contributes to high and low energy

security performances along with their (strong) correlations with the other dimensions.

To conclude, the study suggests these four dimensions, namely infrastructure, environment, governance and societal effects, as an alternative energy security concept for studying and assessing the energy security of CESs. Using the concept presented in [74] is recommended to study and assess the CESs' energy security among the already available energy security concepts. Although the study systematically approached the contribution and prioritisation of different dimensions in measuring and assessing CESs' energy security and provided its results, conclusions, and recommendations constructively, it is crucial to keep in mind that it is the first attempt of its kind. Energy security is important for any energy system, particularly for CESs as alternative, collective, and renewable energy systems, which are gaining momentum. There is a need for further constructive and comprehensive studies on measuring and prioritising the energy security of CESs. Therefore, the insights and limitations of this work could also be seen as avenues for further research. Although the study is primarily focused on CESs, the findings and recommendations are also useful for the broader context of energy systems.

CRediT authorship contribution statement

Javanshir Fouladvand: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Yasin Sarı:** Writing – review & editing, Visualization, Software, Methodology. **Amineh Ghorbani:** Writing – review & editing, Validation, Formal analysis.

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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