Journal of Cleaner Production 556 (2026) 148238

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

The cloud has wires: Toward circular governance of smart grids

Georgios Pardalis *, Jenny Palm, Katharina Reindl

International Institute for Industrial Environmental Economics (IIIEE), Lund University, P.O Box 117, 221 00, Lund, Sweden

HIGHLIGHTS

- Introduction of Circular Grid Governance framework for sustainable smart energy systems.
- Integration of circular economy, lifecycle, and energy justice frameworks.
- Reveals material, temporal, and equity gaps in Swedish smart-grid governance.
- Proposes lifecycle synchronization and circular procurement reforms.
- Offers actionable levers for durable, inclusive digital energy transitions

ARTICLE INFO

Keywords:
Circular grid governance
Smart grids
Energy justice
Digital infrastructure
Circular economy
Lifecycle synchronization
Circular procurement

ABSTRACT

Smart grids are widely promoted as efficient, low-carbon solutions for energy transitions, yet their governance often treats digital infrastructure as immaterial and uniformly beneficial. This obscures the material, temporal, and justice dimensions that shape real-world outcomes. We introduce Circular Grid Governance (CGG), a framework that integrates circular-economy principles, lifecycle thinking, and energy justice, and apply it to Sweden's smart-grid development. Organized around three analytical layers (material–temporal, social, institutional), we compare 26 consultant reports with 19 interviews across public, private, and research sectors. Consultant reports emphasize digital optimization and system efficiency, while practitioners foreground mineral dependencies, depreciation-driven asset turnover, digital exclusion, and fragmented coordination. Two central governance priorities emerge. First, lifecycle synchronization: aligning regulatory, financial, and technical lifetimes to avoid premature replacement of still-functional assets. Second, equity- and circularity-by-design: embedding affordability, access, procedural safeguards, and circular requirements into rules, procurement, and program design from the outset. We identify actionable governance levers, including depreciation reform, circular procurement and reuse certification, and renter-inclusive participation. CGG offers a practical lens for steering digital energy transitions toward material durability, social inclusion, and institutional integration. Grounded in Swedish evidence, the framework is advanced as an adaptable heuristic for other digitalizing infrastructures.

1. Introduction

Smart grids have become central to national and global energy transition strategies (Tuballa and Abundo, 2016). Promoted as innovations capable of decarbonizing power systems, managing variable renewable energy, and integrating electric mobility, they are widely framed in terms of efficiency, digitalization, and flexibility (Powells and Fell, 2019; Uslar et al., 2019; Moreno Escobar et al., 2021). These framings dominate consultant reports, policy evaluations, and techno-economic models.

However, this framing is increasingly being challenged. A growing body of critical research in infrastructure and energy justice highlights the material and social dimensions of digital energy transitions. These include the environmental impacts of smart grid components (Durillon and Bossu, 2024), misalignments between investment cycles and technological lifespans, and the risk of exacerbating inequalities through digital exclusion and techno-centric planning (Kojonsaari and Palm, 2023). Research on circular economy in smart grids shows that resource scarcity, early replacement of components, and limited attention to lifecycles challenge sustainability claims, and pointing to a field still in

* Corresponding author.
E-mail address: georgios.pardalis@iiiee.lu.se (G. Pardalis).

https://doi.org/10.1016/j.jclepro.2026.148238
Received 14 October 2025; Received in revised form 16 March 2026; Accepted 7 April 2026
Available online 8 April 2026

its infancy that needs further research (Reindl et al., 2024). National scenarios and policy tools often overlook these dimensions, treating digitalization as inherently clean, seamless, and universally beneficial.

This article argues that current smart grid governance frameworks are inadequate to address the systemic risks, resource intensities, and justice-related challenges of digital transitions. In response, we propose Circular Grid Governance (CGG), a conceptual and policy framework that integrates perspectives from the circular economy, lifecycle assessment, and energy justice. Rather than viewing infrastructure as disposable or digital systems as dematerialized, CGG puts physical material, infrastructure lifespan, and social inclusion at the center of energy transition planning.

Existing research has linked smart grid development with energy justice concerns, particularly in relation to user participation, tariff design, and local energy experiments (e.g. Knox et al., 2022; Milchram et al., 2020), CGG builds on this work but shifts the focus from project- and user-level design to the governance of infrastructure lifecycles. Instead of asking only how smart grid projects are designed or how users participate, the framework examines how institutional arrangements shape the long-term material and social consequences of smart grid transitions. In particular, CGG highlights how depreciation regimes (i.e., the regulatory and accounting rules governing how infrastructure assets are written down over time), asset valuation practices, procurement rules, and cross-sector institutional coordination influence infrastructure replacement, upgrading and maintenance. These institutional rules affect material throughput, technological obsolescence, and the distribution of costs and benefits across actors. CGG therefore focuses not only with who benefits from smart grids, but also on how governance arrangements shape material flows and long-term justice outcomes.

This paper shows how a layered analytical lens can identify governance blind spots in smart grid development and highlight reforms that better align material durability, social justice, and institutional coordination. In doing so, it not only strengthens the critique of current governance approach but also points towards pathways for more sustainable and inclusive futures.

The framework is empirically grounded in an analysis of Swedish consultant reports, national strategies, and interviews with key system actors. These data reveal a significant gap between high-level visions for smart grids and the practical infrastructural and institutional realities encountered by practitioners. Importantly, CGG is not presented as an external critique, nor as a practitioner-authored framework. Rather, it is an analytically constructed perspective developed through abductive engagement with empirical material, in which recurring practitioner-identified governance tensions and constraints are interpreted and systematized. In this sense, CGG is informed by practitioners' perspectives, without implying that they themselves articulated it as a coherent framework. We derived CGG from what people said, but they did not express it in this form. We use CGG here as an analytical lens to interpret governance dynamics and institutional frictions in the material. It serves to structure and interrogate governance tensions that cut across material lifecycles, institutional arrangements, and justice concerns in smart grid development, while remaining open to contextual adaptation rather than proposing a fixed governance model or transferable policy template.

The remainder of the article builds the theoretical foundation of CGG, outlines the methodology and empirical materials, and presents a comparative analysis of strategic framings and practical experiences. We conclude by discussing how governance approaches can be made more materially grounded, socially inclusive, and structurally sustainable.

2. Framing the problem: Smart grids, materiality, and justice

This section reviews dominant narratives surrounding smart grids and introduces critical perspectives on their material and justice dimensions. Rather than treating smart grids solely as technical or market innovations, the section brings together insights from energy studies, critical digitalization research, lifecycle and circular economy scholarship, and energy justice. For analytical clarity and readability, the discussion is organized into three thematic blocks. First, we examine dominant smart grid narratives and their limits. Second, we analyze the material and temporal dimensions of digital energy infrastructures, explicitly integrating materiality and lifecycle thinking. Third, we review energy justice frameworks and their application to smart grids, highlighting persistent blind spots. Together, these strands establish the conceptual problem space to which the CGG responds.

2.1. Dominant narratives of smart grids in policy and research

Since the early 2000s, smart grids have been championed as transformative solutions for modernizing electricity systems (Tuballa and Abundo, 2016; Judge et al., 2022; Khalid, 2024). Early visions emphasized improved reliability, real-time monitoring, and seamless integration of variable renewable energy (Amin and Wollenberg, 2005). These themes continue to dominate both policy and academic discourse, where smart grids are often positioned as essential tools for achieving low-carbon, efficient, and flexible energy systems (Hielscher and Sovacool, 2018; Kojonsaari and Palm, 2023; Verbong et al., 2013).

Consultant reports and strategic documents frequently highlight the advantages of digital optimization, such as demand-side management, automated fault detection, operational cost savings, and consumer empowerment through data transparency (Aghahadi et al., 2024). In these accounts, digitalization is framed as an inherently positive and necessary pathway towards sustainability (Baidya et al., 2021; Borowski, 2021; Çelik et al., 2022; Di Silvestre et al., 2018).

However, these narratives often marginalize the material and infrastructural foundations of smart grid systems. The dominant emphasis on platforms, data, and algorithms (Butt et al., 2021; Moreno Escobar et al., 2021) tends to obscure the physical technologies, meters, sensors, communication networks, servers, that enable grid functionality (Charfeddine and Umlai, 2023). As a result, smart grids are frequently portrayed as immaterial (i.e., weightless/virtual and impact-free) or virtual systems, overlooking issues such as resource extraction, component aging, and embodied environmental impacts.

Moreover, these framings typically abstract away from questions of governance, ownership, and long-term design. Techno-economic models often assume seamless deployment and widespread adoption (Dedrick et al., 2015; Lyulyov et al., 2021), with limited consideration of spatial inequality, socio-technical complexity, or public accountability.

Critical digital studies challenge the assumption that digital technologies are inherently progressive, neutral, or immaterial. There is previous research which has emphasized that digital systems are deeply entangled with extractive supply chains, surveillance mechanisms, and labor hierarchies (Chilvers et al., 2018; Crawford, 2021; Eubanks, 2018).

2.2. Material and lifecycle of digital energy infrastructures

Although often framed in abstract terms like "data" and "flexibility," smart grids are fundamentally dependent on resource-intensive physical infrastructure (Khalid, 2024; Monaco et al., 2024). Beneath sleek digital interfaces lies a vast system of hardware, including smart meters, control units, data centers, and communication devices. These components rely heavily on critical minerals and rare earth elements such as lithium and copper, whose extraction and processing entail significant environmental and geopolitical consequences (Van Opstal et al., 2025; Wolsink, 2024). Their environmental profiles also depend on how long devices are kept in service versus replaced with more efficient generations, a trade-off that shifts as electricity mixes decarbonize (Richter et al., 2019).

A central critique is that digital infrastructure, including servers, data centers, and communication networks, is highly resource- and energy-intensive. As Crawford (2021) observes, "the cloud is not weightless"; it demands significant power, water, and hardware, often sourced through carbon-intensive and socially problematic supply chains. In smart grid contexts, these impacts are rarely acknowledged, despite their increasing scale and environmental significance.

Despite these realities, the material footprint of smart grids remains largely overlooked in both policy and academic discussions (David and Koch, 2019; Durillon and Bossu, 2024; Verdejo-Espinosa et al., 2020). Lifecycle impacts, such as emissions from production and the generation of e-waste, are rarely integrated into transition strategies (e.g., national electrification plans, utility/Distribution System Operator (DSO) roadmaps, integrated resource plans, and municipal climate action plans). Recent industrial-ecology work cautions that assessments often assume simple "longer is better" lifetimes or one-to-one displacement of new products, assumptions that overstate benefits and ignore rebound and user behavior, calling for LCAs that reflect evolving energy systems and realistic replacement dynamics (Richter et al., 2024). The assumption that digital systems are inherently clean and lightweight continues to obscure the energy and infrastructure demands required to operate and cool these systems (Lacey-Barnacle et al., 2020; Kloppenburg and Boekelo, 2019).

Additionally, rapid technological turnover exacerbates the misalignment between digital and physical infrastructures (Reindl et al., 2024). Components are often replaced prematurely due to software upgrades, shifting standards, or business cycles, creating what scholars describe as "temporal mismatches" (Bakke, 2016; Almihat and Munda, 2025; Haque et al., 2023). This dynamic reflects a deeper tension between digitalization logics that prioritize speed, upgrading, and platform compatibility, and circular economy principles that emphasize slowing material flows, extending lifetimes, and minimizing replacement. Device-level studies show that, in some contexts, replacing longer-lived electronics with improved, more efficient models can reduce impacts, yet these gains shrink as the grid decarbonizes, underscoring the need to synchronize upgrade cycles with system-level carbon intensity and product maturity (Richter et al., 2019). This results in growing volumes of e-waste and underinvestment in repair, maintenance, and reuse. Scaling reuse requires access to quality-assured spare parts, testing standards, and data to identify reusable components, areas where documented barriers (labor/skills, design complexity, storage/logistics) currently limit value retention (Richter et al., 2023).

Furthermore, the social and environmental injustices embedded in global supply chains for smart grid components are largely ignored. From the extraction of conflict minerals to the informal processing of e-waste in the Global South (Brodie, 2025; Ciplet, 2021; Mulvaney, 2024; Roos, 2023), these costs are sidelined within dominant energy transition narratives, the mainstream policy–industry storylines found in national roadmaps/National Energy and Climate Plans (NECPs), utility and DSOs strategies, consultant reports, and techno-economic studies that foreground efficiency and digital optimization while treating supply-chain and end-of-life impacts as out of scope.

Labor is another dimension frequently overlooked. From artisanal cobalt mining in the Democratic Republic of Congo (Das et al., 2024) to the behind-the-scenes roles in software development, system monitoring, and customer service (Bonina et al., 2021; Cenamor et al., 2017), smart energy systems rely on human labor that is often invisible in dominant narratives. These systems are frequently portrayed as autonomous and self-regulating, obscuring the continuous work and socio-technical maintenance they require (Ertugrul, 2024).

A circular perspective adds concrete levers, repair, refurbishing, and harvested-parts markets, to keep grid-edge electronics in service longer and share benefits locally, provided governance tackles the above bottlenecks and avoids rebound (Richter et al., 2023). Addressing these issues is central to the CGG framework, which underscores the importance of recognizing the physical realities and embedded resource flows of smart infrastructure.

Smart grid development typically follows a linear model: build, operate, discard. This approach pays little attention to material circularity or the long-term environmental consequences of infrastructure systems (Rommens et al., 2024). In contrast, lifecycle thinking offers a systems-oriented perspective, assessing environmental and resource impacts across the stages of production, use, and disposal (Ahmad et al., 2022; Bluhm et al., 2025; Wohlschlager et al., 2023). Richter et al. (2024) cautions that LCAs often assume simple one-to-one displacement and "longer is better," overlooking rebound and user behavior; it calls for LCAs that reflect evolving energy systems and realistic replacement dynamics.

Circular economy strategies, such as design for disassembly, modularity, and service-based business models, aim to extend infrastructure lifespans and reduce material waste, particularly e-waste (Awan et al., 2021; Kirchherr et al., 2023; Stahel, 2019). However, these principles are rarely applied to high-tech energy systems. Where digitalization is pursued primarily through rapid upgrading and software-driven innovation, circular strategies risk being undermined unless digital change itself is governed with sufficiency and lifecycle awareness. Where circularity is considered in energy transitions, the focus tends to remain on generation technologies such as wind turbines or solar panels, rather than the digital components that support grid operation (Schumacher and Green, 2023; Abdirahman et al., 2025; Kristia and Rabbi, 2023). Device-level evidence (e.g., LEDs) shows that early replacement with more efficient generations can lower impacts, but the advantage shrinks as the electricity mix decarbonizes, implying upgrade cycles should be synchronized with system carbon intensity and product maturity (Richter et al., 2019).

At the same time, resource governance literature emphasizes the political and institutional dynamics surrounding material flows. It examines who controls access to resources, who bears environmental and labor costs, and how the benefits of extraction and use are distributed (Bridge et al., 2018). These questions, central to sustainable transitions, are largely absent from techno-economic models that dominate smart grid discourse.

Taken together, lifecycle thinking and resource governance offer complementary insights. While lifecycle approaches provide tools for assessing environmental impacts, resource governance highlights questions of power, equity, and global supply chain justice (Gargalo et al., 2024; Kortelainen and Hanski, 2023; Hernández-Callejo, 2019; Reindl et al., 2024). A circular perspective thus adds concrete levers, repair, refurbishing, and harvested-parts markets, to keep grid-edge electronics in service longer while avoiding rebound through careful LCA and policy design (Richter et al., 2023). The CGG framework draws on both bodies of literature to advocate for energy systems that are not only environmentally responsible but also governed for long-term social and material sustainability (Munonye, 2025; Van Opstal et al., 2025).

2.3. Energy justice frameworks

Although energy transitions are often framed in technical or economic terms, energy justice research emphasizes that the processes, and beneficiaries, of transition matter deeply (Sovacool et al., 2025). Justice-oriented frameworks introduce core principles of fairness, inclusion, and accountability (Jenkins et al., 2016; Heffron, 2021; Heffron and McCauley, 2017), typically organized around three dimensions: distributive, procedural, and recognition justice. Recent Swedish evidence on smart grid rollouts shows these dimensions intertwine in practice, producing 'bundles' of marginalization that span skills, participation, infrastructure access, and household economy (Tarasova and Rohracher, 2023a). In smart grid contexts, concrete design choices, data governance, user autonomy vs. automation, accessibility, and plans for replication/scale, directly shape distributive, recognition, and procedural outcomes, making justice operational rather than merely aspirational (Milchram et al., 2020).

Distributive justice concerns how the costs and benefits of energy transitions are shared. In smart grid contexts, this includes who pays for infrastructure upgrades, who reaps the benefits of flexibility services, and who is excluded from digital programs (Walker, 2009; Simcock et al., 2021). Studies document cost burdens from devices, subscriptions, and even prerequisite smartphones/Internet access, alongside higher bills for households unable to shift routines under dynamic tariffs (Tarasova and Rohracher, 2023a). Comparative pilot evidence shows that variable-tariff and device-centric designs can shift benefits to already advantaged users unless distribution of profits/costs and public-funding rules are made explicit and fair (Milchram et al., 2020). At a system scale, recent econometric work finds the digital economy can support a fairer transition, by improving factor allocation and fostering environment-biased (energy-saving) technological progress, especially in lagging cities, though effects are heterogeneous across regions (Li et al., 2025).

Procedural justice focuses on decision-making processes, asking who is included in governance and who has influence. Smart grid development often prioritizes utilities, vendors, and technical experts, while sidelining citizens and community stakeholders (Inderberg et al., 2024; Sovacool et al., 2019). Automation and algorithmic control further raise equity issues. Eubanks (2018) shows that digital systems often encode bias while appearing objective. In smart grids, algorithm-driven tools for load management, pricing, and remote disconnection may prioritize efficiency over user well-being, especially in the absence of transparency, accountability, or recourse mechanisms.

Fieldwork from Swedish demonstrations (e.g., Gotland) shows how pilots 'configure' users, favoring high-load households, excluding some prosumers to reduce complexity, and shifting control from users to automation, narrowing participation in practice (Tarasova and Rohracher, 2023b). Case comparisons identify practical levers for procedural justice: open decision arenas for users, transparency, material participation (e.g., user control of HEMS), and fair data governance (Milchram et al., 2020). Yet in many smart local energy systems, justice is not absent so much as cognitively/practically sidelined. Actors voice broad justice-oriented ambitions but leave them underspecified, which allows implementation to drift back to optimization logics unless goals and metrics are defined ex-ante (van der Wel and Akerboom, 2024).

Recognition justice addresses whether the needs, identities, and capacities of diverse users are acknowledged. Idealized portrayals of "smart" users tend to overlook differences in digital literacy, income, housing status, and cultural context (Van Uffelen, 2022; Ramirez, 2025). Tarasova and Rohracher (2023a&b) recommend moving from labeling vulnerable groups to targeting the conditions and practices that create vulnerability (e.g., literacy gaps, routine inflexibility, peripheral internet/electricity) and warn that design/marketing often privilege resource-rich single-family households. Pilot evaluations echo that tenants, lower-income households, and users with low IT literacy are disadvantaged unless accessibility is designed in, for example via community storage or collective ownership models (Milchram et al., 2020).

Technological features like automated disconnection or dynamic pricing may further entrench inequalities if implemented without safeguards (Rossi et al., 2024). These tools risk penalizing those unable to actively participate in energy markets or invest in enabling technologies. Empirical accounts of anxiety around detailed feedback, reluctance to cede control to automation, and uneven reliability of metering/communications infrastructure underscore these risks (Tarasova and Rohracher, 2023a). Energy justice research complements material critiques by highlighting user vulnerability, lived experiences, and structural exclusions (Sovacool et al., 2021; Tarasova and Rohracher, 2023a).

Recent evidence on Smart Local Energy Systems (SLES) helps explain why safeguards are missing: justice is invoked in rhetoric but remains weakly specified in practice, leading to its sidelining unless responsibilities and measurable objectives are defined upfront (van der Wel and Akerboom, 2024).

Much of this literature, however, addresses justice primarily through the lens of system design, participation, and user-facing arrangements, such as tariff structures, data governance, and decision-making processes. While these contributions are critical, they tend to treat infrastructure as a relatively stable backdrop rather than as an object of governance in its own right. Questions of asset lifetimes, depreciation regimes, premature replacement, and the circular management of digital grid components remain largely outside the scope of existing justice-oriented smart grid frameworks.

Emerging research has begun to address these blind spots by examining labor conditions, material sourcing, and end-of-life impacts at the intersection of smart grids and circular economy principles (Reindl et al., 2024). Broader critiques underscore that labor precarity and social inequality are not peripheral concerns, but are, in fact, central to building truly just and sustainable energy transitions (Sovacool et al., 2022; Süsser et al., 2022).

These insights reinforce the CGG framework's core claim: digitalization must be treated as materially grounded and socially embedded, not ethereal or inherently beneficial. A governance approach that recognizes the full spectrum of material, labor, and equity concerns is essential to avoid replicating the very injustices that energy transitions seek to overcome. Taken together, these critiques underscore that digital optimization delivers equitable outcomes only when energy-justice safeguards, fair data governance, user control and avenues for appeal, and accessibility by design, are specified ex-ante rather than assumed (van der Wel and Akerboom, 2024).

The CGG framework integrates energy justice not as a secondary concern, but as a core principle. It redefines sustainability to include not only environmental performance but also social equity, accessibility, and democratic participation in the design and governance of smart energy systems. At the same time, city-level digitalization can, under conditions of strong environmental concern and energy "cleanliness", advance procedural and restorative justice by narrowing regional disparities, even as it introduces labor and wage trade-offs that policy must address (Li et al., 2025).

2.4. Circular Grid Governance: A framework for infrastructure transitions

The previous section examined how smart grid research has often overlooked key concerns around materiality, justice, and circularity. In response, this section introduces Circular Grid Governance (CGG) as a coherent and actionable framework designed to address these gaps. CGG synthesizes insights from literature on circular economy, infrastructure lifecycle governance, and energy justice to analyze how smart grid transitions are governed. It is developed abductively from empirical material and used here as an analytical framework rather than a prescriptive governance model. In the empirical analysis that follows, the three CGG layers are used as an analytical lens to interpret how governance tensions around infrastructure lifecycles, digitalization, and justice concerns appear in policy documents and practitioner accounts. CGG extends existing justice-oriented approaches by shifting the analytical focus from project-level participation and user design to the governance of infrastructure lifecycles, including depreciation regimes, procurement standards, and replacement norms (e.g., Knox et al., 2022; Milchram et al., 2020).

Building on the literatures reviewed in Section 2 and an abductive reading of our empirical materials, we distilled recurring governance frictions into five principles, organized here, for analytic economy, into three overarching layers. Energy justice explicitly threads through all three layers: in the material–temporal layer (who bears the costs of turnover and e-waste), the social layer (affordability, access, recognition), and the institutional layer (accountability for circular design, cross-sector inclusion, and fair data governance). Rather than proposing a fixed indicator set, CGG identifies key governance interfaces, such as depreciation regimes, tariff design, procurement standards, and data and automation governance, where distributive, procedural, and recognition justice are negotiated, debated, and made visible in real-world decision-making.

Circular economy principles, lifecycle assessments, and energy justice perspectives are rarely integrated in smart grid governance. Instead, governance approaches tend to remain fragmented (Damianou et al., 2023; David and Koch, 2019; Jordaan et al., 2021; Rommens et al., 2024). This fragmentation limits the development of strategies that are simultaneously ecologically grounded, socially inclusive, and structurally sustainable (Knox et al., 2022; Milchram et al., 2018; Sovacool et al., 2024). CGG calls for a shift in governance logic, from a focus on optimization and flexibility to one that emphasizes durability, equity, and systemic resilience. In doing so, CGG explicitly responds to the tension between digital acceleration and circular economy objectives, proposing governance mechanisms that discipline and selectively channel digitalization in line with lifecycle and sufficiency goals rather than treating faster upgrading as inherently desirable.

CGG consists of five principles, which are grouped here into three analytical layers to simplify the analysis. The five principles capture governance dimensions identified in the empirical material, while the three-layer structure provides a more streamlined structure for presenting and analyzing these dynamics. Table 1 shows how the principles map onto these layers.

In this consolidated structure, the *Material–Temporal Layer* combines material embeddedness and lifecycle synchronization. Smart grids rely on resource-intensive infrastructures such as meters, sensors, control systems, and data centers that draw on critical raw materials with significant environmental and social risks. At the same time, financial and regulatory frameworks often incentivize premature replacement: depreciation schedules and investment cycles are misaligned with the actual durability of equipment. Together, these dynamics accelerate material throughput and undermine sustainability. Addressing them requires reforms in regulation and asset valuation that treat infrastructures not as disposable add-ons but as durable socio-technical systems embedded in long-term ecological and economic contexts.

The *Social Layer* brings together equity and justice with governance processes. As energy services become increasingly digitalized, questions of affordability, digital literacy, and technology ownership become decisive in shaping who benefits. Without deliberate safeguards, access to smart grid opportunities, such as flexibility services, dynamic tariffs, or energy sharing, risks being restricted to affluent and technologically savvy households. Embedding equity into governance therefore requires participatory mechanisms, targeted affordability policies, and explicit recognition of diverse user needs. Rather than treating citizens as passive market actors, governance must ensure inclusion, representation, and protection for vulnerable groups.

The *Institutional Layer* integrates design for circularity with integrated governance. Current industry norms often prioritize single-lifecycle products and frequent upgrades, leaving little room for reuse, repair, or modular upgrading. Circularity instead demands modular and upgradable infrastructures supported by procurement standards, product-service models, and extended producer responsibility. Yet design choices alone are insufficient without governance integration: smart grid transitions cut across energy, environmental, waste, and digital policy domains, and institutional silos frequently block systemic solutions. Cross-sectoral coordination, shared metrics, and joint incentives are therefore essential for enabling circular system design. In this way, the institutional layer links technical design choices with the governance architectures that make them possible. This three-layer framing enables a more accessible analysis of governance tensions while recognizing that the five original principles remain valuable for future refinement of the CGG framework.

Table 1
Key principles of Circular Grid Governance (CGG).

Principle	Description	Analytical Layer (this study)
Material Embeddedness	Recognizing that smart grids rely on resource-intensive physical infrastructure	Material-Temporal
Lifecycle Synchronization	Aligning financial, technical, and regulatory lifespans to reduce premature waste (including depreciation reform and LCA/LCC that model replacement timing)	Material-Temporal
Equity and Justice	Ensuring affordability, access, and representation across diverse user groups	Social
Design for Circularity	Embedding modularity, reuse, and repair into technical and policy design	Institutional
Integrated Governance	Bridging silos across energy, environment, waste and digital infrastructure	Institutional

To illustrate how these principles operate as a system, CGG can be visualized through three interrelated governance layers, material–temporal, social, and institutional. As shown in Fig. 1, these three layers are analytically distinct but systemically interdependent. Governance choices in one layer shape, enable, and constrain outcomes in the others, rather than operating in isolation. Material–temporal decisions regarding asset lifetimes, upgrade cycles, and durability influence social outcomes by affecting affordability, access, and exposure to cost volatility over time. Social priorities related to equity, participation, and recognition can, in turn, generate pressures for alternative material configurations, such as longer asset lifetimes, shared infrastructures, or different ownership and access models. The institutional layer mediates these interactions by structuring the rules, standards, and coordination mechanisms through which material investments and social objectives are aligned, including depreciation regimes, procurement criteria, regulatory incentives, and cross-sector governance arrangements. Taken together, the three layers form a dynamic governance system characterized by feedback loops rather than a linear hierarchy, highlighting that circular and just smart grid transitions depend on the co-evolution of all three layers rather than optimization within any single domain. Future research with broader empirical material could further differentiate these layers back into five, offering a more fine-grained model of Circular Grid Governance.

Fig. 1 visualizes the three CGG layers and their interactions. Governance decisions in one layer influence outcomes in the others through feedback loops between material infrastructures, social priorities, and institutional arrangements.

Conceptually, the mechanisms through which these layers interact can be specified more concretely. Material–temporal decisions shape social outcomes through governance pathways such as cost allocation, technology access, and lifecycle externalities. For example, depreciation schedules and replacement cycles influence the cost trajectories of grid infrastructure, which are ultimately reflected in tariffs and network charges and therefore affect affordability and distributional outcomes. Decisions regarding technology standards, upgrade frequency, and system architecture also influence which actors are able to access and benefit from digital grid services. Furthermore, the pace and governance of material turnover determine the volume and geographical distribution of e-waste and end-of-life burdens, whose environmental and health costs are frequently externalized onto less powerful communities within global supply chains, rendering material-temporal governance decisions a matter of transnational justice as much as local infrastructure management. Conversely, social priorities, such as affordability concerns, inclusion requirements, or recognition of vulnerable user groups, can generate regulatory and political pressure to adjust infrastructure planning, technology deployment, or asset management strategies. For instance, affordability obligations or universal service requirements embedded in regulatory frameworks can constrain viable infrastructure procurement strategies, effectively requiring longer asset lifetimes, modular upgrade pathways, or alternative ownership arrangements that redistribute lifecycle costs more equitably. The institutional layer mediates these interactions by translating material constraints and social priorities into governance instruments, including depreciation regimes, tariff regulation, procurement standards, and coordination mandates.

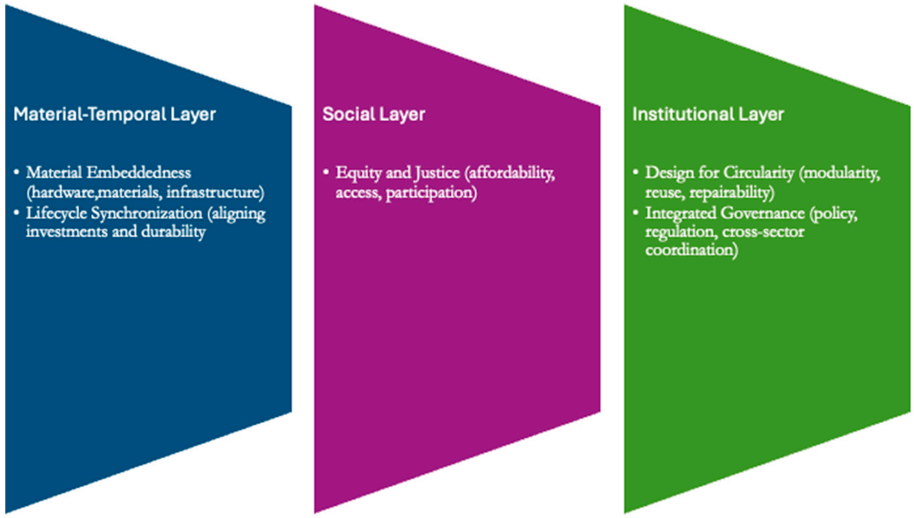

Fig. 1. The three layers of Circular Grid Governance: material–temporal, social, and institutional.

The following sections describe the empirical materials and methods used to examine how these governance dynamics unfold in practice.

3. Methodology

This study employs a qualitative, abductive research design that integrates document analysis and semi-structured interviews (Charmaz, 2017; Timmermans and Tavory, 2012). The goal is to examine how smart grid development in Sweden has been framed, implemented, and contested, particularly in relation to materiality, infrastructure longevity, and justice concerns. The objective of this qualitative design is to generate analytical insights rather than statistical generalization. The study seeks to identify governance logics, institutional frictions, and justice-relevant dynamics within smart grid development rather than to measure their prevalence across the electricity system.

Sweden offers a strategic case for investigating smart grid governance due to its early adoption of digital energy systems, strong public-sector involvement, and widespread reliance on consultant-led policy-making. As a technologically advanced welfare state with ambitious decarbonization goals, Sweden exemplifies the tensions between efficiency, equity, and material sustainability that shape contemporary energy transitions.

3.1. Document collection and analysis

Relevant documents were identified through systematic desktop research, supplemented by snowball sampling. Initial searches targeted publicly available reports on smart grid development in Sweden, with updates conducted in autumn 2021, 2022, and 2024. All documents were catalogued using a structured spreadsheet that recorded metadata such as authorship, commissioning body, and institutional affiliation.

Document identification followed a structured search protocol combining targeted keyword searches and institutional source tracing. Searches focused on publicly available reports relevant to smart grid development and electricity system governance in Sweden, using keywords such as “smart grids” (smarta elnät), “grid digitalization” (elnätsdigitalisering), “flexibility” (flexibilitet), “capacity adequacy” (effekt), and “future electricity grids” (framtidens elnät). This was supplemented by backward and forward snowball sampling from cited policy documents and publications associated with Forum for Smart Grids (Forum för smarta elnät). Sweden's smart grid policymaking involves a diverse range of actors. This analysis focuses on reports commissioned by public authorities and authored by consultant firms. Key governmental agencies include the Swedish Energy Markets Inspectorate (EI), the Swedish Energy Agency, and regional administrative boards. Major consultancy contributors include Profu, Ramböll, Sweco, and WSP. These actors have participated in all significant national smart grid initiatives since 2010.

Consultant reports were treated not as neutral representations of system reality, but as institutional artefacts shaped by commissioning arrangements, policy mandates, and client expectations. The analysis therefore focused on how problems, solutions, and priorities were framed, rather than taking claims at face value. Attention was paid to recurring assumptions, silences, and boundary-setting choices (e.g., which impacts were considered in or out of scope), and findings from reports were systematically triangulated with interview data to identify divergences between formal strategy and practitioner experience.

Table 2 summarizes the key governmental initiatives and the consultancy firms involved.

In total, 26 consultant reports were analyzed, of which 20 directly addressed smart grid development and 6 were indirectly related, as summarized in Table 3. Reports were classified as “direct” when smart grid development constituted their primary analytical focus and mandate, and as “indirect” when smart grids were addressed as a secondary or contextual element within broader analyses of electricity system development, flexibility, or electrification. Indirect reports were included to capture the systemic assumptions, boundary conditions, and scenario framings that shape smart grid governance but are not articulated as smart grid policy per se.

3.2. Interview design and sampling

To complement the document analysis, 19 semi-structured interviews were conducted between March and April 2022. Participants represented a broad cross-section of institutional roles, including government agencies, municipal utilities, research institutions, technology

Table 2
Overview of governmental smart grid initiatives and reports, showing the involved consulting companies for their development.

Governmental Initiatives and Reports	Consultancy Firms Involved and Number of Reports
Swedish Government Official Reports (SOU) 2012-2014	Profu, NEPP, Ramböll, STRI, SWECO (17 reports)
Forum Smart Grid 2016-2019	Copenhagen Economics, WSP, SWECO, Profu, NEPP (7 reports)
EI Smart Grid Costs, 2021	DNV GL (1 report)
EI Smart Grid Indicators, 2021	WSP (1 report)

Table 3
Overview of the reports addressing smart grids and related topics.

Source	Directly Addressing Smart Grids	Related to Smart Grids	Total Reports
SOU	13	4	17
Forum Smart Grid	5	2	7
EI	2	0	2
Total	**20**	**6**	**26**

providers, consultants, and international organizations. The number of interviews was guided by the aim of capturing governance-relevant perspectives across key institutional positions rather than achieving representativeness within any single sector.

The interviewees were selected using purposive and strategic sampling based on three main criteria. First, individuals had to hold roles with direct relevance to smart grid governance, including areas such as infrastructure planning, regulatory design, digitalization, flexibility markets, or sustainability integration. Second, the selection aimed to capture institutional diversity across the energy system, spanning public authorities, municipal and national utilities, research institutions, consultancies, industry organizations, and international agencies. Third, we prioritized individuals whose professional roles suggested potential engagement with cross-cutting themes such as lifecycle planning, user inclusion, circularity, or technology deployment. This criterion was intended to maximize analytical exposure to governance tensions and coordination challenges that cut across established policy domains, rather than to select participants based on alignment with specific analytical concepts or normative positions. While not all interviewees focused explicitly on these dimensions, the sample was designed to surface underexplored aspects of smart grid governance beyond the dominant digitalization and market narratives.

This sampling strategy reflects the study's analytical focus on system-level governance logics rather than on end-user experience. Accordingly, interviews prioritized actors positioned to influence, interpret, or implement smart grid policy, such as regulators, utilities, consultants, and technology developers, rather than households or civil-society organizations. This choice was intentional, as the analysis examines how institutional arrangements, regulatory incentives, and expert framings shape infrastructure lifecycles and justice-relevant outcomes upstream, before users experience them.

While not all participants explicitly focused on CGG-related themes, the sampling strategy was designed to elicit underexplored governance dynamics beyond dominant market or digitalization narratives. Across interviews, recurring problem framings and governance challenges began to stabilize across sectors, suggesting diminishing analytical returns from additional interviews at the system level. Table 4 provides anonymized profiles of the interview participants.

Interviewees were not asked to evaluate or articulate CGC as a framework. Rather, interviews focused on practitioners' experiences, constraints, and problem framings related to smart grid development, from which analytically relevant governance tensions were later interpreted. Interview material also included views that were supportive of prevailing smart grid strategies or skeptical of structural reform. Such perspectives were retained in the analysis and treated as analytically significant rather than excluded, particularly where they aligned with or reinforced dominant framings identified in policy and consultancy documents. All participants provided informed consent. Interview data were anonymized and processed in compliance with General Data Protection Regulation (GDPR) and institutional ethical protocols.

3.3. Data analysis

Interview transcripts were thematically coded using NVivo. The analysis followed an abductive approach. Initial open codes were

Table 4
Overview of anonymized interview participants.

Interview ID	Sector/Organization	Role/Position
I01	Energy Company	Business developer with focus on grid, flexibility, and integrated energy systems
I02	Research Institute	Researcher and project leader focused on sustainability in data centers
I03	Technology Provider	ESG strategy lead at an international smart grid technology firm with global operations, including Sweden
I04	Government Agency	Project leader and analyst focusing on electricity market investigations, scenarios, and electrification at a national energy agency
I05	Government Agency	Project leader in a county administrative board, responsible for smart grid projects and policy consultations
I06	International Organization	Renewable energy analyst responsible for medium-term capacity forecasts at an international agency.
I07	Energy Company	Business developer at a utility company working on grid design, new connections, and flexibility solutions for capacity-constraint areas
I08	Regional Government (Development)	Environmental and energy specialist at a regional development department
I09	Research Institute	Researcher focused on solar power, battery storage, and DC grid systems
I10	Energy Company	Program leader for smart meter rollout at a major electricity distribution company
I11	Consultancy	Management consultant at a firm specializing in digitalization and smart infrastructure
I12	Government Agency	Program manager at a Swedish governmental agency with nearly a decade of experience in R&D funding for renewable electricity generation
I13	Consultancy	Partner at a consultancy firm specializing in energy sector strategy and policy
I14	Technology Provider	Manager of product development and R&D at a Swedish technology company
I15	Government Agency	Analyst at a Swedish governmental agency working on energy market regulation and policy
I16	Research Institute	Senior researcher in power systems focusing on grid stability, frequency regulation, electrification, and integration of solar, storage, and microgrids.
I17	Research Institute	Researcher in sustainable energy transitions with a focus on local energy systems, energy communities, and flexible grid solutions.
I18	Independent Consultant	Former consultant and policy advisor specializing in public energy strategies and market development
I19	Industry Organization/ Former Consultant	Director of energy policy and operations at a national industry federation, with over two decades of experience in market analysis, regulation, and strategic advisory across the European energy sector

developed inductively, then refined in relation to the five CGG principles, material embeddedness, lifecycle synchronization, equity and justice, design for circularity, and integrated governance. Analytical memos and code clustering were used to identify recurring patterns across sectors and roles. This refinement involved iteratively grouping inductive codes into higher-order categories based on recurring governance tensions, which were then interpreted through engagement with relevant literatures on circular economy, infrastructure governance, and energy justice. CGG principles thus emerged as analytical abstractions that stabilized when multiple empirical patterns converged across sectors and data sources, rather than as predefined coding categories.

CGC thus emerged through this abductive process as an analytically constructed framework. While practitioners did not explicitly advocate CGG or its principles as a unified model, recurring concerns and governance frictions articulated across interviews and documents, such as misaligned depreciation rules, pressures for premature infrastructure replacement, fragmented responsibility for end-of-life assets, and uneven distributive effects of digitalization, were systematically interpreted and synthesized into the CGG framework. Deductive reasoning entered the analysis not as hypothesis testing, but as a sensitizing device, helping to assess whether emergent empirical patterns resonated with, extended, or challenged existing theoretical constructs.

As is typical in abductive analysis, not all emergent themes initially aligned neatly with the five CGG principles. Such themes were not set aside or forced into predefined categories. Instead, they were retained as open codes and examined iteratively to assess whether they pointed to limits, tensions, or refinements of the framework. In some cases, these themes informed the consolidation of principles into the three analytical layers; in others, they are reported as empirical frictions or governance blind spots that CGG helps to diagnose rather than subsume. This iterative movement between data and framework ensured that CGG remained analytically generative rather than prescriptive.

The coding process unfolded in three stages. First, all interview transcripts were subjected to open, inductive coding to capture problem framings, constraints, and governance tensions as articulated by participants. Second, these inductive codes were iteratively clustered and refined through analytical memo writing, during which recurring patterns across interviews and documents were identified and compared. Third, emergent categories were interpreted in dialogue with relevant literatures, allowing higher-order analytical constructs to stabilize abductively rather than being imposed ex ante.

To reduce the risk of confirmation bias, the analysis incorporated several reflexive practices. Analytical memos were used not only to develop interpretations but also to document uncertainties, alternative readings, and emerging tensions in the material. Preliminary interpretations were discussed within the research team at multiple stages of the analysis, enabling peer scrutiny and challenge of dominant readings. In addition, attention was paid to deviant or contradictory cases, including interview statements that questioned or resisted CGG-aligned interpretations, and these were retained as analytically significant rather than treated as outliers.

The primary coding and analysis were conducted by one researcher. Analytical quality was supported through regular discussion of coding decisions and emerging interpretations within the author team, as well as through systematic triangulation between interview and document materials. Rather than inter-coder reliability checks, which are less suited to abductive and interpretive analysis, these procedures functioned as qualitative quality checks by challenging consistency, plausibility, and alternative readings. In this interpretive research design, analytical rigor is achieved through transparency of analytical decisions, reflexive engagement with the empirical material, and systematic comparison across data sources rather than through statistical measures of coding agreement. Triangulation involved systematically comparing how specific governance issues were framed in consultant reports and articulated in interviews, allowing areas of convergence to reinforce interpretations and areas of divergence to signal implementation gaps, contested assumptions, or institutional frictions.

Findings from interviews were triangulated with consultant reports to identify points of convergence (e.g., concerns about asset obsolescence) and divergence (e.g., gaps between high-level strategies and local practice). This comparative approach reinforced the study's empirical grounding and interpretive depth.

The study acknowledges several limitations. First, the interview sample consists mainly of actors involved in system-level governance, such as regulators and consultants and therefore captures governance perspectives rather than end-user experiences. Second, the empirical material is limited to the Swedish context, where institutional arrangements may differ from those in other countries. Finally, as an interpretive qualitative study based on interviews and policy documents, the findings aim to generate analytical insights rather than statistically generalizable conclusions.

4. Empirical findings

This section presents the empirical findings of this study. Findings are organized by the three CGG layers, material–temporal, social, and institutional, and are presented separately for reports and interviews to surface contrasts between official narratives and practice. Reports typically foreground efficiency, digitalization, and technical optimization, whereas interviews reveal on-the-ground tensions, overlooked risks, and systemic blind spots. Where relevant, we note distributional, procedural, and recognition justice implications to connect evidence to the CGG layers. A cross-source synthesis consolidates patterns across interviews and consultant reports to identify shared themes, practitioner-identified tensions, and persistent blind spots across the three CGG layers closes the section. Quoted excerpts are used as illustrative examples of recurring framings in the material. Where relevant, we explicitly flag minority or dissenting perspectives to avoid implying uniformity within either data source.

4.1. Findings from the interviews

4.1.1. Material-temporal layer

Many interviewees recognized that smart grids are not purely digital or “weightless,” but dependent on substantial physical hardware and supply chains. Physical infrastructure, from transformers to smart meters, was repeatedly described as resource intensive. Several participants mentioned growing concerns over rare-earth metals, electronic waste, and carbon footprints associated with batteries, sensors, and data center infrastructure. As one of the interviewees mentioned:

> “Smart grids are mostly about software, but of course, we also need more measurement, control components, and electronics … so in that sense, it does have an impact.” (I01)

Some interviewees highlighted supply chain audits or material efficiency comparisons (e.g., transformer lifecycle emissions vs. station construction). However, others admitted that material concerns remain peripheral in procurement or business modeling. Even where awareness exists, cost continues to dominate decisions, with environmental performance treated as a secondary criterion or externality. A minority of interviewees downplayed the governance relevance of material considerations, framing them as marginal compared to system efficiency or reliability goals.

The interviews revealed a deep tension between the technical lifespan of components and the economic or regulatory frameworks governing their replacement. Several utility representatives criticized regulatory depreciation models that incentivize premature equipment replacement.

> “Often things are replaced after 40–50 years, even if they still work, because we stop earning money on them after they’re depreciated.” (I07)

Others noted a mismatch between fast-moving digital components (e.g., sensors, smart controllers) and slow-moving physical grid assets, raising concerns about system integration and maintenance. Still others saw potential in new service models (e.g., leasing, shared battery use) to better align investment cycles with use value, although these were often constrained by ownership regulations and risk models. However, a minority questioned whether alternative ownership or service models would address a clearly defined governance problem or improve end-user outcomes (I05).

4.1.2. Social layer

Equity emerged as a contested and unevenly acknowledged theme. While some interviewees framed smart grids as democratizing tools, offering participation and cost savings, others expressed skepticism about who benefits, who participates, and who is excluded. The digital divide, homeownership, and ability to invest were common axes of inequality. These concerns map directly to distributional (who benefits/pays), procedural (who participates/has recourse), and recognition (who is seen/served) dimensions.

> “It costs money to have solar panels and batteries and EVs and to be engaged. That’s not available to everyone.” (I07)

> “Flexibility favors those with many devices at home , those with resources.” (I17)

At the same time, a minority of interviewees explicitly rejected the relevance of social or justice-related concerns for smart grid governance, framing smart grids as a technical or economic matter rather than a social one. One interviewee stated: “I see no social aspects … I don't consider any especially relevant.” (I05)

Several interviewees warned of regressive cost redistribution, where grid users without flexibility assets subsidize others via fixed tariffs or unbalanced incentives. Others emphasized the need for automation, nudging, and feedback systems to enable broader inclusion without relying on active consumer behavior. However, interviewees also acknowledged that smart grid programs currently privilege the already engaged and technologically savvy.

4.1.3. Institutional layer

Circularity was discussed unevenly. Some actors experimented with second-life batteries, component reuse, or data center heat integration into greenhouses (I02, I09, I12). These pilots showed potential but lacked institutional support. Others noted that product lifespans are often governed more by procurement policy and regulation than technical limits, with some components replaced prematurely due to standards upgrades or misaligned depreciation rules. Circular design was thus often seen as desirable but peripheral, lacking institutional support.

Governance fragmentation was a recurring theme. Interviewees described coordination gaps between DSOs, municipalities, regulators, and aggregators. While some praised regional collaboration (I08), others noted that smaller operators lacked the resources to engage beyond compliance.

> “It's that interface with the market and the network where a lot of confusion arises, I think.” (I15)

> “Smart solutions aren’t always aligned, flexibility is often a way to buy time, not necessarily the cheaper or greener solution.” (I18)

Many interviewees described relying on workarounds: informal collaboration, renting batteries, or resisting regulatory incentives. These everyday frictions reveal how practitioners navigate misaligned systems through pragmatic improvisation. Renting batteries, informally coordinating with users, or resisting regulatory incentives are not marginal practices but central to making the system work. Such institutional improvisation remains largely invisible in formal policy design yet contrasts sharply with the technocratic optimism found in consultant reports. It suggests that smart grid governance depends as much on institutional negotiation and compromise as on digital optimization or market-based coordination.

Interpreted through the lens of energy justice, these institutional frictions also have important justice implications. Governance fragmentation and misaligned depreciation rules influence who can shape infrastructure decisions and whose concerns are reflected in planning processes, raising questions of procedural justice. At the same time, limited institutional support for circular design and lifecycle coordination can obscure the long-term material and social consequences of infrastructure turnover, raising recognition concerns about which impacts and actors are taken into account. Together, these dynamics also shape distributive outcomes, as the costs and benefits of smart grid transitions are mediated through governance arrangements that structure investment, replacement, and access. In the absence of explicit redistributive measures, these arrangements tend to concentrate benefits among larger and more resource-rich actors while shifting costs onto smaller operators, renters, and digitally excluded households.

4.2. Findings from consultant reports

4.2.1. Material temporal layer

Reports predominantly portray smart grids as immaterial, data-driven systems. The focus lies on demand-side flexibility, pricing signals, and system optimization, while physical infrastructure is treated as a passive carrier of services. Environmental impacts of hardware, such as smart meters, sensors, and batteries, are largely absent. Even when storage technologies are discussed, they are framed as functional assets, with no reference to lifecycle impacts, rare earth minerals, or e-waste. Long-term scenario models (e.g., projecting to 2030 or 2050) support strategic foresight but obscure frictions such as aging assets or depreciation schedule mismatches. Technical, financial, and regulatory lifespans are rarely analyzed together, leaving premature replacement due to outdated valuation models unaddressed.

4.2.2. Social layer

Consumers are consistently represented as rational market actors who respond to price signals. This framing assumes universal benefit while ignoring issues of affordability, access, or digital exclusion. Key justice concepts, such as “energy poverty,” “digital divide,” or “procedural fairness,” are notably absent from the reports, despite their relevance for smart grid implementation. Across reports, justice remains largely implicit, with distributional assessments, participation safeguards, and recognition of digitally excluded users rarely specified.

4.2.3. Institutional layer

Innovation is overwhelmingly equated with digitalization and flexibility. Circularity concepts such as modularity, reuse, or repair receive no systematic attention, with only occasional references to second-life batteries or leasing models. More recent reports (post-2018) begin to acknowledge the need for coordination among DSOs, regulators, and aggregators, but this is framed in narrow technocratic terms, clarifying roles and improving metrics, rather than addressing deeper institutional silos or enabling participatory governance. Municipal actors remain largely sidelined. These shifts show a gradual widening of focus in some consultancy work, but they still rarely address material lifecycles, distributional impacts, or justice issues, which remain on the margins.

4.3. Synthesis and implications across interviews and consultant reports

The contrast drawn between consultant reports and interview accounts reflects dominant patterns rather than uniform positions within each source. Some recent reports, particularly after 2018, acknowledge coordination challenges and experiment with pilot circular practices, while a minority of interviewees articulated more optimistic views aligned with prevailing efficiency and flexibility narratives. However, these exceptions do not overturn the broader pattern observed across the material. Consultant reports tend to abstract from material lifecycles and distributive effects due to their forward-looking, mandate-driven orientation, whereas practitioners’ accounts foreground these issues because they encounter their consequences in implementation. The analytical distinction therefore captures structural tendencies shaped by institutional roles and knowledge practices, rather than a strict dichotomy of viewpoints.

Taken together, the interview and report evidence reveal two contrasting views of smart grid governance. To make these patterns explicit across the three CGG layers, material–temporal, social, and institutional,

Table 5
Cross-source synthesis by CGG layer: shared points, interview tensions, report blind spots, and governance implications.

CGC Layer	Shared Points	Interviews-Tensions/Gaps	Reports-Blind Spots/Gaps	Governance Implications
Material-Temporal	Flexibility, storage, and digital control seen as central to grid modernization	Mineral dependencies; e-waste; lifetime mismatch between fast electronics and slow grid assets; depreciation drives premature replacement	Hardware treated as neutral platform; lifecycle/material impacts rarely analyzed; lifetimes (technical/ regulatory/financial) not coordinated	**Synchronize lifecycles:** reform depreciation rules; require LCA/LCC on **replacement timing**; pilot service/leasing models linking performance with durability
Social	Demand response and automation expected to reduce system costs	Exclusion of renters, low-income, or digitally limited users; new vulnerabilities from automation	Universal, price-responsive consumer assumed; affordability and access omitted	**Justice-by-design:** ex-ante tariff distribution tests; procedural safeguards for remote control/ disconnection; renter-inclusive and non-digital participation routes
Institutional	Coordination among DSOs, regulators, and aggregators viewed as necessary	Informal coordination and workarounds; circular pilots (reuse, heat recovery) lack support; smaller actors lack capacity	Innovation equated with digitalization; municipal role minimal; circularity absent from mandates	**Institutionalize circularity/coordination:** repairability/parts access/take-back in tenders; certify harvested parts; align energy–digital–waste mandates; resource smaller DSOs/municipalities

Table 5 consolidates shared points, the tensions/gaps identified by practitioners, the blind spots/gaps in consultant reports, and the resulting governance implications.

Smart grid policy documents cast the transition as a problem of data and optimization, while practitioners describe systems constrained by materials, unequal access, and fragmented coordination. Read together, these views crystallize two priorities. First, lifecycle synchronization: current rules and procurement reward fast digital upgrades inside slow physical assets, pushing still-functional equipment into early replacement. Governance should align technical, regulatory, and financial lifetimes so durability and reuse are rewarded rather than penalized. Second, equity- and circularity-by-design, grounded in energy-justice principles (distributional, procedural, recognition). Today, flexibility benefits accrue mainly to households with capital and connectivity, while circular pilots stall without institutional backing. Energy justice and material stewardship must be designed upfront, via distributional checks on tariffs and automation, renter-inclusive participation routes, and procurement that requires repairability, parts access and take-back.

Across the material–temporal, social, and institutional layers, the pattern is consistent: reports imagine a neutral digital platform; practice reveals mineral dependencies, e-waste, depreciation-driven turnover, uneven participation, and everyday workarounds to bridge siloed mandates. While digitalization can widen participation, its system-level justice effects are heterogeneous across places, strengthening the case for ex-ante distributional testing and targeted inclusion measures. The remedy is not more optimization metrics but a shift in governance logic toward durability plus inclusion, operationalizing energy justice: model replacement timing in LCA/LCC, reform depreciation schedules, contract for performance and lifetime together (e.g., service/leasing models), add procedural safeguards for automated control and disconnection, and coordinate energy, digital, and waste agencies so circular measures can scale. Concretely, this would involve, for example, energy regulators and revenue-setting authorities aligning depreciation schedules with technical lifespans or allowing performance- and service-based asset valuation rather than rapid write-downs tied to digital upgrading; public authorities and DSOs embedding circular procurement criteria, such as repairability, modularity, parts access, and take-back obligations, into tendering processes despite existing legal constraints and supplier lock-in; utilities and municipalities designing renter-inclusive participation mechanisms that rely on automation and tariff design rather than asset ownership, while addressing data governance and split-incentive barriers; and strengthened coordination between energy, digital, and waste policy domains to clarify responsibility for end-of-life assets and enable circular measures to scale beyond pilots.

Fig. 2 synthesizes these findings in a color-coded heatmap, highlighting where the three CGG layers, material–temporal, social, and institutional, are acknowledged, underemphasized, or overlooked across both sources. This comparison sets the stage for the next section, which develops governance implications and shows how CGG can help bridge the gaps. The color coding in Fig. 2 represents an interpretive synthesis of the findings rather than a quantitative frequency analysis. "Strong engagement" (green) denotes recurring, explicit, and sustained attention to a given CGG layer across interviews or documents, including discussion of governance implications rather than isolated mentions. "Partial engagement" (amber) indicates selective, fragmented, or indirect treatment, for example through pilot-focused examples, problem framings without follow-through, or acknowledgement of issues without systematic elaboration. "Minimal or absent attention" (red) indicates

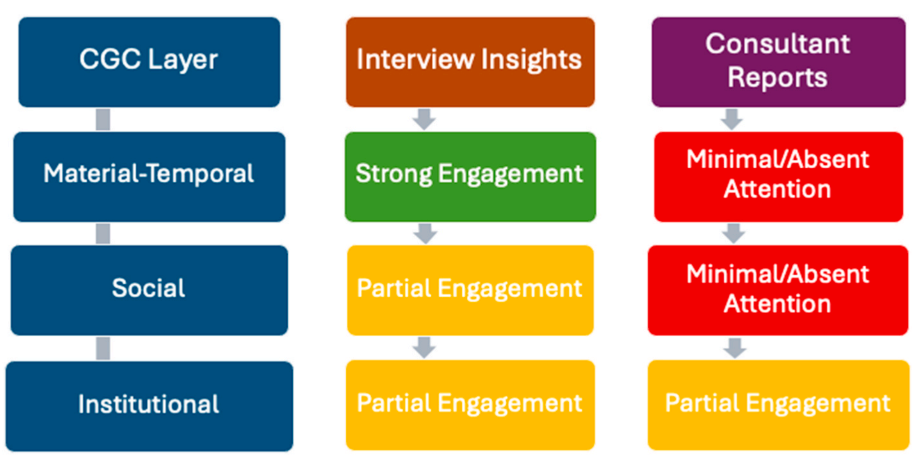

Fig. 2. Heatmap comparison of CGG layer engagement across consultant reports and interviews. Red indicates minimal or absent attention, amber indicates partial engagement (acknowledged but not embedded), and green indicates strong and systematic engagement. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

that a CGG layer was largely overlooked, treated as out of scope, or only implicitly referenced. These categorizations emerged inductively through comparative reading of interviews and consultant reports and were stabilized through analytical memos and team discussion.

Implementation feasibility and political economy constraints warrant explicit consideration. Interview material suggests that several of the proposed governance shifts face institutional resistance rooted in existing incentive structures. Depreciation reform challenges established revenue models for distribution system operators, where accelerated write-downs and reinvestment cycles are embedded in regulatory frameworks and reinforced by accounting practices that reward capital turnover. Circular procurement requirements confront risk-averse procurement cultures, long-standing supplier relationships, and legal constraints that prioritize cost certainty and standardization over lifecycle performance. More broadly, interviewees described how fragmented mandates across energy, digitalization, and waste governance generate organizational inertia, with actors benefiting from current role separations and limited responsibility for end-of-life impacts. These dynamics help explain why practitioners often rely on informal workarounds rather than formal reform and underscore that CGG's governance levers require not only technical design but institutional negotiation and coalition-building to become feasible in practice.

5. Discussion

The findings presented above show a persistent tension in smart grid governance. While policy documents and strategic reports commonly frame smart grids as data-driven systems of optimization and flexibility, practitioners describe infrastructures shaped by material constraints, institutional fragmentation, and uneven participation. Interpreted through the CGG framework, these differences point to governance misalignments between digitalization, infrastructure lifecycles, and social inclusion. Rather than reflecting isolated implementation challenges, these tensions indicate structural gaps in how smart grid transitions are currently governed. This section interprets these findings through the CGG framework and explores their implications for smart grid governance. We first identify two cross-cutting governance gaps found in the empirical analysis. We then outline four governance steps that translate the three CGG layers into practical governance directions.

5.1. Identified gaps

The comparative analysis points to two cross-cutting gaps that run through the material–temporal, social, and institutional layers. First, lifecycle synchronization is weak: depreciation schedules, standards updates, and software-driven obsolescence drive the premature replacement of still-functional assets. Second, equity and justice are barely addressed in the studied documents, even though the interviewed practitioners describe them as central concerns. In practice, the benefits of flexibility and automation tend to favour digitally literate homeowners, while renters and lower-income households face higher barriers to participation and fewer protections. Institutional fragmentation then keeps promising circular practices, component reuse, second-life storage, service-based models, bounded within pilots rather than mainstreamed. Together, these findings indicate that material, temporal, and social sustainability are tightly coupled. Without synchronization and justice, digital optimization risks reproducing the very sustainability challenges it is meant to resolve. The four steps discussed below translate the three CGG layers, material–temporal, social, and institutional into analytically distinct but interrelated governance moves.

Step 1: Making the Digital Material

Research on platforms and data infrastructures has long challenged the notion of an "immaterial" cloud (Kloppenburg and Boekelo, 2019; Charfeddine and Umlai, 2023; Crawford, 2021). In smart grids, meters, gateways, controllers, communications, and data centers draw on critical minerals and energy-intensive manufacturing, with uneven environmental and geopolitical consequences (Khalid, 2024; Monaco et al., 2024; Van Opstal et al., 2025; Wolsink, 2024). Practitioners in our study foreground these realities, rare-earth dependencies, e-waste risks, embodied emissions, whereas the reports largely treat hardware as a neutral carrier for digital services. Industrial ecology research complicates the simple rule that extending product lifetimes always reduces environmental impacts: early replacement can be beneficial under certain conditions, but these gains diminish as electricity systems decarbonize and as rebound and user effects are considered (Richter et al., 2019, 2024). The implication is not that "longer is always better," but that replacement timing should be governed rather than taken for granted. The findings suggest a model of digitalization where digital upgrades are adopted selectively, when they provide lifecycle or system-level sustainability benefits, rather than being pursued simply because new technologies become available. This is precisely the ambition of CGG's material–temporal layer. The notion of sufficiency-oriented digitalization is, however, normatively contested. Different actors may draw the boundary between justified and excessive upgrading differently depending on regulatory mandates, economic incentives, technological expectations, and sustainability priorities. CGG does not attempt to resolve these political and economic debates. Rather, it highlights the need for governance processes that make replacement timing and lifecycle impacts explicit objects of evaluation rather than leaving them to default assumptions of continuous technological upgrading. Specifically, an upgrade is considered justified within CGG's framework when LCA/LCC evidence, incorporating replacement-timing scenarios and system-carbon trajectories, demonstrates net sustainability gains that outweigh the embodied costs of early replacement, a threshold that draws directly on Richter et al.'s (2019; 2024) finding that upgrade benefits are context-dependent and require system-level evaluation rather than blanket rules. This is not a fixed technical standard but an institutionally negotiated threshold, to be embedded in regulatory appraisal processes, procurement criteria, and depreciation regimes through the governance mechanisms described in the following step.

Step 2: A Shift to Lifecycle Governance

The second step is to shift from lifecycle analytics to lifecycle governance, which provides the institutional decision criteria through which such sufficiency considerations can be evaluated in practice. Lifecycle tools (LCA/LCC) urge system-wide accounting yet often rely on simplifying assumptions about displacement and time, and they are commonly appended/applied after decisions are made rather than shaping them (Bluhm et al., 2025; Richter et al., 2024; Wohlschlager et al., 2023). Our interviews show that lifecycles are effectively set by institutions: accounting norms, depreciation regimes, standards cycles, and procurement routines decide when devices are retired, upgraded, or repaired. This resonates with resource-governance perspectives that emphasize the politics of material flows (Bridge et al., 2018). CGG repositions LCA/LCC as ex-ante decision rules, that is, clear criteria written into appraisals and tenders that determine when to replace, upgrade, repair, or redeploy assets: synchronize technical durability with regulatory and financial horizons; require replacement-timing scenarios and system-carbon trajectories; and create testing/certification infrastructures that make harvested-parts reuse bankable (Richter et al., 2023). In this way, the sufficiency principle is operationalized not as a normative ideal but as a procedural requirement. Replacement and upgrade decisions must be justified through explicit lifecycle and system-level evidence rather than driven by default assumptions of continuous technological innovation. This step operationalizes the material–temporal layer of CGG by shifting attention from measurement to the governance of asset lifetimes and replacement decisions.

Step 3: Designing for Energy Justice

A third step is to bring energy justice in at design time, not afterward. Energy-justice research distinguishes distributive, procedural, and recognition dimensions (Jenkins et al., 2016; Heffron, 2021; Heffron and McCauley, 2017), and Swedish studies have shown multiple forms of exclusion exist around s digital skills, participation opportunities, connectivity, and household financial capacities (Tarasova and Rohracher, 2023a, 2023b). Our material corroborates these dynamics: flexibility markets and dynamic tariffs tend to privilege homeowners with capital, devices, and digital literacy; renters and low-income users face higher exposure to risk and fewer channels of influence. Digital systems also introduce risks of opaque automation and remote control unless counter-balanced by due process (Eubanks, 2018; Rossi et al., 2024). CGG translates these concerns into justice-by-design: distributional checks for tariff reforms (who pays/benefits and who is exposed to risk); renter-inclusive participation routes and non-digital pathways; and transparency, limits, and appeals around automated control and disconnection. In practice, these checks would be applied at concrete decision points, including tariff-setting processes, regulatory approval of automated control systems, design of flexibility programs, and public procurement of digital grid technologies. This step corresponds to CGG's social layer, emphasizing how distributive, procedural, and recognition justice must be co-designed with digital and infrastructural choices rather than addressed retroactively.

Step 4: Institutionalizing Circularity

A fourth step is to institutionalize circularity. Circular-economy research offers well-known levers, repair, refurbishment, modularity, service-based models (Awan et al., 2021; Kirchherr et al., 2023; Stahel, 2019), but scaling remains difficult without enabling institutions. Our evidence echoes this: reuse, second-life storage, and heat-recovery pilots exist but are bounded by procurement liabilities, lack of testing standards, and siloed responsibilities across energy, waste, and digital policy (David and Koch, 2019; Schumacher and Green, 2023; Reindl et al., 2024). CGG's institutional layer links design for circularity to integrated governance: circular procurement requirements (repairability, diagnostic access, parts availability, take-back), certification pathways for harvested components, and joint mandates/metrics across authorities. Without these institutional supports, circular practices remain exceptions rather than standard practice.

5.2. Positioning CGG withing existing research

Research on smart grids and sustainability transitions provides important insights but remains fragmented across several strands of literature. Circular economy research highlights design strategies for extending product lifetimes, such as repairability, modularity, and service-based models, but often pays limited attention to the accounting rules and regulatory arrangements that govern infrastructure replacement (Stahel, 2019; Awan et al., 2021; Kirchherr et al., 2023[JP1.1]). Lifecycle-oriented studies refine environmental assessment methods and provide increasingly sophisticated tools for evaluating the impacts of infrastructure systems, but they rarely address the institutional decision rules that determine when infrastructures are upgraded or retired (Richter et al., 2024; Wohlschlager et al., 2023; Bluhm et al., 2025). Meanwhile, energy justice research has highlighted important inequalities in energy transitions, particularly in relation to participation, affordability, and access, but seldom examines how these outcomes are shaped by infrastructure lifecycles and the governance of material systems (Jenkins et al., 2016; Sovacool et al., 2021; Tarasova and Rohracher, 2023a, 2023b).

Against this background, CGG contributes to the research in three ways. First, CGG reframes lifecycles as governance outcomes. Smart grid research has addressed lifecycle issues primarily through technical planning stages and lifecycle assessment tools that evaluate environmental impacts across component specification, operation, and decommissioning (Wohlschlager et al., 2023; Bluhm et al., 2025). CGG does not claim to introduce lifecycle thinking to this domain. Rather, it highlights how depreciation regimes, procurement standards, regulatory incentives, and coordination arrangements shape when infrastructures are maintained, upgraded, or replaced. In this sense, CGG shifts analytical attention from lifecycle analytics to lifecycle governance.

Second, CGG integrates lifecycle governance with energy justice. While justice-oriented smart grid research has highlighted issues of participation, distribution, and user inclusion (Jenkins et al., 2016; Sovacool et al., 2025), it rarely examines how institutional rules governing infrastructure lifecycles shape these outcomes. Conversely, lifecycle-oriented frameworks typically focus on environmental metrics while paying limited attention to distributive and procedural justice dimensions. CGG therefore brings these strands together by examining how material lifecycles, institutional incentives, and justice outcomes are co-produced within infrastructure governance.

Third, CGG provides an analytical lens for identifying governance tensions in digital energy transitions. Rather than proposing a prescriptive policy model, the framework highlights structural misalignments between material lifecycles, institutional incentives, and justice considerations, thereby offering a conceptual basis for analysing how sustainability outcomes are shaped by infrastructure governance.

5.3. Practical implications

In practical terms, several implications follow. These implications are not intended as prescriptive policy recommendations or implementation roadmaps, but as governance levers and design principles derived from recurring frictions identified in the empirical material. Aligning depreciation schedules with technical lifetimes to reduce premature replacement incentives is a key governance lever. Depreciation and investment appraisal should therefore be aligned with technical durability by requiring LCA/LCC that include replacement-timing scenarios and system-carbon pathways. Circular practices need to be supported through procurement rules and standards. Otherwise, repair and reuse depend on exceptional individual effort rather than being economically viable. Institutionalizing requirements for repairability, access to repair information, parts availability, take-back systems, and certification for refurbished components can make these practices scalable (David and Koch, 2019; Reindl et al., 2024). Such reforms would inevitably involve complex negotiations among regulators, utilities, ministries, and market actors, and their political feasibility will vary across institutional contexts, an issue that warrants dedicated political-economy analysis beyond the scope of this article. Consumer-facing smart grid programs, by which we mean dynamic tariffs, automated load control, home energy management, and Distributed Energy Resources (DER) enrolment, should be fair, accessible, and affordable, with due-process protections so automation and market signals do not amplify inequality. Within CGG, these implications function as evaluative questions rather than performance metrics, for example, which user groups bear costs and risks, who participates in decision-making, and whose needs and capacities are recognized in system design, providing a structured basis for assessment without presupposing a single quantitative indicator set. Finally, mandates and budgets should be coordinated across energy, waste, and digital agencies; without such cooperation, material and data systems will continue to be planned separately (David and Koch, 2019; Reindl et al., 2024).

Although this analysis is rooted in Sweden's high-capacity setting, the framework can be applied to other digitalizing infrastructures, such as mobility, water, and broadband, where similar material, temporal, and justice tensions surface. At the same time, the justice implications of digitalization vary significantly between contexts, which strengthens the case for targeted inclusion and affordability measures rather than one-size-fits-all approaches.

5.4. Limitations and future research

This study has limitations and points to next steps. On transferability, institutional logics vary across countries and market designs, thus comparative applications are needed to understand how CGG performs under weaker regulatory capacity or different ownership structures, and how its principles must be adapted rather than directly replicated in other institutional and welfare-state settings. Importantly, while this study explicitly highlights supply-chain and end-of-life injustices, such as mineral extraction and e-waste processing, that disproportionately affect regions in the Global South, the empirical analysis itself is grounded in a Swedish, Global North context. This creates a risk that Global South regions appear primarily as sites of extraction or disposal rather than as locations of smart grid development and governance in their own right. We therefore emphasize that CGG is not intended as a context-neutral or universally transferable model. Applying CGG beyond Sweden requires careful attention to context. In practical terms, the framework is most readily applicable in settings with relatively strong regulatory capacity, formalized asset governance, and public accountability in infrastructure planning, while its application in more fragmented, market-driven, or resource-constrained contexts, particularly in parts of the Global South, would face substantial implementation barriers related to state capacity, institutional coordination, data availability, and socio-economic inequality. In such settings, CGG would require substantial adaptation, including greater attention to informal institutions, development priorities, and locally grounded forms of participation. Exploring how lifecycle governance, justice, and circularity intersect under these conditions is an important direction for future research building on the CGG framework.

The study also has temporal limitations. The interviews were conducted in 2022, prior to a number of regulatory developments in Swedish electricity governance. Since then, the Swedish Energy Markets Inspectorate has revised continuity-of-supply regulation, introducing new derogation possibilities for distribution system operators from 2024 onward, and has continued to adjust and review revenue-cap regulation and quality incentives for the 2024–2027 regulatory period. These developments indicate that governance arrangements around reliability, investment incentives, and grid operation continue to evolve beyond the period of data collection. While many of the frictions identified in this study, such as depreciation-driven turnover, institutional fragmentation, and uneven inclusion, reflect structural dynamics unlikely to change rapidly, future research should examine how such dynamics are reshaped under evolving regulatory conditions.

At the sector level, the empirical focus on electricity and smart grid development necessarily excludes other increasingly digitalized energy domains, such as heating, transport, and integrated multi-energy systems, where material lifecycles, institutional arrangements, and justice implications may differ. Applying CGG to these sectors provides a valuable opportunity for empirical testing and refinement.

On operationalization, the contribution of this study is diagnostic rather than metric based. Accordingly, the qualitative design enables in-depth analysis of governance logics, institutional frictions, and justice implications, but does not quantify the scale or prevalence of these dynamics across the system. We translate lifecycle and circular insights into governance levers, but the quantitative coupling of asset registries with lifecycle and equity metrics remains a necessary next step to implement lifecycle synchronization and to evaluate circular-procurement pilots using justice-sensitive outcomes (Bluhm et al., 2025; Richter et al., 2023). These directions point to an agenda for future research and policy experimentation.

6. Conclusions

This article shows that prevailing smart grid governance often treats digital infrastructure as if it were immaterial and uniformly beneficial, obscuring the material, temporal, and justice dimensions that shape real-world transitions. Using Sweden as a strategic case, we introduced CGG, a layered lens that integrates circular-economy principles, life-cycle thinking, and energy justice. By comparing consultant reports with practitioner interviews, the analysis reveals a persistent gap: policy documents tend to frame smart grids as systems of digital optimization, while practitioners foreground mineral dependencies, depreciation-driven infrastructure turnover, uneven participation, and fragmented governance arrangements.

The findings highlight two key governance priorities. First, .lifecycle synchronization is required so that depreciation schedules and investment incentives reflect actual technical lifetimes rather than encouraging premature replacement of still-functional infrastructures. Second, equity- and circularity-must be built into governance arrangement from the outset through renter-inclusive participation models, distributional safeguards in tariff and automation system and procurement frameworks that supports repairability, modularity and component reuse. Achieving these goals also requires stronger coordination across energy, digital and waste governance domains.

By linking circular economy thinking, lifecycle governance, and energy justice within a single analytical framework, this study contributes a governance perspective on smart grid transitions that foregrounds infrastructure lifecycles as central determinants of sustainability outcomes. More broadly, the findings show that the environmental and social impacts of digital infrastructures are shaped not only by technology but also by institutional rules governing infrastructure lifecycles, investment incentives, and access to energy services.

Although grounded in the Swedish context, CGG offers a heuristic that can inform analyses of other digitalizing infrastructures. Future research should examine how lifecycle governance and justice considerations interact across different regulatory settings and socio-economic contexts. Ultimately, making energy systems “smarter” is not sufficient: digital infrastructures must be governed for durability, inclusion, and coordination if digitalization is to advance rather than undermine sustainability.

CRediT authorship contribution statement

Georgios Pardalis: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jenny Palm:** Writing – review & editing, Writing – original draft, Resources, Funding acquisition. **Katharina Reindl:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition.

Declaration of competing interest

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

Acknowledgements

The authors would like to express sincere gratitude to the individuals who generously shared their time and insights during the interviews. Their perspectives were invaluable to the development of this study. This work was supported by funding from IIIEE Foundation, the Kamprad Family Foundation and the Swedish Energy Agency under grant number 50538-1.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.148238.

Appendix A
Acronyms and Abbreviations (Energy-Sector Terms Only)

CGG:	Circular Grid Governance
DSO:	Distribution System Operator
DER:	Distributed Energy Resources
GDPR	General Data Protection Regulation
LCA:	Life Cycle Assessment
LCC:	Life Cycle Costing
NECP	National Energy and Climate Plan
SLES:	Smart Local Energy Systems
HEMS:	Home Energy Management Systems

Data availability

Data will be made available on request.

References

Abdirahman, A.A., Asif, M., Mohsen, O., 2025. Circular economy in the renewable energy sector: a review of growth trends, gaps and future directions. Energy Nexus, 100395. https://doi.org/10.1016/j.nexus.2025.100395.

Aghahadi, M., Bosisio, A., Merlo, M., Berizzi, A., Pegoiani, A., Forciniti, S., 2024. Digitalization processes in distribution grids: a comprehensive review of strategies and challenges. Appl. Sci. 14 (11), 4528. https://doi.org/10.3390/app14114528.

Ahmad, T., Madonski, R., Zhang, D., Huang, C., Mujeeb, A., 2022. Data-driven probabilistic machine learning in sustainable smart energy/smart energy systems: key developments, challenges, and future research opportunities in the context of smart grid paradigm. Renew. Sustain. Energy Rev. 160, 112128. https://doi.org/10.1016/j.rser.2022.112128.

Almihat, M.G.M., Munda, J.L., 2025. The role of smart grid technologies in urban and sustainable energy planning. Energies 18 (7), 1618. https://doi.org/10.3390/en18071618.

Amin, S.M., Wollenberg, B.F., 2005. Toward a smart grid: power delivery for the 21st century. IEEE Power Energy Mag. 3 (5), 34–41. https://doi.org/10.1109/MPAE.2005.1507024.

Awan, U., Sroufe, R., Shahbaz, M., 2021. Industry 4.0 and the circular economy: a literature review and recommendations for future research. Bus. Strat. Environ. 30 (4), 2038–2060. https://doi.org/10.1002/bse.2731.

Baidya, S., Potdar, V., Ray, P.P., Nandi, C., 2021. Reviewing the opportunities, challenges, and future directions for the digitalization of energy. Energy Res. Social Sci. 81, 102243. https://doi.org/10.1016/j.erss.2021.102243.

Bakke, G., 2016. The Grid: the Fraying Wires Between Americans and our Energy Future. Bloomsbury Publishing USA. ISBN: 978-1-60819-610-4 (HB).

Bluhm, H., Wohlschlager, D., Pohl, J., Beucker, S., Bieser, J., Schien, D., et al., 2025. Understanding digitalization's environmental impact: why LCA is essential for informed decision-making. npj Clim. Action 4 (1), 41. https://doi.org/10.1038/s44168-025-00246-1.

Bonina, C., Koskinen, K., Eaton, B., Gawer, A., 2021. Digital platforms for development: foundations and research agenda. Inf. Syst. J. 31 (6), 869–902. https://doi.org/10.1111/isj.12326.

Borowski, P.F., 2021. Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector. Energies 14 (7), 1885. https://doi.org/10.3390/en14071885.

Bridge, G., Özkaynak, B., Turhan, E., 2018. Energy infrastructure and the fate of the nation: introduction to special issue. Energy Res. Social Sci. 41, 1–11. https://doi.org/10.1016/j.erss.2018.04.029.

Brodie, P., 2025. Smarter, greener extractivism: digital infrastructures and the harnessing of new resources. Inf. Commun. Soc. 28 (6), 1061–1080. https://doi.org/10.1080/1369118X.2024.2341013.

Butt, O.M., Zulqarnain, M., Butt, T.M., 2021. Recent advancement in smart grid technology: future prospects in the electrical power network. Ain Shams Eng. J. 12 (1), 687–695. https://doi.org/10.1016/j.asej.2020.05.004.

Çelik, D., Meral, M.E., Waseem, M., 2022. Investigation and analysis of effective approaches, opportunities, bottlenecks and future potential capabilities for digitalization of energy systems and sustainable development goals. Elec. Power Syst. Res. 211, 108251. https://doi.org/10.1016/j.epsr.2022.108251.

Cenamor, J., Sjödin, D.R., Parida, V., 2017. Adopting a platform approach in servitization: leveraging the value of digitalization. Int. J. Prod. Econ. 192, 54–65. https://doi.org/10.1016/j.ijpe.2016.12.033.

Charfeddine, L., Umlai, M., 2023. ICT sector, digitization and environmental sustainability: a systematic review of the literature from 2000 to 2022. Renew. Sustain. Energy Rev. 184, 113482. https://doi.org/10.1016/j.rser.2023.113482.

Charmaz, K., 2017. The power of constructivist grounded theory for critical inquiry. Qual. Inq. 23 (1), 34–45. https://doi.org/10.1177/1077800416657105.

Chilvers, J., Pallett, H., Hargreaves, T., 2018. Ecologies of participation in socio-technical change: the case of energy system transitions. Energy Res. Social Sci. 42, 199–210. https://doi.org/10.1016/j.erss.2018.03.020.

Ciplet, D., 2021. From energy privilege to energy justice: a framework for embedded sustainable development. Energy Res. Social Sci. 75, 101996. https://doi.org/10.1016/j.erss.2021.101996.

Crawford, K., 2021. The Atlas of AI: Power, Politics, and the Planetary Costs of Artificial Intelligence. Yale University Press, ISBN 978-0-300-20957-0.

Damianou, A., Vayona, A., Demetriou, G., Katos, V., 2023. An actionable maturity planning model for smart, circular cities. Cities 140, 104403. https://doi.org/10.1016/j.cities.2023.104403.

Das, J., Kleiman, A., Rehman, A.U., Verma, R., Young, M.H., 2024. The cobalt supply chain and environmental life cycle impacts of lithium-ion battery energy storage systems. Sustainability 16 (5), 1910. https://doi.org/10.3390/su16051910.

David, M., Koch, F., 2019. "Smart is not smart enough!" anticipating critical raw material use in smart city concepts: the example of smart grids. Sustainability 11 (16), 4422. https://doi.org/10.3390/su11164422.

Dedrick, J., Venkatesh, M., Stanton, J.M., Zheng, Y., Ramnarine-Rieks, A., 2015. Adoption of smart grid technologies by electric utilities: factors influencing organizational innovation in a regulated environment. Electron. Mark. 25, 17–29. https://doi.org/10.1007/s12525-014-0166-6.

Di Silvestre, M.L., Favuzza, S., Sanseverino, E.R., Zizzo, G., 2018. How decarbonization, digitalization and decentralization are changing key power infrastructures. Renew. Sustain. Energy Rev. 93, 483–498. https://doi.org/10.1016/j.rser.2018.05.068.

Durillon, B., Bossu, A., 2024. Environmental assessment of smart energy management systems at distribution level, a review. Renew. Sustain. Energy Rev. 203, 114739. https://doi.org/10.1016/j.rser.2024.114739.

Ertugrul, N., 2024. Reinventing the Power Grid: Renewable Energy, Storage, and Grid Modernization. CRC Press, Boca Raton, Florida, USA. https://doi.org/10.1201/9781032692173.

Eubanks, V., 2018. Automating Inequality: How high-tech Tools Profile, Police, and Punish the Poor. St. Martin's Press. ISBN: 9781250074317.

Gargalo, C.L., Yu, H., Vollmer, N., Arabkoohsar, A., Gernaey, K.V., Sin, G., 2024. A process systems engineering view of environmental impact assessment in renewable and sustainable energy production: status and perspectives. Comput. Chem. Eng. 180, 108504. https://doi.org/10.1016/j.compchemeng.2023.108504.

Haque, A., Hussain, M.N., Ali, M.S., Khan, M.Y.A., Halim, M.A., 2023. Technical and economic challenges and future prospects of a smart Grid-A case study. Contr. Syst. Optimizat. Lett. 1 (3), 186–193. https://doi.org/10.59247/csol.v1i3.57.

Heffron, R.J., 2021. The Challenge for Energy Justice. Springer International Publishing. https://doi.org/10.1007/978-3-030-80097-0.

Heffron, R.J., McCauley, D., 2017. The concept of energy justice across the disciplines. Energy Policy 105, 658–667. https://doi.org/10.1016/j.enpol.2017.03.018.

Hernández-Callejo, L., 2019. A comprehensive review of operation and control, maintenance and lifespan management, grid planning and design, and metering in smart grids. Energies 12 (9), 1630. https://doi.org/10.3390/en12091630.

Hielscher, S., Sovacool, B.K., 2018. Contested smart and low-carbon energy futures: media discourses of smart meters in the United Kingdom. J. Clean. Prod. 195, 978–990. https://doi.org/10.1016/j.jclepro.2018.05.227.

Inderberg, T.H.J., Palm, J., Matthiasen, E.H., 2024. Flexible electricity consumption policies in Norway and Sweden: implications for energy justice. Energy Res. Social Sci. 110, 103466. https://doi.org/10.1016/j.erss.2024.103466.

Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016. Energy justice: a conceptual review. Energy Res. Social Sci. 11, 174–182. https://doi.org/10.1016/j.erss.2015.10.004.

Jordaan, S.M., Combs, C., Guenther, E., 2021. Life cycle assessment of electricity generation: a systematic review of spatiotemporal methods. Adv. Appl. Energy 3, 100058. https://doi.org/10.1016/j.adapen.2021.100058.

Judge, M.A., Khan, A., Manzoor, A., Khattak, H.A., 2022. Overview of smart grid implementation: frameworks, impact, performance and challenges. J. Energy Storage 49, 104056. https://doi.org/10.1016/j.est.2022.104056.

Khalid, M., 2024. Smart grids and renewable energy systems: perspectives and grid integration challenges. Energy Strategy Rev. 51, 101299. https://doi.org/10.1016/j.esr.2024.101299.
Kirchherr, J., Yang, N.H.N., Schulze-Spüntrup, F., Heerink, M.J., Hartley, K., 2023. Conceptualizing the circular economy (revisited): an analysis of 221 definitions. Resour. Conserv. Recycl. 194, 107001. https://doi.org/10.1016/j.resconrec.2023.107001.
Kloppenburg, S., Boekelo, M., 2019. Digital platforms and the future of energy provisioning: promises and perils for the next phase of the energy transition. Energy Res. Social Sci. 49, 68–73. https://doi.org/10.1016/j.erss.2018.10.016.
Knox, S., Hannon, M., Stewart, F., Ford, R., 2022. The (in) justices of smart local energy systems: a systematic review, integrated framework, and future research agenda. Energy Res. Social Sci. 83, 102333. https://doi.org/10.1016/j.erss.2021.102333.
Kojonsaari, A.R., Palm, J., 2023. The development of social science research on smart grids: a semi-structured literature review. Energy Sustain. Soc. 13 (1), 1. https://doi.org/10.1186/s13705-023-00381-9.
Kortelainen, H., Hanski, J., 2023. Asset life cycle management for smart grids: challenges and implications. Int. J. Strat. Eng. Asset Manag. 4 (1), 26–46. https://doi.org/10.1504/IJSEAM.2023.136185.
Kristia, K., Rabbi, M.F., 2023. Exploring the synergy of renewable energy in the circular economy framework: a bibliometric study. Sustainability 15 (17), 13165. https://doi.org/10.3390/su151713165.
Lacey-Barnacle, M., Robison, R., Foulds, C., 2020. Energy justice in the developing world: a review of theoretical frameworks, key research themes and policy implications. Energy Sustain. Dev. 55, 122–138. https://doi.org/10.1016/j.esd.2020.01.010.
Li, G., Wen, H., Sun, Q., Xue, J., 2025. The role of the digital economy in promoting energy justice: evidence from procedural justice and restorative justice. China Econ. Rev. 89, 102334. https://doi.org/10.1016/j.chieco.2024.102334.
Lyulyov, O., Vakulenko, I., Pimonenko, T., Kwilinski, A., Dzwigol, H., Dzwigol-Barosz, M., 2021. Comprehensive assessment of smart grids: is there a universal approach? Energies 14 (12), 3497. https://doi.org/10.3390/en14123497.
Milchram, C., Hillerbrand, R., van de Kaa, G., Doorn, N., Künneke, R., 2018. Energy justice and smart grid systems: evidence from the Netherlands and the United Kingdom. Appl. Energy 229, 1244–1259. https://doi.org/10.1016/j.apenergy.2018.08.053.
Milchram, C., Künneke, R., Doorn, N., van de Kaa, G., Hillerbrand, R., 2020. Designing for justice in electricity systems: a comparison of smart grid experiments in the Netherlands. Energy Policy 147, 111720. https://doi.org/10.1016/j.enpol.2020.111720.
Monaco, R., Bergaentzlé, C., Vilaplana, J.A.L., Ackom, E., Nielsen, P.S., 2024. Digitalization of power distribution grids: barrier analysis, ranking and policy recommendations. Energy Policy 188, 114083. https://doi.org/10.1016/j.enpol.2024.114083.
Moreno Escobar, J.J., Morales Matamoros, O., Tejeida Padilla, R., Lina Reyes, I., Quintana Espinosa, H., 2021. A comprehensive review on smart grids: challenges and opportunities. Sensors 21 (21), 6978. https://doi.org/10.3390/s21216978.
Mulvaney, D., 2024. Embodied energy injustice and the political ecology of solar power. Energy Res. Social Sci. 115, 103607. https://doi.org/10.1016/j.erss.2024.103607.
Munonye, W.C., 2025. Circular economy meets smart energy grids: designing systems for resource optimization and carbon reduction. Front. Sustain. 6, 1568254. https://doi.org/10.3389/frsus.2025.1568254.
Powells, G., Fell, M.J., 2019. Flexibility capital and flexibility justice in smart energy systems. Energy Res. Social Sci. 54, 56–59. https://doi.org/10.1016/j.erss.2019.03.015.
Ramirez, B., 2025. Smart Cities. Publifye AS. ISBN: 9788233997021.
Reindl, K., Dalhammar, C., Brodén, E., 2024. Circular economy integration in smart grids: a nexus for sustainability. Circ. Econ. Sustain. 4 (3), 2119–2145. https://doi.org/10.1007/s43615-024-00375-5.
Richter, J.L., Makov, T., Parajuly, K., Bakker, C., Fitzpatrick, C., 2024. Product lifetimes and industrial ecology. J. Ind. Ecol. 28 (6). https://doi.org/10.1111/jiec.13489.
Richter, J.L., Svensson-Hoglund, S., Dalhammar, C., Russell, J.D., Thidell, Å., 2023. Taking stock for repair and refurbishing: a review of harvesting of spare parts from electrical and electronic products. J. Ind. Ecol. 27 (3), 868–881. https://doi.org/10.1111/jiec.13315.
Richter, J.L., Tähkämö, L., Dalhammar, C., 2019. Trade-offs with longer lifetimes? The case of LED lamps considering product development and energy contexts. J. Clean. Prod. 226, 195–209. https://doi.org/10.1016/j.jclepro.2019.03.331.
Rommens, T., Van Opstal, W., Caers, B., Ysebie, W., Desmet, J., 2024. Blueprint for a circular smartgrid. Lessons from the transfo-demonstrator. Urban Innovative Actions, Lille, France. https://www.researchgate.net/profile/WimVanOpstal/publication/381786950_Blueprint_for_a_Circular_Smartgrid_Lessons_from_the_Transfo-demonstrator/links/6841543c6a754f72b5908f13/Blueprint-for-a-Circular-Smartgrid-Lessons-from-the-Transfo-demonstrator.pdf.
Rossi, A., Carli, R., Botes, M.W., Fernandez, A., Sergeeva, A., Chamorro, L.S., 2024. Who is vulnerable to deceptive design patterns? A transdisciplinary perspective on the multi-dimensional nature of digital vulnerability. Comput. Law Secur. Rep. 55, 106031. https://doi.org/10.1016/j.clsr.2024.106031.
Roos, A., 2023. Solar Technology and Global Environmental Justice: the Vision and the Reality. Routledge, London, United Kingdom. https://doi.org/10.4324/9781003292319.
Schumacher, K.A., Green, M.L., 2023. Circular economy in a high-tech world. Circ. Econ. Sustain. 3 (2), 619–642. https://doi.org/10.1007/s43615-022-00220-7.
Simcock, N., Jenkins, K.E., Lacey-Barnacle, M., Martiskainen, M., Mattioli, G., Hopkins, D., 2021. Identifying double energy vulnerability: a systematic and narrative review of groups at-risk of energy and transport poverty in the global north. Energy Res. Social Sci. 82, 102351. https://doi.org/10.1016/j.erss.2021.102351.
Sovacool, B.K., Carley, S., Kiesling, L., 2024. Energy justice beyond the wire: exploring the multidimensional inequities of the electrical power grid in the United States. Energy Res. Social Sci. 111, 103474. https://doi.org/10.1016/j.erss.2024.103474.
Sovacool, B.K., Geels, F.W., Andersen, A.D., Grubb, M., Jordan, A.J., Kern, F., et al., 2025. The acceleration of low-carbon transitions: insights, concepts, challenges, and new directions for research. Energy Res. Social Sci. 121, 103948. https://doi.org/10.1016/j.erss.2025.103948.
Sovacool, B.K., Hess, D.J., Cantoni, R., 2021. Energy transitions from the cradle to the grave: a meta-theoretical framework integrating responsible innovation, social practices, and energy justice. Energy Res. Social Sci. 75, 102027. https://doi.org/10.1016/j.erss.2021.102027.
Sovacool, B.K., Hess, D.J., Cantoni, R., Lee, D., Brisbois, M.C., Walnum, H.J., et al., 2022. Conflicted transitions: exploring the actors, tactics, and outcomes of social opposition against energy infrastructure. Glob. Environ. Change 73, 102473. https://doi.org/10.1016/j.gloenvcha.2022.102473.
Sovacool, B.K., Martiskainen, M., Hook, A., Baker, L., 2019. Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions. Clim. Change 155, 581–619. https://doi.org/10.1007/s10584-019-02521-7.
Stahel, W.R., 2019. The Circular Economy: a User's Guide. Routledge, London, United Kingdom. https://doi.org/10.4324/9780429259203.
Süsser, D., Martin, N., Stavrakas, V., Gaschnig, H., Talens-Peiró, L., Flamos, A., et al., 2022. Why energy models should integrate social and environmental factors: assessing user needs, omission impacts, and real-word accuracy in the european union. Energy Res. Social Sci. 92, 102775. https://doi.org/10.1016/j.erss.2022.102775.
Tarasova, E., Rohracher, H., 2023a. Marginalising household users in smart grids. Technol. Soc. 72, 102185. https://doi.org/10.1016/j.techsoc.2022.102185.
Tarasova, E., Rohracher, H., 2023b. Democratizing energy through smart grids? Discourses of empowerment vs practices of marginalization. In: Energy Democracies for Sustainable Futures. Academic Press, pp. 311–316. https://doi.org/10.1016/B978-0-12-822796-1.00033-4.
Timmermans, S., Tavory, I., 2012. Theory construction in qualitative research: from grounded theory to abductive analysis. Sociol. Theor. 30 (3), 167–186. https://doi.org/10.1177/0735275112457914.
Tuballa, M.L., Abundo, M.L., 2016. A review of the development of smart grid technologies. Renew. Sustain. Energy Rev. 59, 710–725. https://doi.org/10.1016/j.rser.2016.01.011.
Uslar, M., Rohjans, S., Neureiter, C., Pröstl Andrén, F., Velasquez, J., Steinbrink, C., et al., 2019. Applying the smart grid architecture model for designing and validating system-of-systems in the power and energy domain: a European perspective. Energies 12 (2), 258. https://doi.org/10.3390/en12020258.
van der Wel, K., Akerboom, S., 2024. Overlooked, misunderstood, or sidelined?: explaining why energy justice is not safeguarded in smart local energy systems. Energy Res. Social Sci. 118, 103785. https://doi.org/10.1016/j.erss.2024.103785.
Van Opstal, W., Bocken, N., Brusselaers, J., 2025. Smart, circular and renewable: the role of cooperative governance in accelerating a sustainable energy transition. Energy Res. Social Sci. 123, 104049. https://doi.org/10.1016/j.erss.2025.104049.
Van Uffelen, N., 2022. Revisiting recognition in energy justice. Energy Res. Social Sci. 92, 102764. https://doi.org/10.1016/j.erss.2022.102764.
Verbong, G.P., Beemsterboer, S., Sengers, F., 2013. Smart grids or smart users? Involving users in developing a low carbon electricity economy. Energy Policy 52, 117–125. https://doi.org/10.1016/j.enpol.2012.05.003.
Verdejo-Espinosa, Á., Espinilla-Estévez, M., Mata, F., 2020. Smart grids and their role in transforming human activities—a systematic literature review. Sustainability 12 (20), 8662. https://doi.org/10.3390/su12208662.
Walker, G., 2009. Beyond distribution and proximity: exploring the multiple spatialities of environmental justice. Antipode 41 (4), 614–636. https://doi.org/10.1111/j.1467-8330.2009.00691.x.
Wohlschlager, D., Bluhm, H., Beucker, S., Pohl, J., Fröhling, M., 2023. Overcoming challenges in life cycle assessment of smart energy systems–A map of solution approaches. J. Clean. Prod. 423, 138584. https://doi.org/10.1016/j.jclepro.2023.138584.
Wolsink, M., 2024. Conceptualizations of smart grids–anomalous and contradictory expert paradigms in transitions of the electricity system. Energy Res. Social Sci. 109, 103392. https://doi.org/10.1016/j.erss.2023.103392.