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Review

Agent-based modelling and socio-technical energy transitions: A systematic literature review

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ABSTRACT

Agent-based modelling has the potential to provide insight into complex energy transition dynamics. Despite a recent emphasis of research on agent-based modelling and on energy transitions, an overview of how the methodology may be of value to understanding transition processes is still missing from the literature. This systematic review evaluates the potential of agent-based modelling to understanding energy transitions from a social-scientific perspective, based on a set of 62 articles. Six topic areas were identified, addressing different components of the energy system: Electricity Market, Consumption Dynamics/ Consumer Behaviour, Policy and Planning, New Technologies/ Innovation, Energy System, Transitions. Distribution of articles across topic areas was indicative of a continuing interest in electricity market related enquiries, and an increasing number of studies in the realm of policy and planning. Based on the relevance of energy transition specific complexities to the choice of ABM as a methodology, four complexity categories (1–4) were identified. Indicating the degree of association between the complexity of energy transitions and ABM's ability to address these, the categorisation revealed that 35 of the 62 studies directly linked the choice of ABM to energy transition complexities (complexity category 1) or were set in the context of energy transitions (complexity category 2). The review further showed that the greatest potential contribution of ABM to energy transition studies lies in its practical application to decision-making in policy and planning. More interdisciplinary collaboration in model development is recommended to address the discrepancy between the relevance of social factors to modelling energy transitions and the ability of the social sciences to make effective use of ABM.

1. Introduction

The notion of energy transitions has become increasingly relevant to policy-makers and academics alike [1], as efforts to reconcile the energy trilemma of affordability, security and environmental sustainability [2,3] have gained momentum over recent years [4]. The importance of technological innovation, and changes to the way energy is utilized, are common themes in the discourse on energy transitions [3] and is most evident in the discussion around renewable sources of energy. Current changes to social aspects of the energy system have also been observed, and include; increasing numbers and variety of stakeholders involved in the energy system [5], the importance of communities in facilitating the process of decentralisation [6], a general growth trend in community-based (energy) strategies [7]. The energy transition is defined here as the agglomeration of these (and related) concurrent trends.

In social scientific transitions research this occurrence of diverse changes to different parts of the energy system has been conceptualised as socio-technical dynamics. One theoretical approach that has been extensively applied to the study of transitions, especially that of energy systems [8], and is well-established in the transitions research community [9], is the multi-level perspective, or MLP [1,10]. The MLP structures the energy system into a multi-level nested hierarchy, in which an external landscape (macro-level), incumbent regimes (meso-level), and technological niches (micro-level) interact [3,4,8] (cf. Fig. 1). As the macro-level encompasses a multitude of possible regimes, which in turn may contain multiple niches, the system is described as a nested hierarchy.

Transitions occur when processes within and between all these levels align [11]. In line with this multi-level conceptualisation, the

Abbreviations: ABM, agent-based model or agent-based modelling; MLP, multi-level perspective; SLR, systematic literature review; TPB, theory of planned behaviour

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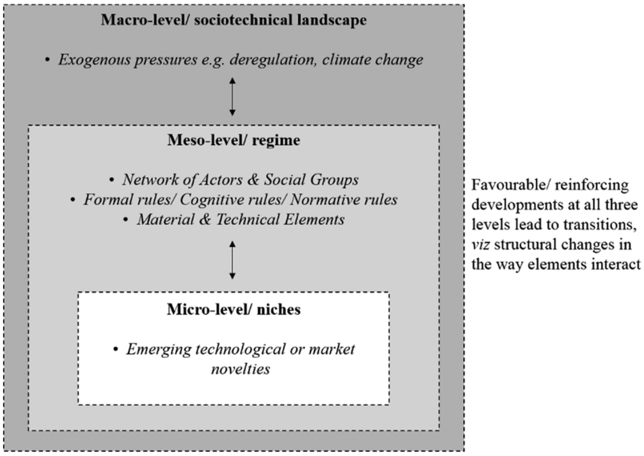


Fig. 1. Conceptualisation of the energy system following the Multi-level Perspective (adapted from [1,10]). As the three levels interact and influence each other, the energy system, in the present study, is understood as the whole of the three levels. This diagram is simplified in that it shows only one regime. However, multiple regimes can exist within the same landscape level.

energy system is understood here as the whole of all levels and their (relevant) constituent components which include networks of social groups and actors (such as household users and utilities); rules; technical and material elements (such as grid infrastructure); external pressures such as climate change [1,8,10]; and technological niches.

The interactions of technological and social system components, influenced by network and governance structures [2], has led to an increasing degree of complexity [5,11] in the energy system. At the same time, solutions to ensuring the sustainability of the energy system need to be multidimensional, involving changes in social, economic, institutional, political and technical spheres [12]. With a rising interest in understanding the dynamics underlying transitions [1] this complexity creates a need for research methods that can account for an individual phenomenon (*e.g.* a social trend in the energy system) as well as emergent phenomena arising from their interplay [2]. Traditionally, transition studies have largely relied on case study analyses [13,14]. Techno-economic approaches have also been employed in view of managing transitions [11]. While valuable insights have been gained from these approaches they are not suitable to addressing the dynamics between micro-level behaviour and macro-level emergence. Especially in techno-economic approaches, the multitude of actors involved in the energy system and its transition, and their decision-making cannot adequately be accounted for [11]. There is thus a need for research methodologies that can address the (increasing) complexity of confluent technical and social phenomena, diverse social actors, and nonlinearity [11].

Agent-based (ABM) modelling is a methodological approach which has the potential to deal with this complexity. As a computational simulation technique, ABM enables the modelling of individual, heterogeneous, autonomous agents – or, decision-making entities [15]. In addition to heterogeneity, a distinct feature of agent-based models is the ability to account for emergent patterns and self-organisation through simulation [16]. In short, ABM allows the modeller to observe the effect of interactions between agents whose behaviour is described (encoded) in simple rules [17]. With its origins in the study of complex adaptive systems, ABM is increasingly being recognised as a suitable tool for studying complex societal challenges such as energy transitions and has been applied across a wide range of academic and professional disciplines [16,17]. An insightful discussion on the synergies between energy studies and complex systems is provided in Bale, Varga and Foxon [2]. The application of ABM to the study of socio-technical systems is particularly promising, as it allows for the co-evolution of technical and social elements of a system, and the results of their interactions, to be modelled [7,18].

In the context of energy transitions, the specification of social and technical elements in a model, as well as the way they interact, may vary greatly. One may for example imagine individual households influencing each other's opinions or attitudes about a certain technology; or, in contrast, government actors and private firms making investment decisions depending on other actors' past performance. Bale, Varga and Foxon [2] referred to five co-evolving, (potentially) interacting systems as central to analysing complex energy transition processes; namely technologies, institutions (e.g. rule systems related to policy or investment), business strategies, user practices, and ecosystems (factors such as carbon emissions). As such, one may expect ABMs in the context of energy transitions to focus on any combination of interacting entities from these categories. Holtz [14] reviewed a selection of models in the context of transitions. In those employing ABM, the identified main model elements ranged from consumers, innovating firms, a product market and demand side networks; to power producers, physical assets, electricity markets; and households, their social networks and a variety of technology types [14]. Further illustrating the diversity of possibilities afforded by ABM, Heath, Hill and Ciarallo [19] conducted a comprehensive survey of ABM practices. Based on a model's purpose, they differentiated between generators (in which little is known about the system and the purpose is to generate hypotheses and theories about the real system), mediators (where the simulation provides insight into the real system) and predictors (the system is well understood) finding that generators and mediators were most commonly used.

With regards to the social sciences, the potential relevance of ABM is commonly linked to the unsuitability of other modelling approaches to solving social scientific research problems and the issue of emergence [20]. In addition, being based on (individual) agents may serve as a natural ontology for social sciences and could therefore offer a powerful formalism [20], and aid in the formal presentation of theories [14,21]. In the context of transitions research, Hoekstra, Steinbuch and Verbong [22] compared ABM with a range of other computational approaches and found that the agent-based paradigm was the only one able to model emergence, agent interactions, as well as agent learning. ABM (in contrast to equilibrium models) can represent complex (adaptive) systems, and can model pathways in transitions [22]. Similarly, Ponta, Raberto, Teglio and Cincotti [23] found that ABM may be an appropriate approach to modelling transitions (to low carbon economies) because it allows for such transitions to be studied as dynamic paths emerging from the interactions of heterogeneous agents – rather than equilibrium suboptimal solutions. Feedback mechanisms are another feature of transitions that ABMs can incorporate [24].

Discussing the interface of (computational) modelling and societal transitions, Squazzoni [21] concluded that the ideal way forward for transition studies would be "to strengthen formalization, modeling, theoretical parsimony and generalization, thereby avoiding the risk of formulating the societal transition models on weak social science theories" – an important implication of this is the *need* for interdisciplinary collaboration [21]. At the same time, others have pointed to the *potential* of ABM to be used in multidisciplinary collaborations [22]. Beyond the realm of academia, there have also been calls to enable participation of diverse actors in model development given the importance of establishing shared understandings of complexity [25]. Against this backdrop, the present study systematically reviews the literature at the interface of agent-based modelling and energy studies in view of understanding the methodology's past and possible future contribution to socio-technical energy transition research. While both fields of research have gained traction over recent years, a current systematic literature review (SLR) at the interface is missing from the literature. Holtz [14] noted that a lack of definitional clarity in transition research makes it difficult to discern the kinds of models that should be included in a review. In the present study, a systematic procedure is applied to identify literature at the interface of energy studies and ABM. To address the definitional challenge, a multi-level perspective is adopted to evaluate the contributions of studies to the overarching theme of energy transitions in Section 3.3. The complexities of energy transitions outlined in Section 1 are then compared with the complexities being addressed in the examined studies. Section 3.4 provides an evaluation of the (potential) contribution of ABM to the (social scientific) study of energy transitions.

2. Methods

A SLR procedure was applied to identify and select a relevant and representative set of literature to answer the research question and its sub-questions [26]:

Research Question: How has ABM contributed to an understanding of energy transitions (as socio-technical processes)?
Sub-Question 1: How is the choice of ABM linked to the complexities of the energy transition?
Sub-Question 2: What is the potential of ABM to advance the social scientific discourse on energy transitions?

In line with the characteristics of a SLR, the procedure was designed to be replicable [27] and to reduce bias [28]. To meet these criteria, the first step was to construct a Boolean expression (search string) and apply it to three different online databases – ProQuest, Scopus, and GoogleScholar. Scopus and ProQuest were chosen as they are comprehensive and multidisciplinary databases. GoogleScholar was added as a control to potentially pick up any important publications missed by the other two databases. It was however shown to produce no additional articles and all selected articles were revealed through the ProQuest and/or Scopus searches.

As application of the Boolean expression to anywhere in the texts yielded an unfeasible number of articles (> 2000 articles per database), search queries were refined to apply the search to titles only (for GoogleScholar, Publish or Perish software [29] was used to run the query). The results of this are presented under Step 1 in Table 1. With the assumption that articles containing the chosen key terms in the title should be largely relevant to the topic under investigation, results from this query were then selected for further evaluation. At the same time, this provided 35, 142 and 54 relevant articles to be evaluated for the three database searches (see Table 1). This data was then exported to Excel to allow further analysis.

The key data points exported for each database included the title, author, date of publication, source, and URL. To clean the dataset, duplicates were eliminated, leaving a total of 191 publications. As scanning through the data showed inconsistencies with the original search query, Step 4 consisted of searching all titles for the terms energy and electricity. Another 23 results were then eliminated for failure to meet the original criterion of containing either of the terms in the title. As an emphasis was on quality, any result that was not a journal article (*e.g.* lecture notes, dissertations, conference proceedings) was also excluded. As an exception, three conference papers in the field of computer sciences were included because conference proceedings in this discipline are often peer reviewed and considered important in this rapidly changing field. Based on a manual review of the remaining titles, publications that could positively be identified as being off-topic, or were not written in English, were excluded. Those that could not be accessed due to paywalls were also eliminated. The dataset comprised of 53 articles.

To provide a full account for 2017, the search query was re-run in ProQuest and Scopus at the beginning of 2018. Applying the same criteria as above, an additional 8 journal articles were added to the selected set. Two more conference papers were also included based on an evaluation of titles and abstracts with regards to their potential usefulness to the study. The final dataset analysed in the following sections comprised of 62 scientific papers.

To ensure that the applied search method and the chosen set of articles is broadly representative of the field, an evaluation of related search queries was conducted. The results of this are provided in Appendix A. The assessment showed that despite the chosen search string's restrictiveness and the rigorous filtering, the literature discussed here is a good sample of the field. To the best of the authors' knowledge, no particular area or type of model was categorically excluded by the systematic method.

Table 1
Systematic process of selecting articles for analysis.

Step 1	Boolean expression: *("agent-based model*" OR "agent-based simulation") AND (energy OR electricity)* Directly applied to ProQuest and Scopus, and to GoogleScholar through Publish or Perish [29]			
Number of Results	Results in:	ProQuest	Scopus	GoogleScholar
	Anywhere	2,581	6,081	17,400
	Abstract only	393	662	/
	Title only	41	142	54
Step 2	*In title only* results selected for further evaluation and exported to Excel			
Step 3	Duplicates eliminated			
Number of Results	191			
Step 4	Filter 1: Titles searched for terms energy and electricity as verification of the Boolean expression.			
Number of Results	168			
Step 5	Filter 2: Include only journal articles In addition, include select conference papers and proceedings: most cited conference paper from computer sciences (1 article), (2 articles) most recent conference papers from computer sciences			
Number of Results	65			
Step 6	Filter 3: Exclude results that are: off-topic; unavailable for download due to paywalls or similar; published in languages other than English			
Number of Results	53 *(all selected articles appeared in the ProQuest and/or Scopus searches, meaning there was no added benefit of using GoogleScholar)*			
Step 7	At the beginning of 2018, the search string was re-applied to the Scopus and ProQuest databases to cover the full year 2017. Results were narrowed down to 8 journal articles and 14 conference papers and proceedings that had not previously been identified. The 8 journal articles were added to the selection. Two conference papers were selected for inclusion based on an evaluation of titles and abstracts with regards to their potential usefulness to the study.			
Number of results	62			

3. Results and discussion

3.1. Temporal distribution of studies

Fig. 2 shows the annual numerical article trend for the set of 62 studies. The graph suggests a clear growth trend over the past 17 years. Only 2 articles containing the key words agent-based modelling and energy or electricity in the title were published prior to 2007. Growth in the number of articles published was steady from 2014–17 (Fig. 2). More than a quarter of articles in the set were published in 2017.

This suggests an increased interest of applying ABM in the context of the transition to renewable energy in the past decade. This trend has been observed elsewhere as well (for example, see Macal [30]). A discussion of the possible drivers of the increasing use of ABM -beyond the growing recognition of limitations of traditional modelling approaches to the complexity of current research problems- is beyond the scope of this review.

3.2. Journal article sources

The identified articles were published in 43 different sources (including conferences). The most frequently occurring journals were Applied Energy (6 articles) and Energy Policy (6 articles). This was followed by 3 publications in Energy Conversion and Management, as well as Energy. All other sources (including conferences) had a

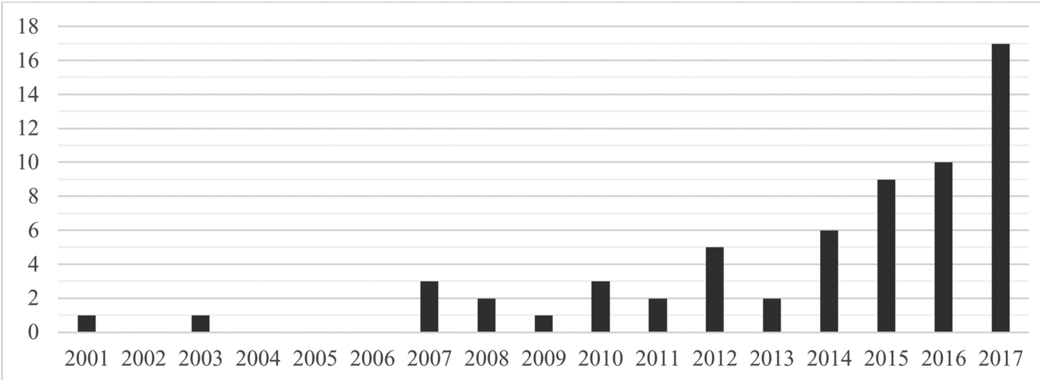


Fig. 2. Number of identified articles per year of publication.

maximum of 2 publications (34 had only 1).

While most of the journals that yielded more than one result have a technical focus, one of the two most frequently occurring sources was Energy Policy which focuses on the economic, social, planning and environmental dimensions of policy implications related to the supply and use of energy [31]. This large variety of sources indicates a wide range of areas of applicability. An interesting observation is an increase of publications in Energy Policy for the year 2017 – potentially pointing to ABM finding increased application in the realm of energy policy. Table 2 illustrates, for the nine sources that appeared more than once, the number of publications in each journal, and the years and count(s) of publications (for example, in the identified set of literature, four articles were published in Energy Policy in 2017).

3.3. *Thematic relevance to (social scientific) transition research*

The 62 identified articles were broadly categorised into 6 topic areas; Electricity Market (25), Consumption Dynamics/ Consumer Behaviour (12), Policy and Planning (9), New Technologies/ Innovation (7), Energy System (6), Transitions (3). To reduce bias, rather than superimposing pre-determined features of energy transitions onto the set of articles, the categories emerged after reading the selected articles. They represent thematic patterns observed independently of, and prior to applying any analytical lens. The topic areas therefore do not strictly follow the same terminology or interpretation as the definition of the energy system given in Section 1 (Fig. 1).

The set of 62 articles contained five review articles, four of which were placed in the topic area Electricity Markets. Interestingly, two of these were published in 2007 [32,33] – meaning they cover a period excluded by the systematic procedure applied in the present study. A control search run (see Appendix A) to verify the representativeness of the search results, and scanning of the reference lists in these two earlier reviews, suggests a combination of the term usage and spelling, and a focus on market-centric studies, to be responsible for the difference. Both lists of references also include a number of non-journal sources (*e.g.* technical reports) which were largely excluded here. In Sensfuß, Genoese, Ragwitz and Möst [33] the explicit purpose was to review a novel field of research. The premise for both review articles published in 2007 was similar to the one this study is based on: ABM is a promising tool to study the complex (and novel) changes to the electricity sector [32,33]. In contrast to the identified review articles which focused on particular components of the energy system, the present discourse considers the transition process itself (as defined in Section 1) and draws a map of how the energy transition has been approached with ABM.

3.3.1. *Thematic analysis from a multi-level perspective of energy transitions*

Given the popularity of the MLP in socio-technical transitions research, it was explored how the identified literature addresses energy transitions through this lens. The value of this is twofold: Firstly, energy transition is not a well-defined term [14]. The multitude of actors with potential stakes in it means that definitions vary. In the field of sustainability studies, the MLP is a well-established framework offering conceptual boundaries. An explorative application of the MLP to the identified literature may be valuable to scholars conceiving energy transitions as socio-technical processes. Secondly, a core premise of the MLP is that of interactions between different system elements, a concept for which ABM could provide a natural ontology. As the identified topic areas exhibit a certain degree of overlap with energy system components defined in the MLP (cf. Fig. 1), an exploration of themes in the literature through this lens offers a relational framework.

Technological innovations have the potential to affect systemic change when windows of opportunity open up [34] through tensions or mismatches between regime level components and/or the landscape level. These may be caused by factors such as changes to the landscape level (*e.g.* the effects of climate change); technical problems in the regime, leading actors to explore other options; changing user preferences; or the strategic behaviour of firms, where new technologies may provide a competitive advantage [34]. The niche level may be represented by the topic area New Technologies/ Innovation. Two

Table 2
Number of selected articles per journal and year, showing only journals that appeared more than once. For example, the selected set of literature contains a total of 2 articles published in Annals of Operations Research – one of these was published in 2003, the other in 2016.

Name of Publication/ Year of Publication	2003	2009	2010	2012	2014	2015	2016	2017	*Total*
Annals of Operations Research	1						1		*2*
Applied Energy				1	2	1		2	*6*
Energy		1				1		1	*3*
Energy and Buildings							2		*2*
Energy Conversion and Management					1	2			*3*
Energy Policy			1		1			4	*6*
Environmental Modelling and Software						1		1	*2*
IEEE Transactions on Power Systems						1	1		*2*
Journal of Computing in Civil Engineering				1				1	*2*

approaches to studying new technologies were identified in the selected literature: studies focused either on the techno-economic implications of a particular technology, such as storage [35], or electric vehicles [36]; or on processes of change and innovation adoption [37,38]. Ma and Nakamori [38] studied how technological change is treated in three different types of models (ABM being one of them). Their conclusions point to the ease of including adaptive behaviour, and especially adaptive decision-making behaviour, in ABMs. The appropriateness of ABM as opposed to traditional optimization models, however, depends on the decision-making context: ABM is concerned with possible future scenarios based on a given situation and set of assumptions (bottom-up); while traditional optimization models start with an end goal or objective (top-down) [38]. This suggests, firstly, that ABM is an appropriate technique for modelling energy transitions, given the definition applied here for them; but also, secondly, that in modelling energy transitions, the purpose of modelling may be more important than the applied definition of transitions. If the purpose is to develop an energy system towards a certain objective in a controlled manner, the study [38] suggested that optimization models may be advantageous. Similarly based on observations of change dynamics, Hodge, Aydogan-Cremaschi [39] investigated the mechanisms that cause change in energy systems, and how to integrate new technologies into the existing system. By representing each type of energy system entity (such as consumers, raw materials, researchers) as an agent, their framework can easily be translated into the MLP conceptualisation and may be understood as covering interactions between niche and regime level.

In Rai and Robinson [37] the adoption of solar PV was explored. The authors' primary concern however was with two methodological challenges in ABM, namely a lack of consistency in the theoretical and empirical foundations of models. This represents a valuable contribution to the methodological foundations necessary for any models. The study also presented a new approach for producing population-wide estimates for agent attitudes that is general in nature and may be used by other applications (ibid.). In another study of solar PV adoption, Robinson and Rai [40] investigated the effect of using empirical data and integrating behavioural, social and economic factors on model outcomes. Their findings suggested that behavioural and social factors were critical in accurately predicting demographic and spatial patterns; whereas focusing only on the financial factor predicted rate and scale well but not spatial and demographic patterns (ibid.). Overall, the inclusion of all elements let to better fit with empirical data *i.e.* increased the validity of the model [40]. As the study aimed for better prediction of the temporal and spatial patters of solar PV adoption, it implicitly pointed to a significant shortcoming of the MLP: that it largely disregards the spatial dimension of transitions and only vaguely touches on the temporal (transitions typically occur over long periods of time).

In addition to being interested in technology adoption, the above studies could also be conceptualised as micro-level by virtue of focusing on individual (household) level agents. Theory of planned behaviour (TPB) was used by various studies to define agent behaviour [37,40–42]. Zhang and Nuttall [42] compared TPB with four other social psychological theories (technology acceptance model, model of goal-directed behaviour, social cognitive theory, motivational model) in terms of their suitability for formalising agents. Based on this comparison they chose TPB because of the relative ease of translating it into code, and because is stresses psychological, sociological as well as environmental factors in agents' decision-making process [42]. The authors concluded that their model pointed to the benefits of directly integrating social psychological theory (ibid.). As the study [42] focused on the effect of government policy promoting smart metering on the diffusion of the technology, it falls between micro- and meso-level. While the model included micro-level individuals and an interest in technology diffusion, its overarching aim was to evaluate the effectiveness of government policy (ibid.). Interested in understanding how smart metering systems may impact on electricity stakeholders, Vasiljevska, Douw, Mengolini and Nikolic [43] concluded that a good policy for the promotion of smart metering technology should focus on passing information on advantages and disadvantages of the technology on to consumers so as to raise comfort and lower concerns.

The effect of policy interventions on the upscaling of niche innovations is a central concern in the Policy and Planning topic area (other studies focus on technical elements *e.g.* [44,45]). Busch, Roelich, Bale and Knoeri [46] investigated institutional barriers (and the removal thereof) to the upscaling of local energy infrastructure. Their study therefore represents a link between the niche level and the element of (formal) rules in the regime. Chappin, de Vries, Richstein, Bhagwat, Iychettira and Khan [47] found that given complexities such as cross-policy effects, differences in actor behaviour, imperfect foresight and path dependence, determining the side effects that policy interventions might have is difficult without ABM. Alfaro, Miller, Johnson and Riolo [48] took it one step further by aiming to facilitate the direct engagement of stakeholders in the decision-making process for energy planners through ABM. With a similarly practical motivation, Hinker, Hemkendreis, Drewing, März, Hidalgo Rodríguez and Myrzik [49] were interested in the creation of a framework to facilitate ABM in interdisciplinary teams. This in turn is deemed necessary for social factors to be successfully included in modelling efforts [49].

At the interface of Policy and Planning and Consumer Behaviour, Mittal and Krejci [50] evaluated how increased PV adoption affects a utility company's revenue, where consumers, based on financial and attitudinal factors, decide to either adopt rooftop PV, community solar, or a green pricing program. In the same line of research, Kowalska-Pyzalska, Maciejowska, Suszczyński, Sznajd-Weron and Weron [51] examined the adoption of dynamic tariffs based on the discrepancy between consumers' opinions on switching to dynamic electricity tariffs and their actual decision to do so. This was based on the premise that while dynamic tariffs can be beneficial to consumers, retailers and other electricity system stakeholders, convincing people to actually switch has proven difficult. The authors found that the intention-behaviour gap occurred (in the simulation) when levels of indifference were moderate to high regardless of the intensity of advertising [51].

The topic areas of Consumer Behaviour/ Consumption Dynamics, and Electricity Markets predominantly touch on all conceptual elements of the regime level. For instance, a cluster of studies emerged in the Consumer Behaviour topic area that is concerned with the behaviour of building occupants with regards to energy consumption [41,52–55]. Building occupant behaviour is essential to reducing building energy usage and emissions as the built environment accounts for a large percentage of global energy consumption [55]. These studies may thus be interpreted as implicitly incorporating the external landscape pressure of carbon emissions. Pointing once more to the importance of social factors to the energy transition, Azar and Al Ansari [52] investigated the impact of building occupants on a building's energy saving potential. Employing a social network structure, they found that connecting occupants with each other can lead to significant increases and stability in energy savings, suggesting that social connectivity could be leveraged to diffuse energy conservation behaviour. Another study [56] showed that the use of an individual's social network (in an eco-village) could lead to energy savings through the sharing of appliances; *i.e.* exploiting social networks significantly increased potential savings (ibid.). In a similar line of inquiry, Jensen, Holtz, Baedeker and Chappin [41] concluded that the heating energy consumption of a building may be reduced by addressing heating behaviour of occupants. Integrating socio-technical dynamics through the interactions of social agents with each other and with a feedback device, they found that in the case study city (Bottrop, Germany) the introduction of the feedback device (CO_2 meter) could have a significant (positive) effect on the energy efficiency of heating behaviour [41].

An important difference between studies in this topic area and those in Electricity Markets is the level of aggregation. While those in Consumer Behaviour/ Consumption Dynamics considered individual consumers or households, articles in the Electricity Markets were focused on interactions between organisations or firms. While the Electricity Markets topic area is the largest of all topic areas, accounting for about 40% of all articles, a majority of studies in it are of no direct relevance to energy transitions, particularly given the social scientific focus of this review. However, Liu [57] investigated the development of high and low carbon types of energy in relation to the number and performance of firms. Results point to the importance of developing low carbon energy to sustaining security of energy supply for firms [57]. Wittmann and Bruckner [58] focused specifically on the changing market against the backdrop of the diffusion of low carbon technologies and emission reduction targets, thereby providing a rather direct consideration of the transition in the topic area of Electricity markets. Changes in markets or increasing shares of renewables were also observed in [33,59–63].

In articles within the Energy System topic area, a particular focus on the technical components is evident. Whilst alluding to an energy transition to varying degrees in contextualising studies, articles here were centred on future power grids and energy networks [64–66]. As such, these studies provide less insight into the reinforcing dynamics between system components and levels, but instead illustrate the complexity of some of these components.

Three articles provided insight into how reinforcing developments across all three levels can lead to transitions. Despite this commonality, all three differ considerably in thematic focus. Firstly, Chappin and Dijkema [13] investigated energy infrastructure transitions based on the same ontology of socio-technical systems applied in the present study - defining transitions as the occurrence of structural change in technical as well as social parts of the system [13]. They posited that these transitions can be shaped, or managed, and contended that such transition management requires a set of strategies relating not only to technological innovation but also spheres, such as policy, regulation, finance and research – a set of strategies they term transition assemblage [13]. Based on the premise that modelling can enable the assessment of possible strategies or designs before implementation, the authors devised a typology to model transitions with ABM (ibid.). With the aim of assisting modellers in this, their typology suggested that the most useful model for the assessment of transition assemblages allow for the comparison of assemblage alternatives, and are also able to account for regulatory adaptability (ibid.). A key learning for the present study is that ABM can be used to evaluate strategic options for steering transitions.

Kraan, Kramer, van der Lei and Huppes [67] modelled the energy transition in terms of the mitigation of, *versus* adaptation to the issue of climate change. Given the uncertainties related to climate change effects on society and economy, different ethical perspectives exist on addressing climate change, which has resulted in different discount rates being applied to the problem in economic analyses (ibid.). Kraan, Kramer, van der Lei and Huppes [67] devised a proof of concept ABM in which different agents used cost-benefit analysis to evaluate the problem of adaptation *versus* mitigation of climate change. Different ethical perspectives are reflected in differing discount rates that agents apply in their cost-benefit analyses. Agents emitted CO_2 which they were able to mitigate [67], resulting in investments in mitigation technology. The overall system was described in terms of CO_2 equivalent emission levels and system costs. Kraan, Kramer, van der Lei and Huppes [67] built on existing literature interested in the climate-economy interface by combining Integrated Assessment Modelling – traditionally used in the field – with ABM, arguing that such an integration allows for more realistic modelling of the way in which society responds to climate change. ABM offers advantages over the underlying traditional economic paradigm relating to assumptions of stability and rational actor behaviour [40]. By connecting the landscape pressure of climate change with varied actors, and the option of investment into new technologies, they integrated all levels of the MLP. Compared with the study by Chappin and Dijkema [13] their model did not directly provide policy recommendations but rather an economic (and an environmental) indicator.

Shchiptsova, Zhao, Grubler, Kryazhimskiy and Ma [68] discussed a model of the global energy system based on the emergence of new energy technologies and demand for energy services. The model described how the energy system evolves based on six *response indicators*; demand for heat, mobility, modern services, non-fuel, total energy, and primary carbon. They noted that the carbon emissions variable served as an indicator of climate change, while the others described energy demand. Assessing the historical reliability of this model, they found that, concerning carbon emissions and energy demand, the model was not able to predict past developments in the energy system [69]. For the purpose of the present study, one may argue that landscape pressures are represented by the tracking of carbon emissions; and the regime is represented by other indicators and their interplay and influence on niches, which are in turn represented by new technologies.

In summary, the thematic contribution of the selected literature to the study of energy transitions lies more in addressing varied subcomponents of the energy system than in modelling whole transitions. From a social sciences perspective, studies have demonstrated that the inclusion of social and behavioural factors in models can, firstly, show improved outcomes, and secondly, lead to better model validity.

In terms of the MLP, most studies exhibited features or included elements of multiple system components and levels, particularly within the regime. Over and above a superficial thematic discussion, the MLP may not be the most suitable framework for agent-based transition studies as the multi-level structure, albeit based on the notion of scale, does not sufficiently account for the role of individual (agents). For example, studies in the New Technologies/ Innovation topic area were viewed as broadly representative of the niche level, while Consumer Behaviour/ Consumption Dynamics articles were placed in the regime because of the MLP conceptualisation of it (cf. Fig. 1). However, individual consumers arguably interact at a micro-level. This is not accounted for in the MLP.

Considering the three articles placed in the Transitions topic area, energy transitions, as multi-level, complex processes made up of many different interactions, can be addressed through the active management of the process [13]; an overall economic approach, whilst accounting for socio-cultural differences [67]; and/or historical trends based on technology uptake [68]. Moreover, the literature points to a possible role of ABM being its application to policy-making, advancing transition related decision-making practically, by offering a decision-support mechanism. Table 3 provides an overview of some key findings identified in the literature that are of relevance to, or demonstrate the relevance of, social sciences in modelling energy transitions.

3.3.2. Modelling complexity in energy transitions

Section 1 outlines how an increasing degree of complexity is a prominent feature of energy transitions. The present study is based on the premise that given this increased degree of complexity, ABM may be an appropriate means to investigate transitions. This argument appears well supported: The ability of ABM to account for complexity emerged as the predominant reason for the choice of this methodology across topic areas. Section 3.3.1 provided an overview of topic areas through a multilevel lens. Offering an alternative approach to evaluating the extent to which energy transitions have been addressed with ABM, this section compares energy transition complexities with the motivations for using ABM given in the selected set of studies.

The complexity of the research problem and the ability of ABM to deal with complexity was the most frequently cited reason for choosing ABM as a methodology across all topic areas. It was the most often cited reason in both the Electricity Markets [32,57,60–63,70–73] and Energy System [65,66,74] topic areas. As such, the interface of these two dimensions of complexity, as a feature of energy transitions and as a strength of ABM, was explored in more detail. It was found that the common theme of complexity can in fact serve to integrate the methodological choice of ABM with transition traits. Accordingly, articles

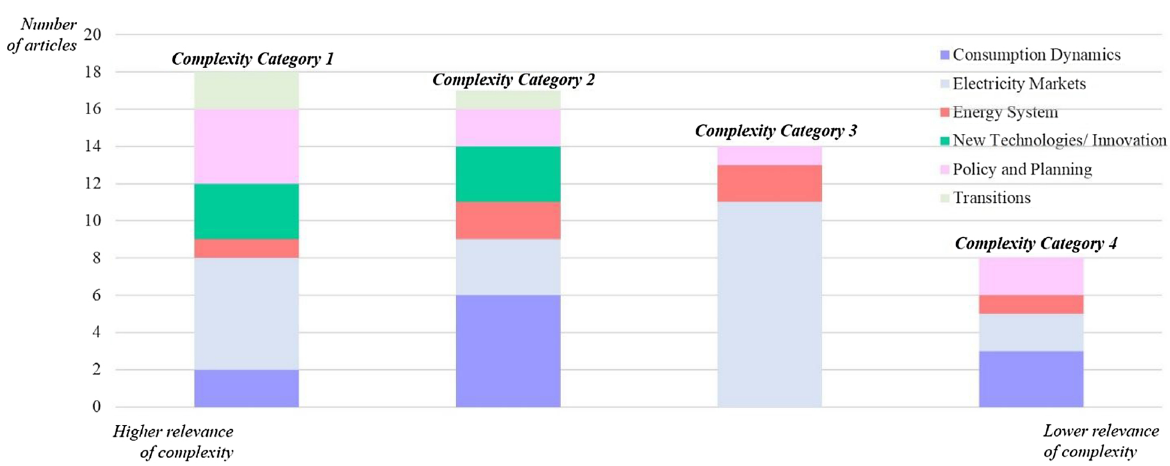
Table 3
Sample of findings illustrating the importance of social factors to modelling energy transition related problems, or otherwise of particular interest to social scientists.

Sample findings of particular relevance to the social sciences:
• Behavioural and social factors were critical in accurately predicting demographic and spatial patterns of solar PV diffusion [40] • TPB may be more suitable for ABM than other theories because of the relative ease of translating it into code, and because is stresses psychological, sociological as well as environmental factors in agents' decision-making process [42] • Directly integrating social psychological theories is beneficial for model outcome [42] • Communication of a technology's advantages and disadvantages to consumers is important and should be the focus of a good policy for the promotion of smart metering technology [43] • Interdisciplinary teams are necessary to successfully include social factors in modelling efforts [49] • Connecting building occupants with each other can lead to significant increases and stability in energy savings [52] • Exploiting an individual's social network (in an eco-village) could lead to energy savings through the sharing of appliances [56] • ABM can be used to evaluate strategic options for steering transitions using a transition assemblage concept based on socio-technical systems [13] • ABM can offer advantage in modelling society's response to climate change; mitigation versus adaptation decisions may be represented quantitatively through application of varying discount rates related to ethical views [67]

were placed in one of four categories depending on the degree to which the ability of ABM to treat complexity was relevant for choosing the methodology; and the degree to which the complexities of the energy transition (as defined in Section 1) were central to the study. The four categories may be understood as a continuum indicating the degree of association between the complexity of energy transitions and ABM's ability to address it in the given studies. As such, at one end, complex energy transitions and the ability of ABM to model these complexities are directly associated; while at the other, neither complexities in the transition nor ABM's ability to model them were of relevance to the study. This is illustrated in Fig. 3.

At the left of the spectrum (i.e., complexity category 1), articles were concerned with features of energy transitions which are described as complex. The choice of ABM as a methodology is linked to this complexity. For example, Chappin, de Vries, Richstein, Bhagwat, Iychettira and Khan [47] stated that challenges related to energy transitions include social elements (such as those noted in Section 1) which represent the type of complexities that ABM is suitable for, *e.g.*, uncertainty [51]. Deissenroth, Klein, Nienhaus and Reeg [75] explicitly discussed the complexity of energy transitions as including uncertainty, changing social configurations, increased numbers of actors, and more complicated market structures; and therefore deemed ABM the most suitable modelling technique [41].

In category 2, transitions or features thereof are still central to the study but the choice of ABM is not directly linked to this (Fig. 3). For example, while a global energy transition was the central topic in Shchiptsova, Zhao, Grubler, Kryazhimskiy and Ma [68], complexities such as an increasing number of actors (see Section 1) are not discussed. While ABM was described as a tool to analyse complex systems, this description is based on the general features and advantages of ABM as such. Hawasly, Corne and Roaf [56] discussed energy saving in an Eco Village: while the interest in energy saving can be linked to the characteristics of the current energy transition, the use of ABM in this study rested on the premise that any community setting in which people interact is complex. Complexity category 3 contains studies that may refer to the ability of ABM to account for complexity but these complexities are not linked to energy transitions or any features thereof as these are



Notation	(Increased) complexity is linked to (changing) structures of the energy system.	The study is set in the context of an energy transition or features thereof (such as climate change), but ABM is chosen for its ability to model complexity inherent in reality (it is not a new complexity).	Real-life systems are complex, and ABM allows for (more) realistic modelling (than other approaches).	The notion of complexity is not relevant to the study.
Description	The ability of ABM to model complexity was used to model (a) feature(s) of the energy transition that are viewed as complex or as adding complexity. This may be linked to the sociotechnical nature of transitions.	The study is motivated by a driver of the transition or is concerned with a feature of the transition. The choice of ABM however is linked to a pre-existing complexity.	Studies employ ABM for its ability to account for complexities which are inherent in real life. Energy transitions or any features thereof are not of concern.	Studies refer to neither the energy transition as a complex process or features thereof, nor to ABM's ability to model complexity.

Fig. 3. Complexity categories and topic composition per complexity category. The bar diagram shows the number of articles per topic area that were placed in each complexity category. Review articles were excluded from this. The notation summarizes the category criteria, while the description explains it in more detail. Given the great diversity of studies reviewed here, complexity categories are not to be understood as absolute. Rather, in category 1, complexity was relatively more central to studies, than in categories 2–4.

not of concern. Lastly, category 4 articles do not refer to complexity in any way. These studies were predominantly published in journals with a more technical focus, which may explain a narrower focus and less contextualisation of research problems (*e.g.* Journal of Computing in Civil Engineering, CIRP Annals - Manufacturing Technology, Energy and Buildings).

The exercise of grouping studies according to their two complexity dimensions provides only an estimate of the centrality of complexities to the selected set of literature. However, it demonstrates that ABM has been employed to cover energy transition complexities from a variety of thematic foci – *i.e.* all topic areas appeared in the first (and second) complexity categories. Although only three studies were placed in the topic area of transitions, when considering the notion of complexity, 18 were identified as addressing transition related complexities and therefore as being directly relevant to the topic under investigation in this study. Furthermore, six of a total of 17 (journal articles and conference papers combined) studies published in 2017 were placed in category 1, representing the largest share (of articles from that year) in any one category (4 in category 2, and 3 each in categories 3 and 4, 1 review article). As with the increasing numbers of studies identified over the past decade (Fig. 2), this might point to an increasing recognition of the relevance or usefulness of ABM for studying transitions.

3.4. Evaluation of evidence: using ABM to understand socio-technical energy transitions

Section 3.3 established the connections between the set of literature and its relevance to the study of energy transitions thematically. It was shown that varied parts, sub-components, and sub-processes of energy transitions have been addressed in the literature, and more so than the whole of the process; and that in a significant number of studies the choice of ABM was directly linked to its ability to address complexities of energy transitions. This section critically evaluates the potential contribution of ABM to the study of (socio-technical) energy transitions. Table 4 summarises the advantages and disadvantages of ABM identified in the literature.

In a practical evaluation of the state of the field of ABM (in general), Macal [30] proposed a set of four informal definitions of agent-based modelling and simulation. In order of increasing sophistication with regards to the individuality, behaviours, interactions, and adaptability of agents, he distinguished between individual, autonomous, interactive, and adaptive models [30]. In the latter case, agents are heterogeneous, their behaviours are autonomous and dynamic, interactions occur between different agents as well as with the environment, and they are adaptive, i.e. their behaviour changes over the course of the simulation [30]. Considering this differentiation, a large majority of studies examined here fall under the interactive or adaptive types, indicating a generally high level of sophistication and potential complexity. However, as pointed out by Robinson and Rai [40], the usefulness of an ABM (over other methodologies) rests on rigorous integration of theoretical and empirical foundations. As such, while the set of examined studies exhibit a generally high degree of sophistication, the degree of model implementation rigour is more varied.

One potential issue with regards to modelling energy transitions that emerged from the literature is a trade-off between model robustness and scale. Rai and Robinson [37] and Robinson and Rai [40] presented detailed and highly sophisticated models, addressing a lack of empirical data being used in initialisation and validation of models as well as the use of appropriate behavioural theories. While these studies have made an important contribution to the literature, the simulations were run on the 10 PF Stampede Supercomputer (at the Texas Advanced Computing Center) [37,40]. The rigorous design and validation of the models in these studies resulted in robust simulations of residential solar PV adoption in Austin, Texas.

The computing power required to execute them however suggests that modelling larger scale transitions involves a trade-off with the level of detail and model robustness – or, the collaboration with an institution with the necessary computing requirements. Holtz [14] asserted that reduced scope of a model improves the likelihood of good model performance. This supports the notion that the more methodologically robust contributions to modelling energy transitions will, or should, focus on parts of the system and processes. This also relates to an observation made by Hinker, Hemkendreis, Drewing, März, Hidalgo Rodríguez and Myrzik [49] - integrating social aspects appropriately in models is difficult because of their complexity – i.e. problems can never be modelled in all their complexity. Considering the complexities attributed to whole energy transition processes, including spatial, temporal, social and technical, this would certainly hold true for transition models. Moreover, the appropriate integration of empirical data in model initialisation and validation would arguably become increasingly difficult with increasing model scale.

The above example of a sophisticated model of Austin, Texas, also points to another issue present across the literature: as models are often case-specific, findings are difficult to generalise [47]. The way agent behaviour is modelled varies drastically and there is a lack of conventions regarding this (ibid.). In addition, a lack of consistent model descriptions throughout the literature makes it difficult to compare studies along the same criteria. While some studies use the ODD (Overview, Design concepts, Details) protocol originally proposed to address this issue, there is still a large number of studies not using it, and a considerable degree of divergence as to how its three components are addressed in individual studies. A possible partial solution to these problems could be the development of more generalizable models and conceptual frameworks. This would also play into the need for and potential of interdisciplinarity alluded to in Section 1. Two examples of generalizable frameworks from the reviewed set of literature are from the Policy and Planning topic area. One important advantage that is reflected in ABM applications to energy transitions is the possibility of determining the side effects of policies [48]. Building on this, Chappin, de Vries, Richstein, Bhagwat, Iychettira and Khan [47] presented EMLab (Energy Modelling Laboratory) which describes the impact that (EU) policies have on investment in the electricity sector in a flexible, open source platform. Alfaro, Miller, Johnson and Riolo [48] developed BABSTER, a model integrating technical, social and environmental factors, that is similarly aimed at enabling decision-makers to flexibly and easily test their strategies. This model is also interesting in that its development included participation by stakeholders, an important step to be addressed as outlined in Section 1.

Gallo [62] noted that in order to be able to model and build power systems (under high penetration of renewables) more accurately, a multidisciplinary approach is needed that includes all actors in the system. Similarly, Ringler, Keles and Fichtner [60] pointed out that an increased degree of multidisciplinarity would improve future work (on smart grids) through better integration of environmental, social, and technical elements. Hinker, Hemkendreis, Drewing, März, Hidalgo Rodríguez and Myrzik [49] argued that not just multi- but interdisciplinary work is needed to appropriately integrate social factors such as legal frameworks into optimization and simulation models; and that a common language is needed to enable this participation. Hence, rather than focusing on a specific topic, their study was concerned with the creation of models as such in interdisciplinary teams. Their proposed conceptual model is designed to enable interdisciplinary work in simulating socio-technical systems [49]. This is an important contribution to the advancement of ABM for energy transition studies for two reasons. Firstly, the study of energy transitions is inherently discipline-transcending, and, from a systems perspective, a model of a transition or part thereof should include social as well as technical components. The second reason relates to the accessibility of ABM for social scientists. Although the agent concept may be intuitive to the social sciences and provide a natural ontology [20], developing an ABM is not an easy task. Collaborations between social and computer scientists could therefore be particularly fruitful. Thus, interdisciplinarity

Table 4
Advantages and disadvantages of ABM as identified in the literature.

Advantages of ABM	Disadvantages & challenges of ABM
• Determining the side effects of policies [47] • Accounting for role of communication in technology diffusion models; modelling household choice [76] • Enables the modeller to build on practical and existing theoretical knowledge [41] • Can represent complexities of energy demand such as social interactions [77] • Attractive tool for study of human-technical systems because it can more flexibly describe detailed behavioural and structural system elements [37] • Technological learning can be introduced without requiring large scale computational capabilities [38] • Being able to focus on individual level rather than the whole system [55] • Can address institutional and governance barriers [46] • Agent autonomy and interaction skills; distributed/decentralized control; high flexibility in execution of tasks [64] • Useful when dealing with various agents with diverse behaviour [53] • Good to model complex behaviour of participants and for modelling large-scale systems where different types of participants interact [32] • Can account for diverse heterogeneous actors making it suitable for studying dynamics of electricity systems undergoing transitions [75] • Allows experiments to be run multiple times with varying market and agent characteristics [51]	• Challenges regarding validation, verification, calibration and model description [60] • Lack of relevant empirical data [37] • Difficulty of validation [73] [70] • Lack of data for validation and calibration [46] • In context of consumer behaviour: lack of spatial representation and validation [77] • Integrating social aspects appropriately is difficult because of their complexity – i.e. problems can never be modelled in all their complexity [49] • Behavioural rules are often ad hoc and not based on systematic theories of behaviour [37] • When modelling human agents their 'soft' features (psychology, values, behaviour etc) are difficult to quantify [78] • ABMs are often one-offs exploring specific cases, making insights difficult to generalise; ABMs difficult to develop and interpret; the way agent behaviour is modelled (theory or empirical basis) varies drastically which means models are diverse and there is a lack of conventions; ability of ABMs to analyse uncertainty in-depth makes it less relevant to policy-makers because it makes results less tangible [47] • Despite advances in ABM and energy research models are still limited with respect to agent types, behavioural variety and interactions [53] • In context of consumer energy technology adoption: integration of theory and empirical evidence in model structure, validation and initialization [40] • Results are not optimal solutions but rather scenarios based on different assumptions [38]
Compared with other approaches • Compared with SD and game theory, ABM can integrate larger number of actors and their decision-making behaviour [69] • Compared with game-theoretical models, ABM has the advantage of being able to model heterogeneous actors and observing dynamic evolutionary processes [79] • Compared with equation-based diffusion models, ABM may be a better alternative for evaluating complex policies and targeted interventions aimed at increasing technology uptake [76] • Compared with conventional discrete event simulation approaches ABM is more suitable for modelling complexity of electricity markets [32] • Compared with field experiments, simulations are more cost-effective and require less bureaucratic efforts [52]	• Extent to which ABM is advantageous depends on the (rigour of) theoretical and empirical underpinnings being used [40]

is both a promising feature of, and a challenge for ABM; while various authors point to the importance of multi- or even interdisciplinary teams, few models are actually designed to enable this.

Lastly, the potential of ABM to aid in the formalisation of theories (such as transition theory, which is lacking formal presentation [14]) touched on in Section 1 could not be confirmed in this review. While Rai and Henry [77] discussed the importance of better theories (of energy demand of consumption) in advancing knowledge of complex energy systems, none of the identified studies focused on the testing or formalising of (new) theories. In this context, considering the integration of social factors into models, it was noted that behavioural rules are often ad hoc rather than being based on systematic theories of behaviour [37]. Related to this is the difficulty of quantifying features such as values or behaviour [78] that characterise human agents.

The value of current ABMs to the study of socio-technical transitions, based on this review, lies in its ability to address transition-related questions, and in modelling sub-components of the energy system. A particular appeal lies in the application of ABM to policy and planning and thus in aiding in the effective management of energy transitions. Models that enable collaboration between disciplines and sectors, thereby promoting knowledge sharing, and models that are easy to use by non-computer scientists, are promising areas for furthering energy transitions in practice. Nevertheless, the full potential of ABM in this respect has not yet been exploited.

4. Conclusion

The application of ABM to energy transition related questions is gaining popularity. The variety of identified topic areas illustrates, on one hand, a continuing prominence of technical and market focused studies; and on the other, an increasing share of studies interested in the application of ABM to policy and planning (as evidenced by the number of articles published in Energy Policy in recent years). The pattern of topics uncovered in the present study is similar to trends described by others, who have, as here, proposed that many different types of models may contribute to a partial understanding of energy transitions [14]. The application of a multilevel perspective to topics covered in the literature showed that regime-level interactions have received particular attention. Further application of the MLP in this context, beyond the explorative evaluation done here, may prove problematic, as the framework does not adequately account for individual agents and their roles. On the other hand, the complexity based evaluation of the relevance of studies to energy transitions in Section 3.3.2 showed that an increasing share of studies do link their choice of ABM to the complexities specific to energy transitions and therefore position themselves as contributing to this body of research.

A particularly valuable area of research in the energy transitions domain may be the application of ABM to policy and planning. This conclusion is motivated by two reasons. Firstly, studies in this topic area may contribute to practically driving energy transitions by informing (and improving) decision-making. Secondly, studies in this area identified here addressed the issues of interdisciplinarity and participation more directly than other topic areas. Given the relevance of policy-making to managing energy transitions, and the usefulness of ABM as a practical tool, it is likely that increasing numbers of studies will be in the Policy and Planning area. This is also suggested by temporal trends observed in this study, where 6 of 9 articles in this topic area were published in 2017. As the structure of the changing electricity market is high on the agenda of policy-makers and academics alike, it may also be expected that the importance of this topic in the context of energy transition studies will remain.

The increasing application of ABM to the policy and planning domain, and contributions to sub-components of energy transitions in general, support the promising contribution the methodology can make to the study of transitions. However, particularly from a social scientific perspective, areas of improvement were also identified. While the possibility of interdisciplinary research through ABM has been noted in the literature, the need for it has not been adequately addressed. An increase in interdisciplinarity will be needed if ABM is to advance as a transitions tool. This is, firstly, to ensure the appropriate integration of social elements into models. The reviewed literature has shown that such integration can have a significant effect on model outcomes; further, thus far, techno-economic problem statements are still more prominent than social ones in energy-related ABMs. Secondly, increased interdisciplinary collaboration will be needed to ensure the computationally adequate development and implementation of socially focused models. While the relevance of social factors to energy transitions and model outcomes has been demonstrated, the building of useful models still requires a considerable degree of ABM specific knowledge and skills. Collaboration could overcome this barrier to social scientists unfamiliar with computational techniques. This also implies a call for easily adaptable and understandable conceptual models to increase the accessibility of ABM to social scientists (and non-academic actors), and to potentially increase the comparability of modelling frameworks. In this regard, the authors recommend a review of socio-technical approaches used in ABM to complement the present study. These may exist outside the limited scope of energy specific studies.

While technical model specifications were not the focus of this article, the exercise of analysing studies nevertheless revealed the lack of consistency, or standardised formats, in which studies present and report on agent-based models. As has been commented by other authors (e.g. [60]), this makes it difficult to compare modelling studies across the literature through common criteria. Notwithstanding, future reviews of ABM and energy transitions would benefit from an in-depth evaluation of the technical details. Methodologically, it is also recommended that similar systematic reviews be conducted based on more comprehensive analyses of the quantitative data along the selection pathway to verify the temporal and topical patterns uncovered here.

In summary, ABM can advance energy transitions practically and will be particularly valuable in this area if issues of interdisciplinarity and accessibility are addressed; its potential to contribute to the theoretical foundations of energy transitions research could not be confirmed in this review but could be investigated further using alternative review approaches.

Conflicts of interest

There are no conflicts of interest to declare.

- The manuscript has not previously been published and is not currently under consideration with another journal.
- The submitted manuscript is an original piece of work.

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Appendix A. Testing search string robustness

To verify the representativeness of the selected sample of literature and evaluate search string effectiveness, three additional queries were run in ProQuest and Scopus (as the original search showed that GoogleScholar did not generate any results not already contained in the other two databases it was not used again) (Table A1). While the focus of this review is on energy (transitions), the word electricity was included to account for inconsistent and varied usage across the literature. A majority of studies containing the term electricity in the title are in the Electricity Market topic area. However, the term also appears in the Policy and Planning and Consumption Dynamics/ Consumer Behaviour topic areas. This illustrates that while the term is pre-dominantly used in market-centric studies, this is not always the case. Inclusion of the term therefore proved sensible.

Table A1
Alternative search query evaluation.

(agent-based OR multi-agent) AND (energy OR electricity)		
Results in	ProQuest	Scopus
Anywhere	23,612	34,195
Abstract only	2,701; peer-reviewed: 1,191	3,332; article, review, article in press: 1,234
Title only	645; peer-reviewed: 265 Of these 265 results, 10 were published between 1999-2007.	657; article, article in press, review: 238 Of these 238 results, 28 were published between 1999-2007.
→ This query was run to test the robustness of the search string applied in this study. The first expression is more flexible compared to the original ("agent-based model*" OR "agent-based simulation"). Scanning through titles within in the "titles only" search, results generally show little potential relevance to the topic under investigation; many seem highly technically focussed or centred on electricity markets. Limiting the date range to studies published before 2007 showed that the large majority of studies were published after 2007. This suggests that the date distribution observed in the present study is representative and not due to search string design.		
(agent-based OR multi-agent) AND (energy OR electricity) AND (transition)		
Results in	ProQuest	Scopus
Anywhere	10,963; peer-reviewed: 2,861 Date range of peer-reviewed results: 1992-2017; 491 results are from before 2007	4,141; limit to article, review, article in press: 3,025 Date range of peer-reviewed results: 1976-2017; 267 results are from before 2007
Abstract only	86; peer-reviewed: 46 These 46 include 20 duplicates; of the remaining set of 26 articles 4 are part of the selected literature in this study; a few others could be relevant	110; limit to article, review, article in press: 49 5 of these are included in the selection in this study; a few other could be relevant

(*continued on next page*)

Table A1 (*continued*)

Title only	5; 4 peer-reviewed; 2 of these results is an article that is included in this review (duplicate); the other 2 are not included and are relevant to the topic, however, 1 proofed to have been published in 2018 Date range of results: 2010-2017	5; 1 article, 1 review (3 conference papers); of the 2, one is included here, 1 is not but could be relevant Date range of results: 2008-2017

→ This query was run to test the robustness of the search string applied in this study. The first expression is much more flexible compared to the original (“agent-based model*” OR “agent-based simulation”). On the other hand, and in contrast to the above, a third expression, “transition”, was added. Unsurprisingly, the addition of the expression let to a smaller number of results in “anywhere” compared with above; and a drastic decrease in results when restricting the search to abstracts only (and even more when limited to titles only). 1 article was identified within the title search that suggests potentially high relevance to the topic under investigation. Within the abstract search, a few articles could be relevant based on their titles. However, none appeared to address a new topic area not covered here. In fact, a large portion of articles appeared market centric.
The representativeness of the date range observed in the selected set of literature was verified with a majority of studies in the much broader search having been published after 2007.

("agent-based computational" OR “agent-based spatial” OR "agent-based diffusion" OR "agent-based adoption" OR "agent-based analysis" OR "agent-based micro*") AND (energy OR electricity)

Results in	ProQuest	Scopus
Title only	30; peer-reviewed: 21; duplicates eliminated, remaining: 8 results Of these 8, 5 contain the phrase “agent-based analysis” in the title; the other 3 are: “agent-based spatial”, “multi-agent based microgrid energy management”, “agent-based computational modelling”; 5 of 8 contain the word market in the title	16; article, article in press: 10; 5 of these 10 contain the phrase “agent-based analysis” in the title; “agent based computational economics”, “agent-based spatial simulation”, “agent-based computational economics simulation”, “Agent-based microsimulation”, “multi-agent based microgrid energy management”; 6 of the 10 contain the word “market” in the title

→ This query was applied to test whether a significant number of potentially relevant articles was lost by including only the restrictive phrases “agent-based model*” and “agent-based simulation” in the search string. The results suggest that this was not the case. Firstly, the majority of articles contained the term “agent-based analysis” rather than the more specific terms of diffusion or adoption. In ProQuest only 3 of the peer-reviewed articles contained other terms; these were “multi-agent based microgrid energy management”, “agent-based computational modelling”, and “agent-based spatial”. In Scopus, in addition to “agent-based analysis”, the terms “agent based computational economics”, “agent-based spatial simulation”, “agent-based computational economics simulation”, “Agent-based microsimulation”, “multi-agent based microgrid energy management” appeared. This shows that no articles containing the terms agent-based diffusion or adoption in the title were lost due to search string construction.
Secondly, the majority of these articles appeared to be market-centric or technical studies; across ProQuest and Scopus, 11 of 18 results even included the word market in the title. They are therefore unlikely to have added insights to the present study, particularly given the focus on social components of the energy transition in this analysis.

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