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Review

Why and how can agent-based modelling be applied to community energy systems? A systematic and critical review

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A R T I C L E I N F O

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A B S T R A C T

Community energy systems (CESs) are key elements for the local energy transition and are receiving considerable attention. In this context, agent-based modelling and simulation (ABMS) is becoming one of the prominent computational modelling approaches for studying CESs. However, no systematic and critical review of such models has been conducted. Therefore, this study investigates the studies that used ABMS to study CESs, comprehensively analyse and structure this branch of literature, and suggest future research avenues. The six following elements from the Overview, Design concepts and Details (ODD) are used: (i) modelling purposes, (ii) agents and their variables, (iii) concepts and theories, (iv) initialisation and narrative, (v) network structures and interactions, and (vi) input data. The analysis demonstrated that particular purposes (e.g. social learning) and specific agents (e.g., energy companies) are neglected in the modelling practices. Furthermore, the developed ABMS are mainly focused on economic discipline, including topics such as local market design, and topics related to environmental and behavioural/institutional disciplines are largely missing. Such domination also reflects on the narratives and the networks used in the modelling. The most studied cases are focused on European countries and electricity-generating CESs based on solar photovoltaics. Further insights and future research avenues are elaborated on in detail.

1. Introduction

Local community initiatives for renewable energy resources, namely community energy systems (CESs), are considered key elements for the local energy transition [1]. Although there are different definitions in the literature (e.g. [2,3]), CES is a term used to represent initiatives that aim to generate, distribute and consume renewable energy resources (with energy-saving measures) locally for all involved participants [4,5]. In other words, CESs can be defined as individual households in an urban neighbourhood who jointly invest in renewable energy technologies (RETs) and generate the energy they consume [6]. The essence of such an initiative is the individuals' joint effort and collective action to address their energy-related issues [6,7].

Therefore, in addition to technical design and configuration, participants' behavioural attributes, motivations and decision-making processes are decisive for the establishment and functioning of CESs, and various studies explore such topics in this context (e.g. [8–10]). For instance, the socio-psychological factors that influence the participation of individuals in a CES are studied in [10]. The impact of households' environmentally friendly behaviour on greenhouse gas emissions and climate change mitigation in the residential sector are also investigated in [11,12]. An overview of the required conditions for flourishing energy communities for heating purposes in Europe is provided in [13]. As performing such real-world empirical studies would be time-consuming and costly, computational social simulation has been seen as an alternative approach to conducting experiments in a virtual simulation environment [14,15].

Computational social simulation is a well-established field of research [16] at the crossroads between technical design, social sciences, computer sciences, and mathematics [17]. Agent-based modelling and simulation (ABMS) is specifically promising for such research as it facilitates the exploration of artificial societies of autonomous agents as representatives of the real world [18,19]. Like other modelling practices, ABMS represents a simplified version of reality [20]. In an

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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" [21]. Agents are heterogeneous, autonomous and individual decision-making entities (such as individual households) that can learn and interact with each other and their environment [18,22]. In addition, ABMS also provides the opportunity to explore the emergent behaviour of the system [20]. Emergence relates to the notion of "the behaviour of the system", which results from individual actors' behaviour on lower levels and their interactions [20]. Moreover, ABMS provides the ability to add the temporal scale, which allows for examining different scenarios throughout time [19,20].

For these reasons, different studies, such as [23,24], used ABMS to study various topics in the energy literature, specifically in the context of CESs. For instance, multi-agent modelling was employed in [25] to analyse the energy-saving behaviour of urban residents in China. Another ABMS is presented in [23] to study the energy security of thermal energy communities. Studies such as [24,26] also employed ABMS to explore the influence of institutional settings and leadership on the establishment and functioning of (thermal) energy communities.

Although using ABMS to study CESs is becoming more prominent, no systematic and critical review of such studies has been conducted to date. Few studies provide an overview of the developed ABMS in the broader energy-related literature. For instance, a structure and analysis of the studies that employed ABMS to study complexities in the energy transition is presented in [27]. Different climate-energy policies aimed at emissions reduction, product and technology diffusion, and energy conservation are presented in [28]. A review of ABMS with a focus on the adaptation of energy efficiency by households is presented in [29], while [30] provides a review of ABMS for decarbonising urban district energy systems. A deliberate overview of ABMS for urban neighbourhoods is presented in [31]. However, none of these studies focuses specifically on CESs; therefore, none investigate the state of the art of employing ABMS to study CESs.

On the other hand, few studies, such as [32,33], focusing on the application of ABMS for CESs are limited to peer-to-peer (P2P) electricity networks within smart communities rather than focusing on CESs as collective energy systems with electricity and heating applications. Furthermore, such studies mainly focus on the energy-related insights these models brought to light rather than the model and modelling approach. Such studies are missing an investigation on identifying modelling strengths and gaps that could be addressed in future research.

However, to address this gap, it is necessary to analyse, navigate and reflect on this branch of literature and provide recommendations as future research avenues. Therefore, this paper aims to outline and structure the existing studies on CESs, which employ ABMS as their modelling approach, to delineate why and how ABMS is applied to studying CESs. The research question is formulated as follows: "How has ABMS been applied to studying community energy systems as collective, local and renewable energy systems?". To achieve this goal and answer the research question, with the emphasis on the ABMS as a modelling approach, the Overview, Design concepts and Details (ODD) [34] is used to structure and analyse the literature. The ODD protocol is a well-known protocol in computational social simulation for standardising the model descriptions [34]; therefore, it could also be highly instrumental in structuring the literature.

The structure of the paper is as follows. After this introduction, Section 2 elaborates on the research approach, mainly systematically collecting literature and adapting the ODD protocol. Section 3 provides structuring and analyses of the literature. Section 4 delineates the discussion and analysis. Conclusions and future research avenues are presented in Section 5.

2. Research approach

This section first explains the approach to finding the literature and selecting the studies to be included in the literature review based on studies such as [35,36]. Secondly, the Overview, Design concepts and Details (ODD) protocol [37] and its operationalisation for this research are presented for structuring the literature.

2.1. Literature review

An extensive literature search was conducted on computer modelling and simulation of CESs. This literature review was based on material collected from www.webofknowledge.com and www.scopus.com that were published by the beginning of August 2023, using combinations of keywords as presented in Table 1.

Following studies such as [38,39], the choice of keywords is to cover the studies on the collective, small-scale and bottom-up renewable energy systems (e.g. "energy community", "energy cooperative", "energy initiative", "local energy system", "distributed energy system", and "decentralised energy system"). To focus on the CESs' concept as an alternative, decentralised and collective energy system, rather than only emphasising renewable energy technologies or specific applications (e.g., electricity or heat), the keywords did not include a specific technology or resource (e.g., solar photovoltaic, electricity and district heating). All these 65 documents were considered initially, and their abstracts, keywords, and introductions were carefully studied. However, since the goal of this study is to provide a critical overview and suggest research avenues for studying CESs while using ABMS, the study deliberately left out research that does not address the bottom-up and collective nature of these systems (e.g., [40–44]). For instance, studies that focus on the decision-making of other actors (e.g., policy-makers, investors and community boards) do not specifically model the collective action households (e.g., [40,41]). Several studies, such as [42,44], employed ABMS to optimise a specific parameter (e.g., energy costs and generation) rather than collective action's aspects (e.g., behaviours and regulations); therefore, they are left out. Furthermore, studies such as [45] that provide a general framework rather than present a specific model are also left out. Lastly, literature reviews such as [46] and conference reports (that only provide an overview of all presentations) are excluded. To summarise, studies that did not specifically discuss the social aspects (e.g., collective action), dynamics and interactions within CESs are not taken into account. After all these step-by-step systematic scoping, 40 peer-reviewed English articles (including scientific journals and conference proceedings) were left for final careful consideration, as demonstrated in Fig. 1. After carefully studying these 40 articles, they are structured and analysed systematically using the ODD protocol.

Table 1
Keywords.

Combination of the keywords	Number of articles
"agent-based" AND "energy community"	43
"agent-based" AND "energy initiative"	3
"agent-based" AND "energy cooperative"	1
"agent-based" AND "local energy system"	5
"agent-based" AND "distributed energy system"	14
"agent-based" AND "decentralised energy system"	4
Total, excluding the duplicates	65

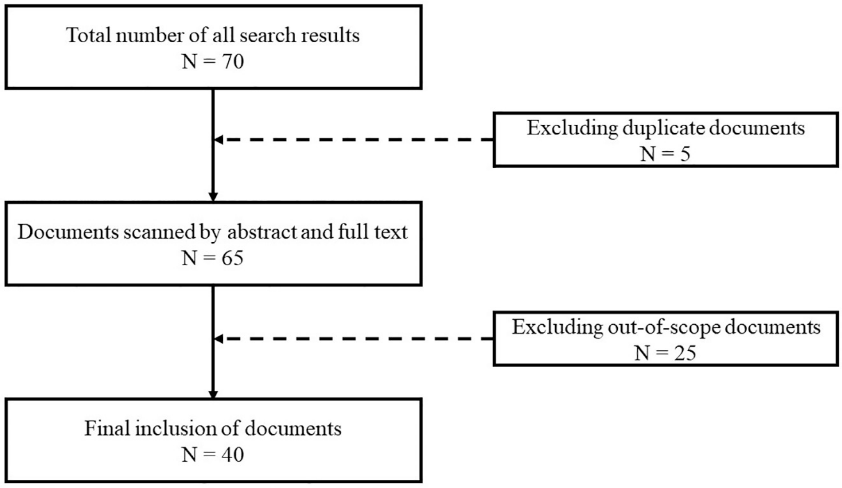

Fig. 1. Prisma Flow diagram literature search.

2.2. *The ODD protocol a framework for describing ABMS*

The Overview, Design concepts and Details (ODD) protocol is a recently developed protocol aiming to standardise the description of ABMS and other simulation models [37]. The ODD protocol is a well-known and accepted approach to documenting such models [34]. This protocol consists of three blocks (Overview, Design concepts, and Details) [37], which cover elements such as the model's purpose(s), variables and scales, concepts and inputs [47]. Later on, the ODD + D protocol, which includes human decision-making in detail, is also presented as an extended version of the ODD protocol [47], which includes (i) the modelling implementation details and (ii) further details on explaining and discussing the human decision-making processes [47].

By using the ODD protocol, several studies in the CES literature, such as [48–50], described their ABMS. Few studies with a focus on using ABMS to study CESs in urban areas also employed the ODD + D protocol for describing their models (e.g., [51,52]). Compared to the available frameworks for describing and structuring the ABMS, such as MAIA [53], Mesa [54] and the Matrix [54], the ODD protocol is employed more in this branch of literature and could be more instrumental. Furthermore, along with the structured freedom that the ODD protocol offers to describe the models and their higher popularity in the literature (compared to the ODD + D protocol), and following [34], which argues that the essence and purposes of using such a protocol continue to be persistent, the current study employs the ODD protocol to structure the literature. This aligns with this research's goal of delineating why and how ABMS is applied to studying CESs. Furthermore, studies such as [30,31,55] also argued for employing the ODD protocol for structuring their respective literature reviews.

However, as presented in [30,31], most of the developed ABMS in the energy-related literature do not follow the ODD protocol in their modelling description. This limitation implies speculation for interpreting different modelling elements for structuring and analysing them through ODD protocol building blocks. For instance, not all the studies followed the ODD protocol to clearly and structurally describe their design concept (e.g., emergence, fitness and stochasticity). In order to analyse and structure the studies fitting such design concepts, there is a need for hypothesizing to some extent the modeller's intentions and conceptualisation, which might be deviated (even being too far) from their initial intention. However, structuring and analysing the decision-making points and processes (i.e., narrative) and the concepts and theories (including the disciplines that the modelling are contexed in), could provide the necessary overview. In order to avoid such speculations and minimise their influence, the adaption of the ODD protocol seems to be necessary; therefore, the following elements from the ODD protocol (and also the ODD + D protocol) are included in this study: (i) Modelling purpose (i.e., goals and reasons for employing computer modelling), (ii) Agents and their variables (i.e., different types of entities represented in the model), (iii) Concepts and theories (i.e., different design concepts and approaches implemented in the model), (iv) Initialisation and narrative (i.e., different decision makings and implementation details), (v) Network structures and interactions (i.e., interactions, dynamic and learning between agents), and (vi) Input data (i.e., the context that the modelling take place in and the required data).

Table 2
Elements adopted from the ODD protocol.

Elements	Short explanation and reason
Modelling purpose	Goals and reasons for employing computer modelling
Agents and their variables	Different types of entities represented in the model
Concepts and theories	As an indication for process overview and design concepts
Initialisation and narrative	To understand the processes within the model, key decision-making points and the basis of interactions
Network structures and interactions	Conceptualising and determining how the agents interact and influence each other
Input data	As an indication for the initialisation and final application

Considering that these six elements cover all three main building blocks of the ODD protocol (i.e., Overview, Design concepts, and Details), as presented in [34,37], they can be seen as an adapted version of the ODD protocol. As the study aims to provide an overview of the literature to provide insights on how the ABMS is applied on CESs (and does not delve into all details of each model), such adaption (i.e., including only these six elements) offers the necessary structure without rigidness to analyse and study the models that did not employ ODD protocol initially. Furthermore, studies such as [48] used the same elements to describe their ABMS. Table 2 provides an overview of the six elements inspired by and adapted from the ODD protocol for this study.

3. Structuring and analysing the literature

This section presents an overview of the 40 selected articles that employed agent-based modelling and simulation (ABMS) for studying CESs. As presented in Section 2, following the ODD protocol, the six following elements are used in structuring and analysing the literature: (i) modelling purposes, (ii) agents and their variables, (iii) concepts and theories, (iv) initialisation and narrative, (v) network structures and interactions, and (vi) input data.

Before going into the structuring and analysing the literature, an

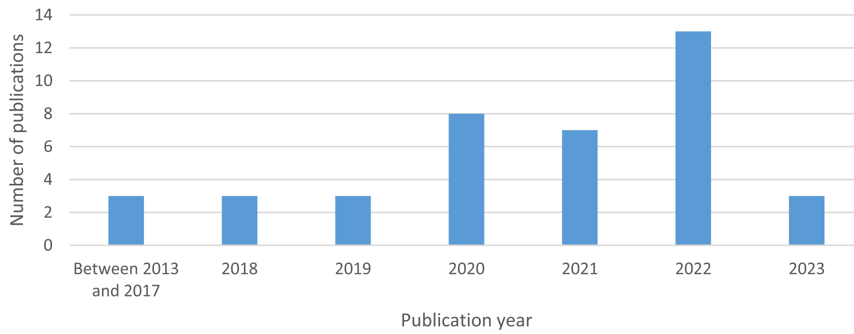

Fig. 2. Timeline of published articles.

overview of the publication time of these studies is presented. This branch of literature is relatively new; the oldest study was published in 2013 (i.e., [56]). The number of studies related to this branch of literature has grown rapidly in recent years. As Fig. 2 demonstrates, 40 % of all studies (16 articles) were published in the last 2 years from 2022 onwards.

3.1. Modelling purposes

The modelling purpose is about the main reason and aim that a model and simulation is developed to study. There are various purposes for developing a model and simulation (such as ABMS), as [15] conceptualise such purposes in seven categories: (i) prediction, (ii) explanation, (iii) description, (iv) theoretical exploration, (v) illustration, (vi) analogy, and (vii) social learning. Although all the studies were reviewed carefully, they did not explicitly and clearly specify their modelling purpose (mainly because they do not follow frameworks such as the ODD protocol for describing their models). Therefore, each model and manuscript needed to be read carefully and assigned to a modelling purpose. The first four modelling purposes are the only ones that are identified in the literature.

First, the models presented as decision-making and estimation/measurement tools are considered ABMS with prediction purposes. Also, the models (and the studies) are focused on forecasting different aspects related to the establishment and functioning of CESs. For instance, a simulator to support developing and evaluating pro-social energy management schemes in CESs is presented in [57]. A model that can be used to quantify the real-world performance of microgrids with peer-to-peer (P2P) trading, and therefore, it can serve as an emulation tool for microgrid projects, was developed in [58]. A tool to model heating and electricity networks integrated with cogeneration units and solar photovoltaic (solar PV) installed in urban areas is presented in [59]. Such a tool can be used for (i) energy flow management and power sizes of both heating and electric networks and (ii) evaluation of the electricity sharing configurations arising within energy communities. As a decision support tool to simulate energy transactions in local and national energy markets, [60] presents an ABMS for CESs with solar PV and batteries. Also, an ABMS was presented in [61] to validate and estimate the agents' interactions and electricity export/import of CESs.

Secondly, various studies have an explanation purpose, which aims to understand and explain agents' behaviour within a system, leading to the emergence of the system's behaviour. Furthermore, studies explaining the use of a specific technology for establishing and functioning CESs are also related to the modelling purpose of explanation. For instance, the effects of increased participation on the establishment and function of CESs based on solar energy are examined in [62]. An ABMS is presented in [63] to analyse the expected socio-economic outcomes from a local energy market operation under a double-sided auction with uniform pricing. Another agent-based model explaining the strategies and interactions in an energy-sharing community where each agent individually and collectively attempts to maximise renewable energy self-consumption is presented in [64]. The use of storage systems in the CESs' performances is explained in [65], while [66] focuses on net-zero energy communities based on solar energy in urban areas. Different factors influencing thermal energy communities' formation and functioning are explored in [5]. An ABMS is presented in [67] to explain the role and influence of prosumers in local and national electricity systems. The ABMS developed in [48] aims to explore and explain how the behavioural attributes of CES participants influence collective energy security by employing ABMS.

For the third category, the mathematical models and their development frameworks, aiming to represent what is important for a specific case, can be seen as models with description purposes. For instance, a description of an ABMS and framework for local market cleaning mechanisms and a specific bidding strategy (i.e., interval-based) for CESs is presented in [68], while [69] proposes a model and framework for the P2P business model for CESs. In addition, a self-organised multi-agent framework for autonomous charging and discharging electric vehicles to maximise self-consumption within CESs is discussed in detail in [70]. An open-source framework and model are presented in [71] for multi-agent systems able to work in simulated, emulated, and real environments that can be used in the several steps of the creation of new smart grid management models: conception, testing, validation, demonstration in pilots, and real deployment.

Furthermore, studies demonstrating the integration of novel approaches and methods in the ABMS could also potentially be considered for description purposes. For example, the ABMS presented in [56] describes two recent research approaches for the geo-localised simulation of heat energy demand in cities based on 3D morphological data and spatially explicit model to simulate smart grids. An integrated ABMS and GIS model for investigating solar energy in CESs is presented in [72]. A novel incentive-compatible scheme for CESs to achieve a collective goal of reducing price risk for the participants while enabling the prospect of reduced average price for individual consumers is described in [73]. By combining ABMS and other approaches (such as digital twins), studies such as [74,75] aim to demonstrate the use of collaborative behaviours and networks. By using deep reinforcement learning to optimise the participation of agents in a local energy market and a P2P market, [76] demonstrates a new method to approach CESs. A novel model of opinion formation that has higher applicability and validity regarding opinion formation within CESs is developed in [77], while [78] presents a hierarchical model for the organisation of ABMS in CESs and local energy markets. By developing ABMS, studies such as [79,80] also described new configurations and insights related to local energy markets and systems.

Lastly, there are several studies with the purpose of (theoretical) exploration, aiming to explore and test hypotheses. Such studies investigate "what if" questions to bring insights into the establishment and functioning of CESs. For instance, the concept of energy security in CESs is explored in [50] and later on [23] contributes to having a more comprehensive understanding of energy security in CESs by integrally looking at energy security, going beyond the mere security of supply in

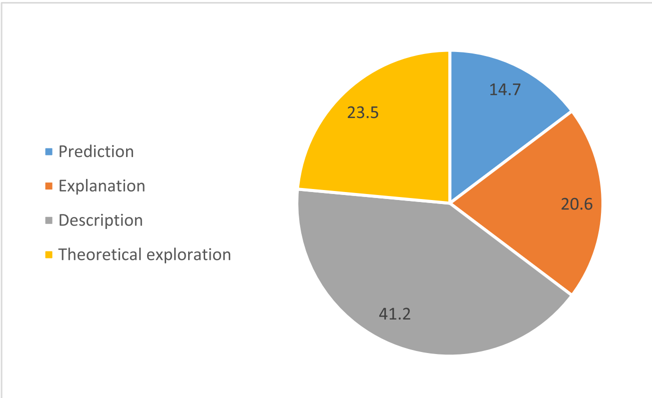

Fig. 3. Overview of modelling purposes in percentages (%).

these systems. To explore capability conflicts in deploying decentralised energy systems and identify the affected population, an ABMS is demonstrated in [51]. An exploratory study on the creation and evolution of Smart Grid Social Networks using ABMS is presented in [81]. The role of community leaders and the behavioural factors that influence the emergence of local energy initiatives are explored in [26]. To explore the different technical and institutional conditions that could potentially influence the formation of CESs, a detailed explorative ABMS is developed in [24]. Different market regulations and household interactions are explored and evaluated in [82]. The distribution of the four identified modelling purposes is presented in Fig. 3.

Although this branch of literature is growing fast, different models and their modelling purposes are presented; three modelling purposes are missing: illustration, analogy, and social learning. The modelling purpose of illustration potentially includes using ABMS to communicate and validate different parameters, theories and hypotheses related to the CES concept. The modelling purpose of analogy involves using ABMS to draw parallels with other, more familiar complex (energy) systems to enhance understanding and make inferences in CESs more clearly. Social learning refers to using ABMS (and the model development process) to encapsulate a shared understanding of a group of people (e.g., households) regarding the CESs. Social learning would contribute to the learning and adapting participants' behaviours over time to enhance the interactions in the real world. Missing these three purposes can translate to a lack of knowledge and understanding of their contributions to this branch of literature.

3.2. Agents

Agents are autonomous and heterogeneous entities that interact with each other (and their environment), learn and make decisions [18,22]. Such entities mostly represent different actors within a system [24]. In the specific case of CESs, various actors are involved, such as individual households, policy-makers, energy companies, and energy distributors (as presented in [83,84]). In studies that employed the ABMS to investigate CESs, the following three types of agents are identified: (i) households, (ii) municipalities/local policy-makers, and (iii) community boards/community leaders.

As the focus of CESs is on the collective action of individual households, all the studies included individual households in their ABMS. Therefore, individual households are the dominating category of agents within this branch of literature. However, the presentation and the number of households are different. For instance, agents presented in [58,60] are two types, consumers and prosumers, who are heterogeneous based on their demand and solar energy generation. On the other hand, the households presented in studies such as [26,48,50], in addition to having different demands, are households that are heterogeneous in their motivations and concerns (e.g. environmental concerns or economic concerns) for joining a CES. The number of individual households in the ABMS also varies; the majority of them are lower than 100 households (e.g. [58,76]). Such studies are more conceptual regarding their application and input data rather than representing a real-world case study. Few studies are focused on a larger number of households, between 100 and 1000 individual households (e.g. [48,50]), which can be seen as focusing on a neighbourhood. On the other hand, few studies have focused on several neighbourhoods (and therefore on a municipal level), which include a larger number of individual households between 1000 and 5000 (e.g. [23,24]).

Depending on the other modelling elements (e.g., modelling purpose, concept, and theories), such households as agents in ABMS have various variables and attributes. For instance, studies such as [23,48], focusing on explaining and exploring certain behavioural and institutional settings, included attributes and behaviours such as trust, energy dependence and environmental friendliness. Although such studies included the technical and economic variables (e.g., energy demand and energy prices) and attributes such as economic-driven behaviour, they did not dive into the tech-economic analysis and trade-off details. Another example is the model presented in [26], which, by including environmental friendliness, general trust and personal gain as drivers, explored the role of behavioural attitudes and leadership in joining CESs. On the other hand, studies such as [58,59,78] delved into the technical and economic disciplines, focusing specifically on agent's variables such as energy demand, energy generation and energy prices, to predict and describe the techno-economic trade-offs for establishment and functioning of CESs.

After households, municipalities and (local) policy-makers are the most studied agents in these models. Such an agent is responsible for decisions such as the amount of the subsidy (e.g. [24,48]), the amount of CO_2 taxes (e.g. [24]), and the subsidy allocation strategies (e.g. [23]). Around 15 % of the studies (i.e., 6 studies) explicitly included the policy-makers as decision-making agents. Lastly, less than 10 % of studies, such as [23,26], explore the role and influence of community board/community leaders on CESs' performances. These particular agents are households that are more motivated to establish and function CESs (e.g., they are more environmentally friendly). As elaborated in these studies, studying such actors through ABMS provided new insights into their decision-making processes and potentially facilitated the establishment and functioning of CESs.

3.3. Concepts and theories

To analyse the concepts and theories, which are the backbone of ABMS (and connected to the design concept ODD framework's building block), they are discussed and structured based on their scientific disciplines. As presented in Section 2.2., this is necessary to avoid unnecessary assumptions, which also contributes to having a more holistic view of such topics, as all studies could be related to such disciplines. Following [38,85], the scientific disciplines related to CESs are categorised into the following four main disciplines: (i) economic, (ii) behavioural/institutional, (iii) technical, and (iv) environmental. The following part discusses and analyses the theories and concepts within each discipline.

The economic discipline dominates this branch of literature. For instance, studies such as [63,78] are focused on the design of local energy markets with a focus on CESs. In more detail, the energy market shocks and their influence on CESs are explored in [58], while [60] focuses on different levels of access tariff exemptions within CESs. A demonstration of the influence of double-blind auction mechanisms on

CES establishment and functioning is presented in [63]. There are also other studies (e.g., [86–88]) related to this discipline, which explores various aspects of energy market design. Local energy markets and energy trading schemes for CESs are explored in [62,82]. Business models for individual PV systems are optimised in [69]. Although optimisation and business models are more of a research approach than concepts or theories, such studies present them in their theoretical background. While the topics in the economic discipline are studied extensively in this branch of literature, vital topics such as studying the different business models are missing.

On the other hand, few studies, such as [24,26,48], investigate the institutional and behavioural settings. Within this discipline, institutional and behavioural theories are used. Several studies did not explicitly discuss their theoretical background (e.g. [5,50]). Others discussed the theories and their contribution to the development of ABMS in detail. In addition to employing a conceptual framework presented in [89] to structure the citizens' willingness to participate in CESs, [26] also used the social value orientation (SVO) theory to categorise the motivations and attributes of individuals [90]. The SVO theory is employed in [48] to study the influence of individuals' motivations and attributes on CES's energy security. Furthermore, a comprehensive ABMS is presented in [24] based on three theories: (i) the Institutional Analysis and Development (IAD) framework [91] to analyse the decision-making processes, (ii) the four-layer model of Williamson [92] to structure the actors, and (iii) the behavioural reasoning theory (BRT) [93] to structure the agent's reasoning for CESs establishment and functioning. Collective action theory, specifically the IAD framework, is also the backbone of other ABMS, such as the one presented in [23]. The theory of Planned behaviour (TPB) is employed in [51,72], while the capability conflicts theories are employed in [94,95] to study value conflicts in CESs.

Lastly, there are also a few studies related to the technical discipline, which are mainly concerned with CES energy management (e.g., [70]) and CES design and operation (e.g., [59]). Furthermore, studies such as [24], which are not purely related to a technical discipline, also bring concrete insights into the CESs' technical configuration for establishing and functioning (thermal) energy communities. On the other hand, although various studies included environmental indicators in their analysis (e.g., CO_2 emissions), there was no study to study the environmental discipline specifically and constructively (e.g., CES's environmental assessment performance).

3.4. Initialisation and narrative

This element mainly focuses on the decision-making processes, the connections and the network between agents. Such decision-making processes are related to the CES establishment and functioning, which, as presented in [23,24], can be divided into the following four main stages: (i) the initiation/idea phase: initial mobilization, visioning and discussing the CES; (ii) the feasibility phase (e.g. technical and financial settings): analysing and building consensus on characteristics on the CES; (iii) the procurement and construction phase: arranging and planning the contracts, finances and infrastructure of the CES; and (iv) the installation, generation and expansion phase: operation and maintenance of the CES. As delineated in the following, each of these phases has its own specific decision-making processes that take place in the real world.

Most of the selected studies only focus on one of the four phases. As the majority of them are focused on economic and financial topics, they are either focused on the feasibility or the installation phases. The main decisions in these two phases are about the energy prices, willingness to pay and the amount of available subsidies. For instance, by focusing on having access to tariffs, [60] explores the economic feasibility of CESs. By focusing on energy market shocks and the CESs' performance, [58] studies installation and energy generation within such energy systems. Although these two phases and their decisions are studied the most, certain decisions have not been included yet. For instance, crucial decision-making such as tenders involving the companies, the allocation of subsidies for each municipality on the national level and techno-spatial planning are missing from this branch of literature.

Furthermore, the only study focusing on the initiation phase by focusing on conflicts that might exist in CESs is [51]. However, studies such as [23,24] explore the entire establishment and functioning processes, the four phases together. For each phase, such studies present a decision-making point, such as willingness to join, choice of energy systems, willingness to pay, and future expansion. However, none of these studies dives into detail about the decision-making processes of the procurement and construction phase (and there is no other study with this specific focus). As the procurement and construction phase is complex, this is a crucial knowledge gap. This phase particularly initiated the decisions regarding obtaining permits, designing, and final agreements for installing CESs (before starting to generate energy), including various actors. The main reason for this neglect could be that energy companies and distributors are not included as the main actors for this specific phase (as explained in Section 3.2.).

3.5. Network structures and interactions

Network structures are vital for social computational modelling approaches, such as ABMS, as they determine how the agents interact and influence each other. From the network and interactions perspective, studies are different, as the interaction between the agents (i.e., households) could be modelled vary, depending on the model structure and modelling purpose. Furthermore, some studies used network typology, network structures and interactions interchangeably. Overall, the following two main types of network structures are identified: peer-to-peer (P2P) [96], small-world networks [97] and, as presented in Fig. 4. P2P is based on the transactions between agents without passing intermediary entities [96]; therefore, it is useful for studying local liberal energy market designs for CESs. The small-world is mainly focused on interactions between agents (e.g., households in a neighbourhood), potentially useful for understanding the collective actions of such systems. The other networks include the negotiation networks (e.g. [98]), the Bayesian network (e.g. [77]) and the collaborative networks (e.g., [99]). Although 40 % of studies (16 out of 40) have not specified their network structure (or network typology), they describe the interactions between agents in detail. (See Fig. 4.)

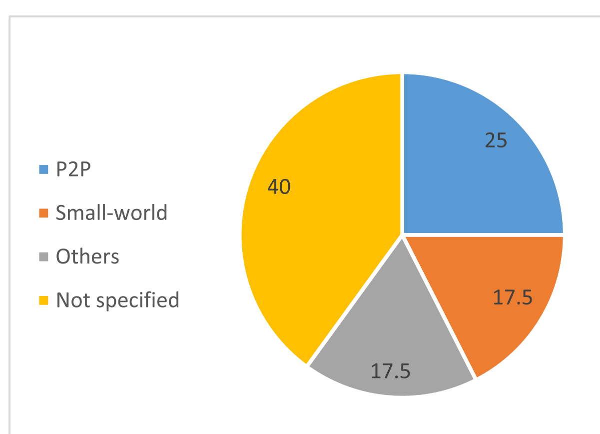

Fig. 4. Overview of employed networks in percentages (%).

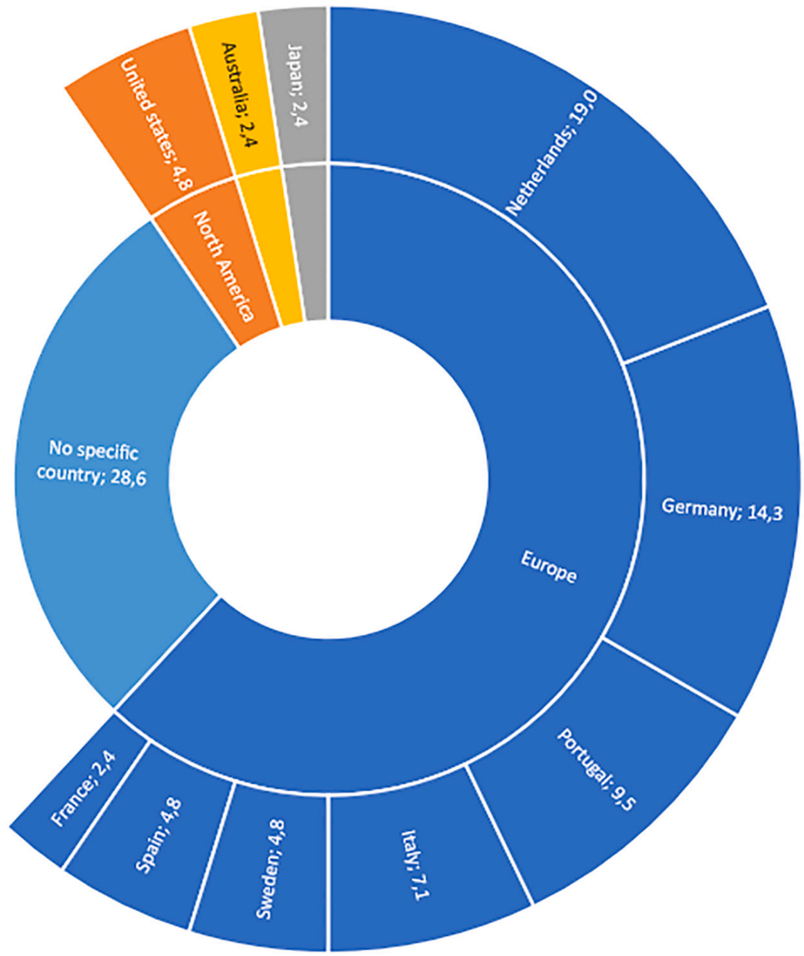

Fig. 5. Overview of studied countries in percentages (%).

3.6. *Input data*

Two categories, namely the geographical location and final applications, are studied to provide an overall understanding of the initialisation and contexts of the ABMS. One focuses on the country as the case study that the ABMS is built in its context (which represents the institutional and behavioural context that the model was built for), and the other focuses on the final application that the ABMS represents (which represents the technical context that the model was built for). As Fig. 5 presents, 62 % of this branch of literature is focused on European countries, which shows their domination in this branch of literature.

Among European countries, the Netherlands (19 %) and Germany (14.3 %) are the countries that are used as case studies (i.e. as input data) the most. This could potentially be related to the many CESs already existing in such countries [100], and therefore, they get more attention in general from academics. After studies with a focus on European countries, with a significant gap, few studies, such as [65,66,77], are focused on the United States of America, Australia and Japan. Such studies applied ABMS in another context (i.e., another region than Europe, with its specific socio-technical conditions), which could also benefit European countries. For instance, the model and results delineated in [77], specifically focusing on the acceptance of geothermal energy in Japan, could be relevant for countries such as the Netherlands, where geothermal is gaining momentum. There are also 12 studies (i.e., approximately 27 % of all studies) that did not specify their country of focus; therefore, their input data are global (or conceptual).

Furthermore, the final application can also be seen as another influential aspect of input data and initialisation. As explained in [13], the CESs as alternative energy systems are focused on providing final energy appliances, mainly electricity and heat. As Fig. 6 demonstrates, among the 40 studies, the majority of them, 77,5 % (31 articles), studying CESs focusing on electricity generation and applications. Within these studies, only [26,98] explicitly include wind energy; the rest mainly focus on solar PV as their renewable energy source. This is in line with previous studies such as [30], which showed that solar PV dominates the ABMS for studying urban district energy systems as their focused technology. 12,5 % of all articles (5 articles) study CESs for heating and cooling purposes (i.e., thermal energy communities), and 10 % are focused on both applications (thorough concepts such as net zero energy communities). This contrasts with a considerable share of thermal energy consumption, between 70 %–75 % of the total energy consumption of (European) households [38].

Finally, as mentioned in other sections (e.g., Section 3.2.), different

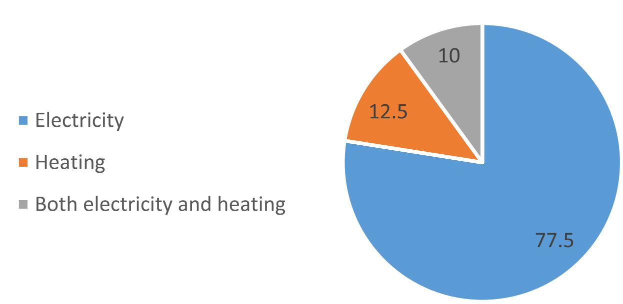

Fig. 6. Overview of types of community energy systems in percentages (%).

parameters and related empirical data were used depending on the location of the case study and final application (and considering other modelling elements, such as the modelling purpose, the agents and design concepts). For instance, the techno-economic models focused on parameters and input data related to energy generation and energy demand. For instance, the input data for studying the local electricity markets used in [87] are overage empirical data on energy demand (TWh), solar PV generation (GW) and aggregated storage (GW). Furthermore, detailed real-world data on Germany's solar PV, public grid, and electric vehicles are used in [58].

On the other hand, studies such as [24,26,48], with a focus on behavioural and institutional settings, along with average technical and economic parameters (e.g., for instance, from sources such as [101,102]), also included parameters and real-world data on energy regulations (e.g., available subsidies and their amount, from sources such as [103]) and behavioural attributes (e.g., parameters for joining CESs, from sources such as [10]). Studies such as [51] also used detailed data on social norms and values to explore the conflicts related to joining CESs.

4. Discussion and conclusions

The literature on community energy systems (CESs) as key entities for the local energy transition is growing fast. One recent commonly used approach for studying CESs is agent-based modelling and simulation (ABMS). This study aimed to structure and analyse the studies that used ABMS for studying CESs, to make a comprehensive overview of this branch of literature, to understand how the ABMS is applied for studying CESs, to highlight the strengths and gaps, and to suggest future research avenues by adapting elements from the Overview, Design concepts and Details (ODD) [37].

The literature review revealed that this branch of literature is relatively new, and a majority of the studies were published during and after 2022 (see Section 3). As presented in different sections such as 3.1., 3.4. and 3.5., there are serious unclarities in the model descriptions. In order to have a useful and valuable ABMS, it should be described clearly. For instance, various studies did not explicitly discuss their modelling purposes or did not clearly describe the interactions between households (i.e., network structures). The studies mainly have the modelling purposes of prediction, explanation, description, or theoretical exploration. However, modelling purposes such as illustration, analogy, and social learning are missing in this literature. Social learning could be particularly beneficial for CES's establishment and functioning as different actors are required to interact with each other in the developing process of a model. From the type of actors, the models are dominated by households, and other actors are under-presented (e.g. energy companies). Such attention was expected, as the study is focused on CESs based on the collective action of individual households. Although individual households are explored extensively, as discussed in the literature (in different studies such as [13,38,104]), the attributes and motivations of the individual households and the related institutions for the collective action still need further exploration.

Furthermore, this overview highlights the minimal attention paid to the actors, such as policy-makers and community leaders/community boards and the lack of attention paid to other actors, such as energy companies and energy distributors. Missing such actors in the ABMS can be seen as a lack of understanding and analysis of the real world. For instance, as elaborated in [105], retrofitting companies are crucial in the local energy transition (i.e., households and neighbourhoods). Another actor gaining importance in the local energy transition is data centres as prosumers [106], which are missing from the studies that applied ABMS. Farmers as manure producers for the biogas infrastructure are also important actors in the energy transition [107], which is missing in this context. Such missing actors in this branch of literature need further attention (as elaborated further in Sections 4 and 5).

While such neglect limits the presented models from capturing the real-world processes, it also reflects on the model's narrative, where particular phases in establishing and functioning CESs, such as the procurement and construction phase, are largely missing. Furthermore, studies mainly focus on economic topics (e.g., local energy market design). In contrast to the vitality of the environmental and behavioural/institutional topics for collective action and the potential that ABMS offers as a modelling approach to study the related interactions, they are largely neglected. Addressing such gaps in the literature requires innovative and rigorous aims (and research questions) to build new ABMS, which could bring insights to light by performing simulations in a virtual environment (e.g., inclusive decision-making processes in the procurement and construction phase).

As discussed in Section 3.5., most studies used peer-to-peer (P2P) as it provides an opportunity to focus mainly on economic and technical aspects with a focus on studying CESs based on interactions of a limited number of households to study local energy markets. In addition to providing the typology for studying the transaction between two specific agents, it also provides the opportunity to study collective action in detail. Other network structures and typologies (such as small-world) have also been identified, which could be more beneficial for studying institutional and behavioural aspects. Although few studies have included other types of agents, such as community boards/community leaders and policy-makers, there is a need for further exploration of various agents (i.e., actors) and their integration into modelling practices.

The studies mainly focus on European countries as their case studies for input data. Particularly, the Netherlands and Germany, by far, have received the most attention. Although the insights of such studies are relevant for other countries (for instance, the importance of the community board/community leaders as explained in [24]), it is crucial to study them specifically as they have unique (socio-technical) characteristics. From a technical point of view, the studies mainly focus on electricity-based CESs with solar PV as the energy source. Other renewable energy technologies and resources, specifically the ones for thermal energy systems such as geothermal valves and biomass, are largely understudied.

Although the study brought insights into this branch of literature and systemically structured and analysed the selected studies, it has certain assumptions and limitations. It should 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 the literature on the CES concept as alternative, local and collective energy systems for households. However, future research could focus on a specific renewable energy technology and resource (e.g. solar and geothermal) and, therefore, use the representative keywords. From the governance perspective, the studies and models with an explicit focus on collective action were analysed. However, other forms, such as energy cooperatives, are excluded from this study (and could also be considered in the future).

From a theoretical point of view, the study's analysis was based on the adaptation of the ODD protocol, as explained in Section 2.2. Although the adoption of the ODD protocol was necessary for this study, depending on the model's description, the entire ODD protocol could be applied to a literature review in future research. Furthermore, other frameworks could be used, particularly MAIA [53], which was developed to help modellers focus on collective action and institutional modelling as a branch of ABMS. The Matrix framework [108], specifically developed for data-intensive simulations, could also be useful. Furthermore, as most of the studies did not follow the ODD protocol to describe their models, assumptions needed to be made, which are all explained in detail in Section 3. Although the arguments and assumptions are clearly stated, future research and further analysis are required to provide further concrete insights.

5. Research agenda and future works

This research aimed to study and structure the literature that employed agent-based modelling and simulation (ABMS) to study community energy systems (CESs). It focuses on why and how ABMS is applied to CESs to highlight the state-of-the-art and propose areas for further research. The study provides a comprehensive and detailed analysis of this branch of literature by looking at different modelling elements through the Overview, Design concepts and Details (ODD) protocol. Such perspective is less highlighted in the literature and led to structurally identifying the areas for further research on CESs from the ABMS perspective and its applications. This is yet another contribution of the current study, as, despite the ODD protocol's proven instrumental descriptive and analytical power for studying social computational simulation models, this protocol has not been used previously to analyse and structure CESs literature. Based on the results and insights, the following recommendations and areas for future research are formulated:

- The researchers are recommended to have more structured and detailed model descriptions of ABMS in their academic studies. Therefore, computer modellers should follow the model descriptive protocols such as the ODD protocol and MAIA framework.
- Computer modellers are encouraged to think of more challenging and less studied questions that could be translated to more diverse modelling purposes. Specifically, illustration, analogy, and social learning purposes are missing and need to be included.
- As the current literature mainly focuses on CESs based on electricity, specifically solar PV (as they are the dominating RETs in this context), other renewable energy resources, technologies and configurations, particularly focusing on heating applications (i.e., thermal energy communities, TECs), need further investigation.
- Current literature lacks a focus on ABMS dedicated to environmental disciplines and indicators. This could contribute to exploring other disciplines, particularly behavioural and institutional topics. Furthermore, institutional and behavioural topics need further investigation to understand and facilitate collective action within such alternative energy systems.
- Along with continuing to study individual households, the literature and the models need to give further attention to policy-makers and community boards/community leaders. Other actors, specifically energy companies, need to be included in the models. These can be translated as a need to study different establishment and functioning phases of CESs in more detail.
- The geographical location of the studies is mainly limited to European countries. Policy-makers, computer modellers and other actors who are studying CESs in other geographical locations and contexts, such as Asian and African countries, are urged to use ABMS as a useful tool.

Along with the mentioned recommendations, which can also be seen as avenues for future research, the limitations mentioned in Section 4 could also be seen as recommendations to be explored. In conclusion, the study and its insights contributed to the literature on (i) computational social simulation, particularly ABMS, and (ii) the literature on community energy systems and complex energy transition as a whole. The study demonstrated the strengths and gaps in applying the ABMS as a power tool for studying CESs. It delved into different modelling elements and how they have been applied to CESs as the conceptual underlying complex (energy) systems. The systematic literature review and the constructive recommendations could be useful for the further development of ABMS. From the theoretical perspective, the novel adaption of the ODD protocol (as presented in Section 2.2.) also contributes to the computational social simulation literature. While diving into details and applications of ABMS (and presenting different modelling purposes and disciplines), the study demonstrates the usefulness of ABMS for studying CESs; it also brings insights (and poses thought-provoking questions) for complex energy systems modellers. Although computer modellers, complex energy system designers and CES practitioners are the primary audiences of this research, the study can also be useful for a broader range of audiences interested in computer modelling and newcomers to the field. By presenting various examples in this branch, the study delineated the use of ABMS for investigating complex socio-technical energy systems such as CESs.

CRediT authorship contribution statement

Javanshir Fouladvand: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

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

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