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Many actors amongst multiple renewables: A systematic review of actor involvement in complementarity of renewable energy sources

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ABSTRACT

Although complementarity achieved by combining multiple renewable energy sources (RES) is an important method to increase shares of RES, it is often overlooked in policy prescriptions supporting an energy transition. Complementarity can be implemented by multiple actors, however there has been little attention to which actors are involved, and their roles. A systematic review was conducted to provide an overview of the state of academic literature on the topic of combinations of multiple RES and the involvement of multiple associated actors. The sample included 78 articles using a range of methodologies to analyze varying combinations of wind, solar, bioenergy, hydro, geothermal, and ocean energy, alongside combinations of traditional, new, and supporting energy actors. Studies included contextualized (location specific) agent-based, techno-economic, economic, business model, and qualitative analyses, and decontextualized reviews, agent-based, and optimization models. Multi-actor complementarity is being addressed by diverse disciplines in diverse contexts globally, across a range of geographic scales. The majority of studies focus on solar-wind, although more diverse RES combinations were found in contextualized studies. New actors usually participate alongside traditional system actors. More attention to supporting actors is required. Findings highlight the need for further research beyond the technical benefits of combining multiple RES, to explore the roles of various actors. This can be accomplished by incorporating more context in studies, for example, using the substantial existing body of data and research, and by including a greater range of RES combinations, and incorporating more perspectives of associated actors.

1. Introduction

Transitioning rapidly to predominantly renewable energy is necessary to mitigate and adapt to climate change [1,2]. A significant technological challenge is how to increase shares of variable renewable energy sources (VRES) in energy systems while maintaining reliability. One important method to increase shares of VRES is to exploit their complementarity. Power production can be smoothed by combining at least two VRES [3]. The complementarity of VRES as a method to increase capacity and reliability of renewable energy sources (RES) and to optimize energy systems is well-established in the engineering and technical literature [4]. Complementarity as a policy tool has been suggested as a means to increase both VRES integration and economic benefits [3]. However, few, if any, policies explicitly support complementarity in the planning and development of new decentralized and renewable energy assets. This study systematically examines both technical and social science academic literature to summarize the key insights and benefits of complementarity, highlight research gaps, and derive academically supported policy positions that can be used to enable diffusion of complementarity and capture its associated social and technical benefits.

Both traditional and emerging energy system actors play important roles in the deployment of VRES. Traditional energy system actors include utilities, conventional generators, system operators, and end consumers. Integration of renewable energy will require institutional and industrial system support and financing for diffusion from these actors [5,6]. Non-traditional, or new, energy system actors, such as

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List of abbreviations

DER	distributed energy resource
EV	electric vehicle
IEA	International Energy Agency
PV	photovoltaic
REC	Renewable Energy Community
RES	renewable energy source
VPP	virtual power plant
VRES	variable renewable energy source

municipalities, prosumers, community energy projects, and non-energy institutions and industries also increasingly play important roles in the implementation and management of renewable energy [7,8]. Future energy systems will be composed of many diverse actors.

Optimizing multiple RES, actors, and end uses in energy systems presents techno-economic benefits that are increasingly recognized in technical and social science literature [9–12]. There is also considerable attention to the potential social and environmental benefits of multi-actor participation in decentralized energy systems in general [13–15]. However, despite clear economic and environmental benefits, it is unclear if the full range of social, technical, environmental, and economic benefits of complementarity are acknowledged or integrated in either social or technical academic literature. This is potentially significant because, despite clear evidence of the techno-economic and environmental benefits of complementarity from the technical literature, and the social and environmental benefits of multi-actor participation in the social science literature, there is currently little attention to complementarity in policy prescriptions supporting the decentralization of the energy system [16].

This study uses a systematic review [17] to summarize the state of academic knowledge on multi-actor, multi-RES complementarity, and to synthesize key findings and reveal key research gaps. This will provide a clear position from which to discuss the benefits and drawbacks of complementarity with policy makers, and highlight the areas where more research is needed in order to ensure the successful implementation of contextually appropriate energy policies. First, the approach used to conduct the systematic review is outlined. Next, relevant perspectives related to VRES, complementarity, and multi-actor participation in energy systems are discussed. This serves to both justify this study's support for complementarity as a general approach to integration of VRES into energy systems, and to further discuss key socio-technical aspects of the concept. Results are next presented and discussed, and the paper closes by situating findings in the context of the current energy policy landscape, with recommendations for policy and research.

2. Methods

To obtain an overview of research to date on developing renewable energy in relation to multiple RES and multiple actors, a systematic review was employed [17]. This method systematically samples literature that has been published on the topic within a specific timeframe. Systematic reviews are useful for identifying gaps in the literature, and assessing what is known on a given topic. The sample was restricted to academic journal articles because the research question sought to identify what is happening in theory and practice within academic literature on the topic. Other types of sources such as books and book chapters were not included to limit the already large sample to a reasonable size, and because it is expected that perspectives published in articles will provide a sufficiently clear assessment of the state of the literature on this topic. Searches were first run on the topic and inclusion and exclusion criteria were then applied to obtain a final sample for analysis (see Fig. 1).

To provide a robust overview of social science and technical literature, the Scopus database was searched. Scopus houses literature from technical disciplines, and from social sciences. The ProQuest database was also searched to ensure complete coverage of social science research but provided no additional results relevant to the research question.

Selection criteria were applied at three stages. In the initial stage, the authors developed a list of key terms and synonyms for the fields of "renewable energy" (primary term), "complementarity" (secondary terms), and "multi-actor" (tertiary terms). This list was iteratively refined by using test searches, adding terms that emerged as relevant, and omitting terms that returned irrelevant results. The final selection of primary, secondary, and tertiary search terms is listed in Table 1. Articles had to contain at least one primary, secondary, and tertiary term either in the title, abstract, or key words. The search was automated using Python and the Scopus API to extract the bibliographic information and abstracts of the articles that contained all three terms. The search process was iterative. For example, it became apparent that virtual power plants (VPPs) can be assumed to contain RES and a search was also run for "virtual power plant" (secondary term) and all tertiary terms, without the primary term and matching the dates of the original search. All searches included articles in the database up until April 23,

Table 1
Search terms.

Primary term	Secondary term	Tertiary term
Renewable*	Complementar*	"Community energy"
	Hybrid	"Energy democracy"
	Cluster*	"Energy communities"
	"Virtual power plant"	"energy community"
	Asynchron*	Prosum*
	microgrid*	Producer*
	"micro grid"	Multiactor
	micro-grid*	Multi-actor
	balanc*	"Multi actor"
		stakeholder*
		actor*
		"Multiple actor"
		"Multiple actors"
		agent*
		member*
		participant*

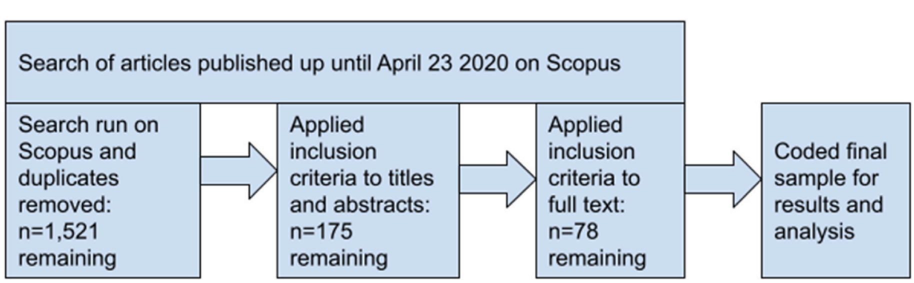

Fig. 1. Systematic search process.

2020, returning 2448 total results (when adding the individual results for each search string), with 1521 results remaining after removing duplicates (see Supplementary table 1).

In the second stage, inclusion and exclusion criteria were applied to determine the final sample of articles to be reviewed in detail. The titles and abstracts of each of the 1521 remaining articles were read and included if they met the following criteria:

- Language: in a language spoken by one of the authors (English, French, German, or Spanish) - 29 articles were excluded due to language, including articles in Chinese, Japanese, and Polish;
- Primary term related to renewable energy (exception – search run for VPP);
- Secondary term gave some indication of potentially including more than one type of RES;
- Tertiary term gave some indication of involvement of multiple actors;
- Availability of the article - 13 articles could not be located/accessed.

Additionally, the explicit goal of the article did not have to be addressing multi-RES and multiple actors. Studies were included as long as these topics were present. For example, studies explicitly focused on optimizing electric vehicles (EVs) or storage were included, as long as they still met the criteria.

While one author was responsible for coding the entire sample, the inclusion and exclusion criteria were adjusted using inter-coder reliability on a random selection of ten articles by the four authors. The authors discussed articles that required clarification as needed throughout the entire review process. In order to apply inclusion criteria consistently, this process was iterative. At the end of this stage of coding, 1346 articles were excluded, and 175 articles remained.

In the third stage, the full text of articles was read and coded manually into a data extraction form [e.g. 17]. The data extraction form was developed and adjusted iteratively as articles were reviewed (see Supplementary table 2). 97 articles were excluded at this stage, as the full text was either unrelated to multiple RES (secondary term) or multiple actor (tertiary term) criteria. One author read all the articles. For each article that was included in the final sample, at least one other team member read it to confirm it met the inclusion criteria. This led to a sample of 78 articles.

In order to systematically examine these studies to summarize the key insights and benefits of complementarity, and highlight research gaps, the following questions were asked of the dataset:

1) What methodologies are being used in studies that address multiple RES and multiple actors?
2) At what scales and in which contexts do these studies operate?
3) What are the main types of renewable energy involved in complementarity?
4) Are studies modelling the future or examining existing scenarios?
5) What actors are involved in systems with complementarity and their governance?

Some studies could have been classified in multiple analytical categories, and were therefore categorized based on which category was most related to the dominant approach described in the study. If the presence of one of the factors (e.g. mention of a RES, an actor, or contextual data) did not have an impact on the analysis, this factor was not coded as present for this study's purposes.

The study methodology refers to the main research approach used (e.g. agent-based modelling, techno-economic analyses, qualitative analyses). The list of methodologies was emergent, based upon the sample content. The full list of methodologies is presented in Section 4.1.

In order to better understand the sample, the authors also investigated whether studies were contextualized or decontextualized. A study was determined to be contextualized when the article gave an exact location for the study, or for a portion of the data relevant to the analysis (e.g. load data, weather data, market data). An article was decontextualized when no location was defined. Studies that gave no indication of context (e.g. no form of locational data) were left out of the step of coding for more specific location and were categorized as 'decontextualized'. Some studies identified and presented analysis on multiple RES and actors in more than one location. In these cases, each location with multiple RES and actors was identified as a separate combination (i.e. one study could have more than one context). There are therefore more combinations of RES and actors than studies, and these combinations are used throughout much of the results section.

Guided by the data extraction forms, the reviewers coded the location(s) where multiple RES and actors were present for scale (e.g., local, subnational, national, multinational) of the studies (Table 2). Scale was coded based on the spatial resolution of the context. For example, when studies analyzed a local level, but the main context given was national, these were coded as national.

RES combinations were coded according to the RES present (e.g., bioenergy, geothermal, hydro, ocean, solar, wind). Due to technology diversity, RES were categorized based on the type of source rather than being identified by their different technologies (see Table 3).

Studies were also categorized according to their temporal focus (i.e. past or future) in order to determine which studies address existing empirical contexts, and which model hypothetical future scenarios. This information makes it possible to determine where practice leads theory with respect to multi-actor complementarity, and vice versa.

To code for actors, three categories were developed based on the literature review (below). The developed categories are traditional market actors, supporting actors, and new market entrants. These are described through examples in Table 4.

3. Defining concepts: renewables, complementarity, and actors

3.1. Renewables

In order to meet the Paris Agreement, it is estimated that renewable electricity needs to reach a share of at least 63% of the global electricity system supply, requiring 22,664 TWh of generation by 2040 [1]. To reach net zero by 2050, the International Energy Agency (IEA) predicts that solar and wind power generation will provide 68% of the entire global electricity demand [18,19]. VRES, biofuels and waste made up 11.5% of the composition of the global energy supply in 2019, with fossil fuels making up ~81%, and nuclear making up ~5% [20]. There is over 2500 GW of installed renewable energy capacity worldwide [21]. Modelling suggests a 100% renewable energy transition using current technology is possible (see e.g. Refs. [22–24], although debates on underlying assumptions remain [25,26]).

Technological innovation and larger production scales are making renewables more affordable [21]. Between 2009 and 2018, solar photovoltaic (PV) installed capacity multiplied by four, and wind power installed capacity multiplied by twenty [27]. Steep cost decreases of VRES are also seen [28], as well as electrification progress in many sectors, for example, transportation [29].

A critical aspect to the technological challenge of increasing shares of renewable energy is the importance of investing in local energy distribution systems [30]. This is because one important technological change

Table 2
Categorizations of scale.

Scale label	Examples from sample
Local	Village, community, municipality, city, university campus, neighbourhood, district, isolated site
Subnational	Region, province, state
National	Nation, country
Multinational	Continent, grouped countries (e.g. Europe, Mediterranean)

Table 3
Categorizations of RES.

RES label	Examples from sample
Bioenergy	Biodiesel, biogas, biomass, biofuel, organic material, marine biomass, bioenergy
Geothermal	Geothermal
Hydro	Hydro, micro-hydro, mini-hydro, run-of-river hydro
Ocean	Tidal, wave
Solar	Solar, solar photovoltaic (PV), solar thermal, solar street lighting
Wind	Wind, micro-wind, mini-wind, offshore wind
NA	When multiple RES were present at a conceptual level, and core to the analysis and/or main argument, but not addressed as having explicit roles in relation to the type of RES

Table 4
Categorizations of actors.

Actor group label	Examples from sample
Traditional	Operators (distribution system, transmission system, independent system) Producers, generators, utilities/main grid, retailers Consumers (residential, commercial, industrial) Agents from agent-based models (load, conventional generation, main grid)
Supporting	Financial support (funders, investors, donors, government) Research and development actors (universities, organizations) Government (regulatory bodies, policymakers) Lobbyists Media
New	Microgrid actors (controller, operator) VPP actors Local people/community members (investors, owners, decision-makers, job opportunities) Prosumers (residential, industrial, commercial, public buildings/spaces) Municipalities SMEs Agents from agent-based models (distributed energy resources, prosumers, communication, electric vehicles) Renewables/storage companies

in a transition to renewable energy is the extent of infrastructure decentralization [31] – the shift from predominantly large thermal dispatchable power generation to smaller scale, lower density non-dispatchable power generation, that has a lower power density and is much more geographically dispersed [8,32,33]. This can include the increase of distributed energy resources (DERs) that produce energy close to the point of use [34]. The cost benefits of localized, decentralized renewable energy are apparent [35]. In a decentralized system, producing, storing, and consuming energy happens in closer proximity, limiting possibilities for losses in transmission, as well as the requirement of investing in and maintaining these transmission lines.

3.2. Complementarity

Energy such as fossil fuels and nuclear power tend to be less resilient than renewables when environmental hazards occur [36]. However, lack of dispatchability is a concern for VRES, and intermittency can pose challenges to energy system reliability in meeting demand needs. Electricity grids face stress from VRES [37], including sensitivity to weather conditions, and the need for back-up and storage to meet supply demand. These are less significant challenges for fossil fuel-based technologies [38]. Short-term, electricity storage in many cases is still expensive, and long-term solutions such as hydrogen necessitate more development for wider adoption [39]. Increasing the share of renewable energy and maintaining reliability requires careful policy and technological design, with increased flexibility measures such as storage and demand response, and major changes to energy distribution systems [30].

Complementarity can be an optimal technical and economic policy solution for the integration of VRES onto the grid in many contexts [3,40]. Exploiting complementarity between RES in locations where it is given leads to reduced storage requirements [11], increased capacity to integrate VRES in the electrical grid [40] as well as to improved grid stability [41]. Furthermore, complementarity can contribute to reducing the necessary VRES generation, storage, and backup capacity to supply a particular demand independently of the scale. Examples of this can be found among others at the country level [42], clusters of residential users [11], municipalities [43], and individual industries [44].

Complementarity may not be conducive to every context, as some locations may have limited RES availability. For example, technical and economic improvements may not always result from addition of wind to a solar system, as shown in examples for locations and different types of uses in Europe [11] and in Chile [44].

There is also increasing attention to multi-actor involvement in integration of multiple resources including RES, but also storage, hydrogen, district heating, electric vehicles, among others, to operate in an integrated manner in a community system. Termed ‘integrated community energy systems’, these systems have the criteria of “locality, modularity, flexibility, intelligence, synergy, customer engagement and efficiency” [9].

3.3. Energy system actors

A transition to predominantly renewable energy requires the involvement of a range of incumbent, or traditional, and new actors to mobilize RES and to participate in market governance and operation [5,7,45].

3.3.1. Energy system governance and operation

Electricity governance has historically been dominated by incumbent, centralized generators, suppliers, transmission and distribution grid owners or operators and policy makers and system regulators. A broader diversity of actors must be meaningfully involved in the production, storage, distribution, and retail of renewable energy in a transition toward renewable energy, which necessitates at minimum some degree of geographical dispersion and decentralization of energy. This involvement of new actors in the energy system is one of the most significant and disruptive features of the transition [46,47].

The involvement of more actors is important for more than just siting renewable energy assets. Improved social acceptance of renewable energy infrastructure can be seen with fairer distribution of costs and benefits, and meaningful engagement of local people, for example, through rendering decision-making and regulatory processes more open [48]. Decentralizing energy systems can enable the mobilization of investment by households, for example through rooftop solar and geothermal investments by prosumers, and participation in renewable energy co-ownership. For example, the German Cooperative and Raiffeisen Confederation estimated that the co-operative energy sector in Germany had invested €2.9 Billion in renewable energies between 2006 and 2019 [49]. This decreases the amount of financing required to be contributed by government and business investors to meet the estimated requirement for US $131 Trillion dollars by 2050 to keep the world below a 1.5 °C average temperature rise [50].

The entry of new actors in energy systems is facilitated by new technology and innovation. For example, new actor involvement in the market is facilitated by micro-grids, virtual power plants (VPPs), blockchain technology, prosumption, peer to peer trading, and storage [15,51,52]. New actors can engage in energy systems as individuals (i.e. a prosumer or individual owner), local authorities, small firms, cross-sector actors (e.g., communications sectors), or collectives (e.g. co-operatives).

The conduct and operations of collective actors are defined by business models and governance structures in energy systems with multiple actors. The “collective” in this case includes community trusts, cooperatives, community associations, and local authorities [53]; community-based Indigenous economic development corporations [54]; and, renewable energy communities (RECs). Newly defined in European Union legislation, RECs are entities with ownership by heterogeneous actors (e.g. citizens, local authorities, and small and medium enterprises (SMEs)) that are in close geographic proximity to the REC [55]. There is still a role for larger firms and incumbent actors in RECs, but this is as supportive or equal partners, rather than as controlling entities. The different types of entities listed above results from different institutional contexts that support different legal forms of community ownership and control [53]. More renewable energy contracts concentrated in one place and using the same grid infrastructure can be enabled by complementarity [3]. Generation ownership can thus be diversified, and power generation's economic benefits, and local economic development benefits can be more broadly distributed [56].

Governance that coordinates across levels (i.e. multi-level governance) will be required as complementarity diffuses, with a greater diversity of actor voices participating in energy system decision-making. This is required for effective coordination of the many actors who are making important electricity system decisions and actions [57]. Studies are now emerging about experiments in multi-actor systems in practice. These focus on singular technologies [52], community-based virtual power plants (cVPPs) with hybrid wind and solar technology [15], and microgrids [12]. Governance systems for complementary, multi-actor VRES will almost certainly need to be emergent and adapted to local contexts, but there is considerable expertise available on governing multi-actor participation in other contexts that is relevant to these emerging dynamics.

3.3.2. Support for renewable energy sources

The diffusion of RES requires the mobilization of institutions, actors, and networks across value chains, some of which overlap with the energy sector, and some of which are from other sectors, such as information technology or manufacturing [5]. In the results and discussion of this study, these are referred to as "supporting actors". The mobilization and coordination of actors and networks is crucial to energy transitions [58]. The diffusion of RES requires investment and policy support from relevant institutions, actors, and networks [5] that influence the emergence and implementation of new energy technologies and innovations [59]. This, for example, includes the firms and organizations across the research, development, deployment, and diffusion stages that provide the supply of innovations and know-how that support socio-technical innovations, as well as the institutions that support financing and regulation [60,61].

Contextual differences in renewable energy transitions mean that factors such as the clustering of low carbon technologies, the built environment, and the presence or absence of liberalized energy markets with different actors will vary from place to place, particularly from urban and rural landscapes [58]. Whether the context is a developed or developing country can also affect the motives behind the implementation of a new energy system. When considering integrated community energy systems, developing countries tend to have motives of "provision of energy access", whereas the array of reasons behind application in developed countries is broader, including "climate change, energy autonomy motives as well as economic reasons inclusive of subsidies for local energy sources" [9].

System actors, networks, and institutions that have an effect on particular energy technologies' roll-out, implementation, and grid-prioritization will vary between contexts and have an important influence on RES complementarity [5,62–64]. Competition or cooperation of different technologies along production chains can be contingent on how institutions, as well as actors and RES implementation networks interact [65]. Japan, for example, favoured solar PV despite its high cost, seeing less of a role for wind despite possible complementarity, due to its renewables market composition [66]. A study by Johannsen et al. [67] found that wind turbines were largely not implemented in small scale solar, diesel, and battery hybrid mini-grid systems because of systemic barriers, barriers related to technological complexity and limited knowledge and capacity, as well as economic barriers of affordability and limited user returns, and financing and bankability.

4. Results

The final sample of the systematic review includes 78 studies with 92 combinations of RES and actors. All of the studies were in English. Publication dates ranged from 2009 to 2020, though the majority (n = 67) were published in 2015 or afterwards. The studies span a range of technical and social sciences journals.

4.1. What methodologies are being used in studies that address multiple RES and multiple actors?

There were 29 decontextualized studies, composed of ten agent-based modelling studies, nine decontextualized optimization modelling studies and ten review studies. There were 49 contextualized studies, composed of ten agent-based modelling studies, 15 techno-economic analysis studies, six economic analysis studies, seven business model studies, and 11 qualitative analysis studies.

4.2. At what scales and in which contexts do these studies operate?

Of the contextualized studies (see Fig. 2), 20 had at least one RES and actor combination in Europe. At least two studies addressed contexts on each of the other continents, though still demonstrating less concentration compared to Europe. Several countries were the context of multiple studies, for example seven in Germany (plus two more, inclusive of multinational studies not on the map), four in the Netherlands (also plus two more multinational), three in Chile, and seven in India.

The most common scale in the contextualized studies was local (n = 31), followed by national (n = 21), with limited studies at the subnational (n = 7) or multinational scale (n = 4). Studies that focused on local scales tended to be smaller-scale system optimization, analyses and/or models. For example, many studies focused on singular traditional grids, microgrids, or VPPs. Studies that focused on subnational, national, and multinational scales often focused on how to plan RES expansion or optimize national RES portfolios. They were often economically, business, or qualitative analysis-oriented. This was not always the case, however, for example when a study may only have provided a larger-scale context but was analyzing or modelling for a smaller scale. As the decontextualized studies were not situated in an existing location, they could not always be coded for scale. For the most part, however, the decontextualized agent-based and optimization studies addressed the local scale, often focused on optimization of a single energy system (e.g. a microgrid or a VPP).

Varying scales were found in studies across the world, not presenting any particular trends between scale and location.

4.3. What are the main types of renewable energy involved in complementarity?

Overall, the studies acknowledged the positive contributions of multiple RES, demonstrating how it can lead to technical, economic, environmental, and social benefits in many different contexts. These benefits ranged from increased system reliability, to improved RES capacity, to reduced carbon emissions, to reduced energy insecurity, to favourable economic scenarios, to increased social involvement and democratization.

The majority of the studies combined only wind and solar (51 out of 92 total combinations) (Fig. 3). Most of the other studies either added another RES to that combination (e.g. solar + wind + bioenergy), or combined one of wind or solar with another RES (e.g. solar + bioenergy). Ocean and geothermal energy were only coded for once each.

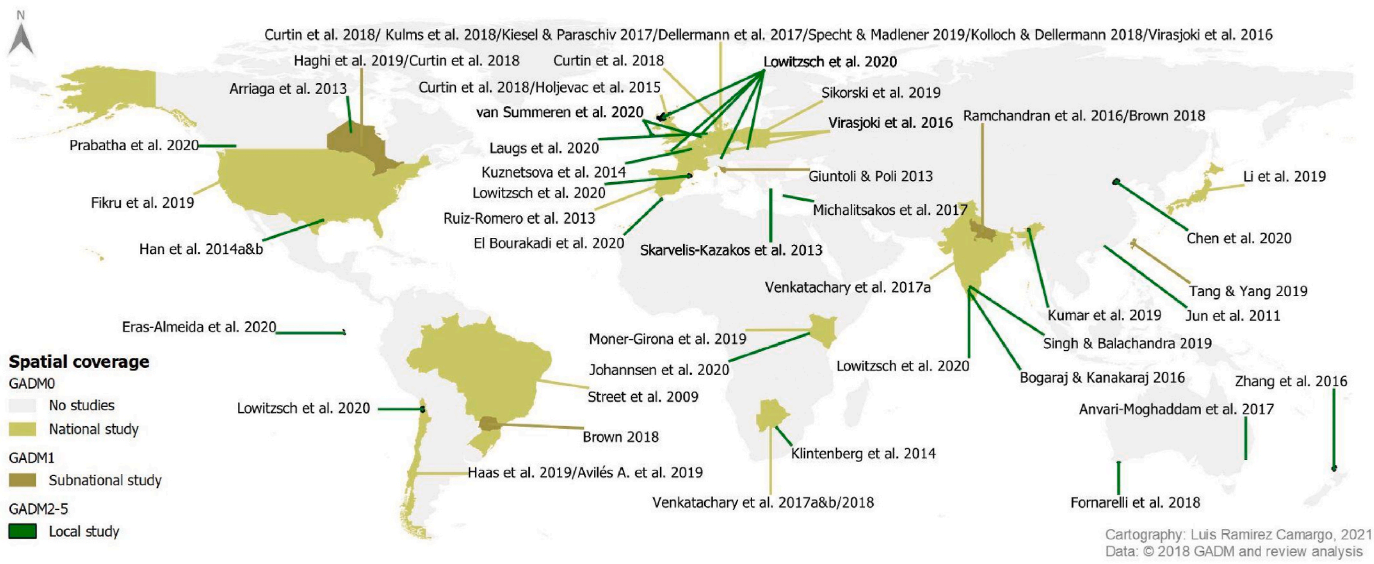

Fig. 2. Locations of contextualized studies. A full list of the references presented here is provided in Supplementary table 3. Three studies were not added to the map that do not address individual countries but large geographical areas at once; two across European context (Lowitzsch, 2019; Moroni et al., 2016), and one in the Mediterranean (Soukissian et al., 2019). Virasjoki et al. (2016) was also coded as multinational, but was added onto the map as it specified the four countries.

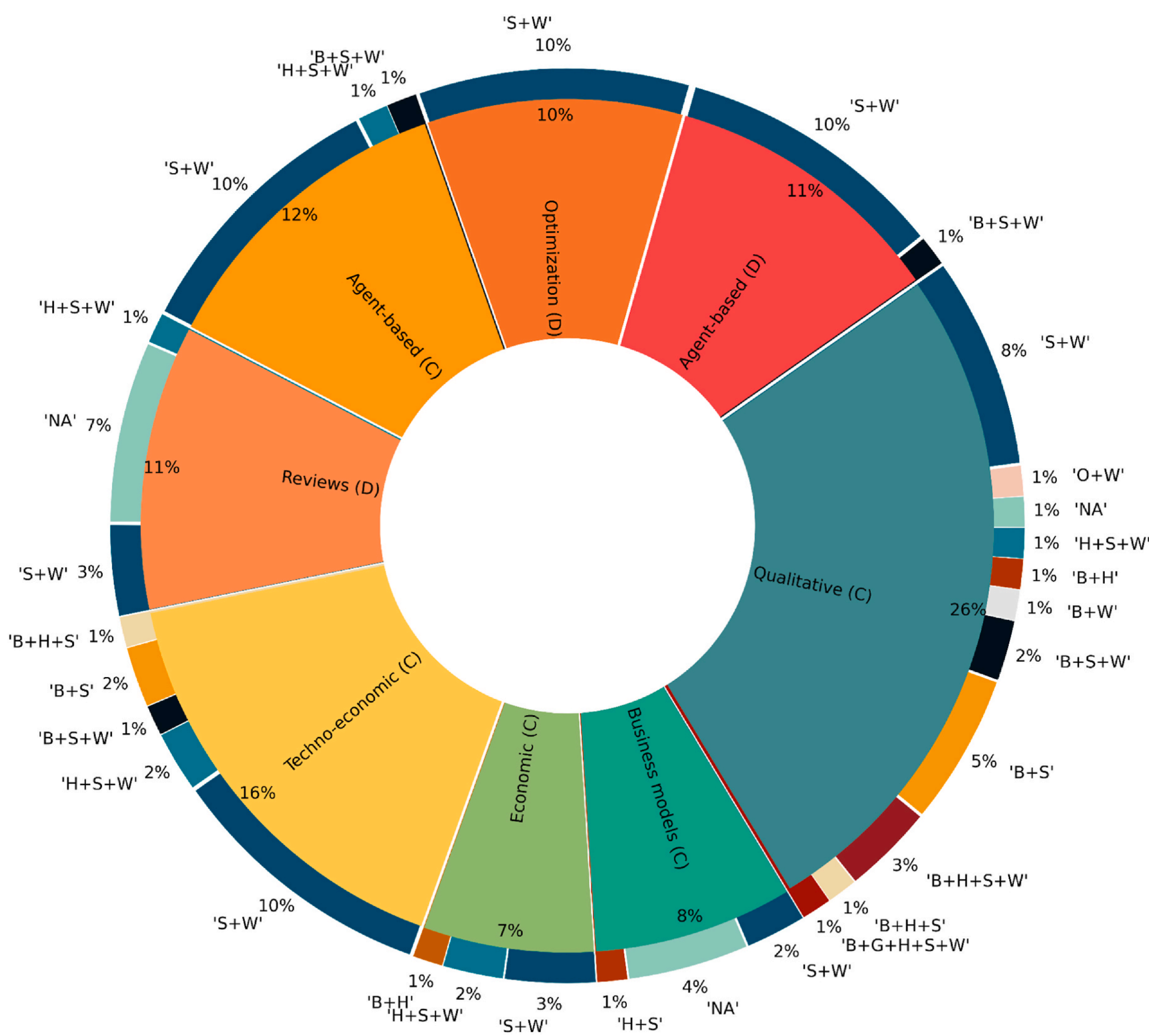

Fig. 3. RES combinations by study category. S: Solar; W: Wind; B: Bioenergy; H: Hydro; O: Ocean, G: Geothermal.

The more diverse RES combinations (i.e. with more than two RES, or beyond wind and solar) were found predominantly in the contextualized studies. For example, a study contextualized in Europe on community-based VPPs, which are VPPs (i.e. aggregations of distributed resources) with community involvement, addressed different combinations including variations beyond only wind and solar (e.g. forms of hydro and bioenergy too), exploring the concept of community-based VPPs as a whole and investigating practical cases [15].

There was less diversity of RES combinations in the decontextualized agent-based and optimization studies, which all combined wind and solar only, with one exception that included bioenergy. The decontextualized review studies tended to include the concept of multiple RES or complementarity without identifying specific RES combinations (n = 6), though when combinations were specific, they tended to be wind and solar (n = 3), with one study adding hydropower to wind and solar.

4.4. Are studies modelling the future or examining existing scenarios?

Several studies presented research on an energy system that did not yet have multiple RES in use; the research was ‘forward looking’ and analyzed how additional or multiple RES could be implemented, in conjunction with multiple actors. Other studies presented research on contexts where multiple RES and actors were already present. These ‘backward looking’ studies were often qualitative analyses, for example which aimed to explore various scales and contexts to analyze how a RES transition took place, areas for further improvement and RES uptake, or assessment of the energy system. There were also cases, however, where a study would still be ‘backward looking’, in that it could already have multiple RES and multiple actors in an existing context, but it could be presenting a forward looking model to further optimize the RES combination’s efficacy and/or performance. For example, a study on the Shire of Denmark, Australia had wind and solar already in use together at the time of the study, but the study aimed to further optimize the energy system using HOMER optimization in the presence of a water desalination plant, while also obtaining social acceptance [68].

4.5. What actors are involved in systems with complementarity and their governance?

Fig. 4 describes the actors present in each study by study category. Almost all of the studies included at least one type of traditional market actor, for example consumers, system operators, utilities, and/or conventional generators.

New actors were present in the majority of the studies, and played diverse roles. New actors could be involved in the operation of newer system logics such as microgrids, VPPs, or could be community actors, individuals, or small organizations playing unconventional or bidirectional participatory roles. Some examples include prosumers or co-investors, as is seen through mechanisms such as the consumer stock ownership plan [69].

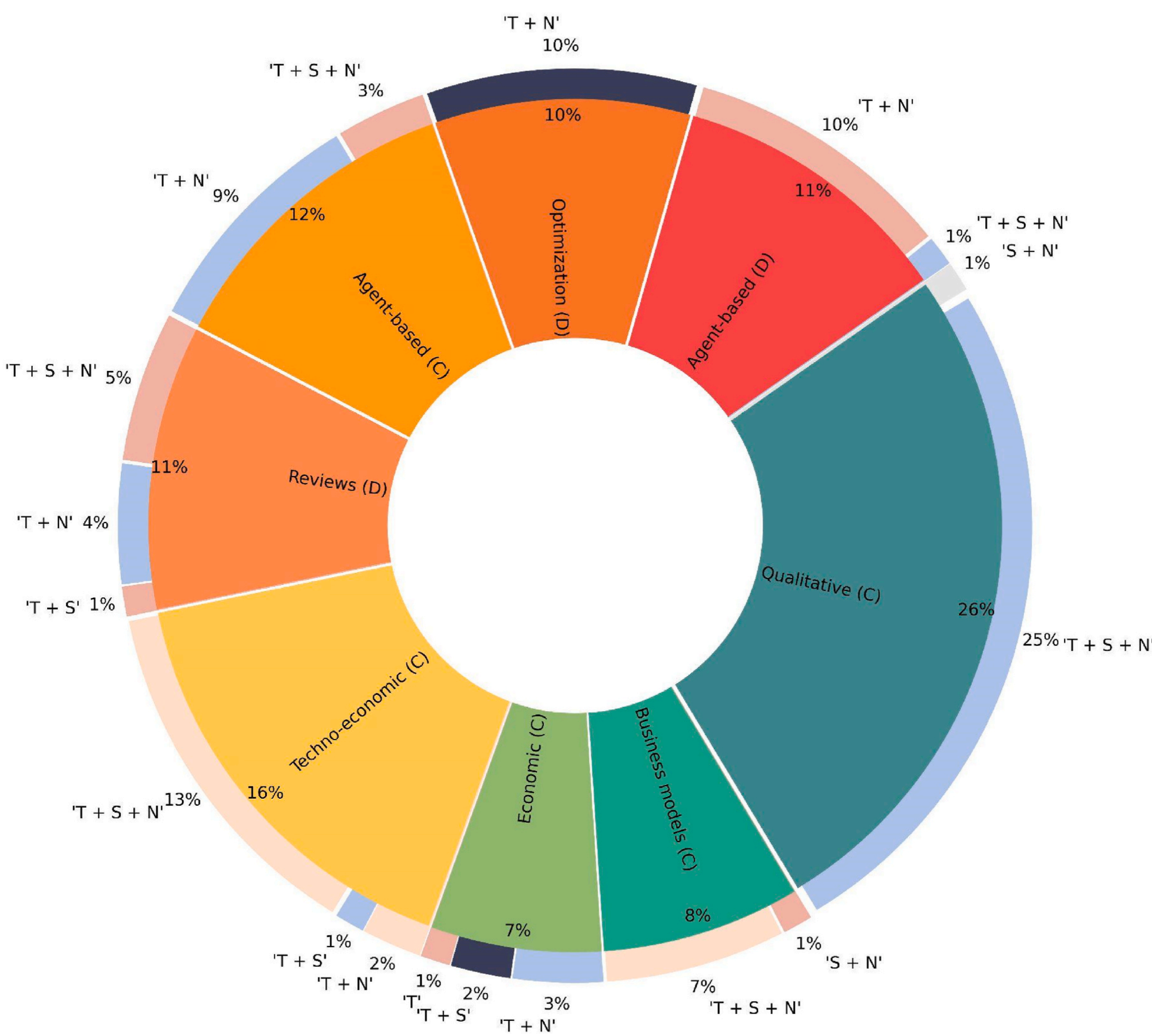

Fig. 4. Actor combinations by study category. T: Traditional market; N: New actors, S: Supporting actors.

The supporting actors were more often present in contextualized studies. These actors included governments, for example making policies, regulations, and/or incentives affecting RES uptake and/or actor participation and involvement [e.g. 70]. They also included providers of financial support, such as donors and various types of investors [e.g. 69]. A third type of supporting actor includes manufacturers and industries providing RES and associated technologies [e.g. 67]. They could also be other influencing actors such as lobbying actors, affecting a move toward RES uptake either by encouraging or discouraging governments to support RES and/or the involvement of actors in energy [e.g. 66].

Patterns were found between actor combinations and study category (Fig. 4). Decontextualized agent-based, decontextualized optimization, and contextualized agent-based categories almost all addressed traditional and new actors, and included few supporting actors. In contrast, the rest of the contextualized studies and decontextualized review studies more frequently had all three actor categories of traditional, supporting, and new.

5. Discussion

In answering the above research questions key patterns and trends were identified in relation to:

- context and scale – where in the world studies were located, and at what scale;
- RES combinations – how do the different RES combinations manifest in relation to different study objectives and methodologies; and
- actor combinations – how do the different actor combinations manifest in relation to different study objectives and methodologies.

5.1. Context and scale

Based on the broad diversity of contexts (i.e. locations) of studies, it is clear that the topic of multiple RES and multiple actors is already being analyzed, modelled, discussed, and addressed in many locations, at many scales, across the globe. This means that there is potential to mobilize energy systems with multiple RES and multiple actors around the world; benefits are already being addressed and explored, and there are lessons to be learned from cases where it is already happening. Of note, however, is that this broad range of research, as well as the range of study objectives and methodologies, shows that the approach to multiple RES and multiple actors in research is being referred to using different names and approaches. This can render finding and comparing these studies difficult. The terminology used in this paper is one option for reconciling language on complementarity across various natural and social science disciplines.

This systematic review reveals the large number of types of analyses (e.g. techno-economic, qualitative analyses) and sources of data (e.g. weather data, consumer profiles) that are being used to study multi-actor complementarity. The approaches identified can support the design and implementation of multiple RES by multiple actors across diverse geographical and legislative contexts. There are, as yet, no jurisdictions with legislative requirements for complementarity [16]. However, this review revealed contexts with enabling, or at least flexible, policy and technical frameworks that can support the development of multi-actor complementarity. Context-appropriate lessons from these frameworks can be extracted. For example, integrating site-specific data such as weather, supply, and load and consumer profiles into the models and policy proposals used to inform decisions around siting of new energy infrastructure can help enable uptake of systems with multiple RES and multi-actor involvement.

The range of geographical scales in the sample indicates the importance of not only considering combinations of RES within a local project or energy system, but also among multiple grids or systems. For example, Johannsen et al. [67] studied the diffusion of RES on the national scale in Kenya, but also assessed how it impacts local scales. Other studies discussed local scales, but based their analyses on data representing regional or national contexts. More consistent multi-level analyses are thus key for conducting effective assessment of policy mixes [e.g. 71] and understanding the implications of multiple RES at different scales for varying actors.

Related, results demonstrate that study objectives tend to vary with scale. Study objectives at local scales tend to focus on system optimization and analyses, while subnational or national scales had a larger proportion focused on portfolio optimization. It is thus also important to assess multi-scalar policy dynamics across national and multinational RES portfolios. They will be key for understanding how multiple RES will integrate in an increasingly decentralized and multi-actor energy system.

5.2. RES combinations

There was a greater diversity of RES combinations in the contextualized studies, demonstrating increased complexity when considering specific contexts, that is not necessarily addressed in the purely modelled or decontextualized studies. This shows that simulated and theoretical modelling with little or no contextual factors are focusing disproportionately on wind and solar, when there are actually many other types of RES combinations that are being addressed in practice. Decontextualized studies are also demonstrating a wide range of frameworks, technologies, and data that can be applied and leveraged. However, they are unlikely to be translatable to empirical applications without attention to social and contextual factors. Given the increasing availability of high resolution (in space and time) multi-annual data for modelling VRES production with global coverage (See e.g. MERRA2, ERA5 and ERA5-land data validated and in use in e.g. Gruber et al. [72], Olauson [73], Pfenninger and Staffell [74], Ramirez Camargo and Schmidt [75]), and that VRES are, by nature, geographically specific, it is surprising that so many studies related to VRES complementarity continue to be performed without a context. Exceptions can be understood, for example when the objective is to test or improve algorithms, but not for assessments of RES deployment.

As RES become more affordable, and as the demonstrated benefits of reliability and increased RES integration from complementarity are acknowledged in studies, implementing multi-RES was often seen as an option for improving energy provisioning and supply in contexts lacking energy security. Multiple RES are being modelled and implemented as an energy solution in parts of the world that may have less economic capacity (e.g. developing economies or countries, or rural, remote and/or isolated areas), and/or where there are high rates of energy poverty and unreliable energy. There were cases where multiple RES was presented as a possible step toward addressing cases of lack of secure and/or reliable energy, for example in off-grid remote communities in Ontario, Canada [76], or in the context of electrifying rural areas in Kenya [e.g. 77]. As established in literature [e.g. 9], ensuring that RES uptake is conducive to local interests, beliefs, and economies was also a common theme in many of the studies in contexts with less economic capacity – although it was not limited to these studies.

Though the benefits of multiple RES are largely acknowledged in the sample, studies were still cognizant of potential drawbacks to including multiple RES (or including RES at all) in their solutions. Some of these barriers and drawbacks included high costs of technology and integration, and concerns regarding social acceptance. There were also some concerns surrounding bioenergy as an energy solution, for example regarding its emissions or potential lack of availability in some contexts. This speaks to the importance of context, and determining what is locally optimal based on factors including RES availability, but also social acceptance, opportunity for diffusion, and other factors that may not always be easily integrated into models.

5.3. Actor combinations

The sample shows that new types of actors are required for the implementation, operation, and maintenance of newer system logics. This includes actors such as microgrid central controllers and aggregators in VPPs, among others. These types of new actors were present in many of the studies, principally due to the large proportion of the sample that presented research on systems such as microgrids and VPPs. The important role of new actors was exemplified in studies focusing on topics of distributing generation and new community governance structures beyond e.g. direct operational roles in microgrids and VPPs. For instance, a study on distributed asset aggregation in Germany identified enabling factors for transitioning from the household consumer into the new actor role of the prosumer [70]. Another study explored the possibility of "polycentric scenarios", including exploring the role of local enterprises and communities in reducing the geographic area required for large amounts of renewable energy generation [78]. Not only are new actors present in such studies, but core to these analyses are the prevalent themes and discussions on the transformation of the energy sector as a whole, and the involvement of new actors.

Despite the large number of studies in the sample on newer system logics such as microgrids, VPPs, and more distributed energy systems, it is clear that traditional actors still play an important role within emerging systems. The fact that both traditional and new actors were present simultaneously in most of the studies supports the notion of a transition. New system logics are not simply aiming to replace traditional actors with new actors, but to transition to a system that can be optimized with various types of actors participating [57,79]. For example, models of microgrids are often designed to work in island mode but the main grid utility and operator is often still present in the models, with some exceptions, for example, in isolated, remote areas. This implies that a partially decentralized system is evolving alongside, and layering onto, the existing system, rather than replacing it.

The distributed nature of RES can help foster involvement of more new local actors. Research suggests that local involvement and consultation through planning, implementation, operation, and maintenance of energy systems can increase social acceptance, provide local jobs, and allow for contextual appropriateness [80]. However, few studies in the sample reported that they consulted with implicated stakeholders, whether for input for their models or analyses, further understanding of local contexts, or otherwise. Despite many discussions on prosumership amongst the sample, many actors such as community actors, municipalities, and local businesses and industries were still analyzed as traditional consumers. Studies often explored different types of consumer profiles in depth, for example households, commercial consumers, and industrial consumers, but did not always necessarily consider these actors in more diverse roles (e.g. as producers, aggregators). These findings present important gaps in analysis to be addressed with new research. For example, stakeholders can be consulted to collect more primary information on local conditions and local needs.

In this sample, fewer than one quarter of the studies reported that they consulted stakeholders in a way that was central to their research. When there was consultation, this enabled a more targeted approach when performing data collection, designing models, or determining what types of solutions are most likely to be accepted by a community. Local considerations, such as cultural and other social characteristics, add value to studies. This can be time-consuming and complex, but it is important for ensuring effective implementation of RES-based solutions, especially given the landscape-specific nature of many RES [81]. For example, Kumar et al. [82] created a framework for decision-making around sustainable microgrids, contextualized to India, but applicable broadly to rural areas in developing nations. The study built load profiles through surveys of local households and buildings, and when exploring energy alternatives, the authors consulted and engaged with experts and community leaders. The authors were ultimately able to incorporate many context-specific factors into the analysis [82]. Additionally, the substantial collection of data on consumer profiles in the studies presents an opportunity to investigate how consumers can become more active actors, owners, and decision-makers in energy systems.

Transitioning toward increasing multi-RES clearly involves traditional and new actors, but also actors to support this transition, for example, policy-makers, investors, and RES technology manufacturers and suppliers. In this sample, these supporting actors were underrepresented, despite the important role they play. For example, they were often represented as enabling factors or through underlying assumptions rather than as actors, although most contextualized studies did still have at least one supporting actor present. Even in cases where a supporting actor was coded as being present, additional potential supporting actors within that study were often presented as enabling factors or as part of the underlying assumptions, or the actor's role may not have been a focus. In some cases, it was outside of the study's scope to include supporting actors. For example, when modelling a theoretical microgrid, it is justifiable to assume the technologies are already in place, as the purpose of the article is not to discuss how the technologies come into place, but rather how they can be optimized to work together. However, in many cases further analysis of the roles and perspectives of supporting actors could be helpful, as they may not always fulfill their roles as assumed in models, and they play key roles in the diffusion of RES [5,62].

Supporting actors are also useful to consider for other reasons. Although RES are becoming less costly in many contexts, it is still useful to apply factors such as technology availability and distribution, possible funding opportunities and investments, enabling government policies, and the impacts of actors such as the media and community members and groups when examining social acceptance and uptake. When supporting actors were found in studies, their inclusion provided clarity around several factors. They can help explain why certain RES are present in some contexts while other RES face barriers, thereby demonstrating how a transition toward decentralization can either succeed or face obstacles. These types of supporting actors were visible in the sample. For example, considering supporting actors can help explain why solar was favoured over wind in Japan, impeding complementarity [66]. The interaction between policy makers and dominant incumbent actors in Germany's energy sector can help to explain the costs of specific energy pathways [70]. The role of financial actors can help to understand how financial mechanisms are able to involve more actors in RES uptake, such as the role of different types of investors in a consumer stock ownership plan [69]. These examples demonstrate where the roles of supporting actors had clear effects on RES uptake. This indicates that more specific attention can be paid to these actors in research in order to gain further insights into how RES transitions are unfolding or can unfold.

6. Conclusion

For a successful energy transition, issues with intermittency, reliability, and lack of flexibility linked to RES must be addressed [30]. Multiple actor systems, such as those legislated by the new European Clean Energy Package, can facilitate complementarity and the optimization of RES uptake [16]. This systematic review makes several contributions by identifying trends, geographical locations, and gaps in research related to the involvement of multiple actors in the implementation of multiple RES.

The sample studies in this systematic review focused on scales from isolated houses, to islands, to cities, to regions, to countries, and to continents, clearly demonstrating that multiple RES, in association with multiple actors, are being addressed in research at varying scales and contexts. The studies in this systematic review come from several disciplines. They strongly acknowledge the role that multiple RES and complementarity have to play in a sustainable energy transition, and in meeting environmental targets, while also addressing issues around reliability of RES integration in an economically optimal manner.

Despite this, there are significant gaps. Many studies do not include contextual information about specific locations and actors. This is a missed opportunity as the study indicates that there are benefits to including contextual information; the studies that considered specific locations analyzed a wider range of combinations of RES as well as a wider range of actors. More specific contextual information will make it possible to address the acknowledged importance of governance for social acceptance of particular types of RES [48], the barriers and supports that traditional incumbent actors can provide [79], and the importance of supporting actors in RES diffusion and implementation [83].

There is increasing availability of resource specific data for sources beyond just solar and wind. More integration of this data into the significant volume of decontextualized modelling that is taking place would be beneficial. Modelling should also be expanded to a wider range of RES combinations than solar and wind. Beyond RES data, there is also scope for greater integration of different kinds of data. For example, the study sample revealed data on load and consumer profiles. As these types of data become more available, they can be mobilized and explored in order to learn from ongoing energy transitions in locations which are actively converting passive consumers into prosumers, or engaging citizens in some form of control or ownership.

Stakeholder perspectives were also not usually integrated into the models and analyses in the sample. This is an important gap as contextually-appropriate research, and the incorporation of local perspectives into energy system planning, implementation, and operation, can lead to social acceptance and improved implementation with increased actor involvement [9,80]. The studies that included perspectives of a broad range of actors were able to incorporate many more contextual factors in their analysis than they could have otherwise. For example, system actors can be asked about their acceptance of the RES technologies that will or could be modelled.

This sample revealed a general lack of inclusion of supporting actors. This is a significant gap to address as supporting actor positions can help explain why certain RES were present in a specific context while other RES face barriers, and can help clarify why some technologies, projects, or locations successfully realize RES implementation. Investigation into the importance of the role of supporting actors should be expanded by exploring their supportive or hindering roles in interventions. There should also be critical investigation into their modelled functions as they may not always fulfill the roles assumed in existing models. This may require methodological interventions and changes to research funding structures.

Although analysis did not address policy because the study sought to review all scientific attention to multi-actor complementarity, there was limited evidence of specific policies that target complementarity amongst multiple actors. In further investigations, it would be worthwhile to investigate how multi-RES energy systems or analyses emerge in place among multiple actors, including the policy supports or conditions that allow this to happen. This can help explain why those energy systems or analyses emerged in those jurisdictions and help to understand the role of supportive policies and actors in implementing complementarity. This could potentially be done with a policy mix analysis or multivariate analysis.

This systematic review of multi-actor complementarity demonstrates promising avenues for integrating technical and social research to advance the energy transition. There are lessons to be learned from existing cases of multi-RES and multi-actors around the world. The sample studies make clear the importance of continuing to consider the roles of traditional actors within energy systems. The diversity of new actors is becoming significant with increasing research attention drawn to new energy system architectures such as microgrids and VPPs. Even when the focus is on traditional consumers, there is space to mobilize research from broad consumer profiles to move beyond viewing citizens as passive, one-dimensional consumers to active multi-RES system participants. There are also increasing opportunities to integrate new actors as prosumers and decision-makers who exercise increasing control in energy systems.

In general, studies that consulted with local interests, and other implicated stakeholders, presented rich data and added additional layers of contextual-appropriateness and detail to their studies. Diverse actors in different contexts have different needs and priorities. Moving forward, studies will need to more accurately profile both the technical and social specifics of the locations they are examining. Simply applying the most 'technologically or economically optimal' model may fail when these models do not represent the needs and interests of the modelled actors.

Credit author statement

Natalia Bekirsky: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. Christina Hoicka: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Resources, Supervision, Project administration, Funding acquisition. Marie-Claire Brisbois: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. Luis Ramirez Camargo: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Resources, Supervision, Funding acquisition.

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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Appendix A. Supplementary data

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