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Focus on community energy and infrastructure resilience

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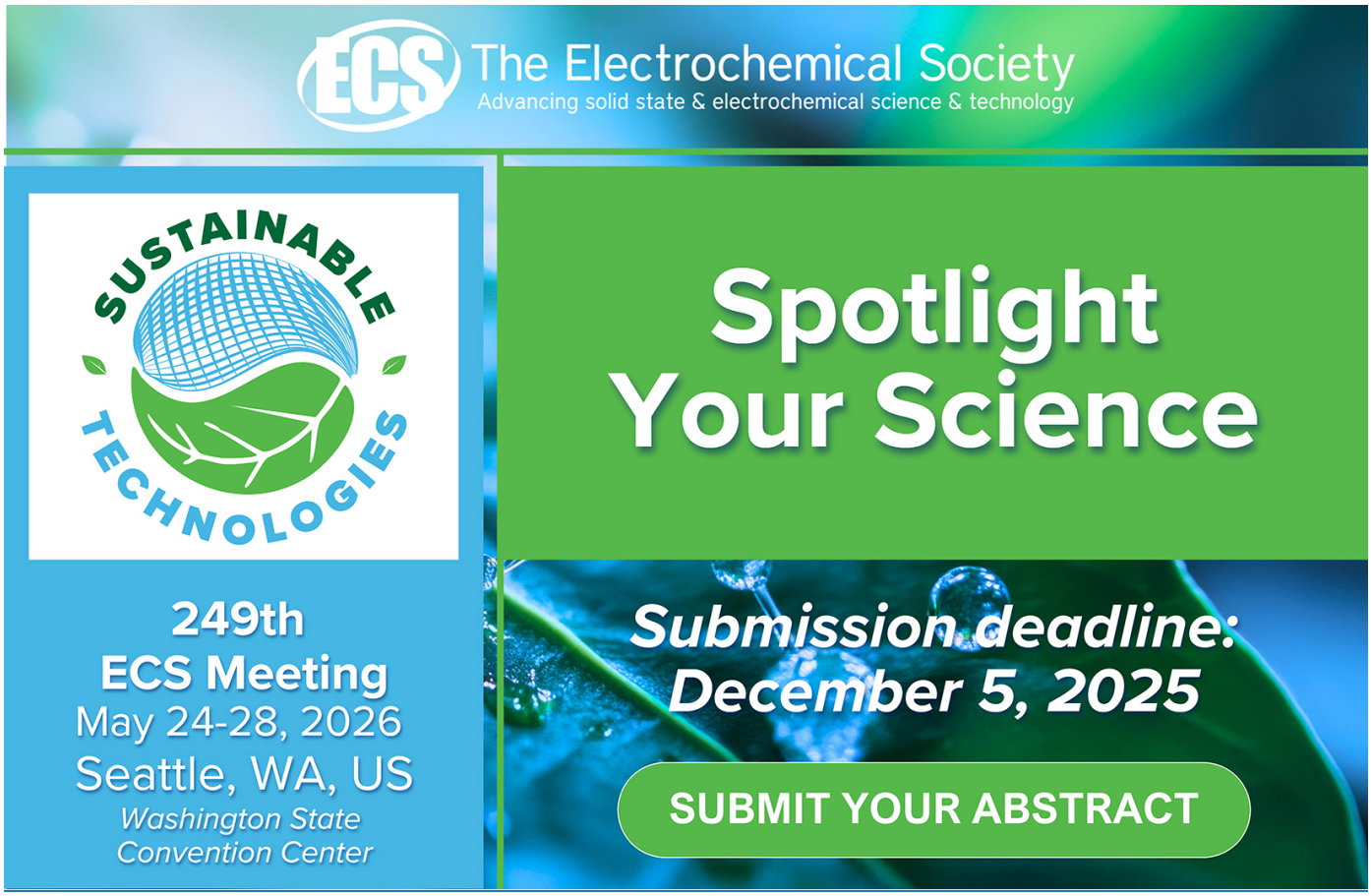

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EDITORIAL

Focus on community energy and infrastructure resilience

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Abstract

This focus issue on *community energy and infrastructure resilience* compiles six contribution that seek to put into context projects that aim to put people at the core of energy development. The promises of community energy are multifold, from facilitating the democratization of energy systems to allowing for the development of decentralized and off-grid networks, which may accelerate the adoption of renewables. However, community energy also faces challenges. In this case, the special issue focused on challenges related to infrastructure resilience, whether they are linked to building resilience in community energy projects or to the contributions that community energy projects make to advance sustainability transitions. This focus issue makes five key thematic contributions: the importance of community engagement in building resilience, analytical tools to understand the multi-dimensional nature of infrastructure resilience, the need to incorporate place-based concerns into policy, the development of tools to evaluate different aspects of resilience, and the explicit consideration of gender equality and social inclusion to facilitate project sustainability.

1. Introduction

The global energy landscape is undergoing a profound transformation, driven by the urgency to decarbonize energy systems, enhance resilience, and ensure equitable access to clean energy. These goals are especially critical in regions with large deficits in energy access compounded with climate vulnerability, weak infrastructure, and socio-economic marginalization [1, 2]. Community energy systems (CESs) have emerged as pivotal in addressing these challenges. By leveraging decentralized renewable energy technologies such as solar mini-grids, biomass, micro-hydropower and peer-to-peer (P2P) energy trading, CESs offer flexible, context-specific solutions governed by the communities they serve [3, 4]. Community-led action is essential for addressing uneven vulnerabilities helping design equitable energy projects that reach the most marginalized.

Community energy can foster a global transition to sustainable energy systems, but the particularities of each geographical location will shape the transition and its impacts. In locations with 100% grid coverage, such as most countries in Europe and North America, community energy is often integrated with other ecological experiments that aim to redefine living practices in response to the ongoing global environmental crisis [5]. In contrast, concerns with energy access take precedence in locations with large electrification and fuel deficits. For example, in Sub-Saharan Africa, over 600 million people lack access to electricity, despite the continent's vast solar potential [6]. Innovative business models, such as pay-as-you-go solar home systems and energy-as-a-service platforms, have begun to fill this gap, empowering millions with clean energy [7]. In South Asia, decentralized renewable energy has similarly transformed off-grid communities, offering enhanced livelihood opportunities and improved health and education outcomes [8]. Community energy holds unique potential to foster both resilience and equity, whether

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this is through providing basic needs, supporting local development visions, or challenging the spatial constitution of racial and class differences.

This focus issue of *community energy and infrastructure resilience* presents pioneering studies that explore the multifaceted roles of CESs in advancing development, equity, and resilience. The contributions offer empirically grounded insights into the design, governance, and socio-technical performance of CES models across diverse geographies. The collection underscores the need for inclusive, context-specific, and socio-technically integrated approaches to infrastructure planning and community energy transitions, that start from the perspectives of community members. A key message emerging from the insights of the collection is the need to consider community energy and resilience in tandem.

2. Community energy

Community energy encompasses energy projects and initiatives that are owned, developed, or controlled by local communities or groups of citizens, aiming to deliver a range of local benefits such as reducing environmental impacts, providing socio-economic benefits such as reductions in household bills or improving social cohesion [9, 10]. Community energy projects adopt a bottom-up approach to energy supply and use by putting people at the center of critical management and operational decisions. Community energy often takes advantage of the opportunity to deliver off-grid infrastructure and develop decentralized systems that enable citizens to take control of the project's governance at different stages, from design and construction to day-to-day maintenance [11]. At the same time, community energy projects facilitate the adoption of renewable technologies such as solar and wind generation, and partially renewable resources (renewable when managed sustainably) such as biomass combustion and small-scale hydropower. The scope of community energy spans various models including cooperatives, community trusts, nonprofit organizations, and partnerships with local authorities or private entities. These models typically prioritize local ownership and democratic control, with profits often reinvested back in the community or used to lower energy costs, increasing access opportunities [12]. Community energy can thus address issues of energy poverty, especially in rural and underserved areas, and enhance public trust in renewable energy developments [13].

However, community energy faces complex contradictions. First, there are questions about the distribution and reach of community energy projects, which may compare unfavorably with large-scale projects in terms of economic performance. Community energy proponents often argue for the recognition of a wide range of social and environmental benefits, alongside economic ones. Still, a central concern remains that many community energy projects are not economically sustainable and depend on grants. Second, identifying and constituting a community as the locus of the project, is not easy. For example, in general, residents in a deprived area may have easier access to management structures than in larger-scale networks, particularly when they rely on partnerships with local institutions, such as local governments. Community energy can thus be deployed to target socioeconomic inequities. However, communities are not immune to structural forms of discrimination such as sexism, racism or ableism. Small community organizations may lack institutional structures to limit the impact of such forms of discrimination, which may exacerbate these impacts. Third, community energy projects are vulnerable to ongoing environmental or economic shocks and often lack sufficient material and human resources to cope with these shocks.

Community energy enhances energy resilience by diversifying supply sources and embedding energy infrastructure within local contexts. The transformation of technological systems and the diversification of energy governance institutions suggest that community energy could play a crucial role in a post-networked, sustainable energy transition [14, 15]. Thus, a range of options to build resilience into community energy have been proposed, whether this is developing appropriate tariff systems, providing direct policy support and grants, developing localized community energy strategies, or building local government partnerships [16, 17]. Resilience is a multi-dimensional characteristic of complex system that depends on technoeconomic factors, but also social and institutional ones. Thus, infrastructure resilience cannot be understood in isolation but in relation to a wide range of factors that determine the success and sustainability of community energy projects.

3. Infrastructure resilience

Infrastructure resilience refers to the ability of infrastructure networks to anticipate, absorb, adapt to, and rapidly recover from disruptions. Resilience is not only technical, but also socioeconomic and institutional. Gaining resilience within the material aspects of infrastructure and its management institutions also increases social resilience. For example, when communities gain access to new sources of energy,

they increase their capacity to withstand and adapt to shocks such as extreme weather events, grid failures, or economic crises [18, 19]. In addition, distributed generation technologies reduce communities' dependency on centralized infrastructure and long transmission lines, which are vulnerable to climate-induced hazards [20]. Key resilience benefits of community energy include the localization of generation, which enables adapting the project to the local terrain, the generation of redundancies in the energy supply, and the diversification of energy resources.

In community energy projects, the emphasis on energy democracy and local governance enables quicker and context-specific responses to crises, through direct involvement of local knowledges. For example, a detailed understanding of the terrain may provide community energy managers with the know-how to reconfigure systems during emergencies and prioritize power supply to critical services such as hospitals, shelters, and communication hubs. The participatory nature of community energy also builds social capital and institutional capacity, increasing the range of people who can actively respond during an ongoing crisis. Community engagement in energy planning and ownership can strengthen trust, enhance preparedness, and foster collective action during disruptions [21].

The contributions to this focus issue explore the multidimensional notion of infrastructure resilience and situate it in various contexts where community energy projects emerge. In the first article of the collection, Raghoo and Shah [22] provide a timely and comprehensive review of the emerging landscape of P2P energy trading, a technological advancement which reconfigures traditional energy hierarchies by enabling prosumers to exchange electricity within decentralized networks. Drawing on operational cases such as Power Ledger (Australia), SOLShare (Bangladesh), and Brooklyn Microgrid (USA), the authors illustrate how P2P markets can enhance energy access, reliability, and consumer agency [12, 23]. Overall, the authors advocate a human-centered approach to infrastructure resilience, highlighting the importance of non-economic forces in sustaining P2P arrangements and the need to go beyond profit maximization as an overall goal.

The second article, by Gebreslassie *et al* [24], investigates the feasibility of jatropha-based biodiesel as a renewable energy alternative in rural Ethiopia, which could facilitate the rapid development of low-cost community energy systems. Combining field surveys, policy analysis, and HOMER-based system modeling, the study finds that jatropha holds promise for off-grid applications due to its adaptability to arid conditions and minimal competition with food production. Yet, the use of jatropha is fraught with contradictions, not least the lack of familiarity with the crop and the potential to displace food crops that are critical to local communities and cultures. The study recommends further research and experimentation, both in pilot projects and integrated policy frameworks, to address the potential challenges of biofuel strategies in achieving rural development and energy sovereignty goals.

In the third article, Khalid *et al* [25] assess over 500 micro-hydropower projects (MHPPs) in Khyber Pakhtunkhwa, Pakistan, to understand what constitutes resilience in fragile and conflict-prone contexts. The study presents a wealth of empirical materials, including site surveys, participatory observations, and stakeholder interviews. The insights of this analysis are not always encouraging. More than 150 MHPPs in this study had failed due to top-down implementation, poor technical design, and lack of post-installation support. To address these challenges, the study proposes a justice-centered approach to infrastructure resilience, emphasizing procedural equity (inclusive decision-making), distributive equity (fair benefit distribution), and the recognition of marginalized voices. Local governance was a means to challenge gender-based discrimination, and advanced models of community ownership led to more resilient projects.

In the fourth article, Sifuentes *et al* [26] present a modeling framework called the equity-climate-optimization of community energy to optimize the allocation of community solar investments across low-income geographies in Washington State, USA. A key objective of the paper is to dissolve the racial divisions that create inequalities in electricity affordability. The model balances three objectives: maximizing household electricity bill savings, minimizing greenhouse gas emissions, and ensuring geographical equity. In particular, the model helps elucidate the trade-offs between maximizing clean energy production and achieving equity outcomes, thus showing how economic optimization also plays a role in delivering energy justice.

The fifth article, by Eales *et al* [27], introduces a Key Performance Indicator (KPI) framework to evaluate the multi-dimensional aspects of infrastructure resilience including measures beyond traditional metrics of technoeconomic performance[9]. For example, the framework emphasizes dimensions such as gender equity and community well-being. The application of the framework in a solar minigrid in rural Malawi shows that the project has delivered strong technical reliability, as well as education and gender equality outcomes. At the same time, the framework also confirms the persistence of economic challenges due to low demand stimulation and tariff inflexibility.

The final article, from Vallecha *et al* [28], explores CESs through a resilience-oriented framework that transcends conventional infrastructural assessments. Drawing on empirical cases in Malawi and Ethiopia, the study evaluates CESs in terms of five forms of community capital: social, human, physical, natural, and economic. The authors propose a resilient community energy system model that encapsulates seven dimensions of resilience, including adaptability, inclusiveness, and learning capacity. The study shows that technological robustness, a traditional measure of infrastructure resilience, is insufficient to ensure CES longevity. Instead, successful projects depend on community participation, skills training, and trust-building for their sustainability.

4. Synthesis and cross-cutting insights of contributions

An analysis of the six studies in this focus issue reveals several cross-cutting themes that reframe how CESs is conceptualized, evaluated, and scaled.

Community engagement as a cornerstone: CESs cannot succeed without deep and sustained community participation. From the KPI framework in Malawi [27] to MHPP governance in Pakistan [25], projects rooted in local co-production processes show higher resilience and legitimacy in enhancing sustainable energy transitions [29]. This necessitates not only participatory planning but also institutional flexibility to accommodate diverse socio-cultural contexts. All the papers contain examples showing that sustained community participation has a direct positive impact on community resilience.

Resilience beyond infrastructure: While technological reliability and robustness are useful measures of infrastructure resilience, they need to be complemented with indicators of social adaptability, institutional learning, and political inclusivity. Vallecha *et al* [28] and Khalid *et al* [25] demonstrate that social capital is indispensable for recovery from disruptions, while Sifuentes *et al* [26] argue that policy design must anticipate systemic trade-offs.

Aligning policy with ground realities: Gebreslassie *et al* [24] illustrate how ambitious national strategies can falter when divorced from local capabilities. A recurring lesson is the need for policy coherence across scales bridging top-down energy agendas with bottom-up knowledge, capacity, and demand. Collectively, the contributions highlight the potential of CESs as platforms for integrated energy, development, and resilience planning.

Expanding the evaluation Toolkit: This focus issue challenges the dominance of narrow techno-economic indicators by proposing multi-dimensional evaluation tools, proposing new frameworks such as Eales *et al*'s [27] KPI framework and the optimization model by Sifuentes *et al* [26]. These approaches allow for more comprehensive assessments that better capture CES contributions to sustainability and justice.

Centering gender and social equity: Across the studies, there is a consistent call to integrate gender-sensitive and socially inclusive design principles [30]. Khalid *et al* [25] and Eales *et al* [27] provide empirical evidence that inclusive participation enhances CES performance and community trust. Raghoo and Shah [22] further warn that without equity-centric governance, P2P systems risk replicating existing socio-economic disparities.

5. Future research directions

The research presented in this focus issue and existing research highlights the importance of an expanded notion of infrastructure resilience to move towards designs that enable community energy systems to achieve their transformative potential. There is a need for further systematic research into community energy that links the practical concerns of design and implementation to the possibility of advancing wider energy justice objectives. Most of the contributions relate to the following questions:

- **How can community energy integrate emerging technologies?** The adoption of blockchain, artificial intelligence, and internet of things technologies can enhance the efficiency, transparency, and scalability of community energy. For instance, blockchain-enabled P2P energy trading platforms can facilitate secure and decentralized energy transactions, empowering communities to manage their energy resources effectively [31, 32].
- **What policy and regulatory frameworks are appropriate?** Developing supportive policies and regulatory environments is crucial for the successful implementation and scaling of CESs [33]. This includes establishing clear guidelines for energy trading, ensuring grid compatibility, and providing incentives for community participation. Lessons can be drawn from existing models, such as the regulatory approaches adopted in Washington State for community solar investments [26].

- **What forms of capacity building enable community inclusion and empowerment to establish local forms of governance?** Empowering local communities through education, training, and participatory planning processes is essential for the sustainability of community energy. Projects that prioritize community involvement tend to exhibit greater resilience and long-term success [21].
- **What financial mechanisms can be developed to value the wider range of benefits provided by community energy?** Innovative financing models, such as pay-as-you-go systems and energy-as-a-service, can lower the barriers to entry for community energy, particularly in low-income communities. These models have been effective in expanding energy access in various regions, including parts of Africa and South Asia [34, 35].
- **What mechanisms foster cross-sectoral collaboration and sustainable partnerships?** Collaboration among governments, private sector entities, non-governmental organizations, and academic institutions can foster the exchange of knowledge, resources, and best practices, accelerating the deployment of CESs globally [36]. Further collaboration across infrastructure domains (such water and energy) and across policy domains (such as development and emergency relief) can build synergies needed to fully realize the potential for community energy and resilient infrastructures more broadly.

Future research and policy can support the development of community energy projects that are not only technologically advanced but also socially inclusive and environmentally sustainable. Such systems hold the promise of transforming energy access and resilience in communities worldwide, thereby advancing the achievement of global sustainable development goals. The extent to which community energy can deliver infrastructure resilience depends on multiple place-based factors that extend beyond techno-economic efficiency, highlighting that the main ingredient in sustainable and just energy transitions is the people who make them possible.

Data availability statement

No new data were created or analysed in this study.

Ethical statement

The research was conducted with ethics approval by the Research Ethics Committee at the University of Sheffield (reference number 033231). The research for this introduction did not involve animal experimentation or human participants.

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