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Research Review

A review of dynamic changes in complementarities and transition pathways toward distributed energy resource–based electrical system

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ABSTRACT

The global increase in renewable energy share and grid-resilience risks posed by climate change make distributed energy resources (DERs) a key priority for sustainable energy. While previous studies have explored the required changes for achieving a renewable energy source (RES)-based system, they have paid little attention to different transition strategies based on grid paradigms and their adaptability to local contexts. This study fills this research gap by showing transition pathways toward DER- and RES-based systems through a literature review of DERs, focusing on complementarity elements in electricity systems. We found that the transition pathway must be associated with changes in the following three complementarity elements: (1) the expansion and empowerment of prosumers; (2) the design and arrangement of the energy market and its mechanism in favor of the DER-based system; and (3) the adjustment of tasks and functions of existing stakeholders. These findings make a novel contribution to arguments about incumbents' sustainability transitions, particularly incumbents' adoption of new business models and adaptation to new institutions.

1. Introduction

Distributed energy resources (DERs) are rapidly emerging to integrate renewable energy sources (RESs) into electricity grids on scale, avoid transmission losses within long distances, and provide reliable energy to consumers [1]. Many distribution grids were designed for 20th-century power systems [2]; thus, they must be renovated. The increasing sharing and integration of intermittent renewable energy requires intelligent power grids that incorporate new information and communication technologies into all aspects of the electricity system, including demand-side devices, widely distributed generation, and various energy markets [3]. The performance and operational range of DERs are enhanced by novel engineering technologies, materials, and designs [1].

The definition of DERs has been varied. The US Federal Energy Regulatory Commission (FERC) considers them as "small-scale power generation or storage technologies" that can enhance or replace conventional electrical systems [4]. The European Commission provides similar explanations but excludes energy efficiency as a type of DER [2].

As for the research gaps this article fills in, first, a number of (even the latest) articles discuss the energy transition while disregarding the distinction of paradigms. These articles majorly provide meaningful insight regarding the transition in phasing out fossil fuel or maximization of RES with less consideration of indicating directions toward different system paradigms [5–9]. Grid system paradigms for RES-based systems can be DER-based or large-grid system paradigms, and this study focuses on the former – it identifies complementarity elements that synchronized changes are required for the systems to move toward DER-based system paradigms.

Second, this study fills in the research gaps in DER-related articles which lack the implication of transition pathways, requirements, or strategies. These articles are devoted to maximizing the potential of DERs in certain subjects, but they provide limited theoretical or empirical implications in terms of transition [10–14]. This study fills in this gap by employing the analytical lens of "complementarities in transition" (see Section 2 for the details) [15,16]. Moreover, this study further specifies complementarity elements in DER-RES-based electricity systems and the direction of transitions more rigorously.

Abbreviations: DER, distributed energy resource; RES, renewable energy source; FERC, The US Federal Energy Regulatory Commission; PPA, power purchase agreement; FIT, feed-in-tariff; SLR, systematic literature review; WoS, Web of Science; BTM, behind-the-meter; EV/EVs, electric vehicles; VPP, virtual power plant, PV/PVs, photovoltaics; V2G, vehicle-to-grid; TSO, transmission system operator; DSO, distribution system operator, PDRP, the Pilot Demand Response Program; P2P, peer-to-peer.

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In addition to the two major research gaps mentioned above, this study further provides visions considering the compatibility between the niches and the local context. The transition will be accelerated when the country's grid system paradigm is compatible with context-specific features. However, in many cases, the compatibility between the development of DERs and the local context remains unaddressed [17,18], despite that the visual compatibility, material compatibility, and reversibility with local context should be deeply considered [19].

To fill in the research gaps, this study pays attention to complementarities in the elements of electricity systems and investigates transition pathways toward DER- and RES-based electricity systems. For this purpose, it poses two research questions:

(1) What complementarity elements constitute the DER-based system paradigm? What relationships exist among the complementarity elements, including positive interactions and negative competition?
(2) What are the required changes and transition pathways in complementarities from traditional fossil fuel-based systems to DER- and RES-based systems?

To answer these questions, this article provides a better-illustrated map showing the co-evolution and bottlenecks among complementary elements. Based on the mapping, we identify transition strategies for achieving the DER- and RES-based systems and propose them as an analytical framework for empirical case studies.

This paper is organized as follows. Section 1 focuses on identifying the research gaps. Section 2 presents the analytical lens to provide the rationale for selecting research keywords. Section 3 describes the criteria, procedures, and other details for conducting the methodology. Section 4 illustrates the findings that identify potential complementarities in different categories and demonstrates the changes from traditional to DER-based systems. Section 5 discusses the required changes in complementarities and transition pathways for electricity system transitions. Finally, Section 6 concludes with the remaining challenges.

2. Analytical lens

2.1. Complementarities in transition

Markard & Hoffman [15] and Mori [16] classified complementarity within a system into technological, organizational, institutional, and infrastructure categories based on performance criticality. Considering that the DER-based system is a paradigm undergoing sociotechnical transitions and configurations, the co-evolution of various complementarity innovations is a key feature in ensuring transitions across multiple sectors, including the electricity sector.

The DER-based system paradigm embodies an energy blueprint primarily consisting of small-scale resources with coordination from the microgrids. It strengthens the grid system in terms of risk diversification, market-friendliness, energy democracy, resilience from power outages, growth of local job opportunities, and the usefulness and attractiveness of PVs [2,20–23]. In contrast, *the large-grid system paradigm* includes operating with a tremendous and centralized grid system, deploying large-scale intermittent RESs, and relying on the long-term energy market. After clarifying the differences between the two paradigms, the following paragraphs discuss the four categories of complementarities.

First, technological complementarities occur when different technologies are horizontally combined such as PV power plants and batteries or vertically linked in value chains such as machinery to produce solar cells [15]. Solar PVs, grid-related innovations, hydropower, batteries, and silicon technologies were categorized as technological complementarities. Engineers, manufacturers, power generation, storage (and battery), smart meters, and grids are general technological complementarities in RES-based systems [16]. Under the DER-based system paradigm, distributed generation with behind-the-meter (BTM) applications, microgrids, and BTM storage are the potential technological complementarities. Conversely, large-scale RES generation facilities, front-of-meter storage systems, and pumped hydropower are installations under the large-grid system paradigm.

Second, organizational complementarities include organizational elements such as resources and capabilities that can influence focal technology [15]. Marketing, distribution, and product-related services can be grouped into this element. Aggregators, system operators, and long-term power purchase agreements (PPAs) are considered organizational complementarities in a general RES-based system [16]. However, the PPAs are more large-grid system paradigm oriented.

Institutional complementarities occur, and focal technology is influenced by institutional elements. Changes in institutional elements or structures lead to the emergence of institutional complementarities [15]. In RES-based systems, day-ahead markets, real-time markets, stable supporting schemes, financial capital, and capacity remuneration mechanisms provide the functions of institutional complementarities [16]. The feed-in tariff (FIT) scheme, a type of long-term contract as institutional complementarities, could exist in both system paradigms. The FIT scheme may incentivize the installation of DERs with appropriate arrangements [24]; however, it may result in expensive electricity bills and technology lock-ins [25,26].

Finally, infrastructure complementarities can be considered as general elements that influence a wide variety of technologies [15]. In a RES-based system, the transmission and distribution networks can be categorized as infrastructure complementarities [16]. The definition range of infrastructure complementarities can be broad and flexible in different contexts and studies as long as the counterpart concepts satisfy the function of "generating positive effects for technologies" [15]. In addition, infrastructure complementarities have the "nonclear-cut boundary" feature; overlapping functions can lead one to categorize them into the other three types of complementarities [15].

Concerning the interactions among complementarities, the direction can be bilateral or unilateral. In addition, the extent of "bottlenecks" can slow or obstruct transition under significant complementarity. They can be created by technological constraints and the asynchronous growth of complementary elements [27].

2.2. Analytical lens

With the rationale provided by the analytical lens of complementarities in transition, this article considers the term "complementarities" as one of the core keywords for conducting the following methodology. Complementarities are considered elements that favor focal technologies [15]. They can upscale DERs to clusters of various DER-related components on a system scale. This view is consistent with Mori [16], who demonstrated the constitution of complementarity elements and dynamic changes in RES-based systems.

Another core concept from the conceptual framework of Markard & Hoffman [15] and Mori [16] is the term "bottlenecks", which is the opponent that the complementarities have to overcome.

Finally, this study adopts other representative general keywords. The criteria, procedure, and details in selecting them have been described in Section 3. Following the rationale provided in Section 2, the concepts and elements under the large-grid system paradigm haven't been adopted as keywords.

3. Methodology

3.1. Literature review of string searches in databases

Filling in the research gaps requires the adoption of abundant and well-organized literature. Considering the expected structure of the DER system, which consists of different types of complementarities, the literature will be interdisciplinary. Researchers can create a well-organized summary of recent literature on a particular topic using a well-organized literature review [28].

For this reason, we adopted the literature review within string searches in databases by conducting the following steps: (1) formulate the problem; (2) develop and validate the review protocol; (3) search the literature; (4) screen for inclusions; (5) assess the quality; (6) review the literature; (7) analyze and summarize the findings; and (8) report the findings [29]. Although this article does not adopt a systematic literature review (SLR) as a methodology, the author still refers to parts of Xiao and Watson’s [29] concepts in SLR (steps 1 to 5) to design the review process of this article. All possible complementarities and bottlenecks are defined in step 7 and transformed into a DER-based paradigm map in step 8.

3.2. Document collection process

For Step 3, we searched for relevant articles from Web of Science (WoS) and Scopus. Since this article discussed the energy system in multiple dimensions, the WoS and Scopus can provide corresponding results with interdisciplinary, comprehensive, and reliable records. Also, these two databases share similar approaches and indicators to filter irrelevant documents.

Considering the major concepts of the theory of Markard and Hoffmann [15], the terms “distributed energy” AND “complementary” and “distributed energy” AND “bottleneck” have been adopted as the major search strings in the literature review procedure.

The previous two search strings are theory-oriented while we also require the search string to consist of the general and representative concepts of DERs. On the basis of the analytical lens, the scope of keywords should also consider the four categories of complementarities based on Markard and Hoffmann [15]. Therefore, we referred to Chicco et al. [30] and IEA [2] to determine general keywords in the DER-based system. The former not only provides the general concepts of DERs but also highlights the embeddedness of DER-related concepts in energy systems, and the features of these concepts could be factors contributing to the complementarities in a system. The latter has compiled key insights into technological niches, institutional design, organization, and infrastructure-related factors. Thus, the concepts of this report are compatible with the analytical framework of complementarities used in this study.

The determined keywords include technology-oriented terms “microgrid,” “storage,” and “vehicle-to-grid,” market-oriented terms “demand-side management,” “energy market,” “demand response,” “system operator,” “virtual power plants,” and “ancillary services,” and institution-oriented terms “regulation,” “law,” and “policy.” Several standards have been set for filtering irrelevant and outdated articles: (i) setting the search to cover the years 2000–2022; (ii) refining the documents based on types of peer-reviewed articles, book chapters, reviews, and books; (iii) limiting the documents to only the subject areas of environmental science, environmental studies, energy (fuels), green sustainable science technology, social sciences (interdisciplinary), economics, finance, business, management, development studies, multidisciplinary sciences, sociology, and law; (iv) excluding documents not written in English; and (v) excluding editorial papers and titles of edited books. From WoS and Scopus, each database applied three search keyword strings. Results for 1,006 documents were searched from all six strings (495 from WoS and 511 from Scopus).

For Step 4, we screened for inclusion and excluded irrelevant and unnecessary documents. Tables 1 and 2 present the literature search results from WoS and Scopus. In addition to the standards mentioned in the last paragraph, we adopted three criteria to filter the irrelevant articles. First, after a thorough reading of the abstract of the documents, the articles prioritized for citation should not only be related to the keywords but also provide implications regarding sustainability or energy transition. In some cases, some studies specifically focus on certain technological niches without any hints into whether they could contribute to the transition at a macro level (e.g., social systems, regimes, and paradigms), and these articles have been excluded. Second, conference proceedings will not be adopted. Although many proceedings provide relevant information and insights, not all are guaranteed to meet academic quality and validity. Finally, after the exclusion process using the two previous criteria, there remain 48 duplications that have to be excluded. Overall, after screening for inclusions, the author collected 235 documents. Then we cited documents outside the database searches as supporting concepts. There are majorly two types of these documents: (1) documents or information published by representative international institutions (e.g. IEA, IRENA, FERC) with high reliability; (2) documents with supporting concepts that can enhance other references in the same citation. We also strictly verified that these documents meet the aforementioned criteria and are highly relevant to the search keywords.

Table 1
Keyword search terms (WoS)—cutoff time: June 2023

Database	Concept	Specific search keywords	Records	Timespan
Web of Science	Complementarity	ALL = (((Distributed Energy Or Distributed Energy Resources Or Distributed Generation) AND (Complementari*)))	121	2001-01-01 to 2022-12-31
	Bottleneck	ALL = (((Distributed Energy Or Distributed Energy Resources Or Distributed Generation) AND (bottleneck*)))	119	
	General ideas	ALL = ((“Distributed Energy” Or “Distributed Energy Resources” Or “Distributed Generation”) AND (“microgrid” Or “storage” Or “Vehicle-to-Grid”) AND (“demand side management” Or “demand response” Or “energy market” Or “system operator” Or “virtual power plants” Or “ancillary services”) AND (“Regulat*” Or “Law” Or “Policy”))	255	
Total WoS	495			

Source: Author.
Note: to indicate a range of characters, including no character, the asterisk (*) acts as a wildcard to expand the scope of a search.

4. Results

4.1. Technological complementarities

The results of the technological complementarities of DER-based systems are mapped out in Figure 1. The BTM applications, grid-related technologies, virtual power plants (VPP), EVs, and storage technologies are representatives of technological complementarities that accelerate the progress of DER deployment. The influences of power curtailment and intermittent power are highlighted as major bottlenecks. Bottlenecks in renewable energy curtailment occur when the power inflow from renewable energy exceeds the grid capacity [31]. The increasing penetration of RESs with intermittent issues has led to concerns about efficient flexibility and system safety [32].

The diffusion of DERs and associated technological

Table 2
Keyword search terms (Scopus)—cutoff time: September 2023

Database	Concept	Specific search keywords	Records	Timespan
Scopus	Complementarity	TITLE-ABS-KEY ((distributed AND energy OR distributed AND energy AND resources OR distributed AND generation) AND (complementari*))	60	2001-01-01 to 2022-12-31
	Bottleneck	TITLE-ABS-KEY ((distributed AND energy OR distributed AND energy AND resources OR distributed AND generation) AND (bottleneck*)	40	
	General ideas	TITLE-ABS-KEY ((“Distributed Energy” OR “Distributed Energy Resources” OR “Distributed Generation”) AND (“microgrid” OR “storage” OR “Vehicle-to-Grid”) AND (“demand side management” OR “demand response” OR “energy market” OR “system operator” OR “virtual power plants” OR “ancillary services”) AND (“Regulat*” OR “Law” OR “Policy”))	411	
Total Scopus	511			

Source: Author.
Note: to indicate a range of characters, including no character, the asterisk (*) acts as a wildcard to expand the scope of a search.

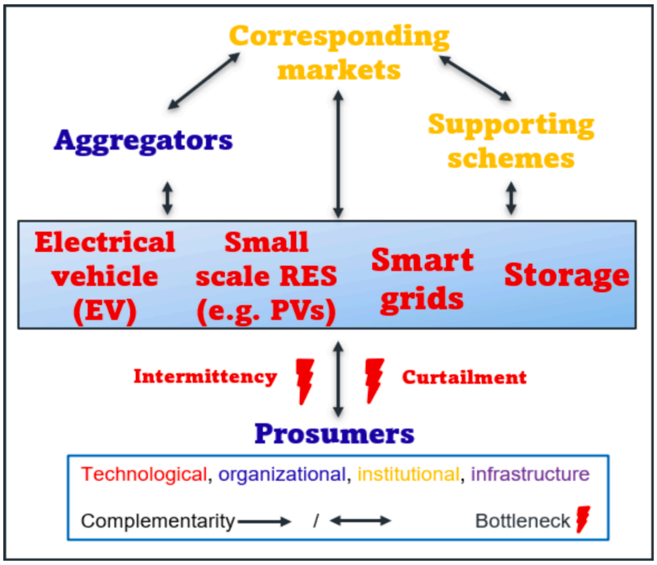

Figure 1. Technological complementarities and bottlenecks. Source: Authors.

complementarities can facilitate the expansion of decentralized RESs. First, BTM installations, such as PV systems with storage systems, embody context-specific technological complementarities that contribute to the decentralized RE sources’ penetration [33]. Second, smart grids, microgrids, and VPPs advance the transition from a centralized to a DER-based system [34]. Horizontally, smart grid technologies help coordinate intermittent and dispersed sources from renewable energy sites such as rooftop solar panels [35]. Vertically, they could be involved in a value chain ranging from the supply side (such as PV) to the consumer side (such as vehicle-to-grid (V2G) services) [36].

Storage technologies also play a vital role in maintaining and managing intermittent resources. Private storage owners are expected to increase in the next decade due to lower costs [37]. Furthermore, battery energy storage systems can help meet peak energy demand, improve the integration of RESs and DERs, and lower the expansion cost of distribution networks [38,39]. They offer spinning reserves, frequency regulation, and balancing power in microgrids [40].

However, EV- and V2G-related technologies remain significant bottlenecks. In addition to providing ancillary services, integrating EVs into distribution systems will affect the security and power quality during both V2G and grid-to-vehicle (G2V) [41]. Once EVs only serve as a type of electric load, the significant power demand from EV charging can result in issues with the power system and even lead to accidents such as power failure [42]. The negative effects would differ by charging/discharging characteristics, including load profile losses, voltage rise/drop, increasing harmonics, intermittent issues from renewable energy, and cost related to power losses [41]. Concerns about extra battery degradation would create barriers to EVs’ economic viability in offering V2G services in electricity markets [42].

In addition, synchronized changes in other elements of complementarities are indispensable to maximize the effectiveness of changes in technological complementarities. A mature electricity market is essential because prosumers require market incentives to adopt PV panels, EVs, and storage batteries. In addition, aggregators play vital roles in pooling small-scale resources from technological complementarities [2]. The aggregators can conduct tasks as vehicle aggregators, RES aggregators, energy storage aggregators, load aggregators, and so on [42–44]. Namely, aggregators drive the changes and transition by maximizing the potential of each technological complementarity from prosumers.

Australia provides a showcase of the co-evolution of technological complementarities for deploying DER-related technologies. By 2050, Australia is expected to develop significant decentralized systems with 44% capacity from BTM [45]. To enhance the robustness of DERs, different forecasting mechanisms have been proposed in Australia, particularly for electrical energy storage [46]. In addition to promoting electrical energy storage, Australia has made progress in expanding DER sites. Within the BTM PV and battery systems, Australia has the world’s highest rate of rooftop PV penetration [45,47] due to incentive policies. The FIT scheme plays a vital role in penetration [47–49].

Unlike the context of Australia, there are also converse contexts that expand RES penetration significantly through the deployment of large-scale facilities, which led to technological lock-ins with less consideration and expense arrangement of the stimulation of decentralized facilities, implying that the technological complementarities from the different paradigms, such as the deployment of large-scale RESs and small-scale DERs, may contradict each other, leading to competition and lock-ins [50,51].

4.2. Organizational complementarities

Prosumers, aggregators, system operators, and demand response measures are identified as potential organizational complementarities because they provide competencies or services to stimulate the diffusion of DERs [2,52–55].

Smart grids as technological complementarities have led to the emergence of prosumers who have transformed from traditional consumers in the energy regime [56]. Prosumers are different from traditional electricity consumers because they actively engage in the energy system [57–59]. Traditional consumers merely receive electricity from the supply side, pay their bills routinely, and have limited opportunities for value creation. In contrast, proactive prosumers are influential market actors who are considered relevant additions to DER-based systems and future sustainable energy systems [59–61].

As intermediaries between prosumers and electricity markets, resource aggregators could represent organizational complementarities in DER-based systems. Aggregating DERs could be an option to address the relevant uncertainties associated with the intermittency of DERs and stimulate DERs to become actively involved in electricity markets [62]. Aggregators can collect DERs from generation sites and prosumers and play a role in the bundling and management of producers, consumers, and prosumers in electricity markets [63]. In addition to enabling prosumers to be involved in markets, aggregators bring a variety of policy implications regarding the energy transition, including being emerging stakeholders in market engagement and system operation, reducing the risks and impacts from DERs to distribution networks, identifying and gathering the demand-side flexibilities, and consequently changing the conventional way of energy system operation [63–65].

VPPs also contribute to DER coordination as production aggregators [66]. They are equipped with technologies, such as specific units, storage, and EVs, and interact with the grid through information communication [67].

System operators are also indispensable for managing the increasing number of DERs and providing the necessary energy and regulation for power systems [13,68]. The role of system operators has evolved during the transition from conventional centralized grid systems to DER-based systems [14,69,70]. In conventional systems, transmission system operators (TSOs) operate an electricity transmission network and transmit electricity from the centralized generation sites (e.g., thermal power plants) to local distribution networks, and distribution system operators (DSOs) deliver electricity from local distribution networks to end users [69]. With the emergence of DERs, DSOs have become more involved in electricity markets by providing price signals to market stakeholders and enabling DERs to contribute to the overall power system [14,69]. The information-sharing tasks between TSOs and DSOs are relevant to maximize the benefits of integrating DERs into the energy system [69]. Instead of the “role shifting” of prosumers, the change in complementarities caused by system operators could be considered “function shifting.”

Demand response measures and programs can facilitate cooperation between aggregators and system operators. This approach allows electricity consumers to be actively involved in the demand shift during peak loads [71]. Resource aggregators could exchange data with DSOs in favor of appropriate in-time adjustments for executing demand response programs [66].

The relationship between organizational complementarity elements and other complementary elements is shown in Figure 2. Many relationships among organizational complementarities are bilateral or multilateral. Resource aggregators can sign bilateral contracts with buyers of demand response services, of which system operators are also one kind of buyers who can pay remuneration depending on the offered demand response resources [66]. The aggregators manage the DERs from prosumers within organizational complementarities. In exchange, they benefit from control and transaction fees and get the authority to manage the DERs [72,73].

Institutional elements such as value-stacking limitations could be bottlenecks in DER deployment [2]. In addition, aggregators and system operators are highly engaged in the wholesale electricity market [72,74–76] which is considered an institutional complementarity.

Brazil can be seen as a high performer of organizational complementarities. Its government has promoted distributed generation from RESs by enacting regulations that address the grid connection of DERs [77]. In 2017, Brazil proposed the Pilot Demand Response Program (PDRP), which is devoted to stimulating qualified consumers’ consumption reduction [78,79]. The PDRP allowed the involvement of various stakeholders. The National Electric System Operator in Brazil evaluates the reduction in consumers’ demand to optimize energy efficiency from the demand side [78]. The corresponding aggregators or

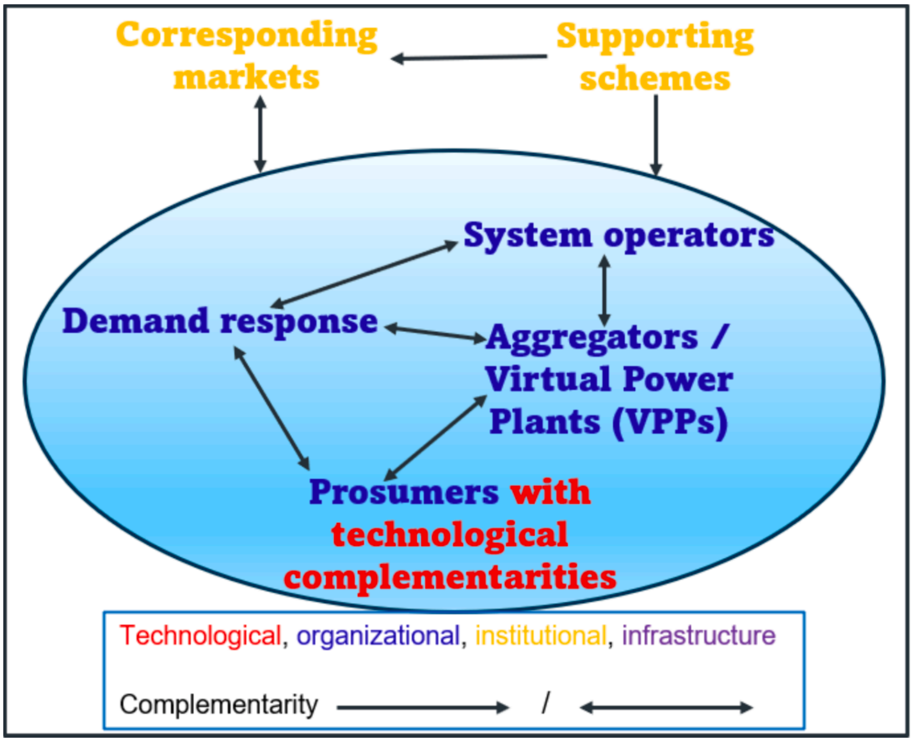

Figure 2. Partial mapping of DER-based systems: Organization-oriented. Source: Authors.

retailers in the program could contribute to load optimization. This program is expected to reduce the demand of some targeted consumers with a minimum of 5 MW per day [78].

4.3. Institutional complementarities

Markets and supporting schemes are indispensable institutional complementarities for the whole system. Markets could always be considered the prerequisites for operating the co-evolution among the whole DER-based system, and the supporting schemes such as policies are significant triggers to stimulate each complementary.

In addition to the wholesale spot electricity market, flexibility, ancillary service, and nonfossil fuel markets would be essential institutional complementarities. Ancillary service markets include the spinning and nonspinning reserve, frequency up/downregulation, black start, reactive supply, and voltage regulation [80]. The expansion of DERs has led to a transition from passive distribution networks to active distribution systems, which has resulted in new financial opportunities for trading flexibility in markets [43].

The energy trading markets must strengthen technological complementarities. Battery energy storage systems require the markets to emphasize ancillary services that could provide or absorb short bursts [38]. The market mechanism for spinning reserves could be attractive for EVs and V2G services because stakeholders can even benefit from the duration for which no energy is produced [36].

Several market-related mechanisms are highly engaged with organizational complementarities. Demand response measures usually operate with a real-time pricing mechanism to encourage consumers to reduce their consumption during peak load periods [52,81,82]. The peer-to-peer (P2P) mechanism enables participants to transact energy with each other directly [83] while P2P markets require coordination mechanisms with system operators to ensure that the distribution networks and power system infrastructure operate correctly [84,85].

Stable supporting schemes are the other major institutional complementarities of DER-based systems. These include policies, legal frameworks, and financial incentives, as observed in the PDRP in Brazil. The stable supporting scheme is especially influential in energy trading market mechanisms. As supporting schemes, regulating and policymaking bodies can stimulate the re-designation of market structures to achieve sustainable emission targets [86]. Furthermore, well-defined rules that enable aggregation services are necessary because the demand for aggregation of DERs was commonly not considered in the original design of wholesale electricity markets [87].

The United States represents the decentralization of grid systems initiated by a series of markets and supporting schemes [74,88]. The FERC orders stimulated the growth of DERs [74], which emerged into various complementarities. The FERC Order No. 2000 resulted in independent system operators' involvement in regional wholesale markets [74]. FERC Order No. 719 in 2008 allowed load aggregators to bid for demand responses on behalf of retail customers, enabling them to engage in wholesale markets [74]. Order No. 841 in 2018 reduced barriers to storage resources and enabled them to become involved in electricity markets [89]. Order No. 2222 in 2021 provided a framework through which DER owners, such as households, could participate in electricity markets and obtain compensation for their DER output via aggregators [90].

However, stable supporting schemes or sociopolitical barriers can reinforce specific complementarities, slowing whole system change. For instance, in Germany, a high FIT created a wind power lock-in that restricted the uptake of various RE sources and decreased the grid's capacity to adopt DERs [50,51]. In many countries, sociopolitical contexts enable incumbent utilities to capitalize on monopolistic power to influence the energy sector's dynamics and policies and block the emergence of a DER-based system [51,91].

4.4. Infrastructural complementarities: Grid infrastructure

Grid infrastructure is a vital infrastructural complementarity under the DER-based system paradigm. Digitalization enables the grid and its control systems to enhance the resilience of electricity systems and coordinate dispersed, smaller-scale DERs into dependable resources [87]. Organizing the microgrid into several “nanogrids” facilitates the aggregation of DERs more efficiently, which promotes the involvement of ancillary services with better controllability [92]. Smart microgrids are potential choices for transitions from an existing fossil fuel-based system to a RES-based and decentralized one [34].

5. Discussion

5.1. Synchronized changes in complementarity elements

Figure 3 shows the review results regarding the DER-based system paradigm described in Sections 4.1–4.4, with some added concepts from the large-grid system paradigm (front-of-meter storage and large-scale pumped hydropower).

The aggregators and prosumers emerge as context-specific components of the organizational element under the DER-based system paradigm. Electricity consumers perform role shifting to proactive prosumers equipped with various technological complementarities (e.g., rooftop PV and EVs) and are deeply engaged in institutional complementarities such as wholesale electricity markets. Aggregators emerge as intermediaries that connect small and distributed prosumers and grid systems. They may capitalize on BTM-related technologies such as low-voltage PV systems and their integration with storage to stabilize and maintain grid systems under RES-based systems. System operators reposition themselves to exert more influence on the whole DER-based system by operating the DERs directly, enhancing their involvement in electricity markets, and delivering pricing signals to market participants. The electricity market is being redesigned to favor low-voltage installation owners and their high-voltage counterparts. The popularization of context-specific market mechanisms, such as P2P trading or V2Gs, would also be stimulated under the DER-based system paradigm.

On the contrary, technological components that serve the centralized RES-E systems, such as front-of-meter storage systems, and large-scale pumped hydropower can be competitors to the DER-based system paradigm. For instance, the liberal electricity markets, which are in favor of the DERs, can stall the development of grid-scale pumped-storage hydropower that requires long-term revenue stability [93].

5.2. Transition pathways

Our review process gives implications for transition pathways that differ according to electricity structure and market mechanisms.

Countries that promote large-scale RES deployment to meet ambitious national sustainable targets may execute the transition with the ignorance of the diffusion of DERs, which is a lock-in situation that should be avoided. Israel is the typical case with unbalanced development between large-scale RES projects and decentralized facilities [50].

Countries that already have a liberal energy market system are concerned with increasing the number of low-voltage prosumers and relevant stakeholders involved in the wholesale market. Their strategies focus on decentralizing grid systems, as represented by FERC orders in the United States, or the diffusion of DER-aggregation businesses [94].

Countries that have installed RES capacity to some extent within the lock-in and rely on the FIT scheme may have to deliberately reconsider this policy instrument's role and function. With appropriate arrangements, the FIT could enhance the incentive for DER installation [24], such as in the expansion case of small-scale PV in Australia. However, long-term FIT contracts may result in costly electricity for consumers and technology lock-ins [25,50].

Finally, countries heavily reliant on long-term contracts, such as

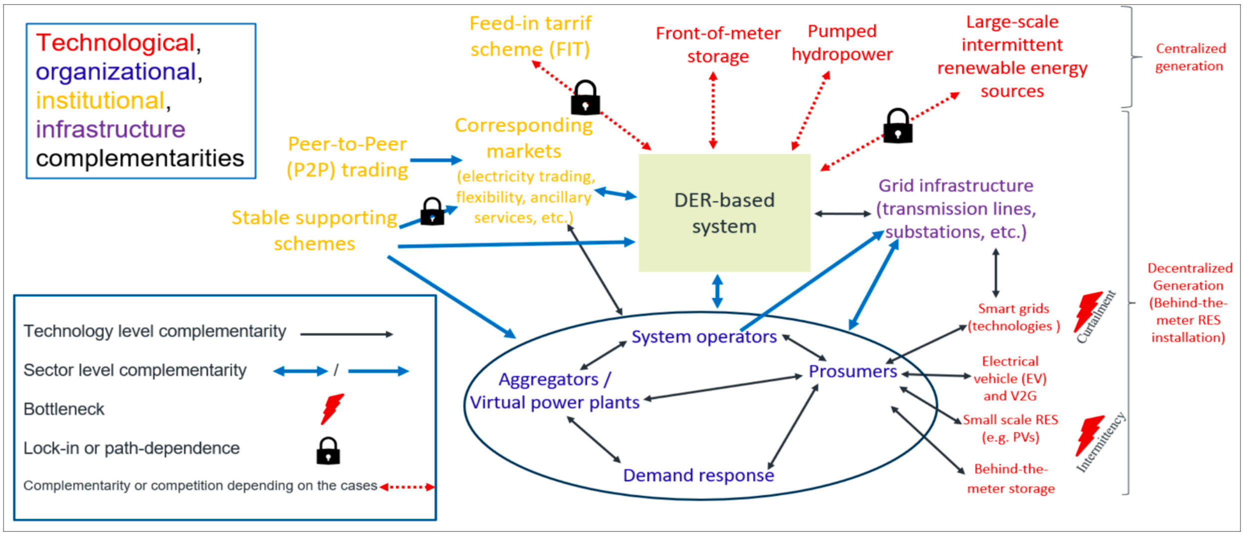

Figure 3. Overall mapping of the complementarities in a DER-based system paradigm. Source: Authors.

PPAs or capacity contracts, should consider the potential risks from the simultaneous growth of renewable and fossil energy. Some stakeholders believe that relying on preferred long-term PPAs could result in a divided market, with one for conventional power operating competitively and the other for low-carbon generation operating under regulation [95].

6. Conclusions

The global trend of increasing the share of renewable energy and the grid-resilience risks posed by climate change make DERs a key agenda for sustainable energy. While previous studies have explored the required changes to achieve RES-based systems, they have paid little attention to different transition strategies based on grid paradigms and their adaptability to local contexts.

Against this background, this study identifies complementarity elements in DER- and RES-based electricity systems and investigates their transition strategies.

This study identified three types of complementarity elements that must be in place in DER- and RES-based electricity systems: technological complementarities such as BTM applications, EVs, and storage technologies; organizational complementarities such as prosumers and aggregators; and institutional complementarities such as supporting schemes and energy and ancillary service markets. Organizational complementarities have decisive tasks relative to operating DER-based systems, and other types of complementarities are fundamental to system operations. In most cases, the relationship among the complementary elements is positive and mutually reinforcing. However, specific complementarities can slow the overall system change and enhance conventional energies.

This study also mapped required changes in prosumers, markets, and incumbents along transition pathways. Traditional consumers must be transformed into prosumers and empowered as influential market actors. Market mechanisms must be (re)designed and (re)formulated in favor of the stakeholders in the DER-based system. These markets can facilitate flexibility and ancillary services trading. Incumbents will reposition themselves from their tasks to exert more influence on the whole system so long as they are not phased out of the new system paradigm.

This study makes a scholarly contribution by providing an analytical framework that can assess the gaps in the direction and speed of changes between technological, institutional, and organizational elements and the consistency between the transition pathway a country is passing through and the local contexts. Previous studies have focused on the development and diffusion of specific DER technologies and analyzed the social acceptability of niche technologies. Our framework enables us to identify institutional and organizational gaps in transition and suggest alternative transition strategies when the consistency with local contexts is substantial.

This study provides a conceptual framework for potential future research within a case study related to the energy transition toward the DER-based system. Future studies can identify the elements in each type of complementarity of selected cases and demonstrate the relationship among them as shown in Figure 3.

This study has a limitation in presenting the benefits of the analytical framework in empirical studies. However, there remain future challenges to employ this framework to provide novel empirical findings and implications for transitioning to DER-based systems. Future studies are expected to confirm transition strategies consistent with local contexts.

Furthermore, this study does not pay attention to the network security issues that could be caused by the absence of coordination mechanisms among the stakeholders (aggregators, DSOs, TSOs, and market operators) [96]. Future studies are also expected to make an in-depth analysis of how to secure network security under the RES-DER-based electricity systems.

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CRediT authorship contribution statement

Yi-Yang Wang: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Akihisa Mori:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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

Data availability

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

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