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REVIEW

Financing electricity resilience in local communities: a review of the literature

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Abstract

Over the last two decades, research increasingly has paid attention to resilience as a way to strengthen electricity systems against the cascading impacts caused by electricity disruptions. Although much of the electricity resilience literature has focused on scale of large grids, a growing segment of research has focused on smaller-scale electricity systems, particularly with applications for communities. Research on financing these systems could encourage their uptake in local communities, particularly by including community in the ownership or operation of these systems; however, much of this research remains comparatively nascent. This paper seeks to review what previous studies have identified as some of the conditions that shape financing electricity resilience in local communities in G7 countries and how this field uses the term "electricity resilience" compared to broader uses of electricity resilience. The review provides a technical overview of smaller-scale systems for communities and a review of three socio-economic research areas—governance, cost-benefits, and business models—which shape financing electricity resilience in local communities. The discussion section finds that costs and the level of community involvement seem to play a fundamental role in shaping the conditions for financing electricity resilience across much of the research. Comparing this field to broader uses of "electricity resilience" suggests that more work is needed to understand the role of adaptation in financing electricity resilience for local communities, particularly over the long term. We posit that the field's approach costs and its inclusion of the community in electricity resilience may contribute to its general lack of attention to long-run adaptation. Despite potential benefits of continued advancements from technical research, the maturity of the field and age of some of the early cases suggests that researchers could begin to study adaptation to electricity disruptions at the community level more than in the past.

Keywords Financing · Electricity resilience · Communities · G7

1 Introduction

Societies have become increasingly dependent on electricity reliability. Widespread electricity outages, such as the 2003 blackout in the Northeast United States or the ones triggered by 2011 triple impact event in Japan, have emphasized the magnitude of cascading effects triggered by sectoral failures and their potential to escalate ongoing emergencies (Pescaroli and Alexander 2016). Events such as blackouts have the potential to disrupt all levels of societal functions (Hallegatte et al. 2019). Electricity disruptions can be considered a common point of failure that could be triggered by both independent and compounding hazards, including weather extremes, along with other points of human-induced failure (Pescaroli and Alexander 2018). The complexity of cascading risk posed by electricity disruptions is hard to encapsulate within "traditional" approaches to risk management. It has been suggested the need for a paradigm shift toward system-based resilience (Linkov et al. 2014), intended as an electricity system's capacity to perform under extreme and uncommon events, including its ability to adapt and withstand future uncertainties (Roege et al. 2014).

Academic research increasingly has used new metrics and concepts to study the strengths and weaknesses of electricity resilience (Linkov et al. 2014). Much of the research on the subject has taken a technical approach focused on the scale of electrical macro-grids (Liu et al. 2020a, b). There has been a growing technical focus on smaller-scale electricity systems, which has paid particular attention to

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how distributed energy configurations like microgrids can increase redundancies in electricity generation and streamline operations (Jirdehi et al. 2020). Despite evidence that smaller-scale systems can produce electricity reliability benefits, socio-economic literature on the uptake of these systems at the local community level has remained comparatively limited (Allan et al. 2015). Increasing understandings of how financing and funding these systems could be a critical element to expand this process (Dudka et al. 2023).

This review seeks to address this gap by reviewing what socio-economic research has identified as some of the key conditions that impact financing and funding resilience of electricity systems in local communities. Understanding some of the conditions of financing and funding may help researchers understand the baselines of scalability and replicability across systems and local communities, particularly in countries with similar electricity grids and economic and political characteristics like the Group of Seven (G7 countries), which is the focus of this study (IqtiyaniIlham et al. 2017). More work is needed to compare this field's use of the term "electricity resilience," which tend to be more praxis-based, with theoretical studies' uses of the term electricity resilience. This literature review tries to answer two questions: (1) *what are the main factors that affect the financing and funding resilience of smaller-scale electricity systems in local communities across G7 countries?* (2) *How does the field's use of electricity resilience compare with a theoretical definition of electricity resilience to understand general differences in the uses of resilience across fields*?

The paper is structured into a methodology section, a technical overview section, a socio-economic review section, and a discussion section. This review does not focus on distributed generation only, as research in the technical overview is organized into generation, transmission, and distribution. The socio-economic part of the review identifies three areas of research that shape financing and funding of electricity resilience in local communities. The discussion highlights key takeaways from the review areas and compares the literature's use of electricity resilience with a theoretical understanding of electricity resilience. The conclusion section highlights areas for future research based on the three main takeaways identified in the discussion section.

2 Methodology

This paper follows a narrative or literature review as outlined by Booth and Grant (2009). The methodological flexibility of this approach allows researchers to integrate studies across a range of disciplines, which can help identify gaps across current research and can facilitate the creation of new frameworks to understand current and future research (Grant and Booth 2009). In this section we explain the boundaries used in the selection of papers for the review, including key terms used in the research, the region and time period for selection, the approach used, and its limitations.

2.1 Key terms

Defining key terms performs two key functions for the purposes of the review. First, it helps to clarify what topics and fields are within the scope of electricity resilience for local communities and, by extension, this review. Secondly, it helps to establish a baseline definition of electricity resilience that will be used to compare literature on financing and funding electricity resilience in local communities with theoretical concepts of electricity resilience:

2.1.1 Electricity resilience

Academic research has not reached a consensus on the term resilience and electricity resilience, nor does a consensus look probable for the field given its current trajectory (Alexander 2013). This review focuses on the financing of electricity systems, which include the physical components of electricity systems and the technological management of these systems. It does not seek to review the state of art on uses of electricity resilience, which has already been completed by other studies (Jasiūnas et al. 2021). Instead, the paper applies a theoretical definition of electricity resilience in the introduction of this paper to compare its use to the general ways that literature on financing and funding define it. The "theoretical" definition used for comparison is considered theoretical since it outlines normative characteristics of an electricity system but does not test these characteristics empirically (Roege et al. 2014). The theoretical definition was selected since it includes common characteristics for resilience studies, including the ability to rebound, adapt, and meet uncertainties (Plotnek and Slay 2021; Schweikert and Deinert 2021).

2.1.2 Local communities

The use of the term "local communities" varies widely in academic research on risk and disaster reduction. A review of how previous studies of electricity systems have used the term "community," particularly "local community," highlights several shared characteristics across these systems. The base elements of a community seem to be electricity consumers, whether they are businesses, households, or individuals (Huang et al. 2015). Research on electricity systems for communities highlights the importance of geographical boundaries for communities, with much of literature concentrating on communities of less than ten-thousand consumers (Gjorgievski et al. 2021). Electricity purchasing agreements, which can constitute a first step in furthering community participation in electricity resilience, can exceed ten-thousand customers (Dudka et al. 2023; Jones et al. 2017). The participation of consumers in the ownership and operation of electricity systems features as a core tenant in many of these conceptions of community (Dudka et al. 2023; Reis et al. 2021), while other studies adopt the opposite approach by minimizing the role of electricity consumers altogether (Mendes et al. 2011). Electricity resilience for local communities does not require any direct involvement from the community; however, this is not the focus of this study. "Communities," for this review, are characterized by a smaller number of electricity consumers (typically less than ten thousand) in a discretely bounded geographically area, which involve consumers or community entities in the ownership, operation, or direct financing of the electricity system (Dudka et al. 2023; Tiwari et al. 2022).

Although the actions of individual customers or grid-wide impacts could improve the electrical resilience of communities as a secondary effect, these studies are outside the scope of the review and do not always improve overall resilience (Baca et al. 2021; Thompson and Pescaroli 2023). Similarly, enhancing the resilience of an entire electrical grid can enhance the electricity resilience of communities (Hughes et al. 2021). This review focuses on community level interventions, as they may offer specific advantages from grid-wide solutions due to their scalability and ability to meet community contexts, such as the existence of residential photovoltaic generation (Gholami et al. 2016). Other small-scale electricity systems in military installations (Kashem et al. 2018) and academic centers (Muqeet et al. 2021) may mirror some of the technical and socioeconomic research at the community level (Gholami et al. 2016), which deserves further attention. Nonetheless, a comparative analysis is outside the scope of this work.

2.1.3 Other terms

This review's use of several auxiliary terms also should be clarified. Electrical disruptions and blackouts refer to partial or complete loss of electricity for electricity consumers (Disaster Risk Reduction UNDRR 2020). Many researchers use the terms "electricity" and "energy" interchangeably. We consider electricity resilience as distinguished from energy resilience, as energy resilience can include energy generation sources, such gravitational and thermal, which are not converted into electricity (Gatto and Drago 2020; Tiwari et al. 2022).Financing refers to the process of generating sufficient funds to pay for electricity resilience (typically upfront or in a discrete period), while funding refers to the act of paying for electricity resilience, typically over a longer period of time (United Nations Development Group 2018). In combination, these terms address how people pay for electricity resilience. Financing will be used as a shorthand to refer to both terms.

2.2 Rationale for countries and the time period of selection

The G7 countries were selected for a combination of financial, governance, and technical reasons. From a financial and governance perspective, studies focused on the G7 contain many cases of formal power-sharing agreements and other contractual arrangements for study (Brummer 2018; Wagner et al. 2021). From a technical perspective, research on G7 countries often face similar challenges with designing and implementing electricity resilience for local communities within existing electrical grids, at least electricity distribution networks (Chen et al. 2020; Mola et al. 2018).

Although the development of localized systems of electricity generation, transmission, and distribution long predate the twenty-first century, the review is constrained to from September 2001–March 2023, due to the importance of technology the development of electricity resilience for local communities. As demonstrated in the technical review, technological advancements during this period facilitated the advent of more localized electricity sharing during disruptions, particularly contractual models of distribution (Barker et al. 2001; Dwivedi et al. 2022). This period also marks a general expansion in research attention to communities from the perspective of resilience, which was propelled in part from terrorist attacks like September 11th, 2001, and was driven by increasing understanding that resilience could address the fragility of systems to natural and human-induced threats (Coaffee 2016).

2.3 Approach

Three research databases were used to explore the subject: Google Scholar®, Scopus®, The Institute of Electrical and Electronics Engineers (IEEE) xplore®. Google Scholar was selected due to the size of its search engine (Gusenbauer 2019). Google Scholar queries provide a broad range of published sources with some academic relevance in addition to peer-reviewed publications, such as conference briefings, posters, and other grey literature ("grey literature" used in this case to refer to published materials from established organizations that are not subject to academic peer review). Scopus compliments the expansiveness of Google Scholar's search engine with narrower focus on peer-reviewed studies, as Scopus has an established reputation of providing some of the best peer-reviewed academic results for scientific and social science queries (Norris and Oppenheim 2007; Zhu and Liu 2020). The IEEE xplore database was selected as it contains grey literature relevant to the topics of electricity resilience for local communities in addition to relevant academic studies, particularly on microgrids.

Recognizing that word selection and spelling can influence research results, this review conducted several different variations of search terms to minimize the impact of word choice on the bias of the results (Lune and Berg 2017). A list of research themes, along with relevant search terms is outlined in the appendix. All databases were both queried for the same search terms. Google Scholar was queried with the both the “review articles” filter and no filter to capture a more comprehensive range of studies including grey literature. Scopus was queried using the “article title, abstract, keywords” filter. Both databases’ default relevance filters were used, in addition to sorting by date from September 2001–July 2023 for every query. A summary review of grey literature was generated using the same keywords (Table A1 in the appendix) on the IEEE xplore database and Google Scholar (no filter), with a focus on working papers and conference papers. All research was conducted in English and only English-language results were analyzed. As previously identified, many papers in the field use the term energy as a direct substitute for electricity, which explains why energy was also queried.

Each search query produced hundreds to thousands of results. Journal and article titles were reviewed to determine relevance. Most of the queried results were not directly relevant to the study or focused on technical applications only. These technical studies included mostly engineering disciplines and some computer science studies related to the application of smart technologies for electric grids. Phrases that indicated themes outside the scope of the paper, including specific sectors like “gas” or “healthcare,” or more technical journals were not considered. Abstracts and keywords for potentially relevant articles were reviewed, with particular attention to words or phrases related to “electricity resilience,” “resilience, power outages/disruptions” and community elements like “consumers, prosumers, users, community.” Articles with relevant abstracts and keywords were reviewed fully. References of the fully reviewed articles were also analyzed systematically for additional sources.

The technical and socio-economic review sections were organized into categories of research after analyzing the literature that had been collected. This approach aligns with one of the five methods in Wurman’s (1989) approach to organizing data, which has been replicated in subsequent research (Kumar and Priyadarsini 2022). Organizing information by category during and after data collection also may avoid minimizing information—previous research in this case—which does not align with categories established at the beginning of the research (Stemler 2001).

2.4 Limitations

The review’s methodology contains several limitations that may bias its conclusions (Grant and Booth 2009). Its focus on formalized arrangements and technologically advanced countries may bias its conclusion that most studies on electricity resilience for local communities do not consider adaptation, as a reliance on adaptation may be more present in informal arrangements or in arrangements with minimal technological automation (Rateau and Jaglin 2022). Informal sharing among electricity consumers, such as linking electrical wires and meters from structure to structure, deserves further as an electricity resilience strategy but were not considered in this analysis since informal arrangements are more difficult to capture outside survey data and may not always improve electricity resilience (Rateau and Jaglin 2022). A focus on G7 countries may overlook opportunities for comparison across similar countries and global regions, countries at different economic and technical baselines of development, or areas within other countries that have similar economic and technical baselines to the G7 (Jiménez-Estévez et al. 2017; Sharma and Sood 2022; Ferguson et al. 2000). This review also assumes certain conditions about current technical limitations for electricity resilience for local communities as derived from existing literature, such as limits on systems’ ability to deliver power over longer disruption periods.

The selection of key terms and language use adds other limitations. Selecting different definitions of terms for study, particularly “electricity resilience” and “local communities” may change aspects of the discussion section. Selecting a different focus for the role of community members or governing bodies in the financing or operation of electricity resilience also could bias the review and the discussion section, depending on the focus. The use of English queries only could have impacted the availability of local and regional documentation in some countries.

3 Technical overview of electricity systems for local communities

This review classifies technical interventions by their impact on the generation, transmission, or distribution of electricity. Generation refers the conversion of energy into electricity, traditionally from centralized generation sources, like power plants, or from smaller power sources, including portable generators. Very few centralized generation systems fulfill the definitional criteria of electricity resilience for local communities, and therefore were eliminated from this overview (Mola et al. 2018). Transmission refers to the transfer of electricity from generation sources, usually over longer distances and high voltages. Distribution refers to the final phase of electricity consumption, as voltages are lowered to usable levels and dispersed to consumers (Energy Information Administration 2022).

The technical inventions also were evaluated on how easily community members could own or operate the technical assets, given the review's focus on the relationship of community members to its own electricity resilience.

Operation of electricity assets refers to community members who are selected to operate local assets because of their location. Ownership refers to the partial or complete ownership of an electricity asset by a community member or community members collectively.

3.1 Transmission & distribution systems

Academic research on transmission and distribution for electricity resilience for local communities seems to be more limited (Mishra et al. 2020), which Mishra et al. (2020) suggest is due to their limited use in smaller-scale systems, particularly transmission, while Cain et al. (2013) note that some communities are opposed to transmission lines altogether. Distribution and transmission system resilience are addressed jointly in this section. A review of technical literature on transmission and distribution systems suggests that hardening and islanding are two technical interventions that can strengthen electricity resilience for local communities. Technical research on hardening and islanding seems limited compared to distributed generation studies. Additionally, hardening and islanding research at the community level often presuppose the existence of distributed generation (Liu et al. 2020a, b; Wang et al. 2019; Jahdi and Lai 2011).

The first resilient intervention considered, "hardening," seeks to strengthen physical assets of transmission and distribution systems, like telephone poles and substations, to withstand natural hazards and some human-induced events (Mishra et al. 2020). The relocation of physical assets can be considered a hardening action. Relocation encompasses moving and burying these physical assets ("undergrounding"), such as moving a transmission station out of a known floodplain or burying electrical wires to reduce their exposure to hurricane winds (Jufri et al. 2019; Salman et al. 2015). Yuan et al. (2016) have demonstrated that interventions to distribution systems have received comparably less research attention to transmission interventions, which they suggest may result of the complexity of modeling distribution systems compared to transmission systems. Despite the technical differences between transmission and distribution, governance and financial barriers may explain a lack of scholarly attention with transmission and distribution systems.

The few studies that focus on hardening electricity assets at the level of communities seem to assume the existence of distributed generation within the models (Liu et al. 2020a, b; Wang et al. 2019), which reinforces the prominence of distributed generation in technical discussions of electricity resilience for local communities. Results from a recent literature review of electricity resilience tools for communities indicates that all tools that addressed hardening in their models situated hardening interventions within models that necessitated some form of distributed generation (Wang et al. 2019). Subsequent research in this area also has highlighted the importance of hardening strategies within distributed generation systems (Liu et al. 2020a, b).

The other applicable technical community resilient intervention apart from hardening, often termed "islanding," presupposes the existence of distributed generation. Islanding refers to the ability of a subsection of the grid to remove itself from any reliance on a larger electrical grid during an electricity disruption event. This definition of islanding does not include unplanned islanding, which occurs when distributed energy sources continue to produce energy for the grid without any physical separation from the grid. Unplanned islanding can prove hazardous for repair crews working to restore power lines and can damage physical aspects of the electrical system (Jahdi and Lai 2011). Resilient islanding involves a planned separation of a subsection of the grid from the rest of the grid during a power disruption. The separation of the subsection of the grid assumes the existence of distributed generation since alternative generation sources are required to maintain electricity continuity in the subsection of the grid during a disruption (Jahdi and Lai 2011).

3.2 Distributed generation systems

Most of the technical interventions relevant to electricity resilience for local communities can be classified as type of distributed generation, also referred to as distributed generation resources (DER), which is reflected by the volume and range of scholarly attention to the topic. Distributed generation often uses the same transmission and distribution systems as centralized generation sources. Academic and grey literature most commonly refers a discrete system of distributed generation sources as a microgrid (Lasseter and Paigi 2004). The relative physical proximity of distributed generation sources to their point of use inherently locates distributed generation systems within a bounded geographic area, making them more applicable to electricity resilience for local communities.

Much of the research on distributed generation has integrated multiple electricity conversion processes and inputs (Gomes et al. 2020; Rajashekara 2005). A review of technical literature reveals that all the energy conversion processes and energy inputs (Table A2 in the appendix) were considered to some degree by the early to mid-2000s (Zareipour et al. 2004). Lasseter et al.'s work (2002, 2004) on these systems was an early contribution that considered how these systems could integrate into larger grids. Discussions of these systems' ability to function during a disruption event received secondary focus within some of these earlier studies (Shapiro et al. 2005). Some of the early research also considered the use of distributed generation as a backup to critical facilities within communities, like hospitals (Klein et al. 2005). These research areas have continued to the present (Siritoglou et al. 2021).

The technical composition of distributed generation interventions also makes many of these interventions more accessible for communities and community members, which is critical for their direct involvement in resilient electricity systems. Electricity consumers, including community members and community entities, who produce energy via distributed generation sources are often called "prosumers" (Siritoglou et al. 2021). The modular nature of distributed generation, which allows prosumers to "integrate" their distributed generation source within existing distribution and transmission infrastructure, has facilitated the creation of additional monetary incentives for distributed generation ownership (Gibbs 2022).

Advancements in technology seem to have helped advance the size and scope of academic interest in distributed generation as a resilient measure for communities. A comprehensive review of technical advancements in distributed generation is outside the scope of this review; however, advancements in battery and digital technologies seem to have played a leading role in developing some of the more recent technical areas of focus in distributed generation and resilience (Manzetti and Mariasiu 2015; Poullikkas 2013). Significant improvements in electrical battery storage technologies have enabled models and empirical studies to demonstrate the multiutility of batteries as an independent storage measure, as a multipurpose technology (e.g., V2G), and as a key component of a multisource distributed generation system (Amrouche et al. 2016). Batteries have enhanced the feasibility of renewable distributed generation sources to serve as resilient measures during electricity disruptions (Moore et al. 2020). Although renewable technologies have improved over the last two decades, battery technology advancements mitigated critical issue facing some of the most prominent renewable distributed sources—photovoltaics and wind—which could not guarantee a continuous supply of energy during disruption events (Kwasinski et al. 2012).

3.3 Electricity system management

Technological advancements in electricity system management seems to have received increased research attention to improve electricity resilience from the demand side; however, much of this research includes or necessitates distributed generation sources or technologies (e.g., islanding). Technological developments in sectors including communications, sensing and detection, and data processing have enhanced the speed and complexity of managing electrical systems (Tuballa and Abundo 2016; Norouzi et al. 2022). Researchers have noted that these applications would benefit from some refinement, yet current digital improvements have produced improvements for electricity management and electricity supply during power disruption events (Chen et al. 2020). Paterakis et al. cite (2017) advancements in communications technology as particularly critical for system management.

Technological advances seem to have facilitated the use of demand-side response mechanisms to improve electricity resilience at the community level. Paterakis et al.'s (2017) classification of demand response initiatives into four categories—energy efficiency, savings, self-production, and load management—are helpful to distinguish which types of demand response initiatives apply more readily to electricity resilience, which in this case are self-production and load management. Paterakis et al.'s (2017) use of the term self-production seems to refer to distributed generation, where "self" refers to individual electricity consumers or other entities at the distribution level. Their use of the term overlaps significantly with studies on distributed generation but may be distinguished by its focus on optimizing electricity delivery across the system during routine and disruption events from the demand side, particularly regarding how to price electricity, rather than a focus on the generation source or aspects of the supply side (Erdinc et al. 2015; N. Liu et al. 2017). Load management studies provide an avenue for electricity resilience by mitigating against load shedding events and improving the speed of restoration times (Hafiz et al. 2019). Like self-generation studies, load management studies can be distinguished from distributed generation sources by their focus on optimizing electricity management from the demand side (Paterakis et al. 2017). These studies at the community level often seem to include technical components of distributed generation, particularly when focusing on unplanned changes in load management (Kostková et al. 2013) and improving restoration times (Hafiz et al. 2019). Islanding, for example, seems to play a significant role as a precursor to improve restoration times (Shittu and Santos 2021).

To conclude, technical studies on electricity resilience for local communities reveals that most electricity resilience interventions can be classified as distributed generation or include some form of distributed generation. Technical aspects of distributed generation seem to make these interventions more easily applicable local communities, such as their physical proximity to electricity customers and their relative ease to integrate into existing transmission and distribution networks, which makes them more financially accessible for ownership and operation. These and other factors may explain the comparatively large size and scope of research attention to the intersection of distributed generation and resilience.

4 Conditions for financing & funding electricity resilience in local communities across the G7

Academic studies related to funding electricity resilience for local communities can be categorized the three research areas, which are outlined below:

1. How governance has shaped the landscape of ownership, generation, transmission, and distribution by focusing on similarities and differences across G7 countries. We develop a profile overview for each country to understand commonalities and differences.
2. The costs and benefits of electricity resilience for local communities, which are foundational to investment decisions. Research in this area is organized by technical intervention since most studies focus on one technical intervention.
3. How existing business models on energy communities can categorize financing electricity resilience for local communities. These models highlight differences in how the community and community members develop goals and finance electricity resilience.

4.1 Governance

Governance plays a significant role in shaping financing electricity resilience for local communities, which merits its inclusion in this review. This review uses the International Energy Agency's definition of governance as a "combination of legislative frameworks and funding mechanisms, institutional arrangements, and co-ordination mechanisms, which work together to support implementation of [electricity] strategies, policies and programmes." (Jollands et al. 2009). In the case of this review, "governance" focuses on ownership and operation of these assets, incentives provided by public institutions to encourage development at the community level, and regulatory or policy challenges.

4.1.1 Ownership and operation of electricity assets at the national level

This section discusses government ownership of electricity generation and transmission assets within each G7 country. The analysis outlines ownership in each G7 country broadly finding that a combination of decentralization and public ownership seems to increase the likelihood for direct community involvement. Given its focus on comparing ownership at the national and international levels, this analysis does not seek to be detailed at the sub-national levels for any country.

4.1.1.1 Canada Canada's national ownership of electricity assets is very minimal. Most of the electricity grid ownership and co-ordination of transmission in Canada has been administered sub-nationally, with most of the administration concentrated at the provincial level in Canada's case. Several Canadian provinces participate in trans-national transmission organizations with regions in the U.S. Many Canadian provinces own the main energy company in the province, which can include electricity generation, transmission, and distribution. Several provinces sought to liberalize and move away from provincial-dominated ownership in the 1990s, with varying degrees of success. Currently, most provinces remain dominated by a single public or private company, with other provinces, most prominently Ontario, are characterized by competition between smaller market competitors (Froschauer 2011; Kufeoglu et al. 2018; Roark et al. 2005; Trebilcock and Hrab 2006).

4.1.1.2 France Since the end of the Second World War, France's electricity grid from generation to distribution has been largely centralized at the national level with a few notable exceptions, such as a recent rise in community energy projects. Transmission is coordinated by a single entity. The country has attempted a slow-moving process of decentralization over the last several years (Biancardi et al. 2021; Mignon and Rüdinger 2016; Poppe and Cauret 1997; Poupeau 2020; Sebi and Vernay 2020).

4.1.1.3 Germany Unlike other European countries in this analysis, West Germany did not nationalize its electricity infrastructure following the second World War. Germany's involvement in the EU eventually led to liberalizing market reforms that promoted more centralization by the rise of larger commercial energy companies. In more recent years, German electricity governance has moved again toward a smaller, and more localized forms of electricity ownership. Ownership and operation of transmission is coordinated by four regionally located entities. As of this writing, Germany has one of the most municipally centric grids of the G7 countries (Becker 2017; Hall et al. 2016).

4.1.1.4 Italy Italy nationalized its electric grid several years after the U.K. and France, authorizing a single company the responsibility to transmit, and distribute electricity. Like many other European countries in this analysis, the Italian electrical grid began a process of liberalization and privatization in the 1990s, which was led by EU directives. The Italian electricity grid has since opened to private market competition, which has resulted in an increased proliferation of smaller and more localized grid players in the last several years. Nonetheless, state owned enterprises remain the dominant players in most of the Italian electricity grid, with a single entity responsible for coordinating most of the transmission (Biancardi et al. 2021; Di Silvestre et al. 2021; Goldstein 2003; Kufeoglu et al. 2018).

4.1.1.5 Japan Japan has a long history of nationalization of its electrical grid, which predated the Second World War. Japan engaged later than other G7 countries with market restructuring efforts in last two decades and began a more rapid decentralization process in the last decade. These efforts were complemented by restructuring the co-ordination of transmission operations. Some researchers attribute Japan's more recent restructuring to energy security and climate change considerations. Although the country has begun to decentralize, which is reflected in an increase of smaller electricity projects, most of its grid is not owned by municipalities or small communities, but larger private companies with connections to the Japanese state (Asano 2006; Ichinosawa et al. 2016; Kostková et al. 2013; Wagner et al. 2021).

4.1.1.6 United Kingdom Like other European countries in this analysis, the U.K. nationalized much of its electrical grid infrastructure following the end of the Second World War. The U.K. began a more rapid decentralization of its electricity grid in the late 1990s, which has shifted ownership of the electricity grid to several large, regionally focused corporations. Similarly, bulk transmission is regulated by regional entities. Some authors have argued that this is a form of centralization (Hall et al. 2016; Tabors 1996).

4.1.1.7 United States Electricity grid ownership in the U.S. adheres to a similar pattern of development as Canada, with a patchwork of sub-national private and public ownership. Operationally, much of the centralized generation and transmission is regulated by independent system operators and geographically larger regional transmission organizations, which transmit energy across the U.S. and several provinces in Canada. In terms of customers served, most of the U.S. energy grid is owned privately. Like Germany, however, much of the rural areas in the U.S. are categorized by electricity cooperatives, with many of these cooperatives owned at the municipal level (Boylan 2016; Kufeoglu et al. 2018; Roark et al. 2005).

4.1.2 Governance incentives

Academic studies at the intersection of governance and financing seem to focus on incentivizing electricity resilience for local communities through direct financing and funding mechanisms from government bodies (Hesse et al. 2017; Zamuda and Ressler 2020) or the creation of regulatory and policy mechanisms to incentivize finance for these systems (Cook et al. 2018; Stroink et al. 2022). Despite their variance across geographic areas and time, all G7 countries share a combination of these incentives, which have informed research on electricity resilience for local communities.

Monetary incentives seem to be one of the more common governance incentives for financing electricity resilience for local communities explored in academic literature, either in the form of direct funding and financing or indirectly through other renumeration schemes. As one study of U.S. federal programs suggests, intervention in the form of government financing and funding may be particularly impactful to help develop electricity resilience in low-income communities (Zamuda and Ressler 2020). Economic incentives from governments have shaped research parameters, which is evidenced by a study in Germany that included the impact of a subsidy program for residential battery generators in its backup battery cost model (Hesse et al. 2017). A recent rise economic incentives for microgrids, from prizes to direct investment via grants across G7 countries may offer opportunities to harness this funding for resilience, although much of the funding is focused primarily on promoting a transition to renewable energy sources (Ali et al. 2017; Curtain et al. 2018; Marnay et al. 2008; Sanz et al. 2014). Researchers have commented that the U.S. has focused more money explicitly for community microgrid resilience than other countries, including the G7 countries (Hesse et al. 2017).

Governance also can create incentives by changing regulations and policies, which can change market conditions to favor electricity resilience for local communities. Cook et al. (2018) have shown how changes in policies and regulations have begun to make markets in several U.S. states more amenable to microgrid development, including development at the community level. G7 countries in the EU, for instance, have enacted policies to enable citizen energy communities to distribute electricity across international borders (European Union 2019). Some of these studies explored how electricity distribution regulation could be leveraged to strengthen communities against power outages (Stroink et al. 2022).

4.1.3 Governance challenges

A robust segment of governance literature has highlighted legal and regulatory obstacles facing the financing and implementation of electricity resilience projects for local communities across the G7 countries (Brummer 2018; Koirala et al. 2016). The scope of obstacles can vary by country, sometimes sub-nationally, and by project. Much of the literature for the G7 countries focusing on challenges shares common obstacles to varying degrees, particularly regulatory and policy barriers regarding the generation of electricity (Burch 2010; Cook et al. 2018; Ropenus and Skytte 2005), barriers on the distribution of electricity (Arghandeh et al. 2014; Hirsch et al. 2018; Kosowatz 2015), and a general distrust of electricity governance from electricity consumers and citizen groups (Bauwens 2017; Brummer 2018).

As Ropenus and Skytte indicate in their early review of countries including the U.K., France, Germany, and Italy, current market regulations on smaller distributed system operations may limit their competitiveness (Ropenus and Skytte 2005). Although Burch's (2010) research focuses on electricity resilience for Canadian communities regarding climate change exclusively, her observation that outdated, and occasionally conflicting, regulatory policies created confusion about which resilience measures a community could enact seems to apply to electricity resilience for local communities more broadly (Burch 2010; Cook et al. 2018). Haji Bashi et al. (2023) note some of the difficulties that German and other European communities face to understand and adhere to the patchwork of regulatory and policy frameworks that are the baseline to participate in electricity resilience.

How countries govern electricity sharing within communities also seems to have shaped the development of resilient electricity interventions across these countries. The U.S.'s patchwork of regulations governing the distribution of electricity varies widely, from minimal regulation on who can receive electricity to requiring permission from a local municipal authority, which directly impacts a project's feasibility (Hirsch et al. 2018). Arghandeh et al. (2014) have argued that regulations on the use of distributed generation following a fault or other disruption event may unintentionally cause greater strain on distribution systems. In more extreme cases of regulatory intervention, regulations on transmission or distribution utilities can preclude these utilities from financing any generation sources, including smaller and more localized generation (Kosowatz 2015). Some communities in the U.S. are beginning to surmount some of these barriers by using Community Choice Aggregation (CCA) across several states, which depending on stipulations at the state level, allow communities to share purchase and generate their own sources of power (Jones et al. 2017).

Research like Brummer (2018) suggests that some of these types of regulatory governance challenges may be the result of deliberate collusion between larger players to exclude community level involvement in countries like the U.S. and Germany. Other studies similarly highlight the tension between ownership and control of operators and owners of large generation and transmission systems and ownership and operation of smaller-scale systems at the distribution level, which is due to competing economic or other strategic interests (Gui and MacGill 2018; Haji Bashi et al. 2023).

To conclude, despite a rise in decentralization across several G7 countries at the national level, the prevalence of some forms of governance incentives, which vary across G7 countries, the existence of governance challenges at the national level seem to continue to hinder uptake of resilience for electricity systems at the community level, irrespective of whether these challenges result from misalignment or interference. All G7 countries have experienced an increase in smaller and more localized energy projects, which can be partially attributed to broad changes ownership at the national level and the rise of financial and other incentives. Applying a national lens to the general trends of ownership and operation at the community level may belie a standard of ownership and operation across communities at the national level that does not often exist. Instead, communities are often shaped by a patchwork of more localized regulation and potential conflicting interests across energy operators and providers, (Gui and MacGill 2018; Haji Bashi et al. 2023).

4.2 Costs and benefits of electricity resilience for local communities

Much of the literature evaluating costs and benefits of electricity resilience for local communities overlaps with technical research on electricity resilience for local communities, as researchers have analyzed technical components of system performance as the basis for cost and benefit models (Wu et al. 2020). Not all research that evaluates the costs and benefits of electricity resilience in local communities considers these costs and benefits within a traditional cost–benefit framework, as defined in monetary terms by Brent (2006), but much of this research quantifies costs and benefits in monetary terms to some degree.

4.2.1 Transmission and distribution

Research on the costs and benefits of strengthening for transmission and distribution systems for communities seems very limited, with a substantial amount of the literature concentrating on grid-wide initiatives (Hughes et al. 2021; Späth and Scolobig 2017), which may be attributed to electricity grid ownership outlined in the previous section on governance (4.1.1). Fenrick and Getachew's (2012) analysis of undergrounding electrical power lines, which include smaller community energy cooperatives in the analysis, is an exception to this observation. Academic literature that includes some resilience cost calculations by community, such as Hughes et al.'s (2021) community fragility curves, examines community members' (residents and leaders) desire for electricity resilience to high-impact events in the aftermath of Superstorm Sandy within broader grid-wide initiatives but does not consider community members' economic, social, or political input in their model, which is similar to Kong et al.'s approach (2019). This observation extends to Späth and Scolobig's (2017) research, which includes community members' participation in distribution and transmission improvements but assumes that the resilient initiatives ultimately would be executed by large, centralized utilities.

Despite the differences between transmission and distribution systems, communities seem to face similar financial limitations in terms of investing in the resilience of transmission and distribution assets, which may explain why academic research on this topic has been limited. The heightened cost of hardening physical assets in transmission and distribution systems, which produces an extended return on investment, can make these initiatives prohibitively costly for some communities (EPRI 2016; Salman et al. 2015). Some research also suggests that distributed generation offers more opportunities for monetization and, by extension, renumeration for capital and operation expenditures of a resilient intervention (Di Matteo and Agostinelli 2022).

4.2.2 Distributed generation and electricity system management

Much of the cost–benefit research on distributed generation has emphasized costs, which may be due to the difficulties representing the benefits of resilient interventions monetarily (Gilmore et al. 2010; Pfeiffer 2021; Pudjianto et al. 2005). Academic and grey literature related to the development of new microgrid systems, for instance, highlights the financial barriers to explain the limited uptake of publicly funded community microgrids (Pfeiffer 2021). Early analyses, such as Pudjianto et al.'s (2005) investigation of several European countries including the U.K., emphasizes the capital costs of resilience measures for distributed generation. Cost-centric optimization modeling remains prominent in more recent research (Masrur et al. 2021; Wu et al. 2020). Much of this scholarship seeks to minimize the capital and operational costs of resilient distributed generation, such as recent study of EV microgrid integration in Japan (Masrur et al. 2022). A focus on costs may explain the comparatively large amount of research focused on distributed generation in the U.S., given its comparative advantages from a cost perspective (Kelly-Pitou et al. 2017). In the G7, the financial barrier to purchase a distributed generation asset typically begins from a price floor of several hundred USD/kWh and scales upward depending on the size of the system (Gilmore et al. 2010; Mallapragada et al. 2020). As some studies have shown, the use of existing electrical vehicles as backup sources of electricity (vehicle-to-grid or V2G research) could require even less capital cost (Kempton and Tomić, 2005).

Some cost studies incorporate or optimize other factors that are key to electricity resilience for local communities, such as planning and information sharing, as evidenced by a recent model applied to Canada (Quashie et al. 2018). Much of this research examines these aspects technically, such as planning optimal installation locations and loads for resilient grids (Paliwal et al. 2014; Twitchell et al. 2020). Technical studies on demand-side response initiatives have incorporated community planning and other resilience measures from communities (Hafiz et al. 2019), particularly how to using pricing to inform consumer behavior during high loads or disruptions (Paterakis et al. 2017). Some of the research that examines community preparedness and willingness to pay to minimize power disruption events does not also consider technical aspects of power systems (Baik et al. 2020). Di Matteo and Agostinelli's (2022) recent study of electricity resilience for communities in Italy is a notable exception for its inclusion community participation in costing; however, their work chiefly seeks to address the transition to renewable energy sources and offers minimal discussion to involving community preparation for power disruption events. Bohman et al.'s (2022) recent study of the northeast U.S. seems to offer one of the only strategies that incorporates community preparedness and technical system components into a strategic cost–benefit analysis.

Research that incorporates benefits more prominently in the analysis is divided on the efficacy of using distributed generation for resilience. Some of the research on benefits seeks to calculate benefits in terms of the revenue generated from these systems. Several recent studies conclude that the benefit of resilient distributed generation outweighs the costs (Barker et al. 2001; Dwivedi et al. 2022). Conversely, a recent U.S.-centric model found that the resilient microgrids could not generate sufficient revenue to cover their costs (Wu and Sansavini 2021). Differences in the evaluation of cost-effectiveness of resilient distributed generation partially can be attributed to the difficulty and variability of measuring costs and benefits, which deserves further attention (Stadler et al. 2016). A recent model focusing on the southeast U.S. emphasizes the difficulties of evaluating benefits of electricity resilience due to the uncertainty in valuing opportunity costs of power disruption (Anderson et al. 2020). Research on community members' willingness to pay for electricity resilience may provide an avenue to close the gap in valuing the benefits of resilient distributed generation systems (Baik et al. 2020).

Results from this section indicate that much of the cost–benefit research on electricity resilience for local communities often centers on costs more than benefits. This may in part be due to the difficulties of translating additional benefits from resilience measures to the electrical system into monetary terms, which some recent work has begun to address (Anderson et al. 2020). A focus on cost may help explain the emphasis that this research places on distributed generation, which tends to be more modular and could be more cost effective for communities depending on changes to capital and operational costs (Bell and Gill 2018). More work is needed to understand the role of community willingness to pay as a factor in cost–benefit analyses for electricity resilience for local communities.

4.3 Business models for electricity resilience for local communities

This category of study explores how financing and other business models incentivize community members or key community entities to distribute electricity to other community members or critical lifelines, like hospitals, during disruptions. Academic literature relevant to this subsection is derived chiefly from a broader branch of literature on energy and electricity sharing among communities, which has introduced a range of financing and other business models to categorize electricity sharing over the last several years (Krithika and Palit 2012; Reis et al. 2021). Business models for electricity resilience in local communities can be divided into two subcategories described by Reis et al. (2021), as we combine Reis et al.'s customer-side and community energy business models into a single community electricity business model. In the community electricity business model, community members and citizen groups invest in small-scale systems for local communities, exercising ownership regarding how to use the asset for resilience (Gui et al. 2017). The model also includes individual prosumers if they trade energy within an established business agreement. The "third-party side" model is distinguished by the direct involvement of an entity outside the community that shares direct ownership and operational responsibility of a resilient community electricity asset (Reis et al. 2021).

4.3.1 Community electricity business models

According to Reis et al. (2021), community electricity business models are characterized by the primary ownership and decision-making of electricity resilience assets by community governing bodies and citizen groups. A prominent segment of this research seems to focus on municipalities that own their own generation sources, including microgrid systems (Dudka et al. 2023; Vanadzina et al. 2019; Wagner et al. 2021). Many of these models seek to reduce the high capital costs and some operational costs of resilient electrical interventions, which overlaps literature that measures the costs and benefits of electricity resilience for local communities. Dudka et al.'s (2023) analysis of business models in France apply to resilient distributed generation systems, as they suggest that full citizen ownership of community electricity systems may allow these projects to avoid large discrepancies in goals between citizens and a for-profit third party. They also suggest crowd-funding financing to cover the capital costs of the investment. Like research on France, however, much of the scholarly attention on funding and financing for German and Italian electricity cooperatives or other municipal bodies has not defined resilience as a way to address power disruptions but rather an opportunity to reduce emissions (Brummer 2018). Community Choice Aggregations (CCAs) in the U.S. may provide an avenue for electricity resilience by providing local communities more control over electricity resources, including purchasing and generating their own power. Nonetheless, much of the current research on CCAs as of this writing suggests that their abilities to provide resilience to electricity disruptions remains limited or nascent (Bartling 2018; Deng and Rotman 2023; Jones et al. 2017). Research using Japanese communities as case studies are limited (Wagner et al. 2021). Nonetheless, research teams like Hoppe et al. (2015) demonstrate how German communities financed resilient electricity projects as part of a larger goal for energy independence.

Other models have engaged individual electricity consumers as sources of electricity across the community. Reis et al.'s (2021) framework would consider individuals as part of a consumer model, but this review argues that electricity sharing arrangements among community members and critical facilities during power disruptions constitute a community energy initiative, particularly when considering power-sharing agreements made ex-ante to a disruption event. Financial arrangements like peer-to-peer (P2P) trading offer prosumers compensation for selling power during peak demand for electricity, along with disruptions, although these arrangements are not without technical and regulatory challenges (Schelly et al. 2017; Spiliopoulos et al. 2022). These studies share significant overlap with some demand-side response studies focusing on the community level (Liu et al. 2017). In resilient trading models, prosumers sell electricity from their distributed generation sources to other citizens or critical facilities directly or through a centralized local regulator (Algarvio 2021; Dwivedi et al. 2022). Electricity pricing varies across these models, with some models establishing market price rates (i.e., tariffs) during outages and other models establishing ex-ante electricity prices before a disruption (Das et al. 2023). Research on a resilient microgrid in the northeast U.S. demonstrates that a mixed-price P2P model could enhance resilience. Critical community assets, like hospitals, were sold electricity at fixed rates and additional electricity was sold at variable market rates to other electricity consumers in the community (Candelise and Ruggieri 2020; Mengelkamp et al. 2018).

4.3.2 Third-party side models

The second type of model is distinguished by the direct involvement of an entity or entities outside the community that shares primary or secondary ownership or operational responsibility of a resilient electricity asset within a community. These parties can be a utility, bank, or other investor, which pays for part, or all, the capital or operational costs associated with a resilient electricity intervention, from single electricity asset or an entire microgrid. In return for covering some of the costs of the resilience intervention, the third party retains partial ownership of the asset or system, which can extend to controlling of electricity generation and distribution during disruption events (Reis et al. 2021; Vanadzina et al. 2019). Ownership and operation are the important distinctions between this model and the community models, which may receive funds or technical assistance from entities outside the community, particularly from the public sector (Curtain et al. 2018; Gui et al. 2017; Haji Bashi et al. 2023). From consumer demand and operational perspectives, electricity system management studies often seem to maintain the role of the utility as the central operator in the system, which may be due in part to the utility's role in generating, transmitting, and distributing electricity in most electricity delivery models (Erdinc et al. 2015; Hafiz et al. 2019). The third-party side model also includes third parties that pay prosumers for power during disruption events, which can be seen as a form of resilient net metering (Gibbs 2022). The relative newness of these initiatives may explain why they are infrequently addressed in academic literature. Like community electricity business models, the third party may engage community entities or individual community members. Some of the research focusing on arrangements between communities and utilities to co-finance or fund microgrids can be categorized as a form of public–private-partnership (PPP) between community governing bodies and private partners (Gharieh et al. 2015).

One of main challenges identified with third-party models is a divergence in goals between the community, which often is assumed to desire minimizing costs and maximizing services for community members, and the third-party, which often is assumed to be profit seeking (Dudka et al. 2023; Gui et al. 2017). Another significant challenge is that utilities would view third-party sharing as a threat to their traditional business model, which may disincentivize some utilities from pursuing a third-party model as an option (Nourai et al. 2010). These analyses align with national-level studies that note the tension between utility and other larger players' desire for control of energy ownership and operation with community ownership and control at the distribution level (Gui and MacGill 2018; Haji Bashi et al. 2023).

Despite potential conflicts of interest between third parties and communities, this model may offer advantages over the community electricity business model. Research and the proliferation third-party models, particularly microgrids, have increased in several of the G7 countries over the last several years, including the United States and Canada (Asmus and Lawrence 2016a, b; Vanadzina et al. 2019). Vanadzina et al. (2019) account for this increase by suggesting that third-party models can help cover capital and operational costs resilient systems. In their observation, third-party models often are executed in areas with high levels of institutional trust, which may serve as a buffer against potential differences in goals. A review of third-party models between individual prosumers and utilities highlights similar characteristics (Schoenung et al. 2017). Third parties also can help lower the technical barriers to entry. Asmus and Lawrence's (2016a, b) summary of utility owned microgrid business models also seems to highlight utilities' suitability as a third-party due to their technical expertise in generating and delivering power compared to community members.

In sum, Reis et al.'s model (2021) seems to apply well to the two types of ownership between communities and other parties. Comparing the general use cases of the two models suggests that communities pursue the third-party ownership model to account for the regulatory, technical, and other costs of resilient interventions. An examination of the authors' use of the term "community" does not suggest the same division across the two business models as the role of an entity outside the community, which demonstrates a range of potential avenues for communities. Nor does a trend seem to exist across G7 countries (Table 1). With this said, however, some of the specific types of research (e.g., P2P trading) included more standardized uses of the term. The category individual electricity "consumers and prosumers" received among the most attention, which may be due to its importance in much of the electricity trading literature (Schelly et al. 2017; Spiliopoulos et al. 2022). Many uses of the term "citizen" seemed to differ from electricity consumers by inclusion of all people within a particular political area (Brummer 2018; Dudka et al. 2023; Reis et al. 2021), not only consumers as measured by the number of electricity meters (e.g., households). References to a particular "community group" varied widely. Most of this research did not distinguish explicitly if these community groups were preexisting entities within the community that could be leveraged to serve electricity interests for the community. Nonetheless, terms like "councils" (Haji Bashi et al. 2023; Reis et al. 2021) and "government authorities" (Gharieh et al. 2015) suggest that some of this research advocates for the

Table 1 Focus for the term "community" in research related to business models

General category	Research
Individual electricity consumers (also households), which includes prosumers	Algarvio (2021)*; Asmus and Lawrence (2016a, b); Candelise and Ruggieri (2020); Das et al. (2023); Dudka et al. (2023), Dwivdei et al. (2022); Erdinc et al. (2015); Gibbs (2022); Gui and MacGill (2018); Gui et al. (2017); Hafiz et al. (2019); Haji Bashi et al. (2023); Mengelkamp et al. (2018); Liu et al. (2017); Nourai et al. (2010); Reis et al. (2021); Schelly et al. (2017); Schoenung et al. (2017); Spiliopoulos et al. (2022); Vanadizina et al. (2019)
Citizens	· Algarvio (2021)*; Brummer (2018); Dudka et al. (2023); Reis et al. (2021) · *"Society at large"*—Asmus and Lawrence (2016a, b)
Community group	· *"Citizen councils"*—Algarvio (2021) · *"Citizen groups"*– Reis et al. (2021) · *"Citizen organizations"*—Gui and MacGill (2018) · *"City councils"*—Haji Bashi et al. (2023) · *"Community aggregators"*– Reis et al. (2021) · *"Community choice aggregators"*—Bartling (2018); Deng and Rotman (2023); Jones et al. (2017) · *"Cooperative"*—Dudka et al. (2023); Das et al. (2023); Gui and MacGill (2018); Haji Bashi et al. (2023); Reis et al. (2021); Vanadzina et al. (2019) · "*Council*"—Reis et al. (2021) · *"Government entity"* or *"government agency"*—Gharieh et al. (2015) · *"Local authority"*—Wagner et al. (2021)
Vehicles	Erdinc et al. (2015); Haji Bashi et al. (2023)

*Algarvio 2021 seems to use "electricity consumers" and "citizens" interchangeably

use of existing community entities, the term's use did not seem to be consistent across.

5 Discussion

Research on financing and funding of electricity resilience for local communities has increased for G7 countries over the period studied. The review reveals two factors that shape financing and funding of electricity resilience across the three socio-economic review areas studied, which inform the relationship financing and funding to the theoretical definition of electricity resilience. Firstly, the costs of increasing the resilience of electricity systems—including technical and knowledge costs—are a barrier that shapes much of academic research on financing and funding electricity resilience at the local level. Secondly, much of the research focuses on the community as an electricity asset owner or key stakeholder in the planning process, which may explain why the community plays a significant role in shaping the resilience goals for some of this research.

When compared to broader definitions of electricity resilience, this field's use of electricity resilience generally has overlooked the role of adaptation as a way to improve resilience over time. We find that the difficulty of monetizing adaptation (costs) and the role of community (community involvement) may explain reasons why the field has focused on implementation in the short run rather than adaptation in the long run. Continued advancements on the technical frontier may help surmount some of these obstacles in terms of cost and community involvement; however, more work is needed currently to study existing community initiatives over time (Table 2).

5.1 Centrality of costs in electricity resilience for local communities

Much of the technical and socio-economic research on financing the resilience of small-scale electricity systems has sought to address the costs of electricity resilience in local communities (Kelly-Pitou et al. 2017; Masrur et al. 2022; Vanadzina et al. 2019; Wu et al. 2020), which extends beyond the cost–benefit research area (4.2). Resilience interventions for electrical systems are costly to finance and fund, which is due in part to the cost of the technical components of the intervention and the knowledge to operate and maintain these systems. A review of costs reveals opportunities to integrate socio-economic research on governance, cost–benefit, and business models more fully and demonstrates the importance of technical research as a frontier for all these research areas.

5.1.1 Technical costs

Research on governance, cost-benefits, business models have sought to reduce the technical costs of resilient electricity interventions at the community level; however, more work

Table 2 Impact of research focus and key findings on the discussion section

Research focus		
Focus 1: Factors that shape the financing and funding of electricity resilience across research		
Focus 2: Comparison of the field to a theoretical definition of electricity resilience		
Review sections	Key findings	Key sources
Technical overview	· Distributed generation resources are among the most common technical measures implemented at the community level due to the comparative ease of integrating with electricity consumers and smaller comparative footprint from a technical and potential cost perspectives · Technological advancements have been critical in accelerating praxis-based and academic research, particularly for distribution generation and electricity system management	Amrouche et al. (2016) Hafiz et al. (2019) Jahdi and Lai (2011) Mishra et al. (2020) Paterakis et al. (2017) Siritoglou et al. (2021)
Socio-economic review	· Despite increased decentralization across G7 countries, communities face a complex and interconnected system of regulations and incentives at the level of governance that hinder the uptake of electricity resilience · Cost–benefit research faces difficulty measuring benefits particularly compared to measuring costs, which has divided the literature on the efficacy of focusing on electricity resilience at the community level · Some of the business models, particularly third-party business models, seem to be structured to minimize regulatory burdens and associated technical and knowledge costs with these systems · There is no discernable trend between the research's use of the term "community," which indicates a range of potential avenues for communities	Asmus and Lawrence (2016a, b) Dudka et al. (2023) Haji Bashi et al. (2023) Masrur et al. (2022) Reis et al. (2021) Vanadzina et al. (2019)
Discussion subsections		
Research focus 1	· The centrality of costs across much of the research highlights gaps between literature technical and socio-economic review that may benefit from further integration · The level of community involvement in electricity system resilience can inform the system's resilience goals, which highlights the importance of community context and which may deviate from other financing partners' goals	Asmus and Lawrence (2016a, b) Dudka et al. (2023) Masrur et al. (2022) Vanadzina et al. (2019)
Research focus 2	· There is a gap in studying adaptation in financing over the long run, which may be due to the to the centrality of costs and the role of community involvement in some of the research. Technical advancements may help advance research on longer-run adaptation	Amrouche et al. (2016) Asmus and Lawrence (2016a, b) Reis et al. (2021) Vanadzina et al. (2019)

is needed to offset costs by capturing benefits and streamlining government interventions. Research has improved understandings of how to reduce monetary costs of technical components through improved system design (Masrur et al. 2022) and by reducing the number or cost of technical components used (Moore et al. 2020). The technical approach used by much of this research may explain the field's focus on distributed generation, which offers many opportunities for optimization on design and components used (Kelly-Pitou et al. 2017).

More work is needed to measure the benefits of improving electricity resilience as a way to offset technical costs, particularly in monetary terms (Anderson et al. 2020). Incorporating other elements related to resilience, such as emergency planning of these systems, with these technical studies may offer an avenue to begin to capture additional benefits (Quashie et al. 2018). Integrating technical and other studies more fully with studies on governance incentives may also help defray offset costs to the community since many of these governance studies seek to encourage finance via direct and indirect subsidization (Zamuda and Ressler 2020). Business models have begun to capture the benefits of existing patterns local consumer behavior by establishing formal mechanisms that encourage electricity consumers to share energy with other community members during disruption events (Candelise and Ruggieri 2020). Many of these studies are relatively recent and benefit from technical innovation that is emerging or has recently become more accessible to electricity consumers in some areas (Schelly et al. 2017).

5.1.2 Knowledge costs

From a community perspective, electricity resilience can be cost-prohibitive due to knowledge gaps across all aspects of system development, from initial design to end-of-life decisions (Vanadzina et al. 2019). Some recent technical research has provided additional clarity on resilient design options for electricity systems for community contexts (Mishra et al. 2020). Other research has focused on options for operation and some maintenance for these systems (Jahdi and Lai 2011). Conducting technical research on resilient electricity systems that address all aspects of system development may help reduce knowledge costs, but it remains to be seen whether this research will help reduce knowledge costs from the perspective of local communities.

Technical and socio-economic research areas have examined knowledge costs differently, which highlights opportunities for these research areas to learn from one another. Some cost–benefit analyses have not counted technical expertise as a cost for communities, since much of the cost–benefit literature uses technical approaches and presupposes a level of knowledge in electricity systems and resilience (Wu et al. 2020). This also may explain the gap between the technical expertise required for electricity resilience at the community level and communities' limited implementation of electricity resilience. The gap in the technical research does not explain why much of the governance research has not focused on addressing knowledge gaps in electricity resilience from a community perspective in terms of capacity building, which governance research seems to have done to some degree with related community initiatives like preparedness (Gerber and Robinson 2009). Governance studies have accounted more for other costs related to community knowledge of electricity resilience, such as specific legal, policy, or other mechanisms that may limit the uptake of electricity resilience (Arghandeh et al. 2014). Business models, by contrast, have accounted for community knowledge more explicitly by focusing on systems that require less community knowledge in electricity resilience (Algarvio 2021) or by encouraging third parties with expertise in electricity systems, resilience, or both assume most of these costs (Asmus and Lawrence 2016a, b).

5.2 Levels of community involvement in shaping resilience goals

A review of the literature suggests that research that has involved the community explicitly has focused on the community as owners or key stakeholders in the planning process. This focus on the role of the community as an owner or stakeholder seems to inform what some research has considered as a resilience goal, which varies widely and may be contingent on research focus or community context. A resilience goal refers to an improvement in the system that reduces the frequency or severity of disruptions.

5.2.1 Avenues for community involvement

Much of the research has focused on community members as owners an electricity asset and or key stakeholders in the planning process. A review of governance literature, for example, suggests that ownership of electricity generation assets by a community body (Dudka et al. 2023) or individual members (Mengelkamp et al. 2018) seems to be among the most common avenues for community involvement. Historical community ownership of electricity systems may have shaped the proliferation of electricity resilience at the community level (Hall et al. 2016; Kufeoglu et al. 2018). Research on business models has reinforced this role of community involvement by focusing on near complete ownership of electricity generation assets (Dudka et al. 2023; Schelly et al. 2017), with the community electricity business model, or partial ownership, with a third-party model (Asmus and Lawrence 2016a, b; Vanadzina et al. 2019). Some business models and the cost–benefit research involve communities in the overall vision and planning of resilience assets as stakeholders, even if they may not own the assets outright (Asmus and Lawrence 2016a, b). A focus on planning and ownership may be due lack of community knowledge of the operation, maintenance, and other key functions of electricity systems (Vanadzina et al. 2019; Sect. 5.1). Irrespective of the reason for this focus, a focus on ownership and planning seems to highlight the role of the community in shaping resilience goals for the electricity system, which is addressed differently throughout the research.

5.2.2 Community resilience goals

The level of community involvement in an electricity system can reveal how community context informs electricity resilience goals. Some of the business model literature on third parties makes this observation explicit by commenting on the potential deviation between community goals (disruption mitigation) and third-party goals (profit) (Dudka et al. 2023; Gui et al. 2017). Results across governance, cost-benefits, and business model review areas (Quashie et al. 2018) show that communities can play a role in shaping specific goals within a broader umbrella of electricity resilience. One segment of the research focuses on reducing exposure to higher frequency disruptions as a goal for communities (Bohman et al. 2022), while other research has focused more on low-probability, high-impact disruptions (Twitchell et al. 2020). A substantial number of studies also included a focus on complementary goals like emissions reductions (Di Matteo and Agostinelli 2022) or the use of a specific technology as a key facet of electricity resilience (Dudka et al. 2023). The variation in resilience goals also suggests that financing resilience at the community level may be contingent on specific community desires for resilience, sustainability, or other goals, perceived or otherwise (Gupta et al. 2019). Other studies included a combination of these goals (Dwivedi et al. 2022). Other literature, particularly technical studies, do not consider community goals (Amrouche et al. 2016). Many of these studies minimize the role of community entities or community members in electricity system resilience (Mishra et al. 2020).

Some of the literature also suggests that entities outside the community may influence community goals in some instances, which may indicate the prominent role that these entities play in financing electricity resilience at the community level. Much of the literature has highlighted a common range of challenges that communities face, including costs (Anderson et al. 2020; Vanadzina et al. 2019) and governance hurdles from the public and private sector (Brummer 2018; Haji Bashi et al. 2023). These challenges may help explain the popularity of the third-party model by communities, given the difficulties often communities face to own operate electricity assets (Nourai et al. 2010), let alone financing resilience measures. Although some research has highlighted potential conflicts of interest between communities and third parties (Dudka et al. 2023; Nourai et al. 2010), more work is needed to understand how third parties inform community resilience goals during the process of financing, where communities and third parties may be required to negotiate and synthesize goals. The influence of outside entities extends beyond third-party ownership and operation of electricity assets within the community, as funding from public agencies, which constitute a substantial part of the financial incentives for communities, may include other related goals (Ali et al. 2017; Curtain et al. 2018; Marnay et al. 2008; Sanz et al. 2014). Examining community goals prior to the financing process may help shed light on the impact of outside entities in shaping community resilience.

5.3 Short-term implementation of technical solutions over long-term adaptation

Much of the research on financing local electricity resilience against disruptions has not addressed the role of adaptation (some examples: Gilmore et al. 2010; Pfeiffer 2021; Barker et al. 2001; Vanadzina et al. 2019), which seems to feature in some of the theoretical research on electricity resilience (Roege et al. 2014; Schweikert and Deinert 2021; Plotnek and Slay 2021). Adaptation to electricity disruptions is not the only sub-concept of resilience that remains comparative understudied in this literature, but it deserves attention because it may provide an avenue to understand the impact of costs and community on this field's understandings of resilience. Adaptation in this case refers to how communities alter technical, organizational, or other components in their electricity systems by anticipating future changes and disruptions (*ex-ante*) and by learning from past disruptions (*ex-post*) to be better prepared in the future (Roege et al. 2014).

5.3.1 Difficulties monetizing adaptative behaviors over time against upfront costs

The difficulties of monetizing the benefits of adaptive behaviors into business models and investments may limit research attention on financing adaptation within electricity systems, particularly in the long run. Much of the literature on cost–benefit analyses in electricity resilience for local communities seems to support this assertion, as these studies focus on aspects of electricity resilience are easier to monetize, particularly costs (Barker et al. 2001). Additional research on costs avoided may help monetize adaptive behaviors (Stadler et al. 2016), as would research on community willingness to pay for electricity resilience over time (Baik et al. 2020). Bolstering research to capture benefits of these systems also presents an avenue to offset some costs, which some commentators have noted as a problem endemic to critical infrastructure resilience more broadly (Flynn 2015). Researchers focusing on third-party business models may wish to incorporate the impact of electricity resilience interventions at the community level on grid-wide benefits, such as black start allocations to recover aspects of the grid (Patsakis et al. 2018) and frequency regulation (Razavi et al. 2019; Schoenung et al. 2017), depending on the technical capabilities of the system (Razavi et al. 2019).

Monetizing adaptation over time may conflict with the field's general approach to view financing electricity resilience as a single upfront decision, or a collection of upfront decisions, with long-term consequences. The standard models for financing electricity resilience assume high capital costs of investment that are paid back incrementally (Dudka et al. 2023; Vanadzina et al. 2019; Wagner et al. 2021), which are not unique to financing electricity resilience but typical for electricity investment more generally (Hallegatte et al. 2019). A focus on investment with longer return periods also may be driven by the lifespan of the electricity assets, which can be years or decades (Hallegatte et al. 2019). The model seems to leave little room for adaptation, as communities and their partners are called to make significant investments in a resilience measure during a discrete point in time and bear the consequences of investment over a longer period. Commentators who have focused on infrastructure resilience more broadly have noted a similar trend also have suggested to incorporate investments that are more modifiable over time to account for this challenge (Alderson 2019), which this review has posited to be a potential benefit of distributed generation. The consequence of the model seems to have disincentivized studying the results of the investment or opportunities for financing over a longer period. More work is needed to understand how communities have adapted or have been incentivized to adapt over longer periods of time, such as years and decades, particularly considering the lifespan of infrastructure projects.

5.3.2 Community agency in adaptation

A review of research from the perspective of the community also highlights reasons for limited attention in the current research. Some governance research suggests that adaptation from the perspective of a community presupposes a level of community trust and interest in electricity resilience, which may be limited in many instances across communities in the G7 (Bauwens 2017). Emphasizing the importance of adaptation for research that includes communities seems to assign more responsibility to community members to understand and exercise the technical and economic components of their resilient electricity system (Quashie et al. 2018).A rise in community member ownership and some operation of assets, particularly distributed generation (Reis et al. 2021; Sect. 4.3), presents a case to study the limitations and opportunities of community involvement in electricity resilience at the local level.

5.3.3 Technical frontiers

Technical advancements in distributed generation may help move research on financing toward longer-run adaptation. Repurposing assets like resilient electric vehicles, or assets with diminishing capital cost, like backup batteries, which may present an opportunity to study iterative change in communities by reducing upfront investment required (Kempton and Tomić, 2005; Moore et al. 2020). Technical improvements in resilient electrical systems may reduce operating costs and extend asset lifespans, which presents an opportunity for future research to explore possibilities of leveraging smaller and cheaper assets to promote learning and improvement in electricity business models for communities (Amrouche et al. 2016). These advancements could minimize the emphasis on upfront costs of single investments, leaving open the possibility of studying investments in resilience as a longer-run strategy with opportunities to learn from and adapt to future uncertainties.

Despite their benefits from a cost perspective, increasing the complexity of technical components may perpetuate limited academic attention to community agency in electricity resilience into the future, at least outside the community's current role in ownership and planning (Moore et al. 2020). This may not necessarily limit electricity resilience overall, since current research suggests that the costs of educating the community on other aspects beyond ownership and planning may outweigh their benefits (Asmus and Lawrence 2016a, b; Schoenung et al. 2017). If this continues to be the case, it is likely that how researchers included communities in electricity resilience, particularly in adaptation, will continue to be refined.

6 Conclusion

Our review of the state-of-the-art across G7 countries revealed two factors that inform the financing and funding resilience of smaller-scale electricity systems at the local community level: (1) the centrality of costs and need to capture additional benefits and (2) the community's involvement in the ownership and planning of electricity resilience. Although these outcomes may appear intuitive, they seem to inform how field approaches the term "electricity resilience" compared to more standard definitions of the term—namely that the role of adaptation, particularly over the long run, generally is absent or not completely integrated in financing research. We find that the field's focus on costs and involvement of the community may have limited adaptation over time by focusing a short-run investment (costs) or limiting it altogether by assuming minimal community capabilities or interest (community involvement).

Continued advancements in technical research may offer avenues to encourage adaptation over time by reducing capital costs and by allowing assets to be repurposed, which may help refine the role of the community in focusing on adaptation over time. Nonetheless, more work is needed to integrate current technical work with socio-economic studies to understand how modular systems like distributed generation have enabled communities to adapt over time. The current maturity of the field, with origins and early examples dating to at least two decades (Kempton and Tomić, 2005), suggests that case studies and other data exist to understand the role of adaptation in electricity resilience at the local level. To this end, Alderson (2019) asserts that case studies that demonstrate good practices of resilience deserve further attention for study.

Appendix

The search terms (Table A1) are meant to serve as a shorthand for the terms that were queried across the research databases and are not the exact phrases entered into each database. For instance, "resilience for electricity/energy generation/transmission/distribution in communities/municipalities/localities" is a shorthand for more than five different queries.

Table A2 contains an overview of energy conversion processes and energy inputs in the literature on systems at the community level. Most systems incorporate a range of these technologies.

Table A1 Search terms by section

Tab	Search terms
Section 3. Technical overview of resilience for smaller electricity systems	General · Resilience for electricity/energy generation/transmission/distribution in communities/municipalities/localities Transmission/distribution · Strengthening/improving/[blank] transmission/distribution of electricity/energy in communities/municipalities/localities · Hardening/undergrounding electricity in communities/municipalities/localities Distributed generation · Distributed generation for communities/ municipalities//localities [blank] · Resilient distributed generation for communities/municipalities/ localities/[blank] · Resilient microgrids for communities/municipalities/localities/[blank] · Peer to peer electricity trading · P2P trading · Vehicle to grid Electricity system management · Demand-side/[blank] response for electricity/energy resilience/[blank] · Load management for electricity/energy resilience/[blank] · Optimization of electricity/energy system for electricity/energy resilience/[blank] in communities/households/[blank] · Peer to peer electricity trading · P2P trading
Section 4. Reviewing the conditions for financing & funding electricity resilience in G7 local communities	General · "All terms below" + in G7 countries/all country names/[blank] · Financing/funding electricity/energy/[blank] resilience for/in local/municipal/[blank] communities/municipalities/localities Governance · Governance of electricity/energy/[blank] resilience for/in local/municipal/[blank] communities/municipalities/localities · Electricity/energy/[blank] resilience for/in governance/regulation/ policies/incentives/barriers local/municipal/[blank] communities/municipalities/localities Costs and benefits · Costs/Benefits of electricity/energy resilience for/in governance/regulation/policies/incentives/barriers local/municipal/[blank] communities/municipalities/localities · Cost–benefit/benefit–cost analysis for electricity/energy/[blank] resilience in communities/localities/municipalities Business models · Business models of electricity/energy/[blank] resilience for/in local/municipal/[blank] communities/municipalities/localities · Electricity/energy/[blank] resilience business models for/in local/municipal/[blank] communities/municipalities/localities

Table A2 Overview of technical electricity system components

Electricity component	Technical interventions	
Transmission/distribution	Hardening assets Resilient islanding of distribution (typically for distributed generation)	
Distributed generation	*Electricity conversion process*	*Energy input*
	Combustion	(bio) Gasoline
		Diesel
	Energy storage	Batteries
		Fuel Cells
		Hydrogen gas
	Photovoltaic	Solar
	(micro)Turbine	Wind
		Hydroelectric
		(bio)Gasoline
		Diesel

*Not fully comprehensive

**Does not include electricity system management technologies, given the volume of technologies

Author contributions DT conducted most of research for the literature review and wrote the main manuscript text. GP refined the scope of the review, provided additional research for consideration to frame the review, and provided guidance to further align the research question and methodology with the results and discussion sections. All authors reviewed the manuscript.

Declarations

Competing interests The authors declare no competing interests.

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