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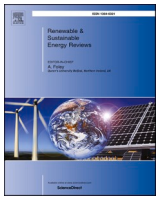
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Participatory methods in energy system modelling and planning – A review

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ABSTRACT

This paper presents a systematic review of participatory methods used in energy system modelling and planning. It draws on a compiled database of fifty-nine studies at a local, regional, and national level detailing analysis on full energy systems down to sectors, modes, and single technologies. The initial aim of the paper is to consolidate and present this growing body of literature, providing a clear understanding of which stakeholder groups have been engaged and what methods have been used to link stakeholder engagement with quantitative analysis. On from this, the progress to date in democratising key decision-making processes is discussed, reflecting on the benefits and challenges of a participatory approach, as well as highlighting gaps within the current body of literature. During the review, two differing spatial levels at subnational (cities, municipalities, or regions) and national scale emerged as separate groups for analysis. A clear distinction between the two groups was the motivation for involving stakeholders. At a subnational level, researchers hoping to build local capacity to bring about real-world change engaged with community representatives, whereas national level studies concerned with generating more impactful energy policy measures involved industry, policymaking, and academic experts. One key finding from the review was that only ten out of the fifty-nine studies reviewed noted some form of collaboration with non-academic stakeholders, and moreover 36% of studies involved just a single interaction with participants. This indicates a lack of progress to date in process democratisation within energy system modelling and planning research.

1. Introduction

The focus of energy system modelling and planning has been undergoing a paradigm shift in recent years, whereby assessing the social and political feasibility has become a policy and research priority. This emanates from a need to build consensus on the best path forward. As Waisman et al. [[1], pg. 262] note, in order for long-term decarbonisation strategies to be implemented they "*must be sufficiently understood and accepted by a working majority of stakeholders, both those responsible for implementation and those affected by the transformation (for example, governments, indigenous peoples' organizations, sector associations, firms, energy utilities, unions, experts, households and non-governmental organizations)*".

In relation to climate change, in light of the urgency needed and inertia present, the value of the engaging with a range of stakeholders is quite clear. The inclusion of factors from social sciences, while increasing model complexity and uncertainty, is an important step towards a better understanding of how the systems may be deployed [2]. Many of the barriers to the development of renewable energy are non-technical challenges that are dynamic and context dependent. In the case of opposition to large-scale wind energy for example, existing research has shown a variety of conditions that shape public perception including physical, contextual, political, economic, social, local and personal aspects [3]. Transcending many of these issues is a lack of trust and openness emanating from a perceived lack of public inclusion in the planning/decision-making process [4].

Similar to the approach of von Wirth et al. [5], this paper conducts a systematic literature review in order to build an understanding of this emergent field. Firstly, to capture the range of existing work in the area, and secondly, to build an understanding of progress to date in democratising the energy system modelling and planning process, by answering the following research questions:

Abbreviations: ABM, Agent-based model; ESOM, energy system optimization model; GHG, greenhouse gas; MCDA, multi-criteria decision analysis; NA, not available; NGO, non-profit organization; SDM, system dynamics model; SWOT, Strengths, Weaknesses, Opportunities and Threats.

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1. What stakeholders have been engaged? Moreover, to what extend has this involved engaging stakeholders outside of energy related fields?
2. To what extend has this involved a collaborative process as opposed to simply a consultation?
3. How have the qualitative outputs from stakeholder engagement been translated for use in quantitative energy system models or assessment tools?
4. What are the challenges and benefits of taking a participatory approach?
5. Within the current body of literature, what are the gaps and subsequent considerations for future research?

As noted by Mirakyan and De Guio [6], due to the fact that energy system modelling and planning crosscuts environmental, social and economic aspects, it thus requires a combination of methods. However, existing literature reviews generally deal with topics separately. Scheller and Bruckner [7] assess how a range of energy system optimization models (ESOMs) may be used for municipal level analysis, but do not discuss the inclusion of local stakeholders in the modelling process. Similarly, Cuesta et al. [8], review a range of tools for designing hybrid renewable energy systems and conclude that these do not consider important social factors. Ribeiro et al. [9], provide an overview of methodologies for assessing social impacts in electricity power planning, with only five of the nineteen studies reviewed including participative approaches. Most recently, Hirt et al. [10], explore the frameworks available for linking socio-technical theories and energy/climate models, and note that transdisciplinary approaches (seeking non-academic participation) were underrepresented in the reviewed studies. This highlights a clear lack of coverage in the literature on the progress to date in combining energy system modelling and planning with participatory methods.

The paper addresses this gap as follows. Section 2 proposes a conceptual framework for understanding what would be considered a meaningful integration of participatory methods, and briefly introduces the systematic review that was carried out. Section 3 examines who has been engaged and how this was done. Section 3.1 and 3.2 highlight what stakeholder groups have been involved to date and then the engagement methods are assessed against a framework to determine the level of collaboration in Section 3.3. Section 4 provides details on the range of methods used; initially to capture the qualitative stakeholder input, how this was interpreted or translated for the quantitative analysis and reflections on the merits of the different approaches. Finally, Section 5 begins by reflecting on the challenges and benefits of pursuing participatory approaches, before reflecting on the progress to date in process democratisation and highlighting some considerations for future research.

2. Methodological approach

This section shall introduce the conceptual framing developed to help define what the meaningful integration of participatory approaches into energy system modelling and planning involves, as well as a brief overview of the systematic review conducted.

2.1. Conceptual framing

As illustrated in Fig. 1, in the past, energy policy was generally assessed against the trilemma of cost, environmental impact and security of supply. However, given the need to build consensus on future energy pathways, it has been increasingly recognised that the societal dimension must also be included. This has subsequently prompted a growing interest in participatory or transdisciplinary approaches to energy system modelling and planning. Two of the key drivers behind this growing interest are; firstly the need to build a broader understanding of the energy transition within socio-political contexts, and secondly, the democratisation of key decision-making processes. On from this, the criteria for understanding progress in this field are:

1. The diversity of inputs and outputs from the research
2. How well these represent the ongoing energy transition
3. Public acceptance of energy policy
4. The extent to which the participatory process has facilitated an open and transparent discussion on the best path forward.

The latter of which is the primary focus of this review.

In order to build an understanding of what process democratisation entails, a conceptual framing was developed. As outlined by Schubert et al. [13], in most cases assessing social acceptance involves acceptance of the outcome, i.e. it takes place after the conventional quantitative analysis and is not considered in line with technical and economic factors. Giving social acceptance equal consideration would be acceptance of the process, established through open and transparent deliberation. Under this framing, we propose that the level of integration can be either shallow or meaningful, as illustrated in Fig. 2.

A shallow integration sees the assessment of social acceptance as an added piece of work separate to the conventional techno-economic analysis performed, whereas a meaningful integration would seek to engage stakeholders throughout the process. There are two common cases of a shallow integration, firstly efforts to incorporate socio-technical theories (such as s-curves, behaviour profiles, etc.) and thus usually only involving academic inter/multi-disciplinary collaborations. Secondly, public attitude surveys that are conducted separately to the energy system analysis and subsequently have no bearing on it. A more meaningful integration that gives the societal dimension an equal weighting to its techno-economic counterparts can be defined as follows:

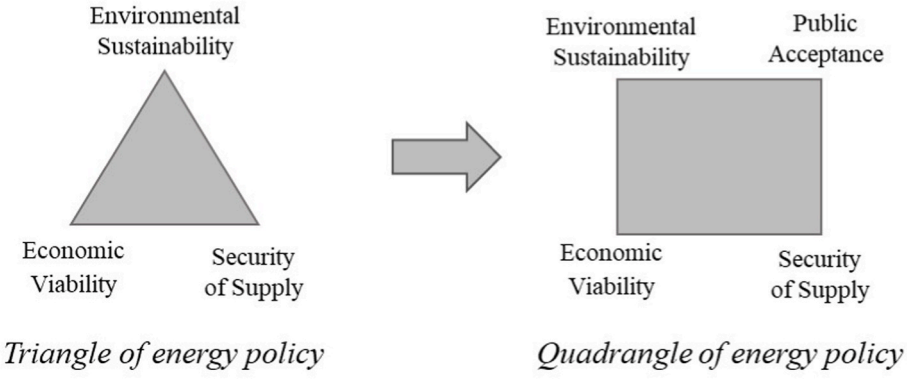


Fig. 1. Paradigm shift in energy policy [11] (as citied in Ref. [12]).

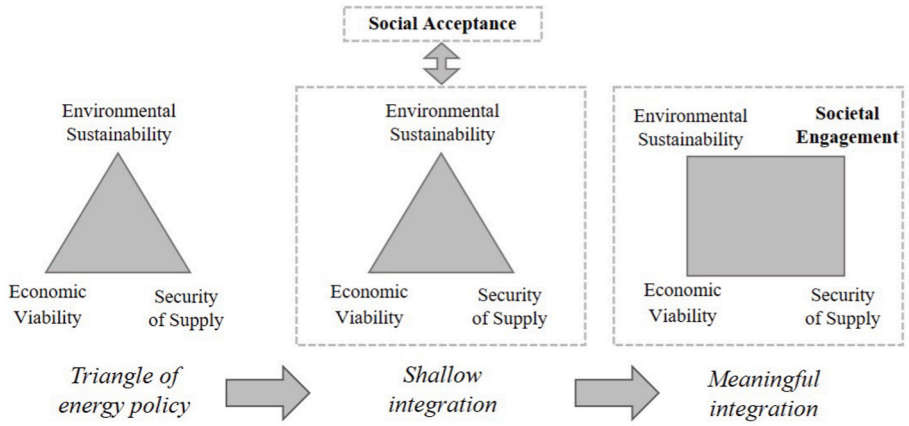


Fig. 2. The integration of a social dimension into energy policy analysis developed by the authors based on [13].

- As a minimum requirement, the stakeholder input needs to be gathered before performing or drawing conclusions from the quantitative analysis. If the engagement process takes place after the analysis, then key decisions have already been made.
- It should ideally involve an iterative process that allows stakeholders to shape the analysis as well as evaluating the results. In cases where the participants are only involved to frame the analysis or provide insights for it but are not given the opportunity to provide feedback on the results/findings, a lot of the key decision-making is still within the hands of the research team.
- Going further, co-production and collaborative approaches have been recognised as providing an opportunity for academic and non-academic partners to work together in achieving vital sustainability goals [14]. This involves engaging stakeholders throughout the entire research process, including at early-stages during problem structuring and research question framing [15]. Thus maximising the relevance of the analysis being undertaken as it can address real-world problems [16]. At a national level, the engagement of decision makers can ensure topical policy assessments [17], while at a local level the public can provide useful 'social intelligence' [16].

As with many academic concepts, transdisciplinary research has prompted much discussion on its definition [18]. This is not a topic for debate within the present review. However, it is important to note that while there is no singular definition of best practice in stakeholder engagement, collaborative/co-production approaches offer useful guiding principles for the democratisation of the process, and are thus important in this context.

2.2. Systematic review

The full details of the systematic review process are outlined in McGookin et al. [19], and a summary of the search results is provided in Appendix A. It provided fifty-nine studies for review, which were identified using the following criteria:

a) Stakeholder preferences, perceptions or opinions had been established through some form of engagement, e.g. interviews, workshops, or meetings.
b) This was a meaningful engagement process (as discussed in Section 2.1) and was not purely in the interest of data collection, awareness raising or validation of results. A significant number of studies were excluded as it became clear that the stakeholder engagement took place after the energy system analysis had already been conducted, and thus had no bearing on it.
c) The output(s) of the engagement were used as input(s) for qualitative or quantitative analysis to inform decisions about future energy system configurations. Studies solely dealing with public attitude surveys toward a particular piece of existing infrastructure were not included.

During the filtering process two clear spatial categories emerged; subnational (or local) and national. In general, the motivation for involving stakeholders differs between the two scalings with national studies focused on policy generation and local geared toward action-orientated research. These different scalings will require specific approaches and involve different stakeholders so are predominantly addressed separately. One study involved both national and local case studies [20], which meant that there were a total of twenty-seven studies for review at a national level and thirty-three at the subnational level. A visual representation of the differing spatial and technology focuses can be seen in Fig. 3. The x-axis relates to the share of the energy system covered. From left to right; a small share with just a single technology focus (e.g. solar PV or bioenergy) to a single or multiple modes (heat, transport or electricity), sectors (e.g. residential) and finally addressing the whole energy system. On the y-axis, the spatial scale goes from top to bottom; national down to regional and then city/town.

It is interesting to note that only twenty-three out of fifty-nine (39%) studies looked at the whole energy system. Roughly one-third (30%) of the national studies had only addressed the electricity system, compared to 15% in the subnational group. Conversely, 27% of subnational studies dealt with only a single technology compared to 7% of national studies. For a full list, see Table B.1 in Appendix B.

3. Stakeholders engaged

Fig. 4 provides a breakdown of the range of stakeholders engaged in the studies reviewed by the share of papers involving each group. Firstly, it looked at the number of studies that had included academic experts. Secondly, the non-academic energy and environment experts involved, primarily coming from government departments responsible for energy policy, actors in the energy market and environmental NGOs or conservation groups. Finally, there was quite a wide range of stakeholders not directly linked to energy and environment issues. The description of participants was generally quite vague, presumably in the interest of anonymity, but still sufficient to categorize them using the adopted framework. A more detailed breakdown can be seen in Appendix B Tables B.2 and B.3.

The number of participants was also recorded to see if there was consensus on what would be a desirable amount. In the subnational studies, very few provided the exact number of participants so no conclusion could be drawn. However, the majority of the national studies provided details on how many participants had been involved. None of them gave explicit justification for the number of participants

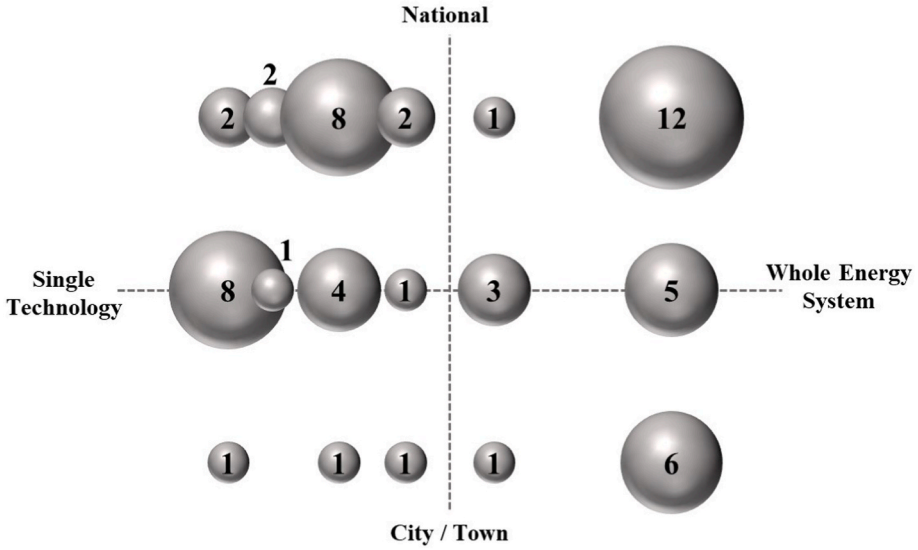


Fig. 3. Number of studies at the different spatial and technology scales within the papers reviewed.

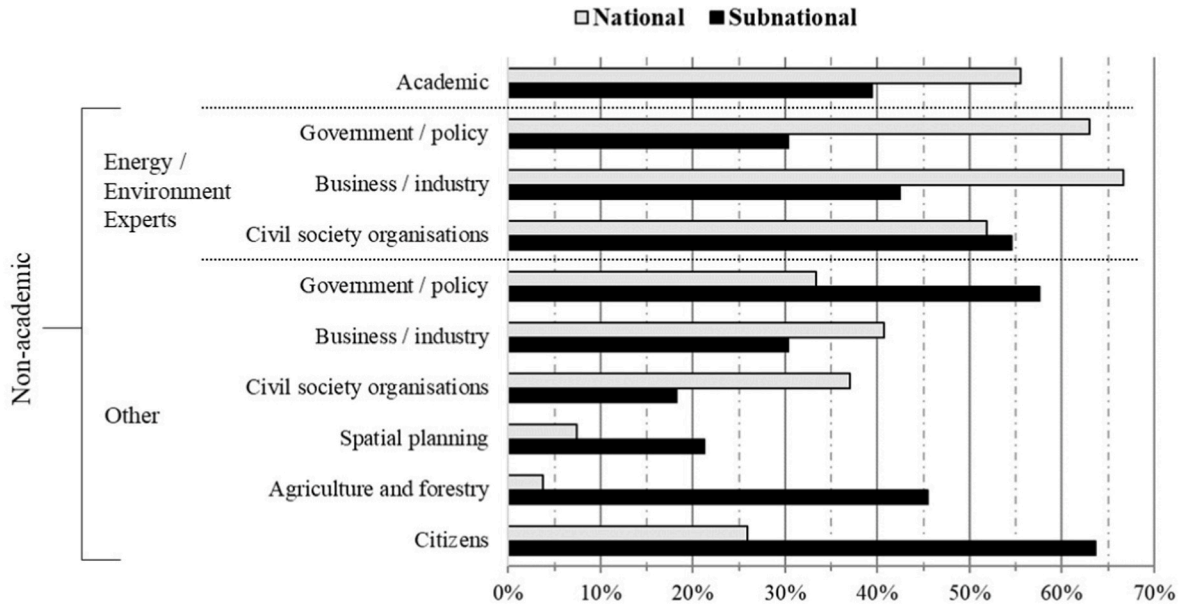


Fig. 4. Range of different stakeholders by share of papers that involved each group.

involved, but having twenty-five participants appears to be the typical amount, with a number of studies having this amount [21–24] and several others having close to it [25–28].

3.1. Subnational studies

Agriculture and forestry was represented in 45% of subnational studies but only 4% of the national. This was largely due to the rural nature of the regions [29–35] or fact the study was investigating the bioenergy resource potential of an area and how it may impact forestry or land-use [36–43]. This highlights one of the main advantages of working on a smaller scale, which allows for more targeted analysis to understand the areas characteristics. There was also a much larger focus on understanding local perceptions and priorities, with 64% of studies involving members of the public compared to 26% in the national studies. This is perhaps to be expected, as studies focused on local energy systems stand to benefit greatly from tapping into the local knowledge. A number of studies concerned with the development of renewable energy in isolated rural communities worked closely with indigenous (or aboriginal) villagers [30,44,45]. In these instances, a key element of the research was building social capital and strengthening relationships with local people in order to build trust and understanding. In the other sixteen studies that had involved citizens there were two predominate motivations. Firstly, to allow local people an opportunity to express their concerns or preferences toward different technology options [20,29,31,32,35,41,46–52]. Secondly, to understand the end-user expectations or lived experience of a particular technology [33,43,53].

Elected representatives and policymakers (not directly linked to energy or environment) were involved in 60% of the studies, compared to only 33% of the national studies. One interesting point to note is the inclusion of mayors; this suggests a keen interest from the local government given that these top-level officials made themselves available for the time needed to participate in the research [20,29,33,41,54,55]. The inclusion of decision makers in the form of planners and elected officials is important as the energy system modelling and planning process can open up insightful discussions on the trade-offs and impacts

of policy measures. As the development of renewable energy transforms the energy system to a more decentralised platform, governance must do likewise. As noted in Sperling et al. [56], while key elements like infrastructure developments and institutional frameworks (such as building codes) have to be stepped up and managed at a national level, there is increasing need for the involvement of local stakeholders, especially local authorities, in the design and planning process.

Only six out of thirty-two studies had no representation from energy or environmental experts. The majority of stakeholders came from energy or environmental related backgrounds, with 85% of studies involving representatives from either the energy industry, government departments, local energy agencies or co-operatives and environmental NGOs. There were, however, some interesting inclusions from outside this field, with a number of studies involving representatives from religious institutions [35,45,49], health [35], education [31,40], tourism [32,40,45], finance [34,37,57], and construction [20,37]. One noticeable omission is civil society organizations not linked to energy or environmental concerns, which featured in just under 20% of studies, with only two noting the involvement of community development organizations. These groups could offer invaluable expertise, with an existing reputation in the area and understanding of its challenges, as well as providing a means of reaching the vulnerable and underrepresented members of the community.

3.2. National studies

At a national level, there was a greater emphasis placed on working with energy experts to get a detailed understanding of a particular sector or how different elements of the energy system interact. The research served as a means to facilitate discussion between key actors from the energy industry (appearing in 67%), government/policymakers (63%) and academia (56%). This is not surprising, firstly due to the fact representatives from the energy industry were specifically targeted in order to better understand the energy market, and secondly, given that participation in the process may provide valuable insights for policymakers or utilities and energy suppliers. As noted in a number of studies, the deliberation process can contribute to the formation of more informed and actionable policy [37,59,67].

However, the prominence of experts in the national studies could be criticised as failing to provide real-world 'on the ground' knowledge, experiences, perceptions and values [58]. As with the subnational, only four studies (15%) had no representation from energy or environment experts. These specifically focused on capturing public perceptions [64,68–70], through a number of innovative ways, covered in detail in Section 4.1.4. There were five studies that involved a consumer association as oppose to actual customers, perhaps reflecting the need for national studies to take a broader perspective.

3.3. Level of participation

There are a number of different frameworks for classifying the level of participation in stakeholder engagement activities. Notably, Arnstein's 'ladder of participation' is a well-known means of classifying stakeholder involvement in the planning system [59]. The "Public Engagement Onion" developed by Welcome Trust offers a similar means of classification based on the level of control given to participants [60]. With regards to energy research, Trutnevyte and Stauffacher during a review of a transdisciplinary research project distinguish between the different activities based on the form of communication and its purpose [61]. From these the following framework was adopted, comprised of three levels of engagement as follows:

- Informing – one-way flow of communication, usually for the purpose of awareness raising or educating, no opportunity for input into a decision-making process, participants cannot influence the outcome of the research.
- Consulting – two-way flow of communication, surveys, interviews or workshops used to elicit stakeholder opinions, participants have opportunity to shape the research results but not the research questions or objectives.
- Collaborating – open and transparent communication throughout the process, participants given the opportunity to shape research questions and direction throughout the duration of the project.

As outlined in the Introduction, public trust in decision-making processes will be key to the success of energy policy. This requires an open and transparent process that facilitates discussion and debate. In light of this, it is good to see that conducting a workshop or series of workshops stood out as the most common form of engagement undertaken. A number of studies in both of the groups, involved multiple interactions, conducting a semi-structured interviewed or survey prior to the workshop(s) [20,29,30,34–36,62–68], see Section 4.1.1.

Lang et al. outline that an important step in the formation of a transdisciplinary research project is that a collaborative team of diverse scientific backgrounds and non-academic representatives should design the research [69]. The process of jointly identifying the real-world problem and research objectives helps to ensure the research is correctly orientated and facilitates the building of trust and understanding between the research team and relevant stakeholders. However, there was a limited number of studies indicating a collaborative approach. As can be seen in Fig. 5, only ten of the studies reviewed (17%) noted some form of transdisciplinary committee or partnership with non-academic stakeholders [25,30,33,35–37,39,42,53,57], with another four mentioning further discussions or meetings outside of the formal engagement process [20,31,48,70]. Moreover, it is striking to note that in 36% of studies the stakeholder participation involved just one interaction.

4. Methods used

This section explores the variety of qualitative and quantitative methods used in the studies reviewed. Firstly, addressing how stakeholders have been engaged as well as the methods used to capture their inputs. Secondly, the quantitative analysis undertaken and how this was shaped by the stakeholder participation. For each of the individual methods a general overview and brief summary of how it was applied in the studies reviewed is provided, noting the linkages between the qualitative and quantitative elements as well as the strengths/weaknesses of the various approaches. Fig. 6 displays the methods used by the number of studies, for the full list see Appendix B Table B.4. There are a couple of methods not discussed due to the limited number of examples in the literature reviewed, these include agent-based modelling (ABM) [34,71] and sensitivity analysis (SA) [29,31].

4.1. Facilitating stakeholder input

4.1.1. Interviews and surveys

Interviews and other surveying techniques were used in a number of different ways. The most common method at both a local and national level was semi-structured interviews, which were conducted in 46% of studies reviewed. This was generally seen as a prerequisite to conducting a workshop with a diverse group of stakeholders, as it is important to first allow the stakeholders to have the opportunity to individually express their views [34,43,44,48,62,63,65,67,68,72–74]. This has the co-benefit of greater stakeholder participation and also gathering useful data for the researchers. The loosely structured nature of semi-structured interviews conducted face-to-face provides a more creative space for discussion, allowing participants to better express their opinions and mitigating against the risk that stakeholder's different views may not be documented when reaching consensus as part of workshop activities. Moreover, it provides a better understanding of potential tensions and synergies by exploring individual motivations or

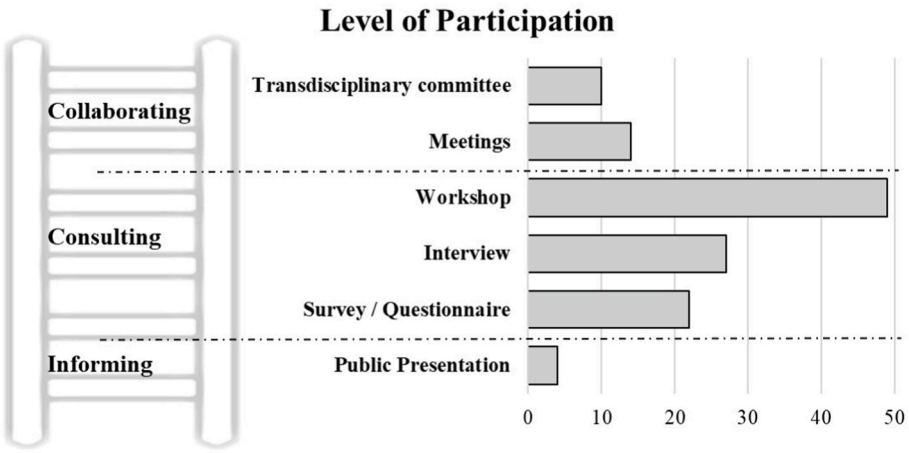


Fig. 5. Level of stakeholder participation in the papers reviewed.

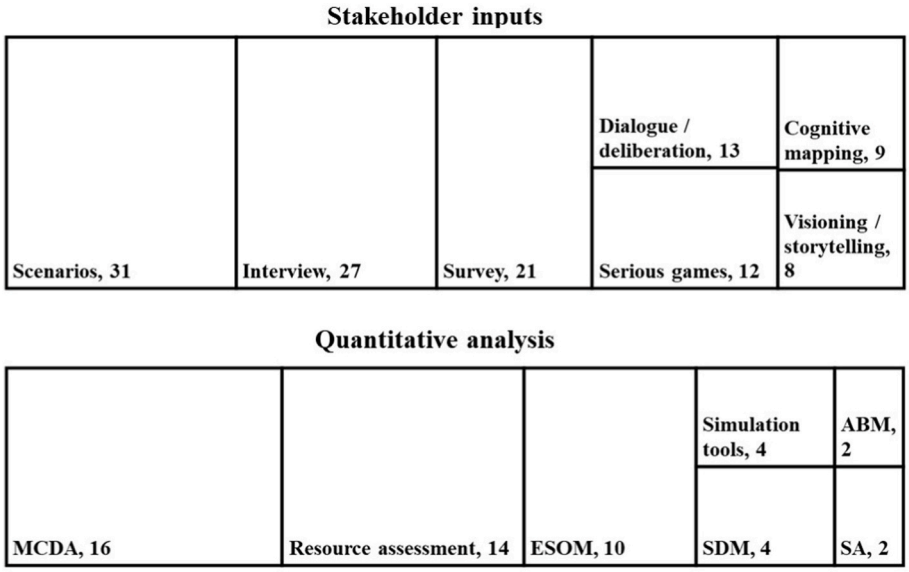


Fig. 6. Methods used in the papers reviewed by number of studies.

worldviews prior to grouped workshop activities.

At a local level, these interactions were noted as being of particular importance as a means of building trust within a community [44], developing an understanding of the local area [30,43,74] and compiling a list of key stakeholders [39,44]. Asking interviewees to identify other stakeholders is a commonly used method of recruitment often referred to as a 'snow-balling' technique [75].

A number of other studies used a more formal approach, opting for quantitative methods of data recording in the form of surveys and questionnaires [12,20,24,26,27,29,31,40,42–44,76–79]. This was generally necessitated by the method being used, although there were a number of different purposes; ranking criteria as a prerequisite for MCDA [12,20,24,29,31,40,42,43,75], ranking options using a Likert scale [25,66,77,79,80], general opinion surveys [26,27,42,76–79], data gathering [81] and evaluation [44,76,77]. The means by which the surveys were conducted varied from; face-to-face interactions as part of a workshop [42,66,77,78], or structured interview [12,20,24,29,42,44,75,81], telephone interview [27] and online surveys [12,26,31,40,43,76,77,79]. In a couple of cases the survey was the only form of participation from the public, and the results of the surveys were then discussed in 'expert' workshops [12,79].

The trade-off between interviews and surveys is quite clear. Interviews can provide descriptive data that is useful for getting a deeper understanding of stakeholders differing perspectives, which is by its nature difficult to integrate into energy system models. While surveys can provide quantitative data that may be more easily integrated into the models but fail to provide any context. For example, in an interview someone could explain the complex variety of reasons for disliking a particular technology but in a survey this may be greatly oversimplified as technology X is less popular than technology Y.

4.1.2. Scenario generation

The generation of scenarios, narratives or pathways based on stakeholder input or dialogue was another common form of qualitative analysis appearing in 53% of studies. This is not surprising considering how widely used scenarios are as a tool in long term energy system modelling [82]. Scenarios are an effective way to specify future visions and are particularly useful for exploring highly complex and uncertain systems.

An important methodological feature in the formation of scenarios is the use of a set of assumptions about key relationships and drivers of change within a system based on historical trends or the current state. In energy system modelling there are two forms of scenarios; descriptive storylines and quantitative projections. The process generally involves

establishing narratives for the future before generating projections of economic and technical parameters like expected growth, resource potential, cost of technologies, etc. Linking qualitative storylines and quantitative elements in this manner improves our understanding of how systems work and evolve, which can provide useful insights on the synergies and trade-offs between different policy options [28,38,45].

Adopting a participatory approach to scenario development can broaden the boundary of analysis into the socio-political context within which the system will be built, providing a platform for the discussion of key trends and drivers with relevant actors. The sharing of real-world knowledge about the deployment of technologies, ensures that all major uncertainties and different perspectives of stakeholders are taken into account [34]. For those involved, this helps to identify areas of common interests [38], while also encouraging practical learning both of energy systems and also creative ways to think about the future [34,47].

Focusing on how scenarios were used within the studies reviewed, in the subnational group it was found that the majority of local studies had either solely involved stakeholders for the purpose of explorative scenario generation [34,38,45,47,53], or agreeing desired outcomes [20,35]. The priority was to develop a shared vison or objective. By contrast, the national studies gave greater consideration to the scenario descriptions, prioritising the discussion of trends and drivers with participants. Primarily involving experts from the energy industry, dialogue through interviews or workshops sought to capture the range of perspectives on market trends that would impact the rate of the deployment of specific technologies [68] or changes within certain sectors [23,28,72]. The emphasis was placed on building consensus and understanding between researchers, government and industry stakeholders in order to develop better aligned pathways and policy recommendations for decarbonisation targets.

4.1.3. Cognitive mapping

Cognitive maps also referred to as mental maps or mental models are a commonly used method of problem structuring or framing. They are effective tools for conceptualising a system and its causal relationships, which makes them useful for identifying values and choices amongst a diverse network [83]. They come in a variety of different forms causal loop diagrams [35], perception graphs [34] or logic trees [47]. A cognitive map is the representation of a problem through the development of a network of nodes and arrows, whereby the links depicted by arrows denote a perceived causal relationship [84]. The objective of this approach is to identify the interactions among variables and the structure of feedback loops, providing a clearer understanding of the cause-effect relationships within a complex system. Given that energy policy is a highly complex and multi-faceted 'wicked' problem, the use of a problem structuring method is warranted.

Within the literature reviewed, the primary use of cognitive maps, across local and national studies, was to capture and conceptualize individual stakeholder's perceptions of the dynamics and interactions within challenging and potentially controversial issues like bioenergy [34,35,45] and housing [65,67]. This was done by first interviewing stakeholders in order to understand the perceptions of the individual actors, before merging them as part of a workshop in order to form an agreed model of the system under investigation [34,35,45,65,67]. In one other study, assessing the social and economic impacts of the policies adopted across the whole energy system within a city, the causal loop diagrams were developed over the course of two workshops and did not involve any interviews [55]. Another made use of a logic tree to map out and explore how proposals made over a series of workshops would contribute to the different energy visions [47].

This provides a holistic view of the system and its causal relationships, which can open up useful insights into the knock-effects and trade-offs of different policy measures, as well as an important understanding of interdependencies within the system. In doing so, facilitating a broader discussion around the social and environmental impacts of policy. For example, in the case of bioenergy giving consideration to issues around land use and forestry, and in the case of housing capturing the health and wellbeing benefits of improved energy efficiency.

The majority of studies used the developed causal loop diagrams as a basis to perform system dynamics modelling [35,45,55,67]. This is covered in Section 4.2. However, in two cases the analysis was purely qualitative, establishing a framework and set of criteria for exploring future policies but not demonstrating its use within the study [34,65]. In one instance, Macmillan et al.'s work [65] is what formed the basis for that undertaken by Eker et al. [41], involving the same stakeholder groups at different stages of the model development process.

A very similar concept to the use of cognitive mapping is mind mapping. In one study, it was used during the first workshop to capture general expectations for the research such as desires for community involvement, objectives and technical options that should be explored [29]. In the other study, researchers performed a stakeholder mapping exercise prior to the engagement process in order to group actors in terms of their importance for planning within the region, as well as highlight potential synergies or conflicts [37].

4.1.4. Serious games

A serious game is an interactive approach that is designed with the intention to teach rather than purely entertain. They often involve imagining alternative realities that can facilitate interesting discussions on complex real-world problems with a diverse group of stakeholders. The use of serious games in climate change research is well documented [85–87]. These games can help raise awareness, build capacity for problem solving and provide a useful space to explore complex problems [88]. Serious games are likewise suitable for exploring the challenges associated with energy system modelling and planning. In contrast to the other methods discussed throughout Section 4, which noted ways of combining the use of qualitative and quantitative analysis, this approach offers a means of merging the two by giving stakeholders tools to see in real-time their energy system configurations and the associated reduction in emissions or spatial trade-offs, etc. However, this comes at the cost of greatly simplifying energy system characteristics or the results of existing energy system models [51,64].

The studies reviewed provided a number of different approaches to develop energy portfolios through the use of; maps [49,54,64] role-playing [52] and computer tools [46,47,50,51,64,66,77,89]. At a local level, maps were used in a number of different ways to develop portfolios to meet a region's energy demand [49,52,54]. One study used a cardboard game approach, pining pieces of card scaled based on a technologies delivered kWh/m^2/annum onto a map of the area detailing general information on topography and land use [54]. In addition, participants were given a booklet containing background information with regard to the existing energy facilities, energy consumption, and renewable energy potentials. Another study used an aerial photograph to identify potential sites for renewable development and modelled a number of different scenarios before producing a scale model of the desired option through a number of interactions between architecture students and the local residents [49]. Another example from Switzerland used the combination of a computer-based portfolio selection tool and map-based board game to initially gather preferences and then discuss spatial issues of actually placing the technologies [64]. Similar to these approaches was the use of energy proposal cards for a fictional town, providing information around plant siting and attributes like the new plants contribution to jobs and climate targets [52]. Participants were then asked to assume the role of local decision makers (in the form of 'town councillors' or 'council members') and rank the proposals as a group.

Interactive computer tools were used at both a subnational and national level, examining portfolios of the whole energy system [47,89] or just electricity [50,51,57,64,66,77]. The general framework applied was to provide members of the public with information on different renewable energy technologies and then ask them to choose a portfolio

of technologies to meet a particular energy or electricity demand. This was done both with and without facilitation; two studies relied on people doing it by themselves [51,89], while the others worked during workshop sessions [47,50,57,66,77]. Flacke and De Boer combined the use of maps and a computer tool using a digital 3D map/visualisation on a tabletop display [46].

The dashboard or interface differed according to the approach being used. One of the studies involved a web-based tool that allowed users to explore their preferences towards different supply and demand options by displaying the changes on an animation at the level of home, city and country [89]. After making adjustments to achieve a CO_2 reduction target, users had the option to submit their scenario to a research database. The other studies involved using a dashboard to select an electricity portfolio, which came in the form of a simplified excel representation downloaded from an online portal [50,51] or was provided during a workshop session [23,66,77]. One study provided a CO_2 simulator for assessing the range of proposals put forward during the workshops [47]. In another interesting example, Droste-Franke et al. developed a web application of the tool that had been used to assess scenarios during a workshop so that it could be further disseminated [57].

The information provided to users or participants likewise differed based on the approach. The primary focus was on CO_2 emissions; however, one dashboard also displayed the impact of chosen technologies on land, water and health [51]. Two of the studies chose to have information on technology impacts provided in the factsheets [47,51,77]. This was done to avoid distorting participants view and allow them to individually assess the importance of environmental, health, or economic impacts. In an interesting example, Xexakis et al. compared the difference between 'informed' citizens given factsheets and a sample that hadn't been provided them [51].

4.2. Quantitative analysis

4.2.1. Simulation and optimization tools

The two prominent forms of energy system models are optimization and simulation tools. Optimization models solve for the least cost solution to satisfy energy service demands under set constraints like the cost of technologies and predictions for when they will become available. On the other hand, simulation models generate projections of the energy demand/supply based on user-defined assumptions like the share of energy supply options, the level of economic activity and energy intensity of different sectors.

This was the most common form of quantitative analysis in the national studies, with 67% of studies (using an optimization tool, and in particular MARKAL/TIMES [22,28,68,70,79]. Others used in-house models such as REMIND-D [25], MOTRiP [73] and Imaclim-R-France [78], or simulation models such as renpassG!S [21,23] and LEAP [72]. One example from Germany used a direct current (DC) electricity grid expansion tool within PERSEUS-NET [12]. By contrast, in the subnational studies this was the least utilized method, with only five examples (15% of studies reviewed). Two made use of optimization models TIMES [81] and RE^{3}ASON [29], while one other example used LEAP [53]. In designing a microgrid system for remote rural communities, another couple of examples used the HOMER-PRO Energy software [30,62].

Across national and subnational studies, the use of simulation and optimization models generally involved a three stage process as follows; i) the development of socio-economic storylines or narratives based on stakeholder workshops or interviews, ii) the translation of these qualitative scenarios into quantitative modelling assumptions, iii) the development and assessment of quantitative energy scenarios [22].

The means of capturing stakeholder's vision for the future and technology preferences varied from solely involving a survey [23,79] or interview [72], a combination of interviews (or survey) and a workshop [25,68,73,78], a once-off workshop [21,22,29,70], and being developed in a series of workshops [28,53,81]. In the majority of cases there was no further engagement with the stakeholders, the research team carried out the translation of the stakeholder inputs into model parameters without any form of evaluation or feedback. Only three studies involved an iterative process whereby the models were revised following a feedback session [28,53,81]. Venturini et al. [28], were the only study that explored the underlying modelling assumptions with the stakeholders involved. In another interesting example, Schmid et al. [25] held a session to discuss the modelling results and the socio-political implications of the different scenarios that had been developed. While Sharma et al. [70] did not hold a dedicated feedback session with the participants, it is noted that during the development of a scenario ensemble based on these inputs there was an ongoing discussion with key policy advisers. Four other studies assessed the modelling outputs using an MCDA method, which was determined during the scenario-building workshop or as part of a dedicated follow-up meeting [21,23,29,81].

4.2.2. Multi-criteria decision analysis

Within the literature reviewed, there are a number of reviews available on the use of multi-criteria decision analysis (MCDA) in energy planning and decision-making [29,31,40]. These provide a detailed overview of MCDA methods, but lack a key focus on the participatory element, which will be covered in this subsection. The name 'multi--criteria decision analysis' was the most commonly used, and thus is used here to also refer to the range of alternatives that appeared within the literature reviewed; multi-criteria assessment [20,33], multi-objective decision-making [38] and multi-criteria mapping [75].

MCDA is a tool for determining the weighted importance of a range of criteria or indicators. It is popular within energy system analysis due to its ability to highlight trade-offs and interconnectedness between a variety of different social, economic, technical, and environmental factors. With regards to taking a participatory approach, the most relevant part is how the criteria were chosen and weightings were determined. In half of the studies reviewed, participants only inputted into the weightings while the researchers chose the criteria based on experience, a review of the literature or policy documents [12,31,33,38,40,57,80]. To evaluate their choice, one study asked participants if they felt any indicators were missing [80].

In the remaining studies, participants were included in the criteria selection, assessment and weighting process through a range of approaches [20,21,29,33,43,75,81]. Trutnevyte et al. [33], decided the relevant criteria in discussions with the transdisciplinary committee set up to oversee the research and several representatives from the energy industry. Kowalski et al. [20], in two separate case studies, at national level did this solely through individual interviews and in the two local areas through reaching a group consensus in facilitated workshops. Vaidya and Mayer [43], used focus groups and interviews before narrowing the list of criteria and determining weightings in a workshop. Zelt et al. [21], gathered the criteria from surveys conducted with the relevant stakeholders, and then determined individual weighting before asking participants to join one of these four groups; techno-economic, societal, environmental or equal preference. Similarly, Simoes et al. [81], agreed criteria in a group discussion, then asked participants to individually weight them before coming together to reach a group consensus. McDowall and Eames [75], made use of the multi-criteria mapping software during an interview to take participants through the entire process. McKenna et al. [29], as part of a workshop, used a mind map initially to capture the community's values and objectives before discussing the criteria to be explored.

4.2.3. System dynamics modelling

System dynamics modelling involves mapping out the relationships between a system's various elements and defining them with a series of non-linear equations [67]. It follows the growth or decrease of a series of variables over time referred to as 'stocks' and the rate at which they change referred to as 'flows'. The involvement of a diverse group of stakeholders in the model development process through approaches like

cognitive mapping (as in Section 4.1) strengthens the underlying assumptions governing the model such as model variables, causal relationships and parameter values. This supports model validation as well as shared learning amongst the participants about the complexity and deeply interconnected nature of the energy system [35].

In the literature reviewed, system dynamics modelling was chosen because of its emphasis on causal relationships and whole-systems perspective [35,45,55,67]. This makes it well suited to exploring the impact of policies on a system's behaviour. The strength of system dynamics models are their ability to demonstrate unexpected behaviour resulting from a system's structure across an integrated network of social, technical and economic elements [35,67]. There are a number of software packages available to develop system dynamics models, such as VENSIM [55,90] or Simile [91], although one study opted for a simple Excel representation [35]. This was justified as a matter of preference for ease of database handling and linking with the graphical tools used to display the model output.

4.2.4. Resource assessment

In the subnational studies, the most common quantitative analysis undertaken was a resource assessment [20,32,33,38,39,41,49,54,80]. Studies that focused on a single technology such as Solar PV or bioenergy analysed the potential for that particular resource in the area [38,39,41,45,80]. This would perhaps be expected as it will produce useable research outputs for the local communities involved, giving them a valuable insight into the renewable energy resource they are interested in developing. The stakeholder preferences were gathered through a variety of means; surveys/interviews [41,80], workshops [32,38,49,54], combination of interviews and workshops [20] or interviews and discussion with project steering committee (or community advisory board) [33,39].

Studies working with an MCDA approach generated simplified quantitative energy scenarios covering only energy demand and renewable energy share for a given year [20,33]. Terrados et al. [32], created a SWOT matrix for a range of renewable energy technologies before deciding on renewable energy objectives. Nabielek et al. [54], assessed the feasibility of locations chosen for development through a serious game approach as discussed in Section 4.1.4. In another interesting example, Krzywoszynska et al. [49], prepared for the local town a useful and easy to understand infographic highlighting three potential renewable electricity scenarios and what share of local electricity use this would be as well as an estimated payback period.

There were only two examples in the national studies [20,26]. Focusing solely on wind energy development, Höltinger et al. assessed the technical feasibility and economic viability of four potential development scenarios covering; min, med, max and suitability zones [26]. Kowalski et al., in one national study and two local case studies, made projections for the future energy demand and share of renewables based on existing government reports [20].

5. Discussion

5.1. Benefits

5.1.1. Legitimacy and robustness

The most commonly noted benefit of taking a participative approach was that this would improve the legitimacy and robustness of results [20,22,23,25–28,30,35,39,42,45,47–49,52–55,67,68,72,76,78,92,93]. As noted earlier, energy transition dynamics go beyond solely techno-economic representations and are more accurately described as systems placed within socio-political contexts. However, most energy system models solely focused on producing technical details, often neglect the interaction between social, political, economic and technological factors [22]. This has led to attempts at combining quantitative energy system models and qualitative scenarios or storylines detailing socio-technical transitions [2,94]. From this, the field of participatory modelling emerges as an approach that can facilitate understanding in problem framing and thus increase the legitimacy and robustness of the resulting model [95].

The value of the participatory approach is that it allows for discussion of the socio-political implications of different technology options, and thus can include the diverse perceptions, values, assumptions, expertise and experiences of actors [22,23,25,28,42,45,49,54,78,93]. This facilitates the production of broader knowledge and richer hypotheses [54,67,68,76,78] as well as helping bridge the gap between abstract global challenges and local realities [20,25,30,52,72], making solutions more practically applicable [26,48,55]. Within the subnational studies reviewed, this was particularly important in tailoring the research to address the issues of concern to the community and building on local knowledge [39,42,45,47,54,55].

Given the significance of the societal transition required makes clear the necessity for deliberation and debate as a democratic right of the citizens involved. The deliberative process provides an important opportunity for stakeholders to be included in decision-making [27,41,52,92]. Making underlying modelling assumptions more transparent, and having an open discussion on the advantages/disadvantages of different renewable energy options builds public trust [21]. This encourages discussion of key drivers of change and trade-offs among different decisions, which leads to solutions that are more socially and politically feasible [23,28,35,45,53,67]. As noted by Schmid et al. [25]; *"the transformation towards a low-carbon energy system constitute as much a societal effort as an engineer's project"*.

5.1.2. Capacity building through mutual learning

The contribution of the research to social capital and learning was discussed in a variety of different ways, with mutual learning being the most commonly noted [20,28,29,33,34,46,49,53,62,64,78,81]. Broadening the scope of the research through participatory methods provides researchers and other actors a valuable understanding of the complex socio-political interactions shaping the diffusion of new technologies as well as educating and supporting the actors involved in their deployment. Deliberations provide an important space for people to learn from each other.

On an individual level, participation in the debate and discussion raises awareness of contemporary sustainability challenges, highlighting the complexity of the problems and potential solutions amongst decision-makers and other stakeholders [28,29,31,38,46,54,62,64,67,77]. This is beneficial in a number of different ways. It gives farmers an opportunity to learn about the potential for income diversification [38]. For researchers, working as part of a diverse trans or multi-disciplinary team deepens understanding and improves individual capacity for problem solving [32,73]. Policymakers, by gaining a better understanding of energy issues and policy options, can make more informed decisions [28,54].

On a community level, a further benefit of the research project was facilitating the formation of new social networks and the strengthening of relationships between various stakeholder groups [30,38,49,53,54,74]. During the evaluation of one study, participants identified that a key benefit of the process was *"meeting like-minded people"* [49]. In addition to the formation of important networks is the transfer of knowledge and strengthening of local decision-making [33,39,67].

Key to the strengthening of decision-making both locally and nationally was the insight into systems thinking and trade-offs or cause-effect relationships that participants gained from the methods used in studies [20,28,29,33,34,54,64,81]. MCDA was noted as a particularly effective tool for enhancing decision-making capacity, through interaction with the method identifying criteria and allocating weightings in order to capture an area's priorities [29,33,81]. In addition to this, the process of identifying the relevant drivers and cause-effect relationships is a useful learning process [28,33]. Scenarios provide a useful means of exploring potential drivers of energy system transformation and conflicting objectives [20,28]. While cognitive mapping improves

stakeholders system knowledge and the complexity of interactions [34].

5.1.3. Consensus building and shared ownership of results

The role of researchers as objective and impartial observers was noted as important to provide a platform for controversial discussion and facilitating mediation between diverse stakeholders [12,20,35,38,41,48,49,74,78]. In several studies, one of the key parts of the research project was to break down barriers in a complex negotiation process between conflicting groups [20,38,41,48]. The creation of jointly owned solutions through debate and collective learning was considered to be an effective means of building trust [12,35,46,49,74,78].

The value of building consensus in this manner is a shared ownership of the process and co-created results [20,26,33,42,49,67,74,78]. Stakeholders gain a better appreciation of alternative opinions and the interdependences among decisions [67,74]. As noted previously, this enhances the robustness and legitimacy of results contributing to the potential for real-world change. This is nicely summarized by a Mayor who took part in one of the studies: "*The case study was very helpful in initiating discussions and raising awareness on energy issues in our community. It strongly helped us to build the necessary consensus to implement further activities in this sector*" [49].

In the national level studies, the creation of more informed or improved policymaking was widely noted [23,24,28,31,45,65,72]. Involving stakeholders during both problem scoping and analysis ensures that suggestions are relevant to policy and management [45]. Engaging private and public stakeholders in the decision-making process makes the set of recommendations more actionable [31,37,40,81]. In both groupings, a number of studies highlighted the increase in efficacy for real-world change and stakeholder's commitment to implementing agreed decisions [31,42,53,81].

5.2. Challenges

5.2.1. Dealing with complexity and transparency

The combination of qualitative and quantitative methods is essential to shift energy system modelling and planning away from an exclusive focus on techno-economic uncertainties [100]. However, a number of challenges were noted around the complexity of energy system modelling, translating qualitative inputs into quantitative parameters and the transparency of this transformation [22–24,27,29,35,53,68,70,76]. Quantitative scenarios are inherently different from their qualitative counterparts as there can be no contradictions or inconsistencies [27]. In addition, a number of studies have highlighted fundamental limitations in quantitative modelling techniques, which cannot represent complex and dynamic systems like the energy transition as societal features (such as governance, institutional changes or energy-related behaviour) cannot be adequately described by numbers [76,94,96]. Furthermore, the translation process is subjective, depending on a researcher's background and expertise, interpretations of qualitative narratives into quantitative parameters may differ [73].

When dealing with scenario narratives combined with quantitative energy system models, researchers noted difficulties both with the translation of the narratives into parameters and communicating this to participants [20,29,35,53,67,70]. Firstly, the quantification of scenarios is done using assumptions based on the researcher's expertise. Secondly, taking the time to explain and justify these assumptions to participants will consume a significant portion of a workshop. However, if the modelling process is not clear then there is a risk that participants may be unsatisfied and thus dismissive of the outputs [24,35]. As noted in Section 3.3 and 4.2, the present review suggests there is still work to be done in this area as it was found that in the majority of cases, the evaluation or assessment of modelling results was conducted by the research team. This issue was well summarized by Simoes et al., "*if stakeholders are engaged to provide feedback (which is not common practice), they are normally presented with a selection of more or less final results. Qualitative criteria are not used to assess them, and the modelling work is not subsequently corrected and redone*" [81].

The challenge of making the modelling process more transparent was addressed in a couple of different ways. One study chose to give a significant portion of the workshop time to deciding with participants what the key drivers would be, thus making the model inputs as transparent as possible [35]. Some other examples held a feedback workshop and allowed for revision/refinement of the modelling [28,53,81]. In the interest of having an interactive display that would enable participants to build their own scenarios and build an understanding of the different configurations a number of studies made use of the serious games approach, as discussed in Section 4.1.4.

5.2.2. Models do not represent reality

In line with the above challenge, a number of studies noted the difficulty of accurately representing the real-world with deterministic computer-based models [22,25,26,28,72,81]. These tools have a number of intrinsic limitations such as; failing to include consumer preferences, assuming perfect foresight and rational choice, not considering the amount of available capital for the purchase of new technologies [81]. As a result, the outputs and results may not match the expectations or everyday experience of participants [22,25,26,28,72,81]. In addition, attempts to capture and quantify the 'social acceptability' of energy technologies risk oversimplifying the complex variety of contextual factors that influence people's opinion [26,76]. The diffusion of technologies will not play out as determined through least-cost optimisations, as there are a complex variety of non-monetary factors that have a strong effect on the individual decision-making of citizens [97].

In one interesting example, technologies that stakeholders thought wouldn't play a part in their energy future were determined to be deployed after 2040, whereas other technologies that stakeholders thought could be promising in the future were determined to remain too expensive [23]. Other studies noted the inability of the energy system model derived to capture institutional aspects that will have a significant impact on the rate of adoption [25,76].

5.2.3. Time, availability, and flexibility

Participatory approaches are very resource and time intensive due to the necessarily interdisciplinary nature of the research team as well as the investment in an engagement process. Dealing with issues around time and availability as well as being respectful of stakeholder's interests requires researchers to be flexible in their approach. This is at odds with conventional research projects that have predefined timelines and goals.

A large number of studies noted having difficulty firstly in recruiting the relevant participants, and secondly keeping them interested or engaged with the process [20,28,29,37,43,65,74,78]. One study experiencing an issue with stakeholder dropout, highlighted the difficulty in compensating stakeholders for their time and effort [20]. Another noted that from the 36 participants that had been involved in the initial stage of the research only 17 were able to attend the workshop held due to time conflicts [43]. Moreover, most studies rely on participants self-selecting, as they don't have the resources to ensure a comprehensive representation of all relevant stakeholders [29]. This issue brings into question the legitimacy of research outputs given the often small sample sizes of people involved or lack of representation from particular stakeholder groups [28,74,76]. Furthermore, in order to reach consensus with a diverse group of stakeholders lengthy discussions are required [35]. However, the time available is often insufficient due to research resource constraints and stakeholder availability [26,39,75]. Having a broad range of worldviews improves the representativeness of the participants but brings with it the challenge that consensus may not be reached, particularly when the interventions take place over a limited timeframe [26,27,78].

Most of the methods discussed in this review sought to reach consensus as part of workshop discussions to agree a particular set of energy system goals or pathways. However, this is perhaps misguided, as

noted by Stirling [98] (cited in Ref. [96]) *'there is a need for caution about how such processes are structured, and what claims are made arising from them'*. The pursuit of consensus, particularly over a limited timeframe, risks oversimplifying the complex societal dynamics at play and shutting out some of the voices in the room. This is highlighted by the example of Sharma et al., who found an "*abundant*" number of 'areas of disagreement' among participants and limited number of 'areas of agreement' [70].

5.3. Considerations for future research

5.3.1. Process democratisation

As noted in Section 5.2.3, the time that participants have available is limited and most be respected as they are often simply volunteering to help the research. However, the engagement process should be as iterative as possible in the interest of transparency, mutual learning, knowledge exchange and the creditability/robustness of the outputs [14]. Simply asking participants their opinions or perspectives and not facilitating feedback or evaluation of the analysis is not a meaningful engagement. It is important that participants understand how their input contributed to the research and results [47]. Otherwise, they may feel disheartened with the process and subsequently loose trust in research and participation more generally, often referred to as 'research fatigue' [99]. In light of this, it is striking that 36% of the studies reviewed involved just a single interaction with the participants.

The value of an iterative process is clear. Interviewing the stakeholders individually before coming together to work in a series of group workshops is useful firstly for understanding the diversity of perspectives and secondly for tailoring the material to ensure workshops run smoothly. In an iterative process, a workshop setting then provides a space for revision of both the qualitative descriptions and quantitative analysis [25,28,38,76]. Allowing the participants to review the integration of their inputs into the quantitative analysis can help to alleviate this major methodological challenge. In one interesting example, the results of a series of workshops were evaluated by a public survey of 418 residents from the city of interest [47]. This allowed the outputs from a selected group to be assessed against the concerns and priorities of the wider public. In the subnational studies, it was noted that the iterative nature of the process is particularly beneficial in building a relationship with local stakeholders [38,45].

On from an iterative consultation process, the pursuit of co-production and collaborative approaches is seen as the most meaningful way to engage stakeholders in the energy system modelling and planning process. However, only ten of fifty-nine studies (17%) reviewed noted some form of collaboration outside of the formal engagement process, with just eight involving a transdisciplinary committee. In one instance although no formal committee or team was formed to oversee the research, the researchers took the time during the first in a series of workshops to agree with the stakeholder group the rules of collaboration [26]. This is a very important trust building exercise as it hands over some of the control to the participants. Jointly defining the research questions and process facilitates the formation of a working relationship, while also ensuring that the research is of relevance and use to the stakeholders involved [25,30,39,45]. This is of particular importance for subnational studies, where the 'co-management' of the research project by representatives from the community provides an opportunity for them to build capacity, which is vital to the legacy of a project [30]. It is essential to facilitate extensive dialogue with the relevant stakeholders in order to facilitate an adaptive and flexible management of the research project to stay in line with the objectives, which helps to ensure real-world impact and value.

A further consideration is the practical running of the engagements and representativeness of stakeholders involved. As outlined in Section 2, the vast majority of studies involved consultation with energy/environmental experts, failing to reach beyond an already interested and engaged group. In addition, in most cases it appeared that the studies had relied on their own researchers to fulfil the role of facilitators during these events. This is perhaps because funding for such research projects generally does not allow for external facilitators to be used. However, its importance was noted in a number of different ways. Olabisi et al. note that "*We used a highly skilled and experienced facilitator …. his involvement was a critical aspect of the project's success, as indicated by workshop participant comments on post-workshop evaluation forms*" [35]. While Kowalski et al. note "*being led by professional facilitators, ensured that all participating stakeholders had opportunities to speak and that minority views were also heard*" [20].

5.3.2. Future research direction

There are a number of emerging research directions in this area, two of which stand out in the context of this review and offer exciting prospects for future research. Firstly, as has already been suggested in other reviews [101], in order to more accurately represent the interaction of technical, economic, societal and environmental factors new models and approaches are needed. This has prompted much debate on the topic of so-called socio-technical energy transition (STET) models [102], and the prospect of modelling the dynamics of sustainability transitions as oppose to simple techno-economic representations of the energy system [103]. Out of this, a number of opportunities have been highlighted [94]. However, this comes with a trade-off. These efforts may provide a more accurate representation of the energy transition and societal dynamics at play leading to more diverse and interesting research but will increase model complexity, which could be counter-productive to the goal of process democratisation.

Secondly, as highlighted by MacDowell and Geels [96], there are a number of fundamental and operational challenges to explain why quantitative computer-based models cannot represent complex non-linear societal dynamics. Thus, perhaps the two should be addressed separately [104]. This review has highlighted that there is still work to be done in opening up the energy system modelling and planning process, which calls for greater attention to be given to the participatory elements. The limited progress to date is perhaps reflective of the fact that climate funding to date has favoured the technical sciences and failed to provide adequate capacity in the social sciences [105]. Further investigation into what collaborative and co-production approaches can offer is needed. This will require open and transparent models in line with growing trends within the modelling community [106], as well as the use of creative ways of dialogue and deliberation. This will help to build trust and understanding, but it is not without its own challenges. There are a range of unresolved questions such as the tensions between real-world impact and research outputs, representativeness of stakeholder groups involved, evolving role of science in society and changing responsibilities of researchers.

5.3.3. Limitations of the study

As with any systematic review process, a limitation and potential bias within the present study is the search terms used to identify literature for analysis. Although, as outlined in McGookin et al. [19], a range of different terms were explored and 715 studies analysed, the keywords were chosen to cover a broad range of practices and analysis. This was done to establish an understanding of this new and emergent field. There may be scope for further investigation with the use of more specific keywords. For example, the different quantitative analysis identified in Section 4.2 like 'agent-based modelling' or 'MCDA' could have subsequently been used as search terms in place of 'energy system modelling' or as oppose to using the term 'energy', the sectors of 'heating', 'transport' and 'electricity' are also potential search terms.

For the propose of this review, the progress in process democratisation was the primary focus. However, there is perhaps also scope for review of how participatory approaches have increased the diversity of energy research outputs or to what extend it improves our representation and understanding of the energy transition.

6. Conclusion

This paper provides a comprehensive review of participatory methods combined with energy system modelling and planning. The review explores two differing spatial scales and motivations; national policy-focused and local action-orientated research. The primary focus was to build an understanding of the range of qualitative and quantitative methods available, as well as assessing progress to date in the democratisation of key energy system decision-making processes. As part of the review a conceptual framework has been developed to help understand what the integration of participatory methods in energy system modelling and planning entails. The complied database of fifty-nine studies highlights the breadth of knowledge already available in this emergent field. However, one of the key findings from this review is that there is still work to be done in following the principles of collaborative/co-production approaches. Only ten of the studies reviewed noted some form of collaboration with non-academic stakeholders. In the vast majority of cases, the engagement process was solely a consultation to extract information and had not allowed participants to shape the research direction or discuss and provide feedback on the results. This highlights that there is still work to be done to with regard the democratisation of energy system modelling and planning processes. In addition, a number of other considerations for future research have also been discussed such as the prospects of modelling socio-technical transitions, difficulty in dealing with complexity, the transparency of the model building process and challenge of recruiting a representative participant group.

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.

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Appendices A and B. Supplementary data

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