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SPECIAL FEATURE: EDITORIAL

Urban Sustainability and the Governance of Heterogeneous Energy Systems

Urban sustainability and the governance of heterogeneous energy systems

Jochen Monstadt[1,2] · Kei Otsuki[2] · Shaun Smith[2]

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Abstract

This special feature brings into dialogue debates that have evolved mainly separately: scholarship on infrastructural heterogeneity in Southern cities and research on distributed and decentralized energy transitions in the North. Drawing on empirical cases from Africa, the Middle East, Asia, Europe, Australia, and North America, the contributions show that heterogeneity is no longer an exception but a defining feature of contemporary urban energy landscapes, characterized by varied technological configurations and diverse forms of (co-)provision and energy use. While acknowledging the fundamental differences between these contexts, urban energy landscapes reveal striking commonalities from which we draw key lessons: the contributions to this special feature show how heterogeneous energy systems emerge from diverse context-specific drivers, create new governance and spatial planning challenges, and are increasingly accompanied by processes of digital re-homogenization and coordination. The papers also demonstrate that heterogeneous energy systems yield uneven sustainability outcomes, raising critical questions about equity, accountability, and the distribution of costs and benefits. By moving beyond simplistic North–South binaries, this special issue advances a comparative and cross-contextual perspective on the governance of heterogeneous energy systems. Ultimately, we argue that heterogeneous energy systems have become a shared global condition whose governance requires comparative, context-sensitive approaches that explicitly confront coordination challenges, power asymmetries, and sustainability trade-offs across diverse urban settings.

Keywords Heterogeneous energy systems · Urban sustainability governance · Distributed and hybrid infrastructures · North–South comparative urbanism · Infrastructural (re-)homogenization

Introduction

The global transformations of urban energy systems are central to cities' efforts to tackle the interconnected challenges of climate mitigation and environmental sustainability, social inclusion and energy justice, and economic prosperity and competitiveness. Long predicated on the "networked city ideal" of centralized, uniform networks and standardized access to infrastructure services, dominant energy transition pathways—both in policy and scholarly discourse—have assumed the universal rollout of large-scale, grid-based systems to be the most rational and equitable solution. Until today, the ideal of the networked city (Coutard and Rutherford 2016; Monstadt and Schramm 2017) continues to underpin global sustainability agendas, which aim to ensure access to affordable, reliable, sustainable, and modern energy for all (SDG 7) and to promote sustainable cities and communities (SDG 11).

However, ideals of a universally networked city have never been achieved in many cities in the global South, where multiple energy systems overlap and are characterized by the co-existence of centralized grids with micro- and off-grid systems, public with private and user-driven modes of service provision, as well as planned and incrementally developed energy infrastructures (Jaglin 2014, 2016;

✉ Jochen Monstadt
monstadt@difu.de

Kei Otsuki
k.otsuki@uu.nl

Shaun Smith
s.r.smith@uu.nl

1 German Institute of Urban Affairs, Zimmerstraße 13-15, 10969 Berlin, Germany

2 Department of Human Geography and Spatial Planning, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, The Netherlands

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Koepke et al. 2021; Smith et al. 2022). This heterogeneity, i.e., the co-existence of diverse socio-technical arrangements of energy systems, is a key feature of the urban fabric in the global South, driven by rapid and informal urban growth, limited state capacity, and scarce financial resources to roll out or access universal grids. More recently, the focus has shifted from documenting socio-technical heterogeneity to understanding the processes through which heterogeneous energy systems interact with centralized grids and centralized service provision (Verdeil and Jaglin 2023). The authors argue that processes of hybridization do not replace the conventional grid but rather transform it into an "augmented grid," characterized by new interfaces, intermediaries, and combinations of centralized and decentralized technologies. Notwithstanding the ongoing expansion of the heterogeneity and hybridity of energy systems worldwide, this has attracted little attention in studies of energy transitions in the global North.

In this editorial, we argue that debates on heterogeneous and hybrid energy systems in the South and on decentralized and distributed systems in the North have evolved mainly in isolation from one another, despite describing strikingly convergent sociotechnical patterns of more heterogeneous, layered, and diversified urban energy landscapes. This disconnection has left a conceptual and empirical research gap, as the two strands rarely engage in dialogue or comparative theorization. This partly reflects a broader tendency in Southern urbanism debates to emphasize local specificity and particularity over generalizable mechanisms, which can inadvertently reinforce the divide between Northern and Southern theoretical trajectories (see, for a similar argument, Storper and Scott 2016; Randolph and Storper 2023). At the same time, Northern urban debates frequently neglect and marginalize Southern urban debates, and knowledge production on energy transitions remains dominated by Northern experiences.

Contributions to this special feature point to increasingly heterogeneous energy constellations in North America, Europe, and Australia (Cudd et al. 2026; Karvonen et al. 2026; Otchere-Darko et al. 2026; Pellegrino and Rupeka 2026) and their importance for urban sustainability transitions. Here, decentralization, digitalization, and diversification—amplified by geopolitical shocks, climate policy, and technological innovation—are driving equally heterogeneous energy landscapes (see also: Ajaz and Bernell 2021; Bögel et al. 2021; Karvonen and Guy 2018; Basu et al. 2019). Globally, socio-technical heterogeneity is becoming the norm rather than the exception, encompassing new assemblages of technical artefacts—such as generation, storage, and grid structures—with a diversification in service (co-)provision and governance approaches and arrangements.

Based on this empirical reality, this special feature advances the conceptual and empirical understanding of heterogeneous and hybrid energy systems and explores their implications for urban sustainability, governance, and for energy justice in variegated urban contexts. While acknowledging the fundamental differences between urban contexts, we consider it increasingly important to foster conceptual and empirical cross-fertilization and learning across diverse cases of heterogeneous infrastructure constellations, both to deepen our understanding of their dynamics and to draw lessons for governing cities towards more just and sustainable futures. We define heterogeneity not only in terms of technological diversity and multiplicity but as a broader socio-material condition shaped by diverse actor constellations, co-existing technological constellations, and multiple, sometimes competing, drivers and logics of service provision and use.

These heterogeneous socio-technical arrangements become interconnected and co-evolve, and together form hybrid energy systems, in which users combine and switch between grid and off-grid electricity, and new market participants and political alliances emerge. Crucially, the special issue shows how infrastructural heterogeneity is not only driven by localized adaptations to infrastructure gaps in the global South, or by decentralization in the global North, but by an increasingly diverse set of (overlapping) drivers including the availability of new digital technologies, disaggregated renewable supply sources, attempts to speed up energy transitions through localized energy ownership and management systems, and by other intuitional and political logics encouraging governments and energy providers to move away from monolithic energy provision models. Thus, debates on heterogeneity do not necessarily represent novel attempts to theorize infrastructural change. Rather, they encourage new comparisons across different forms of infrastructure and raise important analytical and normative questions about sustainability, governance, and justice.

The contributions assembled here reflect a deliberately interdisciplinary and transregional perspective. Drawing on empirical cases from Africa and the Middle East, Asia, Europe, Australia, and North America, the articles examine how heterogeneity is produced, governed, and contested in urban energy transitions. The contributions to this special feature are structured around five interrelated themes: First, all contributions point to the *variegated drivers* of heterogeneous energy infrastructures that emerge in response to either structural limitations to universalizing centralized networks, or to new socio-technical opportunities, such as renewable energy technologies, new digital technologies, or new forms of local management or autonomy. Second, all papers highlight the governance challenges of heterogeneous sociotechnical contexts, which necessitate navigating overlapping regulatory domains, institutional fragmentation, and contested political economies. Third, several papers emphasize the need to address spatial heterogeneity directly through situated *territorial and spatial planning approaches.* Fourth, several papers highlight emerging trends of (*re-)homogenization*, particularly in the global North, where novel digital tools and new intermediary actors aim to reintegrate fragmented energy systems. Finally, all papers illuminate both the *obstacles and openings* that heterogeneous energy systems pose for sustainable urban futures.

While this is beyond the scope of this introduction, these interrelated themes also offer an opportunity to further assess energy justice through heterogeneity. In each empirical context, the papers pose questions about how heterogeneity (re)distributes the costs and benefits of energy access, and whether the decision-making procedures for increasingly diverse energy systems are sufficiently inclusive. The papers generally show that heterogeneity can exacerbate socio-spatial inequalities and ecologically unsustainable energy practices and complicate energy governance, it also enables adaptive, locally grounded solutions. The special issue thus interrogates not only how and for what reasons energy systems have become heterogeneous, but also in whose interests or at whose expense they operate and how this heterogeneity might be governed toward more inclusive, just, resilient, and sustainable outcomes. We do so by critically rethinking simplistic North–South binaries and advancing context-sensitive comparisons alongside more sustained cross-regional dialogues.

The remainder of this introduction to the special feature is divided into five sections. First, it situates the special issue within academic debates on infrastructure heterogeneity, calling for a critical rethinking of the entrenched South–North divide that persists in studies of energy transitions. Second, it explores the forms, drivers, and frictions of both heterogenization and homogenization processes as they manifest across diverse urban and energy geographies. Third, we examine the sustainability challenges posed by these dynamics and consider how governance approaches—formal and informal, centralized and distributed—attempt to respond. Fourth, we reflect on the broader governance implications, emphasizing the evolving roles of policymakers, utilities, market actors, and citizens in navigating energy heterogeneity. Finally, the paper synthesizes the special feature's key findings and discusses their significance for reorienting academic debates on the urban governance of energy transitions.

Rethinking infrastructural heterogeneity and hybridity: beyond southern particularism?

Over the past two decades, urban energy systems worldwide have undergone a significant departure from the ideal of the "networked city" (Coutard and Rutherford 2016). Rooted in the modern infrastructural ideal (Graham and Marvin 2001), this model prioritized universal coverage, public utility companies acting as territorial monopolists and providing ubiquitous and standardized infrastructure services (or for 'public utilities'), and the belief that service efficiency increases with scale and network expansion. However, the once-hegemonic vision of a networked city has either been destabilized—materially, ideologically, and politically—by shifting political economies, infrastructural failures, or technological innovation—or has never conformed to the realities of the urban fabric in the first place.

Today, increasingly heterogeneous, decentralized, and often spatially fragmented energy constellations shape the fabric of cities across both the global North and South. These configurations are characterized by the coexistence and coproduction of diverse systems—networked and non-networked, centralized and distributed—operated by users, private providers, and public authorities alike. Rather than replacing one another, these systems overlap and interweave, adapting to localized needs, affordability constraints, technological possibilities, and distinct governance arrangements. These systems involve diverse energy sources and technologies (e.g., centralized power plants and electricity grids, diesel generators, solar PV, micro-grids, batteries) and various service (co-)providers operating simultaneously and often intertwined in specific urban configurations. Rather than temporary or transitional, heterogeneous energy systems have become enduring infrastructural assemblages, shaping and being shaped by socio-spatial inequalities, political economies, and struggles between actors (utilities, private investors, NGOs, communities) and their interests, regulatory practices, and access to finance.

Despite heterogeneous urban energy landscapes becoming a global phenomenon, scholarly literature on urban energy systems can be characterized by a persistent epistemological divide: while studies of cities in the global North often frame decentralization and distributed systems in terms of their potential for technological or socio-technical innovation, stronger user involvement, energy democracy, or the devolution of responsibilities in energy policies to local authorities (e.g., Ajaz and Bernell 2021; Anfinson et al. 2023; Bauknecht et al. 2020; Lopez 2021), debates on heterogeneous or hybrid energy infrastructures in the global South frequently emphasize the informality and improvisation involved in energy supply and access (Koepke et al.

2021; Verdeil and Jaglin 2023). This divide is not merely geographical but also conceptual. Scholars working on the South often argue for the necessity of developing distinct theoretical frameworks grounded in the unique socio-material and political contexts of postcolonial urbanism (Smith 2023; Pilo' 2023; Späth et al. 2022). While this move rightly challenges the universalism of Northern-centric theories, it can also risk exceptionalizing Southern cities and inadvertently foreclosing productive theorization across contexts. As a result, the notion of heterogeneity—although valuable—sometimes becomes a conceptual boundary marker rather than a bridge.

Scholarship on heterogeneous energy systems in cities of the global South

Building on the work of Jaglin (2014, 2016), the heterogeneity of urban energy systems and, more broadly, urban infrastructures have attracted increasing attention in urban and infrastructure studies in the global South. In many Southern cities, heterogeneous energy infrastructures have become a defining feature of urban energy landscapes—a condition that is not merely transitional or peripheral, but central to how electricity and other forms of energy materialize, are provided, accessed, governed, and experienced. Scholars such as Jaglin (2014, 2016), Lawhon et al. (2018, 2023), Koepke et al. (2021, 2023) or Smith (2023) have emphasized that these infrastructures emerge in response to a complex constellation of drivers, including rapid and unplanned urbanization outpacing infrastructure development, weak state authority, financial resource limitations, institutional fragmentation, socio-spatial inequalities and technological innovation. Rather than assuming a linear evolution toward a universally networked grid or viewing socio-technical components as evolving independently, Verdeil and Jaglin (2023) foreground heterogeneous socio-technical arrangements hybridize, become interconnected, and partly compete within the same urban space. They further show how these hybrid configurations are politically articulated through the interactions of diverse public, private, and community actors.

The concept of heterogeneity, as elaborated by Jaglin (2014) and expanded by several other authors (e.g., Lawhon et al. 2018, 2023; Koepke et al. 2021, 2023; Smith 2023; Pilo' 2023), is useful to capture this diversity. It refers to the co-existence of formal grid services, decentralized renewable systems, informal connections, backup generators, energy storage devices, and other socio-technical arrangements. Lawhon et al. (2018) describe "heterogeneous infrastructure configurations" as dynamic assemblages involving different technologies, actors, and practices, entailing distinct power relations and operational risks. These configurations are not just alternative forms of infrastructure—they are political and material expressions of how access, legitimacy, and urban citizenship are negotiated under conditions of rapid and informal urban growth, splintered infrastructure networks, limited state authority, and limited financial resources of state authorities, public utilities, and users.

Empirical studies support this claim. In Gulu Town, Uganda, Munro (2020) introduces the notion of the "urban bricoleur" to describe how residents creatively patch together energy services from grid electricity, solar panels, car batteries, and mobile charging stations. Rather than interpreting these configurations as failures, Munro argues that they reflect an alternative logic of infrastructural agency, shaped by constraints but animated by everyday ingenuity. Similarly, Pilo' (2023), drawing on fieldwork in Kingston, Jamaica, examines how diverse users—from large commercial actors to low-income households—navigate hybrid arrangements including solar panels, prepaid meters, and informal hookups. Her analysis shows that heterogeneity is not simply the absence of the grid but an active reshaping of the grid-society relationship, entailing differentiated capacities to govern and be governed by electricity infrastructure.

The unevenness of heterogeneous energy landscapes has profound social and spatial implications. As Smith (2023) illustrates in his study of Maputo, Mozambique, infrastructural heterogeneity manifests as a set of dynamic energy practices that reinforce or mitigate inequalities. He highlights how residents shift between energy sources not only for cost or reliability, but also to protect livelihoods, secure autonomy, and navigate socio-political uncertainty. Heterogeneity, in this sense, is not static but temporal, reflecting flux in material conditions, regulatory environments, and household strategies. The dynamic qualities of heterogeneity, Smith argues, should be central to how we conceptualize energy access and sustainability in postcolonial cities.

Governance responses to heterogeneity are equally diverse. Koepke et al. (2023) argue for an approach that acknowledges the coexistence and interaction among multiple governance modalities (hierarchical, market-based, networked, and managerial governance) to better capture the informal practices of service provision, neighborhood-level interventions, and unofficial actors who shape access on the ground. Rather than viewing these arrangements as threats to regulatory coherence, they can be seen as forms of everyday governance that maintain infrastructural functionality under constrained conditions. However, this also raises normative questions. As Pilo' (2023) emphasizes, heterogeneous arrangements often reflect and reproduce inequalities in negotiating power, access to technical devices, and political recognition. Governance frameworks must thus go beyond technical coordination to engage with the social justice dimensions of infrastructural diversity.

The reviewed literature converges on several shared insights: counter to framings of deficiency and developmental delay in much of the developmental discourse, recent debates frame heterogeneity not as a deviation from networked city models, but a constitutive condition of ordinary energy systems in Southern cities. Debates challenge binary classifications of formal/informal, centralized/decentralized, or state/private, but underscore instead the multiplicity of coexisting and entangled socio-technical systems that are spatially embedded, politically contested, and dynamically evolving (see also Baptista 2019). Rather than imposing uniform models of transition, effective governance must engage with this diversity—its risks, its potentials, and its inequalities. The governance of heterogeneous infrastructures requires an adaptive, reflexive approach that recognizes users' situated agency, the multiplicity of infrastructural logics, and the need for solidaristic modes of infrastructural provision. Only by embracing heterogeneity—not as a problem to be solved, but as a condition to be governed—can energy transitions be made more inclusive, equitable, and sustainable.

Scholarship on distributed energy systems in cities of the global North

Over the past two decades, a growing body of literature has investigated the emergence and governance of distributed energy systems in cities of the global North. This literature examines how urban energy systems have evolved into more decentralized forms of power and heat generation, a more differentiated landscape of energy providers, more polycentric forms of governance, and new forms of civic participation, while also grappling with systemic tensions surrounding equity, integration, and long-term sustainability. Outside Southern contexts, this heterogeneity is frequently framed as a desirable feature of sustainability transitions (e.g., Ajaz et al. 2021; Anfinson et al. 2023; Bögel et al. 2021; Skjølsvold et al. 2018).

Much of the engineering literature characterizes distributed energy systems as systems where electricity or heat is generated and stored in smaller, decentralized units closer to the point of consumption, rather than relying solely on large, centralized power plants (or, in the case of heating, on natural gas and oil) and long-distance transmission and distribution grids. These systems are often composed of decentralized energy resources, where electricity sources such as photovoltaics, wind turbines, fuel cells, or heat sources, such as residual heat, combined heat and power systems, or solar thermal energy, are combined with decentralized energy storage systems and smart grid systems (Ajaz et al. 2021). Bauknecht et al. (2020) offer a nuanced typology, distinguishing infrastructural decentralization by grid connectivity, spatial proximity of generation, demand-side flexibility, and control architectures.

However, while the engineering literature dominates debates on distributed energy systems, recent debates have emphasized the institutional, economic, and governance dimensions of these systems, which involve a wider diversity of actors beyond traditional centralized utilities and new forms of governance. This includes a broad range of decentralized energy (co-)providers, including municipal utilities and cooperatives, prosumer households (e.g., individuals or communities with rooftop solar), community energy initiatives, aggregators and energy service companies, private firms developing small-scale renewable installations, and operators of micro-grids (Bauknecht et al. 2020; Skjølsvold et al. 2018).

A combination of technological, political, and socio-economic factors has driven the transition to distributed energy systems in the global North. Key among these are climate change mitigation and energy security policies, as well as technological innovation—such as solar photovoltaics, other small-scale electricity and heat sources, mini-grids, and smart meters. Declining costs of renewable technologies (Valdivia and Balcell 2022), the rise of digital and smart technologies, commercialization and liberalization of energy markets, and normative calls for energy democracy and user-driven innovation have also played significant roles. Lopez (2021) demonstrates how aspirations for energy autonomy and disconnection from centralized grids generate diverse socio-technical configurations of energy provision, thereby illustrating the coexistence of centralized, decentralized, and self-sufficient energy arrangements.

Policy instruments such as feed-in tariffs, subsidies, and market reforms (e.g., emissions trading, liberalization) have created enabling environments, while sociopolitical movements advocating for energy democracy have fostered bottom-up engagement (van Veelen 2018; Anfinson et al. 2023). At the same time, the proliferation of local energy initiatives, community energy projects, or positive energy districts reflects a broader rethinking of energy provision as a site for local experimentation. Van Opstal et al. (2025) note increasing regulatory interest in collaborative urban governance models, highlighting the need to align distributed energy with broader sustainability transitions (e.g., circular design of energy technologies). However, urban governance models vary from municipal-led initiatives to citizen-owned cooperatives and multi-stakeholder polycentric configurations (Anfinson et al. 2023; Baldwin et al. 2018). Skjølsvold et al. (2018) highlight how households are being reconfigured as co-managers of energy, while Baldwin et al. (2018) identify the shift from centralized regulatory models to more collaborative, distributed governance arrangements.

Overall, several authors highlight that managing increasingly heterogeneous energy systems involves various governance challenges in coordinating a complex landscape of actors, infrastructures, and regulations. Key governance challenges include harmonizing technical standards, ensuring grid stability, allocating costs and benefits, and balancing local autonomy with system-wide efficiency (Bauknecht et al. 2020). While the reconfiguration of energy infrastructures can enhance local sustainability, stimulate regional economies, and foster stronger community identities, several studies show how these benefits are unevenly distributed. Anfinson et al. (2023) caution that renewable energy communities promoting distributed systems often remain limited in scale and scope, facing barriers related to regulation, funding, and grid access. Similarly, van Veelen (2018) and Grimley (2023) identify challenges of inclusivity, particularly for marginalized or resource-constrained communities. Also, Valdivia and Balcell (2022) note disparities in the geographical and socio-economic distribution of energy initiatives, while Grimley (2023) underscores tensions within cooperative projects between market logics and collective ideals. While distributed systems can empower citizens and enhance democratic control, they also risk reproducing inequalities if not carefully governed. Baldwin et al. (2018) stress that distributed governance requires mechanisms for deliberation, accountability, and coordination across diverse actors and interests. Valdivia and Balcell (2022) echo this, arguing that decentralization does not automatically lead to more democratic and participatory approaches.

Interim conclusion

Despite the growing prevalence of heterogeneous energy systems across the global North and South, the previous sections show that scholarly debates have remained largely compartmentalized. Research on distributed and decentralized energy systems in Northern contexts has focused primarily on their technological and socio-technical innovation potential, user engagement, energy democracy, and shifts in local governance. In contrast, Southern scholarship has emphasized informality, bricolage, and governance under severe constraints. Building on Randolph and Storper (2023) and Storper and Scott (2016), as well as recent debates in development studies (Mawdsley 2018; Sud and Sánchez-Ancochea 2022), we critique the particularisms of the "North" and "South" and the inherent epistemic fragmentation they entail. Instead, we argue for developing analytical abstractions and comparative frameworks that can be refined across contexts, enabling productive engagement between Southern and Northern debates. By situating diverse cases within broader trajectories of infrastructural change, this special issue seeks to overcome empirical particularism and foster cross-regional dialogue on heterogeneous energy infrastructures. While the essentialization of 'North' and 'South' is increasingly critiqued, we still lack empirical insights into how commonalities and differences play out in practice—underscoring the need for systematic, cross-contextual research on heterogeneous energy constellations and their governance.

Contextualizing heterogeneity: forms, drivers, and governance dynamics

The case studies from Chinese, Australian, North American, African, Middle Eastern, and European contexts assembled in this Special Feature demonstrate that heterogeneity is not a phenomenon confined to the Global South or to impoverished neighborhoods with splintered energy networks. Instead, it is a global characteristic of contemporary energy systems, emerging across urban contexts in both the North and the South. At the same time, the contributions show that heterogeneity manifests in highly context-specific ways, shaped by the distinct spatial, material, economic, and political environments in which energy systems are embedded. Table 1 provides an overview of how each paper demonstrates the (1) local contexts in which heterogeneous infrastructures are embedded; (2) drivers of heterogeneous infrastructures; (3) materialities of the infrastructures; (4) services that the infrastructures provide; and (5) modes of governance. All case studies show that heterogeneous energy configurations generate diverse governance challenges and pose differentiated demands on spatial planning. Overall, the contributions provide four lessons for ongoing debates on heterogeneous energy constellations and their governance.

First, the contributions demonstrate the *variegated drivers* of heterogeneous energy infrastructures. The emerging pattern indicates that such heterogeneity arises from either structural constraints on universal access to centralized networks or from sustainability ambitions and associated regulatory pressures. Monstadt et al. (2026) describe how heterogeneous infrastructures are produced in Dar es Salaam, Tanzania, through the layering of formal and unruly practices of energy access and co-provision, reflecting splintered grid coverage, users' affordabilities, and austerity measures. Kintzi's (2026) ethnography of rooftop solar thermal systems in Amman, Jordan, highlights how heterogeneous, user-adapted, and improvised systems are driven by informal maintenance practices of migrants' family businesses, infrastructural constraints, limited affordabilities, and fragmented governance. Cirolia et al. (2026) show how power shortfalls in African cities led to the Turkish 'powership' being connected to national grids. The deployment

Table 1 Forms and drivers of heterogeneity

Case study	Local context	Drivers of heterogeneity	Materialities	Service provision	Governance
Powerships in African ports (Cirolia et al. 2026)	Port infrastructure to serve urban areas (Sierra Leone, The Gambia, South Africa)	– Government's intention to enhance energy security and improve energy mix – High cost but relatively low risk	Added electricity source in addition to existing grid networks	Private and foreign (e.g. Turkish) business power supplier, public utility	Public-private
Renewable energy hub in the Port of Ravenna, Italy (Ramondetti 2026)	The Port of Ravenna and surrounding logistic zones, off-shore space (Adriatic Sea), nature reserves in Italy	– Diversification needs of energy supply in Europe – Renewed domestic and international interests in revitalizing port infrastructure	Green and multifunctional energy platform (e.g. hydrogen, solar, waste management, carbon capture storages), new industrial spaces with off-grid renewables	Port authority, private business (energy/extractive industries, new tech companies)	Public-private
Eco-cities in China (Liu and Lo 2026)	Eco-city designed in district of Qingdao, China	– Low-carbon transition and local pollution mitigation – National-local government planning of low carbon technologies	Distributed gas and solar power heating systems, passive housing	Local and national government, municipal utilities, international donor (Germany), private business	Public-private
Positive energy districts in Europe (Karvonen et al. 2026)	Districts in Sweden, Belgium, Austria	– Low carbon transitions – Smart city-eco district implementation	District heating networks (from waste) in addition to existing national networks, independent battery storage	Municipalities, private business, civil society organization	Public (local government)-private, academia, community
Renewable energy and digitalization in Australia (Pellegrino and Rupeka 2026)	State of South Australia, Australia	– Low carbon transitions (100% renewable electrification by 2030), with decentralized renewable generation – Digitalization for better policy and technical coordination, consumer participation	Reinforced electricity network (through hydrogen) and renewable distributed system (solar and wind), digital technology	State government, public utility (Distribution Network Operator), private business (e.g. VPP operators)	Public-private, 'prosumers'
Energy communities in California (Cudd et al. 2026)	Low income neighborhoods in California, US	– Low carbon transitions – Reduction of urban energy injustice – Promotion of community participation	Distributed solar and storage technologies in addition to existing grid networks	Nonprofit organization, private business, (state-level) public utility	Public-private, (disadvantaged) community
Battery uses and storages in Nairobi, Kenya (Kasper 2026)	Urban neighborhoods, waste dumpsite, Nairobi, Kenya	– Increased global use of lithium ion batteries due to low carbon transitions (in addition to other batteries) – Promotion of off-grid solutions, increase of e-mobility, rapid increase of battery imports	Various off-grid energy apparatuses (solar, e-mobility) requiring batteries	Independent power producer, international donor, NGOs, business, public utility	Public-private 'informal'
Rooftop solar-thermal system in Jordan (Kintzi 2026)	Urban neighborhoods of Amman, Jordan	– Informal maintenance business – Addressing energy poverty – Existence of off-grid solutions – National energy transition policy	Distributed thermal power system, off-grid solutions	Independent power producer, family business, migrants as informal laborers	Public–private 'informal'
Electricity theft in Tanzania (Monstadt et al. 2026)	High and low income neighborhoods of Dar es Salaam, Tanzania	– Universalization of grid network – Rapid expansion of urban peripheries, existing heterogeneous urban spaces	Types of illicit electricity connections	Public utility, private (informal) engineers	Public-private 'informal'
District Heating in northeast England (Otchere-Darko et al. 2026)	Northeast England	– Decarbonization – Localization	Decentralized heating systems combining local energy sources (gar, geothermal etc.) with housing developments and public facilities	Local municipalities in collaboration with energy providers	Public-private, subsidiary and outsourcing models
Financial value regimes in Mozambique (Baptista et al. 2026)	Maputo, Mozambique	– Needs of private financing for electrification – Creditworthiness and bankability	Financing for electricity generation facilities and grid extensions. Rules over electricity use	Private financiers and the public utility	Public-private

of powerships reinforces ongoing reliance on informal or decentralized systems, layering onto already heterogeneous configurations and reinforcing the hybridity of governance arrangements for electricity supply.

The contributions also show that heterogeneity is increasingly driven by (predominantly) governments' intentions to implement sustainability agendas. However, sustainability discourses driving heterogeneous infrastructures overlap and are often ambiguous. In addition to "low-carbon" energy transitions, governments' agendas include strengthening local autonomy, increasing cost recovery and financial stability, digitalizing to facilitate and aggregate distributed supply, and enabling more efficient load management practices. In extreme cases, as the case of powerships demonstrates, even highly emission-intensive electricity generation facilities are (re-)framed as serving sustainability purposes such as to compensate for temporary power shortages, maintain uninterrupted energy supply, and (allegedly) enable more permanent solutions yet to come (Cirolia et al. 2026). In contrast, Liu and Lo (2026) show how the Chinese government frames state-sponsored, yet locally diverse, configurations of distributed energy supply as low-carbon transitions, despite complex governance arrangements and unequal user rights.

Another example is Ramondetti's (2026) study of the Port of Ravenna in Italy, which demonstrates how (inter-) national sustainability funding opportunities fueled the rise of heterogeneous infrastructure, while neglecting other sustainability challenges, such as soil decontamination. Moreover, several case studies demonstrate how the development of heterogeneous infrastructure coevolves with the rise of "smart" discourses, which promise more efficient grid management (e.g., Pellegrino and Rupeka 2026; Liu and Lo 2026), but also new storage technologies that compensate for fluctuating or disrupted supply and generate e-waste dumpsites (Kasper 2026).

Second, all the papers point to the *governance challenges* posed by heterogeneous sociotechnical contexts. Governing heterogeneous energy systems involves an increasingly complex array of actors, technologies, and institutional arrangements—posing profound but highly situated governance dilemmas. One major challenge lies in the mismatch between formal regulatory frameworks and informal practices of energy use and co-provision, especially in rapidly urbanizing contexts. As Monstadt et al. (2026) show for Dar es Salaam, street electricians and high-income consumers alike engage in "unruly" electricity access practices that defy official plans but reflect socio-economic realities and infrastructural gaps. Effective governance, they argue, must move beyond punitive, technocratic responses and instead acknowledge the informal actors and spatial heterogeneity that shape energy access on the ground. Similarly, the "unruliness" of solar thermal systems, which operate primarily outside state-led energy transition frameworks (Kintzi 2026), challenges existing labor protections and maintenance practices, including the hiring of migrant workers from various countries across the Middle East. The practices of those informal networks are difficult to standardize, regulate, or integrate into official decarbonization approaches. Also in Nairobi's "batteryscape", a key governance challenge lies in the limited and fragmented regulation of domestic battery use, circulation, and disposal, leaving households to manage e-waste individually and to face uneven access to storage technologies (Kasper 2026). Otchere-Darko et al. (2026) examine the UK's district heating networks and show how diverse governance arrangements emerge in response to local material and planning contexts but often rely on ad hoc partnerships and legal agreements rather than comprehensive spatial planning approaches, thereby limiting systemic change (ibid.). These challenges show the influence of materialities on possible modes of governance, also in the global North.

In contexts with higher state capacity, Pellegrino and Rupeka (2026) identify coordination challenges across governance levels and sectors. Their case study of South Australia reveals that governing heterogeneous sociotechnical energy systems involves navigating tensions between decentralization and (re)centralized control via digital platforms, redefining the mandates of private and public actors, and demanding adaptive, spatially attuned governance frameworks. Cudd et al. (2026) examine the governance of California's energy transition through the lens of local agencies and the political economy, showing how efforts to include disadvantaged communities were structured around scalable, profitable techno-economic models. In their case study, the imperative to demonstrate replicability and financial viability privileged particular technological configurations and public–private partnerships at the expense of deeper forms of community co-design and sustained local engagement.

In most case studies, local actors closely collaborate with national and international public and private actors, further complicating governance challenges. Baptista et al. (2026) show how state actors try to align with international financial value regimes—creditworthiness and bankability—that shape the economic logics of electricity access and provision in Mozambique, with implications for both equity and grid stability. In the case of China, distributed heating systems and associated 'passive' housing projects are supported not solely by the national government but by substantial financial commitments from Germany (Liu and Lo 2026). Interventions by international donors and investors are also observed in Kenya, which largely aligns with and reinforces the government's promotion of e-mobility and digitally mediated infrastructures, thereby accelerating the proliferation of batteries in everyday urban life (Kasper 2026). However, these interventions also indirectly shape heterogeneous and uneven battery landscapes in Nairobi: while they stimulate new uses of batteries (e.g. for EVs, solar home systems, and digital work), they leave governance gaps around domestic storage, reuse, and disposal, contributing to spatially unequal burdens of battery waste that concentrate in informal disposal and recycling sites (ibid.).

Across these cases, public actors closely collaborate with private actors through diverse arrangements. In several African coastal cities, for example, private companies directly feed electricity into the national grid during peak loads and/or power shortages (Cirolia et al. 2026). In other cases, they provide technological services to facilitate the installation of new infrastructure (Liu and Lo 2026; Pellegrino and Rupeka 2026; Ramondetti 2026). The services are also actively implemented by civil society organizations (Cudd et al. 2026; Karvonen et al. 2026) and internationally supported NGOs (Kasper 2026), which promote citizen participation in infrastructure management. In Jordan (Kintzi 2026) and Tanzania (Monstadt et al. 2026), small-scale entrepreneurs actively participate in installing and managing infrastructures. These examples show that the governance of heterogeneous energy constellations emerges as a field of collaboration and negotiation between actors with divergent interests and capacities.

Taken together, these contributions highlight that governing heterogeneous energy constellations requires aligning an expanding and increasingly diverse set of technologies across multiple scales, from household-level devices to digitally coordinated electricity grids. At the same time, governance responsibilities have been broadened and redistributed, with users, small-scale entrepreneurs, community organizations, intermediary actors, and international donors taking on more active and influential roles in energy governance. Rather than being steered through singular policy instruments or centralized planning models, heterogeneous energy systems demand adaptive, negotiated, and relational forms of governance to coordinate diversity while addressing emerging inequalities, accountability gaps, and technical requirements.

Third, several contributions underscore the need to address spatial heterogeneity directly and call *for spatial (energy) planning*. Ramondetti's (2026) analysis of the Port of Ravenna illustrates how the superimposition of renewable projects on legacy industrial infrastructures gives rise to contested, composite landscapes that strain conventional planning instruments. He argues that energy transitions not only reconfigure infrastructures but also reshape the territorial fabric—creating frictions between production and conservation, industry and ecology, land and sea. Otchere-Darko et al. (2026) argue, based on the study of cities in Northeast England, that sustainable heat infrastructures must be co-produced through context-sensitive, flexible planning practices that reflect the spatial heterogeneity of existing urban landscapes and legacy systems. Karvonen et al. (2026), based on their study of Positive Energy Districts in European cities, show that their implementation is shaped by place-specific histories, institutional fragmentation, and porous district boundaries, which complicate coherent planning and require adaptive, decentralized governance strategies to orchestrate sociotechnical change. Also, Liu and Lo's (2026) study of Qingdao implicitly addresses spatial planning issues, including land development, infrastructure siting, spatial disparities, and the need for coordination across sectors and scales.

Fourth, several papers point to emerging trends of *(re-) homogenization*, where novel digital tools and new intermediary actors aim to reintegrate fragmented energy systems—such as in South Australia, where Pellegrino and Rupeka (2026) highlight how smart coordination platforms and grid reinforcement aggregate distributed energy resources. Similarly, Karvonen et al. (2026) show how positive energy districts seek coherence through stakeholder orchestration and technical layering, though outcomes remain partial. These cases also show that digital technologies are increasingly important in the process of homogenization. Aided by private service providers, public utilities, and state authorities can monitor and control power use through grid and off-grid installations. The case of virtual power plants in South Australia clearly shows the role of digital technologies in (re)centralizing distributed renewable energy systems (Pellegrino and Rupeka 2026). Another example is TANESCO in Tanzania, the public electric utility, which is promoting smart meters to improve and standardize revenue collection while monitoring informal practices and harmonizing fragmented practices of energy (co)provision across various urban neighborhoods (Monstadt et al. 2026). Such processes of re-homogenization are also widely observed in recent studies on smart urbanism (e.g., Cugurullo et al. 2024; Krisch 2022).

In terms of standardization, regulatory authorities need to monitor and integrate distributed or splintered energy constellations, as seen in California (Cudd et al. 2026), China (Liu and Lo 2026), and Australia (Pellegrino and Rupeka 2026). These trends of harmonization and standardization indicate that, while heterogeneous energy infrastructures are taking various forms and involve different actors, some degree of 're-homogenization' is occurring. This means that, while heterogenization of energy infrastructure continues and the hybridization of centralized and decentralized energy systems will sustain urban energy provision, more technological and institutional efforts are needed to standardize and harmonize the variegated infrastructural practices. Moreover, as several studies in this special feature show, these tensions between heterogenization and standardization pose new questions of coordination between a wide range of public and private actors.

In summary, the papers show that forms and drivers of heterogeneous energy infrastructures are conditioned by materialities, service provision patterns, and modes of governance in local contexts (Table 1). While some features, such as unruliness and governments' arbitrary use of sustainability discourses to promote universalization or address energy poverty, are more prominent in the global South, the effects of digitalization in recentralizing infrastructure management are observed in the global North. However, sustainability and governance challenges—such as the need for standardization through coordination among various actors—are equally evident across the global South and North, whether through incremental energy infrastructure in several Southern cities or through increased investment in distributed renewable energy installations for low-carbon energy. These cases across the South and North also empirically point to governance challenges for ensuring more equitable distributions of energy access or procedurally just decision-making processes. Such governance challenges illuminate key *obstacles and opportunities* that heterogeneous energy systems pose for sustainable urban futures, which will be discussed in the following section.

Sustainability challenges and dynamics of heterogeneous infrastructures

From community solar initiatives in California to powerships in African ports, heterogeneous energy infrastructures reflect a broad spectrum of social, ecological, political, and economic sustainability concerns and trade-offs. Here, generalizations are tricky, as the cases demonstrate multiple overlapping claims of sustainability and show how heterogeneity materializes in markedly different contexts, where the drivers of energy transitions are diverse. Nevertheless, many cases examined in this special feature are, in some way, framed as 'sustainable' (e.g., low-carbon energy transitions, positive energy districts, energy communities, etc.) or are funded by sustainability schemes. As Liu and Lo argue in the case of China, for example, "heterogeneity has emerged in China's sustainable transition to address deficiencies in centralized provision and engage a broader range of actors". Energy infrastructure heterogeneity—in this case, local renewable energy initiatives and increased municipal management—is seen as essential to speed up 'clean' energy transitions. As such, heterogeneous infrastructures, on the one hand, promise adaptability, pragmatic approaches to energy access, localized innovation in renewable energy, and a closer alignment with local needs. Certain immediate sustainability gains can be identified in some cases, such as in California, where increases in distributed solar generation have reduced energy bills for residents, or in Ravenna, where renewable energy initiatives have replaced many previously polluting infrastructure practices.

On the other hand, the sustainability implications of such cases are deeply uneven, often contested across cases, and may entail negative externalities. For example, the Californian BAAEC project aimed to establish replicable and profitable renewable energy configurations in disadvantaged urban areas. While community groups were engaged during implementation, their participation was primarily confined to consultation rather than a deeper co-design. The result was a "weak" energy community in which tailored heterogeneous technological solutions dominated meaningful social participation, with the "community" conceived primarily as units ripe for technological retrofit. A similar tension is observed in the Positive Energy Districts (PEDs) examined by Karvonen et al. (2026). Although strong performance standards and sustainability goals underpin these districts, the ad hoc nature of interventions means they do not necessarily introduce "energy democracy" that represents all stakeholders. In their study of South Australia, Pellegrino and Rupeka (2026) show how digitalization of electricity systems has enhanced system integration (of distributed renewable energy sources), but has also centralized control over energy and data, shifting value creation away from users to intermediaries. Here, the heterogeneity of actor-constellations described in previous sections complicates local benefits and participation.

Furthermore, some cases reveal how infrastructural heterogeneity can exacerbate existing socio-economic inequalities and environmental challenges. In Mozambique, the marginalization of rural communities is compounded by emerging finance models that shift strategic focus toward profitable investments. In Nairobi, Kenya, the fragmentation and unreliability of electricity supply have fostered a booming, diverse battery economy. As Kasper (2026) documents, however, access to backup power via imported batteries is stratified by income, with wealthier residents enjoying greater energy security. While this splintering of electricity uses and access to technologies reinforces socio-economic divides, it also introduces environmental harms, such as concerning batteries which frequently end up in landfills. Likewise, in Jordan, Kintzi (2026) notes that rooftop solar-thermal systems, while revolving around renewable energy supply technologies, potentially contribute to water scarcity and environmental pollution. Moreover, gender and class relations in labor undermine the social sustainability of these interventions. These cases complicate the assumption that technological diversification naturally leads to more resilient or equitable systems based on 'local' needs.

The environmental and social trade-offs of infrastructural heterogeneity are further evident in Cirolia et al.'s (2026) study. Despite their high carbon footprint and reliance on heavy fuel oil, the attractiveness of powerships is sustained by the overriding priorities of reliability and universal supply, which drive energy transitions in different African contexts. Similarly, despite a different context, Otchere-Darko et al. (2026) highlight that diverse district heating schemes in the UK, even when reform-minded, continue to rely on high-carbon fuels due to costs of alternatives, infrastructural lock-ins, strategic use of locally available resources and local institutional arrangements already in place. Such cases highlight the challenge of reconciling environmental sustainability with reliable and affordable energy supply, revealing a form of infrastructural pragmatism that contradicts normative ideals of low-carbon transition. Moreover, financial models that underpin heterogeneous infrastructures often misalign or create tensions with sustainability goals. In Tanzania, Monstadt et al. (2026) show how inflexible cost-recovery approaches, austerity policies, and high connection fees (primarily aimed at improving the utility's financial sustainability) have fueled systems and practices of irregular access. This paradoxically leads to sustained high electricity use, while higher-income users become detached from securing utility revenues. The risk of losing higher-paying customers is also a key driver of the diverse and sometimes flexible arrangements for contracting powerships (Cirolia et al. 2026). The Port of Ravenna's renewable hub (Ramondetti 2026) stands as a partial counterpoint. Significant investments in sustainable energy infrastructure have been made, but the incomplete environmental restoration tempers these achievements.

Taken together, these cases suggest a critical need to question the discourses of sustainability surrounding heterogeneous infrastructures. Firstly, as others have noted, we should avoid generalizing assumptions surrounding sustainable energy transitions 'based on the assumption of clearly identifiable and spatially homogeneous urban energy regimes' (Koepke et al. 2021). The papers in this special issue add to this by demonstrating the diverse ways in which sustainability is mobilized as a driver of infrastructural heterogeneity. In the cases of Karvonen et al. (2026) and Cudd et al. (2026) the sustainable energy transition is conceived as a state-driven attempt to increase local inclusion while driving local innovations in renewables. In papers such Pellegrino and Rupeka (2026) and Baptista et al. (2026), sustainable energy transitions are conceived as internal institutional reforms (either technologically or financially mediated) aimed at increasing the efficiency or performance of existing organisations. The cases from Kintzi (2026) and Kasper (2026) show yet more complexity by demonstrating how local citizens use and manage energy technologies to ensure energy access and livelihoods. Thus, this diversity of drivers cautions against universalist sustainability claims or universal conceptions of sustainable energy transitions. Multiple questions and lenses are needed to critically assess the sustainability of such changes.

Nevertheless, evident across all papers are many recurring sustainability trade-offs: between (reinforced) centralization and procedural justice and participation; between environmental sustainability and universal/reliable access; and between financial security and strategic targeting of marginalized/underserved groups to ensure distributional justice. While heterogeneous systems are promoted to offer greater flexibility, they can intensify inequalities and environmental harm and contribute to deficits in energy democracy. Future research must therefore interrogate not just what heterogeneous infrastructures do, but for whom they function and how their benefits and burdens are distributed. More critically, there is a need to examine how energy governance logics, whether technocratic, market-oriented, or community-driven, shape the trajectories of infrastructural change. Without deliberate efforts to align infrastructural diversity with inclusive governance, environmental integrity, and social justice, the promises of heterogeneity may remain unfulfilled.

Implications for governing heterogeneous energy systems

The increasing heterogeneity of contemporary energy infrastructures presents both governance opportunities and challenges. Central to this transformation is the involvement of a (more) diverse range of actors, including public authorities, private firms, community organizations, "prosumers", and intermediaries, each contributing to the provision, regulation, and management of energy systems in contextually distinct ways. On the one hand, this diversification is normatively framed (particularly in many higher-income contexts) as a desirable goal, reflecting broader aspirations for inclusive, adaptive, and locally attuned governance models that also leverage new digital technologies. On the other hand, it raises questions of coordination, equity, and coherence amid often fragmented institutional landscapes.

A prominent theme across several cases is the emergence and enhanced role of intermediary organizations in orchestrating and mediating energy transitions, as well as hybrid governance arrangements among such actors. These actors occupy strategic positions between state, market, and civil society, often tasked with either (a) managing the complexity of heterogeneous energy artifacts and/or (b) aligning divergent interests of the diverse stakeholders. In Stockholm, for instance, private companies and "citizen-driven innovation organizations" work to "coordinate initiatives, attract funding, and engage in various forms of orchestration to realize the long-term sustainability goals of the district stakeholders" (Karvonen et al. 2026). Similarly, in California, the Bassett–Avocado Heights Advanced Energy Community (BAAEC) illustrates how partnerships between researchers, nonprofits, and local actors evolved into formal collaborations involving public and private entities. In the UK, new governance models for district heating systems bring together local authorities, utilities, universities, and financial intermediaries (Otchere-Darko et al. 2026), while in South Australia, operators of distribution networks "pool thousands of distributed energy assets" to stabilize and optimize energy distribution (Pellegrino and Rupeka 2026).

This growing reliance on intermediaries reflects a governance shift towards what Karvonen et al. (2026) call orchestration, with actors increasingly operating across both vertical (top-down, state-led) and horizontal (networked, collaborative) governance arrangements and objectives. As the authors note, intermediaries must often "orchestrate the contradictions and trade-offs among the multiple sustainability actions within the district" (ibid.). However, the diversity of governance arrangements also exposes competing underlying logics. As Cudd et al. (2026) caution in the Californian BAAEC initiative, "the project is also the product of conventional political–economic thinking about state energy transitions, which holds that private electrical and finance capital possess the greatest power to reshape existing infrastructural configurations." Even in cases where projects claim to be participatory or community-led, such as BAAEC, there remains a tendency to prioritize scalability and replicability for state and market actors, often at the expense of meaningful local involvement. "The BAAEC project provides a window into the state's attempt to enroll public institutions, private sector investment, and local actors in a search for 'replicable' and 'scalable' approaches to residential decarbonization in areas that are socio-environmentally disadvantaged" (Cudd et al. 2026).

Another recurrent governance challenge is the unevenness, ambiguity, and often absence of institutional responsibility and regulations. Particularly in cases such as energy storage, off-grid solar, positive energy districts, etc., governance frameworks often lag technological and market developments. In Nairobi, for example, the widespread use of lithium-ion batteries remains effectively invisible to regulators: "the proliferation and importance of batteries in Nairobi is largely ignored by authorities and regulators, as evidenced by the lack of official governance or regulation of domestic electricity storage and LIB waste" (Kasper 2026). Similar regulatory vacuums are evident in Jordan, where there is minimal regulation of labor relations, environmental standards, or production practices in the solar panel sector. These examples point to a broader problem: the spatial and technological heterogeneity of energy systems often produces regulatory incoherence, institutional misalignment, and ambiguity over governance responsibilities.

These institutional gaps and misalignments often translate into ambiguous or contested roles for local communities and citizens. While participatory governance is frequently invoked in policy discourses, in practice, local voices are often marginalized. In the BAAEC case, for instance, the "intensely technological approach to residential decarbonization crowded local participants out of the planning and engineering of its interventions […] despite the project partners' stated (and demonstrated) desire for 'meaningful' community involvement" (Cudd et al. 2026). Similar dynamics are observed elsewhere, where technocratic and elite actors dominate decision-making, and communities are incorporated primarily as end users. In China, "the role of ordinary consumers in the low-carbon energy transition is diminished" by top-down planning priorities. Meanwhile, in Mozambique, governance systems display a two-tier structure: "pro-market, investor-aligned regulation for on-grid projects, and donor-reliant, under-prioritized governance for off-grid access" (Baptista et al. 2026). This bifurcation reinforces inequities and undermines the potential for transformative, citizen-centered energy systems.

Ultimately, these cases underscore the complexity and tensions involved in governing heterogeneous energy systems. While diversification of actors and technologies may enable greater flexibility and innovation, it also complicates accountability, participation, and justice. Pellegrino and Rupeka (2026) describe a blending of responsibilities in the South Australian case, between traditional grid stability and security and the marketization and integration of decentralized customer devices. This blending happens incrementally but involves 'shifting value towards the management of energy and information flows' which raises critical 'questions about participation and local empowerment'. Such questions arise across the papers: who ultimately decides what forms of decentralization are legitimate, which communities are targeted, and how costs and benefits, as well as roles, are distributed? What compromises are made in terms of the distribution and depth of responsibilities as changes to management systems are made through time?

As Karvonen et al. (2026) warn, even progressive-sounding horizontal governance arrangements "have the potential to maintain or even amplify existing undemocratic power dynamics." Similarly, in China, the integration of heterogeneous energy systems depends on how accountability is structured within China's paternalistic energy governance system, which consolidates authority within state-owned actors. Moving forward, efforts to govern energy transitions must contend not only with technical and environmental challenges but also with the deeply political questions of who governs, in whose interests, and through what mechanisms.

Conclusion

This special feature advances a broadened understanding of infrastructural heterogeneity by bringing into dialogue bodies of scholarship that have evolved mainly in isolation across global North and South contexts. While earlier work in Southern cities focused on pragmatic pathways to energy access to address gaps in centralized provision, and Northern debates emphasized the technical and regulatory alignment of distributed and centralized energy systems, the contributions assembled here demonstrate that shared governance, sustainability, and equity challenges cut across these contexts. Heterogeneity emerges not as a contextual anomaly but as a shared socio-technical condition, generating convergent dilemmas around coordination, accountability, regulation, and the distribution of benefits and burdens.

By moving beyond a North–South binary, this special feature calls for comparative, cross-contextual theorization that recognizes difference without reproducing epistemic fragmentation. We thus argue for developing analytical typologies and comparative frameworks to capture technological, social, governance, and financial configurations and to offer pathways toward more transferable insights that can inform policy and practice across diverse urban contexts. Such an approach challenges both universalist notions of sustainability and particularisms of *the* "North" and "South", while facilitating structured learning across heterogeneous settings.

Finally, the papers highlight the need for more critical engagement with governance dimensions of heterogeneous energy infrastructures. While heterogeneity can enable local autonomy, innovation, and context-sensitive solutions, it also risks obscuring an uneven allocation of costs and benefits, selectivity of participants and shifting responsibilities, and masking environmental and social costs under often untested sustainability discourses.

Future research should therefore focus on three interrelated agendas: first, more research is needed to critically assess the context-specific sustainability—especially environmental sustainability—implications of diverse and layered energy technologies alongside their purported social and economic benefits. Second, researchers and policymakers need to better account for the evolving governance architectures shaping heterogeneous energy infrastructures. This includes a better understanding of the growing role of intermediaries, as well as regulatory gaps and institutional misalignments. Finally, we need to interrogate and eventually theorize the justice implications of heterogeneous infrastructure development across the North and South, asking specifically who benefits, who remains marginalized, and how different governance modalities—hierarchical, market-based, technocratic/managerial, or community-led—shape the trajectories of infrastructural change. Without such critical engagement, the transformation toward greater heterogeneity risks reproducing rather than transforming existing inequalities and unsustainable development pathways.

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