

REVIEW

The Role of Grid Informatization in Mitigating Environmental Impacts: A Global Perspective on Smart Grid Applications

Shuang Yang, Chao Liu^{}, Yuan Cao, Xiaonan Sun, Yaxin Zhao*

Information Engineering Construction Center, Information and Communication Company, State Grid Jilin Electric Power Co., Ltd., Changchun 132000, China

ABSTRACT

The informatization of the grid, i.e., the incorporation of sensing, communications, data platforms, analytics, and automation in the running of power systems, has turned out to be a vital facilitator of environmental mitigation as power systems increasingly take up larger proportions of variable renewables, distributed energy resources (DERs), and electrified end uses. The review summarizes the worldwide evidence related to the ability of informatization-based smart grid applications to lower the environmental impact in six pathways, namely efficiency improvement, flexibility activation, renewable integration, DER coordination, electrification management, and resilience enhancement. Across regions, the most consistently reported benefits arise from reducing waste and improving operational control, including loss reduction, volt/VAR optimization, conservation voltage reduction, and distribution automation, particularly in systems with high baseline losses or frequent outages. Demand response, dynamic pricing, and managed electric vehicle (EV) charging can further lower emissions when they displace high-emitting marginal generation or align consumption with time-varying low-carbon supply; however, outcomes are highly sensitive to marginal emissions profiles and accounting methods. In high-renewable systems, forecasting, congestion management, and curtailment reduction emerge as high-leverage mechanisms, while distributed energy resource management systems/virtual power plant (DERMS/VPP)-enabled coordination can expand hosting capacity and substitute distributed flexibility for carbon-intensive balancing, contingent on interoperability and constraint-aware control. The review also highlights trade-offs that shape net benefits, including embodied impacts

*CORRESPONDING AUTHOR:

Chao Liu, Information Engineering Construction Center, Information and Communication Company, State Grid Jilin Electric Power Co., Ltd., Changchun 132000, China; Email: xtliuchao@163.com

ARTICLE INFO

Received: 2 December 2025 | Revised: 1 February 2026 | Accepted: 6 February 2026 | Published Online: 25 February 2026

DOI: <https://doi.org/10.30564/jees.v8i2.13036>

CITATION

Yang, S., Liu, C., Cao, Y., et al., 2026. The Role of Grid Informatization in Mitigating Environmental Impacts: A Global Perspective on Smart Grid Applications. *Journal of Environmental & Earth Sciences*. 8(2): 278–310. DOI: <https://doi.org/10.30564/jees.v8i2.13036>

COPYRIGHT

Copyright © 2026 by the author(s). Published by Bilingual Publishing Group. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License (<https://creativecommons.org/licenses/by-nc/4.0/>).

and e-waste from digital hardware, information and communication technologies (ICT) energy use, rebound and equity effects, and cyber-physical risks. We conclude with governance and research priorities for verifiable, secure, and lifecycle-sustainable informatization.

Keywords: Grid Informatization; Smart Grids; Environmental Mitigation; Distributed Energy Resources; Demand Response

1. Introduction

Electricity systems are increasingly central to environmental mitigation^[1]. They are a major source of environmental burdens through emissions associated with power generation and fuel supply chains, and they also shape air quality, water use, land occupation, and material demand through the way grids are built and operated. The term “emissions” generally refers to the emission of greenhouse gases like carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), which together account for the majority of power-sector greenhouse gas emissions. CO₂ emissions are primarily attributed to fossil fuel combustion in thermal power generation and backup diesel generation during outages, while CH₄ emissions arise from natural gas extraction, processing, and leakage in gas-fired power systems. N₂O emissions are associated with high-temperature combustion processes.

Simultaneously, decarbonizing electricity will allow more extensive decarbonization of the economy as it will support the electrification of transport, heating, and even industry^[2]. This twofold role implies that environmental progress is no longer hindered simply by what technologies produce electricity, but also how the low-carbon resources can be carefully incorporated into power systems, the demand is met, and the reliability of the system is ensured under variable conditions.

The operational issue of power systems is evolving at a very fast rate^[3]. The growing percentages of wind and solar make it more variable and uncertain, making forecasting, flexibility, and rapid control more important. Distributed energy resources cease to be found on the fringes and are taking a central place as rooftop photovoltaics, behind-the-meter batteries, flexible commercial loads, community energy systems, and microgrids, and are frequently linked to distribution networks, which were never intended to support bidirectional flows. Electrification is introducing new and

high-power loads (electric vehicles and heat pumps), which can either favor the use of renewables or contribute to congestion and peak demand. In the meantime, the threat of extreme weather is escalating due to climate change, and resilience and quick restoration are becoming more pressing. The regulatory and market designs are also changing in most parts to focus more on transparency, performance-based incentives, and the involvement of customers. These trends add complexity at all grid levels and condition the environment results on the level of coordination, timing, and optimization on a system-wide basis^[4].

It is on this background that grid informatization has become a very important facilitator of environmental performance. In spite of the tendency to define a smart grid as a generalized term of grid modernization, in this review, the informatization layer, where traditional networks are transformed into data-intensive cyber-physical systems, is considered. The concept of grid informatization can be interpreted as a possibility to see the system in the finest details, to exchange information safely and efficiently, to derive action out of the information, and to execute decisions with the help of automation and coordinated control^[5]. Practically speaking, it includes sensing and measurement systems; communications systems; interoperable data systems like SCADA (supervisory control and data acquisition)/EMS (energy management system)/DMS (distribution management system) and DER management systems, analytics like forecasting, state estimation, and optimization, and automated control functions, such as voltage regulation and fault isolation, and restoration. This sense–communicate–compute–control stack does not just increase visibility. It alters the way operators plan and operate the grid, the way customers and aggregators are involved, and how distributed assets can be brought into play to meet the needs of the systems. **Figure 1** provides an overview of the conceptual reasoning behind this review, in which the informatization stack is connected to the operational lever and, eventually, to environmental endpoints^[6].

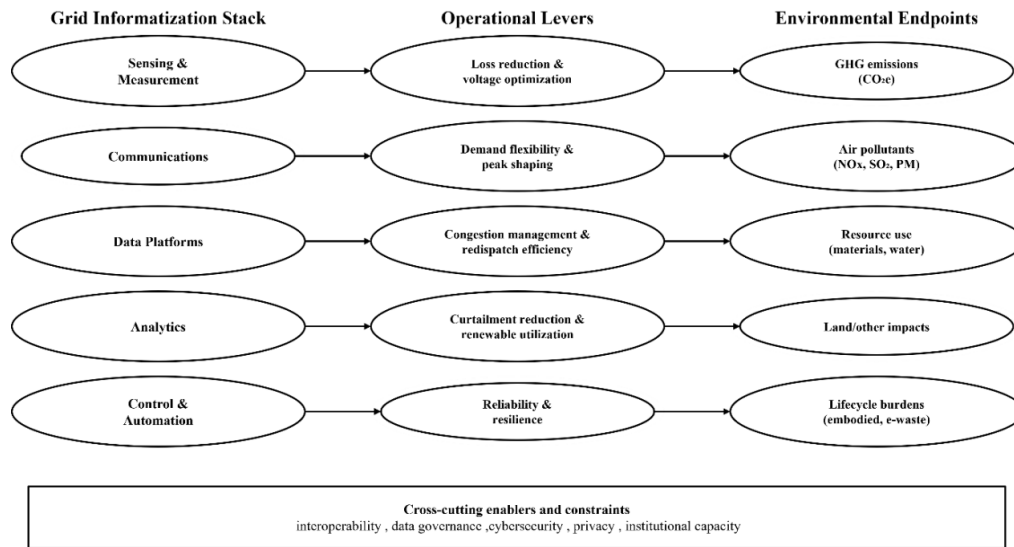


Figure 1. Conceptual framework linking grid informatization to environmental outcomes.

The environmental worth of informatization is realized through several interrelated channels that interface the digital features with physical results^[7]. Efficiency improvements are one of the areas. Technical losses can be minimized, non-technical losses identified, voltage and reactive power optimized, and asset utilization can be enhanced through better monitoring and control. Even small losses could be converted into significant avoided generation, which is particularly true of systems with marginal generation that is still fossil-based. The second route is that of flexibility. Demand response programs and automated load management rely on informatization as they allow for taking measurements at a granular level, signaling prices or incentives, and verifying them. Flexible demand can decrease the role of peaking units that cause high emissions and achieve higher penetration of renewable sources without undermining reliability by shifting consumption not only towards peak periods but also by matching renewable availability to consumption. The third route is focused on renewable integration. Quality forecasting, congestion control, and enhanced timing may reduce renewable curtailment as well as the amount of carbon-intensive reserves. Adaptive operation to changing conditions (e.g., dynamic line rating or more responsive reconfiguration strategies) that can raise usable transfer capacity may also be supported by the same data and control capabilities^[8].

Another related trajectory is associated with the coordination of distributed energy resources. Since DERs are

multiplying, the environmental impact of DERs is highly dependent on whether they are individual devices or interconnected resources. Aggregation can be achieved by informing platforms, e.g., DER management systems and virtual power plants, so distributed assets can offer grid services, e.g., frequency response, voltage support, and capacity contributions. This is able to decrease fossil ramping, postpone network reinforcements, and decrease the necessity of conventional peakers. The other route is associated with the process of electrification, especially the accelerated development of electric vehicles. Local transformer overloads, as well as minimizing peak demand and moving charging to low-carbon hours, may be avoided through managed charging, which is facilitated by communications, user interfaces, and control algorithms. In other applications, the vehicle-to-grid idea will provide more flexibility, but raises new concerns about battery degradation, consumer acceptance, and regulation in the market. Lastly, informatization is useful in reliability and resilience by means of automation and predictive maintenance. Reduction in frequency and duration of outages can be achieved with faster fault location and isolation, better restoration and condition-based asset management. Although reliability as such is not an environmental measure, outages may initiate more emissions from backup generation, inefficient restarts, and disruption that have real societal and environmental implications^[9,10].

These mitigation effects do not occur automatically and they are highly context-specific. The same informatization

intervention may produce extremely dissimilar results based on the blend of generations, the topology of the network, the profile of marginal emissions, regulatory limitations, and the involvement of the customers. The environmental effect of demand response, such as that, will depend on which generators are pushed out at the edge as well as whether the reduction in demand is permanent or just postponed^[11]. The usefulness of renewable forecasting and reduction of curtailment relies on the rules of the market, transmission limitations and flexibility. The loss reduction has greater benefits in systems whose carbon intensity is high, as compared to those that are already dominated by low-carbon generation. It is because of these reasons that a global perspective is necessary. The informatization of grids is approached with very different emphases in systems with vastly different priorities: high-renewable integration and cross-border coordination in parts of Europe; intensive metering, demand response, and distribution automation in North America; a rapid digital modernization as well as large-scale buildout of transmission in parts of East Asia; urgent needs to cut losses, enhance revenue collection, and expand reliable access, often with mini-grids and microgrids that are able to bypass traditional structures. Every situation defines what applications are available, what advantages are most salient, and what obstacles prevail.

The current literature has a representation of this diversity, yet is also characterized by the presence of certain gaps that have been persistent and which make synthesis challenging. The majority of literature measures potential emission reductions without a uniform baseline or counterfactual, and without a distinction between average and marginal emission reductions—an important distinction when dealing with interventions that redistribute the timing but do not necessarily reduce the overall amount of energy consumed. The measurements of the environment are disaggregated: some sources indicate energy savings, others peak reduction, reliability indices, changes in curtailment of renewable, or CO₂ avoidance, each with incompatible assumptions and time scales. Often, empirical deployment experience may not be easily comparable with results of simulation models, especially when models do not include behavioral responses, market constraints, or implementation frictions. Moreover, operational advantages are often highlighted, whereas embodied effects are addressed with a single finger. Digital

infrastructure has material and energy impacts, including meters, sensors, communications equipment, servers, and accelerated replacement cycles, which are among the sources of embodied carbon, resource extraction, and e-waste^[12]. There are also socio-technical risks that informatization creates, which are significant to the environment. Recovery effects may nullify efficiency gains; dynamic pricing may generate equity issues and participation inequities; privacy and data policy may establish equity issues and participation disparities; and cybersecurity threats may have indirect impacts on system stability that may raise emissions or reliability issues.

To meet these challenges, this review provides the organization of the evidence around a clear analytical framework that connects the functions of informatization with environmental mechanisms, quantifiable outcomes, and contextual determinants. It constructs a common taxonomy of technologies and architectures of the sensing-communications-data-analytics-control stack, and transforms this stack onto the key mitigation pathways: efficiency, flexibility, renewable integration, DER coordination, electrification enabling, and resilience. The review combines and draws conclusions on outcomes reported in different regions to locate where the evidence is most robust, where the results are most prone to assumptions, and where enabling conditions most reliably convert digital capability into environmental benefits. Simultaneously, it analyzes the nature of trade-offs and governance provisions that can specify if informatization produces net positive effects such as embodied footprints, ICT energy use, circularity and end-of-life management, cybersecurity, privacy, and energy justice implications^[13]. Combining engineering evidence with the environmental accounting and governance lenses, the article is expected to elucidate not only what grid informatization can theoretically do, but what it actually does and how the benefits of such actions can be quantified, contrasted, and applied to different scenarios in the world.

The rest of the article is based on this rationale. It summarizes the technology stack and system architecture behind informatization after explaining the review methodology and the way to interpret environmental impacts and evidence quality. It subsequently considers the key smart grid applications in terms of environmental minimization pathways, and contrasts results in major world regions in order to reflect

the importance of grid context and policy formulation. The analysis ends with a conclusion about the practical implications of the review on utilities, regulators, and researchers, and highlights the strategies to achieve the maximum number of verifiable benefits for the environment and minimize the number of unintended consequences, and the strategies to make the digital transition of the power systems secure, equitable, and sustainable.

2. Review Methodology and Analytical Framework

This review is based on a systematic evidence synthesis method that summarizes and assesses the international literature on the role of grid informatization in mitigating environmental impact. Since the subject of the topic covers power systems engineering, information and communication technologies, environmental assessment, and energy policy, the methodology will be open to interdisciplinary evidence and be transparent and reproducible. The section outlines the process by which the literature was identified, screened, and synthesized, as well as the method by which environmental effects were specified and attributed to informatization interventions under various regional and grid conditions.

2.1. Review Scope and Guiding Questions

The scope of the review is limited to informatization functions that measurably affect grid operation, planning, or coordination, including sensing and metering, communication networks, data platforms, analytics and artificial intelligence, and automation and control. Studies focused solely on physical hardware additions without an explicit digital or data-driven component are not treated as informatization interventions, although they may be referenced when they interact with digital control layers, as in the case of storage dispatch, inverter-based grid services, or microgrid control^[14,15].

The review is guided by three overarching questions. First, it asks which informatization-enabled applications most consistently yield environmental benefits, and through what operational mechanisms those benefits are realized. Second, it examines how reported outcomes differ across regions and grid contexts, with attention to generation mix, market design, network constraints, and institutional capac-

ity. Third, it evaluates trade-offs and uncertainties, including methodological choices in emissions accounting, embodied impacts of digital infrastructure, and risks that may erode net environmental gains, such as rebound effects, inequity, privacy constraints, or cybersecurity vulnerabilities.

2.2. Literature Search Strategy and Data Sources

A comprehensive search strategy is used to capture peer-reviewed journal articles and high-quality conference papers at the intersection of smart grids, digital power systems, and environmental assessment^[16,17]. The primary databases typically include Web of Science and Scopus for broad coverage of energy and environmental journals, complemented by IEEE Xplore for power engineering and communication-network literature. In addition, targeted searches are used to capture domain-specific outlets where key contributions are often published, particularly those addressing distribution automation, demand response, DER coordination, and grid cybersecurity.

The search strings are constructed to balance breadth and relevance by combining three clusters of terms. The first cluster targets informatization concepts, including smart grid digitalization, advanced metering infrastructure, phasor measurement units, grid-edge sensing, SCADA/EMS/DMS, DERMS, virtual power plants, digital twins, forecasting, optimization, and AI-enabled grid control. The second cluster dwells on environmental performance and processes, including emissions, carbon intensity, curtailment and losses, conservation voltage reduction, peak reduction, demand response, renewable integration, electrification, and resilience. The third cluster introduces the qualifier of regions and applications where needed, so as to provide coverage of the world, as well as without over-representing a few highly studied contexts^[14,18]. The searches are performed iteratively, with the beginning of a generalizing search and narrowing down to the fields that still come out as by-products of environmental issues, such as optimization of voltages, demand response, and controlled EV charging. To minimize missing important work, backward and forward citation tracing are used to seminal articles and big review articles that are found during the first screening. This step is especially significant since the relevant evidence can be located in a wide range of disciplines, and the search based on keywords can overlook

studies that refer to informatization as active network management, distribution system automation, grid modernization, or transactive energy. In regions lacking peer-reviewed data, or areas where the technology is used, a few carefully chosen technical reports by system operators, regulators, and international agencies can be used to put the maturity of deployment into perspective, but these sources are not accorded the weighting given to peer-reviewed studies when making quantitative judgments.

2.3. Eligibility Criteria and Screening Process

Eligibility criteria are designed to ensure that included studies address both an informatization component and an environmental relevance pathway. A study is included when it analyzes, models, or measures a grid informatization intervention that alters grid operation, planning decisions, or resource coordination, and links that intervention to environmental outcomes or to operational proxies that can be credibly translated into environmental impacts. Examples of such proxies include reduced technical losses, lowered peak demand, reduced renewable curtailment, improved utilization of low-carbon generation, or reduced dispatch of high-emitting units. Studies that only describe communication architectures or data platforms without connecting them to operational or environmental consequences are excluded, as are papers that discuss environmental impacts of power systems without a clear informatization mechanism^[14,16,18].

The screening is done in phases to enhance uniformity. Titles and abstracts are then examined to eliminate the obviously irrelevant records after sorting out the duplicates. It is followed by full-text screening to either confirm the intervention as truly informatization-based and the connection of environmental linkage as explicit and methodologically interpretable. In cases where a study describes several scenarios, the preference is made for those that have clear assumptions, well-defined baselines, and an adequate description of methods used to enable cross-study comparison. In the case of work employing simulations, models should provide a system boundary, a framework of dispatch or power flow, and the main assumptions involved in the behavior, market limits, or policy environments. To do empirical studies, it is necessary to describe the context of deployment, data sources, and the method of analysis^[19].

2.4. Data Extraction and Coding Framework

In order to facilitate the systematic synthesis of heterogeneous research, a standard extraction template is used. Bibliographic information, geographic and system context, grid level (transmission, distribution, microgrid), and the informatization components comprised are captured on the template, as well as the sensing/measurement, communications, data platform, analytics, and the control actions involved. It also documents the application field, e.g., voltage optimization, demand response, renewable forecasting, DER aggregation, controlled EV charging, predictive maintenance, or resilience automation^[20].

Environmental variables are extracted in two forms. When studies directly report environmental outcomes, such as CO₂-equivalent reductions, pollutant reductions, or energy savings tied to emissions factors, those metrics are recorded along with the accounting approach used. When only operational outcomes are reported, such as peak reduction, curtailment reduction, or loss reduction, the extraction records the parameters necessary to translate these outcomes into environmental impacts, including carbon intensity assumptions, temporal resolution, and whether emissions are treated as average or marginal.

Because study methods vary widely, methodological attributes are also coded, including whether the evidence is empirical, quasi-experimental, model-based, or scenario-driven, whether uncertainty is quantified, and whether sensitivity analysis is provided. This coding supports later grading of evidence strength and helps interpret why findings differ across contexts.

2.5. Evidence Quality Appraisal and Risk of Bias Considerations

The key issue with smart grid environmental assessment is that the outcomes of measurement usually rely on counterfactual assumptions regarding what would have occurred in the absence of the informatization intervention^[16]. The review thus utilizes the lens of quality appraisal that focuses on baseline clarity, causal attribution plausibility, and strength of results to major uncertainties.

Empirical studies are evaluated based on being based on credible identification methods, i.e., before-after comparisons with suitable controls, difference-in-differences de-

signs, randomized pilots, or statistically based evaluation frameworks to consider weather, economic activity, and behavioral adaptation. The criteria applied to evaluate model-based studies include the specification of dispatch logic and constraints, use of real-world operational data or test systems, and sensitivity to assumed demand elasticity, DER behavior, market rules, or carbon intensity^[21].

In both empirical and modeling literature, some special focus is placed on selection effects and publication bias. When piloting is applied in a desirable situation with greater involvement or more advanced infrastructure, it tends to exaggerate anticipated benefits in generalizing findings. On the other hand, a study can be biased and only report successful deployments, covering up unsuccessful deployments or dampened effects. These are explicit points of concern in the story synthesis, and the results are understood as ranges and not constants.

2.6. Environmental Impact Attribution and Boundary Setting

To assign environmental effects to informatization, it is necessary to have a stable system of definitions of system boundaries and emissions accounting principles^[22]. There are operational impacts and embodied impacts, as characterized by this review. Informatization-enabled decisions influence operational effects in terms of alterations in dispatch generation, energy consumption, loss, and curtailment. Embodied effects are those associated with the production, installation, use, and disposal of digital hardware and associated ICT infrastructure, such as meters, sensors, communications equipment, and servers and data storage.

The reliance on operational emissions estimation on the emissions factors, such as average grid intensity or marginal intensity at particular locations and times, is important. A lot of informatization procedures, like demand response or EV smart charging, do not reduce the overall consumption of electricity but evenly distribute the consumption over time. Marginal emissions and time-varying carbon intensity are usually more suitable than annual average factors to use in such applications. On the same note, the effect of renewable curtailment reduction is on the generators that are displaced and at what time, hence the time resolution and system constraints have a powerful influence on the estimated benefits^[23]. The review records the method by

which studies select emissions factors and, where feasible, reconciles interpretations by bringing out methodological differences as opposed to developing one conversion method that actually is not applicable in other contexts.

The treatment of upstream and downstream effects is also included in setting a boundary. An example is managed EV charging, which can alter electricity generation emissions and decrease internal combustion vehicle emissions, but the benefits of the transport sector require assumptions of vehicle replacement, charging patterns and lifecycle emissions of vehicles and batteries^[24]. This review places more emphasis on grid-mediated effects, and considers cross-sector effects in a cautious fashion, focusing more on transparency regarding assumptions and paying due consideration to over-attributing indirectly-evidence.

The synthesis integrates narrative and semi-quantitative methods to compare diverse study outputs. Narrative synthesis is used to connect informatization mechanisms to grid operational changes and then to environmental outcomes, while also describing contextual dependencies and implementation realities. Semi-quantitative synthesis is used when studies report comparable metrics, such as percentage loss reduction, peak reduction, curtailment reduction, or emissions savings per unit of intervention. Rather than treating these as directly commensurate across all systems, the review interprets them within contextual clusters, such as high-renewable systems, coal-dominated systems, rapidly electrifying systems, or infrastructure-constrained systems.

Regional synthesis is conducted by mapping applications to dominant regional drivers and constraints. This approach avoids implying that one region's evidence automatically transfers to another. For instance, findings about demand response effectiveness in regions with mature retail markets and widespread smart metering may not generalize to regions where metering penetration is low, or tariff structures limit price responsiveness^[25]. Similarly, curtailment reduction strategies documented in systems with strong interconnection capacity may not apply to islanded or weakly interconnected systems.

Finally, the synthesis explicitly integrates trade-offs and risks into the interpretation of net environmental benefits. Informatization can enable emissions reductions, but it can also introduce additional hardware footprints, increase ICT electricity use, and create operational vulnerabilities

if cybersecurity, interoperability, or governance are inadequate^[26]. The review, therefore, treats “net mitigation” as an outcome that depends on both technical performance and socio-technical implementation conditions, setting the stage for later sections that examine governance, equity, and system risk as integral to sustainable grid informatization.

3. Grid Informatization Technologies and System Architecture

Grid informatization is fundamentally a cyber-physical transformation of electric power systems in which operational intelligence is increasingly created, shared, and acted upon through digital infrastructure^[27]. In conventional grids, observability is limited by sparse instrumentation, coarse temporal resolution, and compartmentalized control, particularly at the distribution level. Informatization expands the visibility of system states, accelerates the flow of operational data, and enables decision-making that is both more granular and more adaptive. The technologies involved are not independent building blocks but components of an end-to-end architecture that links measurement, communication, computation, and control. This section synthesizes that architecture and highlights the technical characteristics that matter most for environmental mitigation, including data quality, interoperability, latency, reliability, and security.

3.1. Sensing and Measurement: Building Observability from Bulk Power to the Grid Edge

The first layer of informatization is the expansion of observability through measurement. At the transmission level, phasor measurement units (PMUs) and wide-area measurement systems provide time-synchronized data that can improve dynamic monitoring, state estimation, and stability assessment^[28,29]. Higher-fidelity system state awareness can support more confident operation closer to network limits, reducing the need for conservative reserves and enabling greater utilization of low-carbon generation when transmission constraints would otherwise force redispatch. While the direct environmental link is rarely through PMUs alone, the broader capability to reduce congestion-related inefficiencies and avoid unnecessary redispatch becomes increasingly salient in high-renewable systems where variability

and ramping needs are pronounced.

At the distribution level, the informatization shift is even more consequential because distribution networks historically have far less instrumentation than transmission systems. Advanced metering infrastructure (AMI) enables high-frequency measurement of customer consumption and, in many deployments, voltage and power quality information. Beyond billing modernization, AMI data can support loss analytics, theft detection, targeted voltage optimization, and the validation of demand response performance. In contexts with high non-technical losses, improved measurement and verification can translate into both financial and environmental gains by reducing wasted generation and improving operational efficiency. Distribution automation also relies on feeder-level sensors, fault indicators, transformer monitors, and line sensors that reveal loading, thermal margins, and abnormal conditions. These measurements enable faster fault localization and isolation, reduce outage durations, and support proactive asset management that can extend equipment life and reduce material-intensive replacements^[30].

In addition to dedicated utility sensors, grid-edge measurements increasingly come from inverter-interfaced resources such as rooftop PV and batteries, smart EV chargers, and building energy management systems^[31]. These devices can act as both sensors and actuators, but their contribution depends on standardized telemetry, controllability, and the accuracy of time stamping and calibration. The environmental value of these measurements is therefore closely tied to how data is integrated and operationalized, rather than merely collected.

3.2. Communications Infrastructure: Latency, Reliability, and Coverage as Operational Constraints

Measurement becomes operationally useful only when it can be transported to decision points with adequate speed and reliability. Communications networks in informatized grids span heterogeneous technologies, including power-line communication, radio frequency (RF) mesh networks, cellular systems, fiber backbones, and increasingly low-latency wireless options. The architecture is typically layered, with local field area networks connecting meters and sensors, aggregation nodes or substations serving as gateways, and wide-area networks carrying traffic to control centers or cloud

platforms^[32].

From an environmental perspective, communications performance shapes which applications are feasible and how effectively they operate. Voltage optimization and conservation voltage reduction, for example, require timely voltage data and reliable command channels to regulators, capacitor banks, or inverter setpoints. Fault isolation and restoration depend on deterministic performance under stressed conditions. Managed EV charging and DER aggregation require scalable, secure connectivity that can handle large device populations without excessive latency, particularly when services such as frequency response or fast ramping are provided. In distribution networks with limited communications coverage, informatization may be constrained to slower timescale applications such as day-ahead forecasting, periodic optimization, or supervisory control rather than real-time automation^[33].

Communications infrastructure also introduces design trade-offs. High redundancy improves resilience but increases capital cost and potentially the embodied footprint of hardware. Reliance on public cellular networks can accelerate deployment in resource-constrained contexts, but it raises questions about quality-of-service guarantees during emergencies and the governance of critical infrastructure dependence on third-party networks. As a result, communications choices become an integral part of environmental strategy because they determine the reliability of mitigation interventions such as demand response, DER coordination, and outage reduction, all of which can influence emissions through dispatch and backup generation patterns^[34,35].

3.3. Data Platforms and Interoperability: Turning Heterogeneous Data into System-Level Intelligence

The expansion of sensing and communications creates large and heterogeneous data streams that must be integrated into platforms capable of supporting operational and planning decisions^[36]. Traditional supervisory control and data acquisition (SCADA) systems remain foundational for transmission and substation monitoring, but informatized grids increasingly rely on a broader software ecosystem that includes energy management systems (EMS), distribution management systems (DMS), outage management systems (OMS), and geographic information systems. In distribution

networks, the DMS often becomes the locus where AMI-derived insights, feeder sensor data, switching states, and DER telemetry are combined to support functions such as volt/VAR control, feeder reconfiguration, and restoration.

As distributed resources expand, specialized platforms such as distributed energy resource management systems (DERMS) and virtual power plant (VPP) orchestration tools provide additional layers of coordination^[37]. These platforms enable aggregators or utilities to dispatch fleets of small resources as if they were a single controllable asset. The extent to which this translates into environmental benefits depends on the quality of observability and forecasting, the ability to respect local network constraints, and the market or regulatory rules governing participation. Without constraint-aware orchestration, DER coordination can inadvertently increase losses or create local congestion, undermining both reliability and environmental objectives. To clarify how technical layers translate into operational capability, **Table 1** maps the informatization stack to dominant grid functions and environmental relevance.

Interoperability is central to the effectiveness and scalability of informatization. Grid data originates from devices produced by many manufacturers and is often stored in legacy systems with incompatible formats. Standardized information models, communication protocols, and interface specifications determine whether data can flow across organizational and technical boundaries. Interoperability is not only a technical convenience; it influences the speed at which new applications can be deployed, the feasibility of multi-vendor ecosystems, and the potential for third-party innovation. Where interoperability is weak, utilities may become locked into proprietary solutions that limit scalability and raise lifecycle costs, potentially slowing deployments that would otherwise reduce emissions. Conversely, strong interoperability can support modular upgrades, extend the usable life of existing systems, and facilitate broader adoption of mitigation applications such as carbon-aware dispatch or flexible demand aggregation^[38].

The data platform layer also includes decisions about cloud versus edge computing and the role of data lakes or streaming architectures. Cloud platforms can provide elasticity and simplify analytics deployment, while edge computing can reduce latency, lower bandwidth requirements, and increase resilience by maintaining local control even

when wide-area connectivity is disrupted. These architectural choices interact with environmental objectives through both operational performance and ICT energy use. While the electricity consumption of computing infrastructure is often modest relative to system-wide energy flows, it can

become nontrivial at scale and must be accounted for when evaluating net environmental benefits^[39].

Figure 2 presents the reference architecture used throughout the review to describe data and control flows from the grid edge to operational decision layers^[40].

Table 1. Grid informatization stack and environmental relevance.

Informatization Layer	Typical Components	Primary Grid Function Enabled	Environmental Relevance (Main Channel)	Common Evidence Type
Sensing & measurement	Advanced Metering Infrastructure (AMI)/smart meters, Phasor Measurement Units (PMUs), feeder sensors, transformer monitors, Power Quality (PQ) monitors	Observability of load, voltage, flows, asset condition	Enables loss diagnostics, Volt-Var Optimization (VVO)/Conservation Voltage Reduction (CVR), Distributed Energy Resources (DER) visibility; improves evaluation/Monitoring, Reporting, and Verification (MRV)	Utility deployments; feeder studies; monitoring-based analytics
Communications	Radio Frequency (RF) mesh, Power Line Communication (PLC), cellular, fiber, substation gateways	Timely/secure data transfer and command execution	Determines feasibility of real-time Demand Response (DR)/Distributed Energy Resources (DER) control and restoration; affects reliability-related emissions	Field performance reports; network simulations
Data platforms	Supervisory Control and Data Acquisition (SCADA)/Energy Management System (EMS)/Distribution Management System (DMS)/Outage Management System (OMS), Distributed Energy Resource Management System (DERMS)/Virtual Power Plant (VPP) platforms, data lakes/streams	Data integration, topology/state models, operational workflows	Scales mitigation apps by integrating constraints, devices, and markets	Case implementations; platform evaluations
Analytics	Forecasting, state estimation, anomaly detection, optimization (OPF/UC) (optimal power flow/unit commitment), AI/ML (artificial intelligence/machine learning)	Predictive & prescriptive decision support	Reduces curtailment/redispach; improves dispatch efficiency and flexibility utilization	Modeling studies; pilot evaluations
Control & automation	Volt-Var Optimization (VVO)/Conservation Voltage Reduction (CVR), Fault Location, Isolation, and Service Restoration (FLISR), adaptive protection, Distributed Energy Resources (DER) dispatch, microgrid controllers	Closed-loop operational actions	Directly reduces losses/curtailment and improves resilience; enables low-carbon flexibility	Field rollouts; control experiments; simulation
Security & governance (cross-cutting)	IAM (identity and access management), encryption, segmentation, privacy controls, data governance	Trustworthy operation and data sharing	Prevents disruptions that increase emissions; enables safe scaling of DER/DR	Standards-based analyses; incident-informed studies

3.4. Analytics and AI: Forecasting, Optimization, and Situational Awareness for Decarbonized Operations

Analytics transform raw data into practical wisdom and thus form the main connection between informatization and the environment. Forecasting is a core competency, and it

includes short-term load prediction, forecasting of renewable generation, and probabilistic evaluation of uncertainty. Better forecasting can lead to decreased reserves, better unit commitment decisions, and reduced recourse to high-emission standby generation. Forecast accuracy may also have significant impacts on short-renewable systems on curtailment and redispach

behavior, and thereby on emissions by replacing the low-carbon generation with fossil generation at important times^[41].

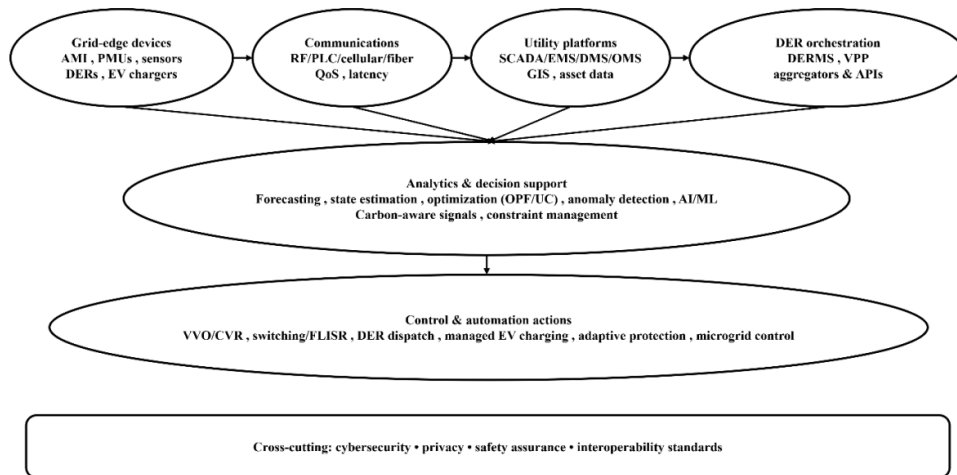


Figure 2. Reference architecture of an informatized power system.

State estimation and topology processing give situational awareness, which is a process by which the states that have not been measured are estimated using incomplete measurements and known network models^[42]. In distribution networks, where instrumentation can be remote when AMI is present, state estimation can provide advanced volt/VAR control and constraint management, higher DER hosting capacity, and minimize the emissions-intensive grid reinforcements. Optimization techniques such as optimal power flow, security-constrained dispatch, and multi-period scheduling are the techniques used to convert system objectives into control responses that are responsive to physical and operational constraints. These formulations can include environmental objectives in the form of carbon costs, emissions limits, or curtailment fines, or indirectly as low-loss and renewable maximization objectives that can vary with grid conditions based on the reduction of emissions.

AI and machine learning are used more often in the detection of anomalies and predictive maintenance, and pattern recognition in the consumption and behavior of devices^[43]. The predictive maintenance models are capable of detecting equipment degradation at the initial stages, and this limits failure, increases the lifespan of assets, and decreases emergency replacements, which have material and logistical footprints. In the case of demand response and DER aggregation, data-driven models will be able to estimate the availability of flexibility and customer response to enhance dispatch reliability and lessen the necessity of purchasing backups in a

conservative way. Nonetheless, AI-based methods pose risks associated with model drift, data quality, representativeness, and explainability, especially when implemented as part of the operational control loops. The green potential of AI thus depends on sound validation, ongoing surveillance, and the connection with physics-based limitations to prevent unsafe or self-contradicting behavior.

3.5. Control and Automation: Translating Information into Physical Action

Informatization has a direct influence on the functioning of the grid at the control layer. Automation may operate at different time scales, ranging from sub-second inverter control scale of minutes, volt/VAR optimization, and hours-scale scheduling. Volt/VAR optimization, used in the distribution systems, coordinates capacitor banks, voltage regulators, and more intelligent inverters to keep voltages within limits and minimize the reactive flows and losses in power. Conservation voltage reduction is aimed at reducing the feeder voltage within acceptable limits to minimize energy used to service the load that is voltage dependent, so that its emissions generate benefits based on the load make-up and marginal generation. Automation of the reconfiguration of feeders and switching may decrease losses and congestion, allowing better utilization of renewables or the dispensing of less emitting resources^[44,45].

Fault location, isolation, and service restoration (FLISR) is a technique that automates switching sequences

to contain outages and restore service faster^[46]. Minimizing downtime can decrease the dependency on backup generators, minimize the needless system restart activities, and offer resilience advantages with indirect yet significant environmental effects. Similar schemes of advanced control and remedial action in transmission systems can stop cascading failures and enable more secure operation in variable situations, and once more, less conservative dispatch policies can be used, which may contribute to higher emissions.

DER control and coordination go further to automate equipment that is not owned by a utility^[20]. Smart inverter capabilities, aggregator dispatch, and microgrid controllers can supply the functions of voltage and frequency support, ramping, and reserve services. These environmental impacts can be determined by whether the services will substitute fossil-based ancillary services or mitigate renewable curtailment, and whether the control strategies will consider network constraints and the device-level constraints. In reality, the control architectures tend to fuse centralization in optimization and decentralization or hierarchy in control as a measure of scalability and latency. Scale environmental benefits require the quality of optimization as well as the robustness in practice of control implementations.

3.6. Cybersecurity, Privacy, and Operational Trustworthiness as Architectural Foundations

This is because informatization broadens the scale of attack in power systems as it enhances connectivity, the population of devices, and reliance on software platforms. As such, cybersecurity is not a support system but a condition of the realization and maintenance of environmental benefits. The successful attacks may lower reliability, cause conservative operation, disrupt DER coordination, or cause an outage that raises emissions by using back-up generation and inefficient dispatch. Weak security will constrain data sharing and interoperability even in the absence of attacks and hinder the implementation of environmental mitigation applications^[47].

The concept of privacy is also ground-level, particularly in situations where high-resolution consumption data and device telemetry is utilized to achieve demand response, dynamic pricing, or personalized energy services. The problems of privacy can decrease the level of participation among

customers or lead to the introduction of regulatory limitations that can limit the availability of data, thereby limiting the utility of flexibility programs. Determinacy of data access, anonymization, and consent governance has an impact on the effective scope of informatization^[48].

Other aspects of operational trustworthiness are safety, validation, and explainability. Choices and data-driven designs are more and more automated, and under rare occurrences, as well as in the presence of changing system circumstances, informatization demands auditability and resilience. Reliability is especially relevant under the condition when environmental goals are factored into the operational control, as carbon-conscious dispatch or flexibility optimization can establish new goal trade-offs that have to be known and controlled by operators. To ensure that informatization provides net environmental benefits, a socio-technical architecture is, however, necessary, one where cybersecurity, privacy, and operational assurance are designed into the system architecture instead of being added afterward^[49].

Across sensing, communications, platforms, analytics, and control, grid informatization forms an integrated architecture that determines what the modern grid can observe, decide, and execute. Environmental mitigation is not produced by any single technology but by how the full stack enables efficient operation, flexible demand, coordinated DER services, and resilient performance under uncertainty^[50]. The architecture also constrains the achievable benefits through latency limits, data quality, interoperability barriers, and the need for secure and privacy-preserving operation. These architectural considerations provide the foundation for the subsequent synthesis of mitigation pathways and applications, where the review evaluates which informatization-enabled interventions deliver the most consistent environmental benefits across global contexts and what enabling conditions are required for their successful deployment.

4. Environmental Mitigation Pathways and Key Smart Grid Applications

Grid informatization affects environmental outcomes primarily by changing how electricity systems are operated and coordinated. The relationship is rarely direct; informatization does not “decarbonize” electricity on its own, but

it enables decisions that reduce energy waste, increase the utilization of low-carbon generation, and improve system flexibility so that higher shares of variable renewables and distributed resources can be accommodated reliably. The strength and direction of environmental effects depend on local marginal generation, network constraints, market rules, and the extent to which digital control is actually exercised rather than remaining a monitoring capability. This section organizes the literature through a pathway lens that links informatization-enabled functions to operational changes and

then to environmental impacts. Across pathways, the review emphasizes how outcomes are measured and what contextual factors condition the magnitude of benefits. **Figure 3** organizes the subsequent synthesis by mapping six mitigation pathways to representative informatization-enabled applications and commonly reported metrics. **Table 2** summarizes the dominant operational mechanisms, environmental linkages, and key dependencies associated with each mitigation pathway, highlighting where emissions accounting choices can change conclusions^[51,52].

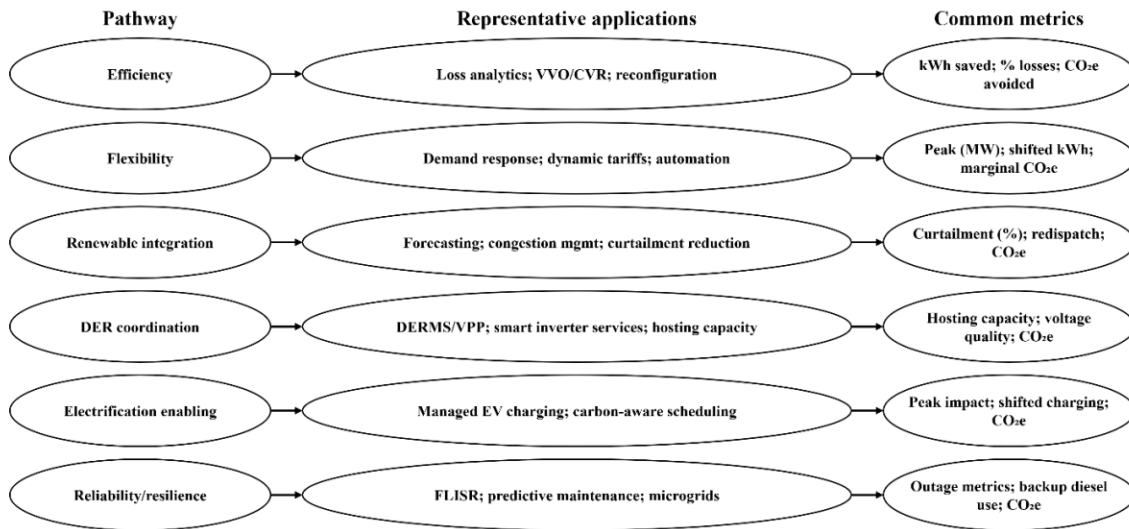


Figure 3. Mitigation pathways map and application taxonomy.

Table 2. Environmental mitigation pathways, applications, and metrics.

Mitigation Pathway	Representative Applications	Primary Operational Outcome	Environmental Metric Linkage	Key Dependency/Assumption
Efficiency	Loss analytics, VVO/CVR, feeder reconfiguration, theft reduction	Lower delivered energy required; reduced losses	kWh saved → CO _{2e} avoided; reduced upstream fuel/pollutants	Correct baseline; feeder/load composition; marginal vs. average emissions
Flexibility	Demand response, automated load control, dynamic tariffs	Peak reduction; load shifting; ramp support	Avoided peaker dispatch; emissions shift across hours	Carbon-intensity correlation with control/price signals; rebound risk
Renewable integration	Wind/solar forecasting, congestion management, dynamic line rating	Lower curtailment; reduced redispatch/reserves	Curtailment ↓ → fossil displacement (context-dependent)	Network constraints modeled correctly; reserve logic; market rules
DER coordination	DERMS/VPP aggregation, smart inverter services, hosting capacity analytics	Constraint-aware DER dispatch and voltage support	Higher DER utilization; avoided upgrades and balancing emissions	Telemetry quality; interoperability; distribution constraints visibility
Electrification enabling	Managed EV charging, carbon-aware charging, sector-coupled flexibility	Peak mitigation; alignment with low-carbon hours	Reduced marginal emissions of new electric load	Access to time/location carbon signals; user participation
Reliability/resilience	FLISR, predictive maintenance, microgrid control/islanding	Fewer/shorter outages; faster restoration	Less backup diesel use; reduced disruption-related inefficiencies	Event frequency; backup generator prevalence; extreme weather patterns

4.1. Efficiency Pathway: Loss Reduction, Voltage Optimization, and Waste Minimization

One of the most consistently reported channels through which informatization mitigates environmental impacts is operational efficiency. Losses in transmission and distribution networks require additional generation upstream to deliver the same amount of useful electricity to end users. Informatization increases visibility of loading, voltage profiles, and abnormal conditions, enabling actions that reduce both technical and non-technical losses. At the distribution level, advanced metering infrastructure and feeder monitoring support more precise loss analytics and can help identify theft and metering inaccuracies. Where non-technical losses are substantial, improvements in measurement and verification can translate into reduced wasted generation and improved dispatch efficiency, even though the benefits are mediated by institutional capacity to enforce interventions and by the reliability of billing and collection systems^[53].

Voltage and reactive power optimization is another central application of informatization under the efficiency pathway. Distribution management systems equipped with feeder models and real-time measurements can coordinate voltage regulators, capacitor banks, and smart inverter functions to maintain voltages within limits while reducing reactive flows and associated losses. In many studies, volt/VAR optimization reduces losses and improves power factor, producing avoided generation that can be converted to emissions reductions when emissions factors are specified. A closely related practice, conservation voltage reduction, lowers feeder voltage within acceptable bounds so that voltage-dependent loads consume less energy. The environmental benefits of conservation voltage reduction are therefore sensitive to local load composition, especially the share of resistive and motor loads, and to whether reduced energy use persists over time or is partially offset by behavioral or operational rebound^[54].

Efficiency-oriented informatization also includes network reconfiguration based on real-time or near-real-time conditions^[55]. By changing switching states to balance loads and shorten power flow paths, utilities can reduce losses and alleviate local constraints. However, the benefits depend on the accuracy of network topology models, the availability of automated switching, and operational rules that prioritize safety and reliability. In some contexts, reconfiguration may be constrained by protection coordination or by limited ob-

servability, which reduces the frequency and confidence with which such strategies can be deployed.

Environmental assessment under the efficiency pathway often relies on converting energy savings into emissions avoidance using average or marginal emissions factors. This conversion can be straightforward in systems where the marginal generator is known and relatively stable, but it becomes more complex where dispatch is highly variable across hours and seasons. The literature frequently reports percentage loss reduction or energy saved, but cross-study comparability is limited unless temporal resolution and base-line conditions are made explicit. In addition, while efficiency interventions generally provide net reductions in generation requirements, the net environmental outcome can be influenced by how reduced demand affects unit commitment decisions, which may shift dispatch among plants with different emission intensities^[16].

4.2. Flexibility Pathway: Demand Response, Dynamic Tariffs, and Automated Load Control

Demand-side flexibility becomes environmentally relevant when it changes which generators operate at the margin and when it reduces the need for high-emitting peaking resources^[56]. Informatization is a prerequisite for scalable flexibility because it enables high-resolution measurement, event signaling, automated control, and verification. The literature on demand response spans industrial interruptible loads, commercial building automation, and residential programs enabled by smart meters and connected devices. When demand response reduces peak demand, it can displace peaking plants that often have high marginal emissions and may also be relatively inefficient. It can additionally defer network investments, which have indirect environmental benefits through reduced materials and construction, although these effects are more difficult to quantify and are often omitted from operational studies.

Dynamic pricing and time-varying tariffs represent another informatization-enabled mechanism for shifting demand. By providing price signals that reflect system conditions, these tariffs can encourage consumption in periods with lower costs and, potentially, lower carbon intensity. The environmental effects, however, are not guaranteed. If price signals do not correlate with carbon intensity, load shifting

may reduce costs without reducing emissions. Moreover, the effectiveness of dynamic tariffs depends on customer responsiveness, the availability of automation, and behavioral persistence over time. Where automation is widely adopted, such as through smart thermostats or building management systems, response can be more predictable and can support grid services beyond peak shaving, including ramp management and ancillary services^[57].

Automated demand response and transactive energy concepts extend the flexibility pathway by enabling devices or aggregators to respond to incentives in near-real time. In principle, such systems can align flexible demand with renewable output, reduce curtailment, and lower emissions associated with balancing. In practice, environmental performance depends on measurement and verification methods, aggregation strategies, and constraints that prevent new peaks or local congestion. The literature highlights that flexibility can also introduce rebound effects, where deferred consumption returns later with reduced efficiency or occurs in higher-carbon periods^[58]. Consequently, rigorous evaluation requires time-resolved emissions accounting and careful specification of baselines, particularly for applications that shift rather than reduce total energy use.

Equity considerations intersect with flexibility outcomes. Demand response and dynamic pricing can disproportionately benefit customers who can invest in enabling technologies or who have more flexible consumption patterns, while exposing fewer flexible households to higher volatility. These socio-technical dynamics are environmentally consequential because they affect program participation rates and the scalability of demand-side mitigation. Studies increasingly acknowledge that the design of incentives, data access, and consumer protections influences not only fairness but also the magnitude and reliability of emissions reductions^[59].

4.3. Renewable Integration Pathway: Forecasting, Curtailment Reduction, and Congestion Management

In high-renewable systems, informatization contributes to mitigation by enabling higher utilization of wind and solar resources and reducing the need for fossil balancing^[60]. Forecasting is the most widely studied component of this pathway. Improved short-term and very-short-term forecasts

for wind and solar can reduce forecast error penalties, lower reserve procurement, and improve unit commitment. Better forecasts can also reduce curtailment by increasing operator confidence in dispatching renewables and by reducing the need for conservative operating margins. The magnitude of environmental benefit depends on which resources are displaced when curtailment falls; in many systems, reduced curtailment primarily displaces fossil generation, but in systems with high nuclear or hydro shares, displacement patterns can be more complex.

Congestion management is another major mechanism. Informatization supports advanced state estimation, dynamic security assessment, and more granular constraint monitoring, which can reduce unnecessary redispatch and allow low-carbon generation to reach load centers^[61]. Technologies such as dynamic line rating, enabled by weather and conductor monitoring, can increase transfer capacity during favorable conditions and reduce congestion-related curtailment. However, the effectiveness of such measures depends on how operational rules incorporate dynamic ratings and how risk is managed under uncertainty. In some jurisdictions, conservative adoption limits the realized benefits even when technical capability exists.

The renewable integration pathway also includes the coordination of flexible resources for balancing, such as demand response, storage, and fast-ramping generators. Informatization provides the measurement and control foundations for these resources to respond to variability, reducing the emissions associated with inefficient cycling of thermal units. Yet the literature shows that benefits can be limited by market arrangements that do not reward flexibility adequately, by interconnection constraints that delay deployment, or by lack of visibility into distribution-level constraints that restrict how much flexibility can be mobilized safely^[62].

Environmental evaluation in this pathway is particularly sensitive to system modeling assumptions. Unit commitment and economic dispatch models must capture reserve requirements, ramp constraints, and network limits to accurately represent how forecast improvements and congestion relief translate into emissions changes^[63,64]. Studies that use simplified models may overestimate benefits by assuming perfect substitutability between resources or by ignoring constraints that drive curtailment. Consequently, evidence

synthesis must distinguish between theoretical potential and operationally feasible outcomes.

4.4. DER Coordination Pathway: Hosting Capacity, Inverter-Based Services, and Virtual Power Plants

Distributed energy resources can reduce emissions by displacing high-carbon generation, but their net system impact depends on how they interact with network constraints and operational needs^[65]. Informatization enables DER coordination through telemetry, aggregation, and dispatch platforms that treat distributed devices as controllable assets rather than passive injections. Hosting capacity analysis, supported by data and network models, helps utilities plan and operate distribution systems to accommodate DERs without triggering voltage violations, thermal overloads, or protection issues. By increasing hosting capacity, informatization can accelerate renewable adoption and reduce curtailment of distributed PV, particularly in feeders where voltage constraints would otherwise limit penetration.

Smart inverter capabilities are central to DER coordination because inverters can provide reactive power support, voltage regulation, and, in some cases, fast frequency response. Informatization determines whether these capabilities are used in a coordinated, constraint-aware manner or left as local controls with limited system optimization. When coordinated effectively through DERMS or DMS functions, inverter-based services can reduce losses, improve voltage profiles, and reduce the need for utility-owned reactive power equipment. Environmental benefits can arise by reducing system inefficiencies and by enabling higher renewable utilization, but the magnitude depends on control strategies and the carbon intensity of displaced services^[16].

Virtual power plants and aggregator models extend coordination to the market level by combining many small resources into dispatchable portfolios. Environmental mitigation occurs when aggregated DERs provide capacity, reserves, or balancing that displaces fossil-based services or reduces renewable curtailment. However, aggregator dispatch must respect distribution network constraints, and the governance of data exchange between utilities and third parties becomes critical. If constraints are poorly represented, DER dispatch can cause local congestion and increase losses, potentially undermining both reliability and environmental

performance. The literature, therefore, emphasizes hierarchical or coordinated control architectures that integrate distribution constraints into aggregation strategies^[66].

DER coordination also has embodied and lifecycle dimensions. Increased deployment of inverters, communication modules, and control hardware adds to material footprints and e-waste. While these impacts are typically small relative to operational emissions benefits in high-carbon systems, they become more important as grids decarbonize and as device replacement cycles accelerate. Robust assessment, therefore, requires acknowledging that environmental mitigation through DER coordination is not solely about operational carbon reductions, but also about sustainable device lifecycles and circularity strategies^[13].

4.5. Electrification Enabling Pathway: Managed EV Charging and Sector-Coupled Flexibility

The electrification has been discussed as a response measure on its own, although its effect on the environment is relative to the carbon intensity of the electricity and to the timing and location of new electric loads. These dynamics are formed by informatization with the possibility of managed charging, carbon-consciousness strategies that determine the price, and coordination of flexible electrified loads, including heat pumps and industrial processes. Managed EV charging has the potential to decrease peak demand and local congestion by shifting charging to off-peak states, which will decrease the requirement for peaking generation and decrease network losses caused by high loading. Charging can be matched to the availability of low-carbon generation when combined with time-varying information on carbon, enhancing the real use of renewables and lowering the emissions in the system overall^[67].

The idea of vehicle-to-grid opens the potential of EV batteries serving as distributed grid services storage^[68]. Aggregation of vehicles, availability prediction, and charge-discharge behavior control with the consideration of the needs of drivers are necessary processes in the context of informatization. The possible environmental advantages are a decreased curtailment of renewable sources, fewer emissions of ancillary services, and prevented Peaker operation. Nevertheless, practical limitations are also mentioned in literature: the battery degradation issues can lessen the participation or

have some further lifecycle effects, the market regulations might not compensate for services sufficiently, and distribution limitations can limit discharge in overcrowded regions. Therefore, the environmental argument of V2G is highly situational and, in many cases, more questionable than the argument of controlled unidirectional charging.

Transport is not the only place where sector-coupled flexibility occurs. Demand flexibility can be provided by heat pumps, thermal storage, and industrial loads under electrification, which can be used to facilitate renewable integration, although this also requires measurement, control, and incentive structures like those needed by demand response. Once again, the environmental impact is determined by the presence or absence of flexibility shifting demand to the lower-carbon periods and the general increase or decrease in energy consumption. Peaks in the electrified heating loads during colder climates, such as winter, may be formed; the impact of informatization-enabled control on these peaks is contingent on the overall generation mix by season and the ability of different loads to interact^[69].

4.6. Reliability and Resilience Pathway: Automation, Predictive Maintenance, and Microgrid Control

Reliability and resilience are usually driven by social and economic interests; however, they also affect the environment, which manifests itself in disruptions. Informatization is known to enhance reliability with the help of automation, e.g., FLISR, better outage management, and better situational awareness. Shorter recovery times mean shorter times customers will be dependent on the use of backup generators, which are usually diesel-based and emit more emissions compared to grid electricity. It also has the potential to lower emergency operational practices, such as inefficient cycling and rapid-start generation, which may increase emissions during the recovery periods. Although these environmental impacts are indirect and episodic, they may be very important in areas where outages occur regularly or where outage-prone critical facilities are highly dependent on backup generation^[70].

Predictive maintenance and condition-based asset management have an impact on the environment in terms of the prolonged lifespan of assets and the minimization of disastrous failures. Monitoring of transformers, breakers,

and lines helps the utility to plan maintenance more effectively, prevent emergency replacement, and minimize material-intensive interventions^[71]. These advantages are more easily defined in terms of indices of reliability and cost reductions than in terms of emissions, but are directly connected with material throughput reduction and minimized operational disruption.

Another unique aspect of the resilience pathway is microgrids and controlled islanding. Microgrids with informatization are able to be autonomous, to balance between local generation and local storage, and to give priority to critical loads when the grid is inaccessible. Microgrids will potentially decrease the use of diesel backup in the event that they effectively incorporate renewables and storage, yet they are also likely to increase the use of diesel in the event that renewable capacity is limited or the control measures do not include an emissions-focused approach to reliability. It is thus noted in the literature that the microgrid environmental performance lies in the asset composition and operation policies, and that informatization is the factor that offers the leverage to optimize these policies in the case that proper resources are at hand^[72].

4.7. Measurement Approaches and Cross-Cutting Determinants of Mitigation Performance

Across pathways, the reported environmental performance of informatization-enabled applications is shaped by how impacts are measured and by structural determinants that differ across regions. Studies commonly use operational proxies such as energy savings, loss reduction, peak reduction, curtailment reduction, and reliability improvements, then translate these proxies into emissions impacts using emissions factors^[73]. The validity of this translation depends on temporal resolution and on whether marginal emissions are represented. Applications that change timing rather than totals require particularly careful accounting, and the most informative studies use time- and location-specific emissions signals or dispatch models that capture marginal changes.

Contextual determinants explain much of the variability in findings. Carbon intensity at the margin is a dominant factor: the same energy-saving intervention yields larger emissions reductions in systems where marginal generation is fossil-heavy. Network constraints and topology matter for

distribution-level interventions, where local congestion or voltage limits can constrain the usable flexibility from DERs and electrified loads. Market design influences whether flexibility and DER services are economically dispatched and whether curtailment reduction is valued. Institutional capacity and data governance shape the feasibility of large-scale deployment, particularly for programs that require customer participation, cross-entity coordination, or extensive data sharing^[36].

Taken together, the pathway perspective clarifies that informatization is most environmentally impactful when it converts data into reliable control actions that either reduce waste, increase low-carbon utilization, or substitute flexible resources for carbon-intensive balancing and peaking^[74]. The following section builds on this foundation by synthesizing evidence across world regions, comparing application maturity and reported outcomes in different grid contexts, and identifying where the environmental case for informatization is strongest and where it remains contingent or uncertain.

5. Global and Regional Evidence Synthesis

The environmental value of grid informatization is captured in a wide range of literature, written in engineering of power systems, energy economics, and applied environmental assessment^[16,75]. The quality of evidence and the practice of reporting depend greatly on geographical location and field of application. In other settings, the results are measured by field deployments where the operational change is measured, and in other settings, the literature is filled with modeling studies that approximate the potential effects under the assumed adoption and control performance. It is a synthesis of the evidence base around the whole world, a comparison of how the results of mitigation can be seen in world regions, and the explanation of the contextual determinants in which the message of environmental performance and the generalizability of results are the most important factors.

5.1. Structure and Distribution of the Evidence Base

The world literature is imbalanced both in the geographical and the application spheres. Research on advanced

metering infrastructure, demand response, dynamic tariffs, and distribution automation is mainly represented by studies out of North American and European literature, to the effect that the region was studied earlier in previous deployment cycles and that research environments have a more mature data ecosystem and regulatory environments conducive to pilot evaluation. The East Asian region has a strong focus on large-scale grid modernization, wide-area monitoring, and scale-based digital coordination of both transmission and distribution expansion, and in most instances, with reliability, system security, and scale-based renewable integration having thematic focus. Loss reduction, theft detection, revenue protection, and access-oriented modernization that are common in South Asia, Latin America, and Africa are more prevalent in the evidence.

In practice, the most visible empirical evidence is usually found in areas where informatization interventions are operationalized in a program with measurable and verifiable demand, e.g., demand response events or voltage optimization rollouts, and where utilities or regulators have reports on evaluation published or have datasets to be analyzed. On the other hand, the multi-actor coordination characteristic of applications, e.g., DER aggregation under network constraints, carbon-aware dispatch across sectors, or large-scale interoperability among vendors, is more typically simulated and studied through scenario studies, since it is practically challenging to test how large fields work in the real world. Consequently, the evidence base tends to be rather confident in the direction of effect of core efficiency applications and basic flexibility applications, and displays broader ranges of uncertainty for advanced orchestration applications and market-integrated applications^[76,77].

There are three general ways of approaching the literature. The former incorporates empirical assessments that deduce effects of deployments, pilots, or even operational histories, with many being concerned with energy conservation, peak reduction, indices of reliability, or even curtailment variation. The second is engineering simulations, which are powered by the flow of power, optimal power flow, unit commitment, or co-simulations to approximate operational effects under specified conditions. The latter contains built-in evaluations that connect the operational output to emissions through marginal emissions estimation or dispatch modeling, or time-varying emissions indicators, and occa-

sionally also partial lifecycle evaluations. The diversity of such approaches makes it difficult to directly compare the numbers, but also shows the pattern of qualitative uniformity with regard to where informatization is more likely to contribute to environmental benefits and where a contingent or two-sided effect can be observed.

5.2. Global Patterns in Reported Outcomes across Mitigation Pathways

Literature indicates that when synthesized on a global scale, informatization offers environmental benefits in the most reliable way with interventions that minimize wasted energy, reduce peak-based dispatch, or lessen renewable curtailment^[78]. These results are manifested again and again in different contexts due to the basis of their behavior in physical systems: losses must be generated, peaks require capacity and ramping, and curtailment of lost low-carbon energy. The informatization enhances the effectiveness of the operator to identify and respond to such inefficiencies.

Another constant pattern of the efficiency pathway is that benefits have a close relationship with baseline inefficiency^[79]. Systems that have greater technical losses or limited voltage management or a large non-technical loss will be more likely to demonstrate large potential gains from the improved sensing, analytics, and specific control. Conversely, already well-optimized systems having already low losses can also be improved, similar to other systems; however, the improvements are incremental, and they can be more responsive to implementation quality and local feeder features. Research also indicates that efficiency gains can be long-lived when integrated into the regular processes in terms of DMS-based optimization, but they can be lost when model maintenance, topology accuracy, or calibration of devices are ignored.

In the flexibility pathway, demand response and time-varying tariffs tend to exhibit operational effects that are easily measured, although unwinding these effects into a reduction of emissions depends on the marginal generation that is displaced. Most of the literature suggests the view that peak reduction has the capacity to reduce emissions in those systems in which peak periods are covered by low-efficiency or high-emitting units, and where reduced peaks can change the unit commitment decisions and not just change the dispatch among two similar units^[80]. In situations where emis-

sions intensity is highly time varying, flexibility can provide significant mitigation benefits through consumption shifting to low-carbon times, but only in cases where price or control signals are associated with carbon conditions. The most common mistake in studies based on average annual emissions factors to estimate the value of load-shifting involves overstating or mischaracterizing such effects; time-resolved accounting is more likely to show that the benefits of emissions can switch sign with time of year when load is shifted.

Proper forecasting, reduction of congestion, and curtailment are continuously reported as high-leverage measures in systems with heavy wind and solar effective integration^[81]. The most compelling case can be found in those systems where the curtailment is not trivial and where the lack of renewable usage is curtailed by operational constraints and not by a lack of resources. The intensity of the emission reduction, however, will be determined by the occurrence of the reduced curtailment, which displaces fossil generation or other low-carbon resources. The marginal displacement can be more complicated in systems where the hydro or nuclear share size is large, and the benefits can be observed in the form of lower costs or higher reliability instead of the huge and obvious changes in emissions.

It is also a common finding of DER coordination studies that coordinated control may enhance voltage profiles, decrease local overload risks, and potentially enhance DER hosting capacity, to enable higher renewable uptake and prevent emissions through displaced conventional generation^[20]. However, it is also recognized in the literature that DER advantages are less linear than basic efficiency measures since they require interoperability, constraint-conscious orchestration, and harmonizing market incentives with the requirements of the system. Experiments based on ideal controllability and complete engagement usually show huge possible benefits, and real field tests usually highlight the practical constraints of telemetry, customer dynamics, and regulatory constraints between utilities and 3rd party aggregators.

Applications in electrification, particularly managed EV charging, are receiving a significant amount of research focus and developing a growing body of evidence that digital coordination has the potential to alleviate local grid stress and reposition demand in ways more conducive to environmental impact. Nonetheless, the overall attenuated effect is

very responsive to the carbon intensity signal and adoption pattern. Charging can just be transferred to another period of high-carbon without carbon-conscious scheduling. Using properly designed signals and automation, the literature recommends that charging can be timed with renewable supply and system requirements; however, at a large scale, it takes strong communications, customer engagement models, and cautious management of distribution bottlenecks^[14,82].

Emissions Applications Resilience applications are harder to synthesize in terms of emissions because most of their benefits are episodic, and tied to extreme events, and not to everyday operation. It is, however, suggested in the literature that the minimization of outage and the acceleration of restoration can help to decrease the use of backup diesel generation and the emission of emissions which correlate with interrupted activities^[83]. In places where outages are prevalent and backup generation is widespread, informatization can also bring material environmental co-benefits when reliability is the main reason.

5.3. Regional Profiles and Dominant Environmental Drivers

Regional synthesis clarifies that the same informatization technology can play different roles depending on system context and institutional design. In North America, a large portion of evidence centers on AMI-enabled analytics, demand response, and distribution automation, frequently

framed through peak reduction, reliability, and customer participation. Environmental benefits often appear via reduced peaker dispatch and improved system efficiency, but results differ across balancing authorities because marginal emissions and market structures vary widely. The literature also emphasizes the growing importance of DER aggregation and managed EV charging, with environmental outcomes increasingly linked to distribution constraint management and the availability of time-varying signals^[20]. **Table 3** consolidates the regional comparison by linking dominant drivers, typical informatization maturity, and the mitigation mechanisms most likely to deliver near-term environmental gains in each context.

In Europe, research frequently foregrounds renewable integration, flexibility markets, and cross-border balancing. Informatization is often evaluated through its ability to reduce curtailment, improve balancing efficiency, and support distribution-level active network management. Because many European systems already have relatively lower average emissions intensity compared with fossil-dominant grids, the marginal emissions story becomes especially important, and the literature increasingly shifts from annual-average accounting toward time-resolved and location-specific perspectives. Europe’s policy environment also motivates attention to data governance, interoperability, and consumer protections, which shape the scalability of flexibility programs and the legitimacy of high-resolution data use^[84].

Table 3. Regional comparison of informatization priorities and environmental implications.

Region (Illustrative)	Dominant Grid/Environment Driver	Typical Informatization Maturity	Most Emphasized Applications	Main Constraints	Environmental “Best Bet” Mechanisms
North America	Peak management, DER growth, reliability	Medium–high, uneven by utility	DR, AMI analytics, distribution automation, VPP pilots	Fragmented markets/regulation; heterogeneous carbon intensity	Peak shaving that displaces peakers; DER aggregation where constraints are modeled
Europe	High renewables, flexibility markets, interconnection	High in many countries	Active network management, congestion/curtailment reduction, smart tariffs	Data governance/consent; distribution constraints	Curtailment reduction + flexibility aligned with time-varying low-carbon supply
China/East Asia	Large-scale modernization, transmission expansion, rapid renewable growth	High (large programs)	Wide-area monitoring, congestion management, dispatch optimization	Evaluation transparency; regional heterogeneity	Congestion relief enabling renewable delivery; system-wide forecast/dispatch improvements
South Asia (e.g., India)	High distribution losses, reliability, rapid load growth	Growing, foundational in many areas	Smart metering, loss/theft reduction, automation pilots	Utility finances; institutional capacity; communications gaps	Loss/non-technical loss reduction; reliability improvements that reduce backup diesel
Latin America	Mixed generation (often hydro), loss reduction, resilience	Medium, variable	Distribution automation, loss analytics, DER integration	Regulatory heterogeneity; investment constraints	Loss reduction; targeted DER hosting capacity improvements
Africa (diverse contexts)	Access, mini-grids, diesel displacement, revenue sustainability	Uneven; leapfrogging opportunities	Mobile-enabled metering, microgrids, modular monitoring/control	Connectivity; financing; capacity building	Diesel displacement via hybrid microgrids + reliable revenue/ops enabled by informatization

The evidence base in China and certain East Asia encompasses much research on grid modernization on a large scale, extensive coverage, and orchestration of intensive infrastructure development with increasing renewable infiltration^[85]. The advantages to the environment are commonly presented with the system security and reliability, which represent the challenges of operationalizing large renewable bases along long-distance transmission corridors and irregular load distribution in regions. The importance of informatization in the field of congestion management, dynamic evaluation of system constraints, and enhanced dispatch under uncertainty is often emphasized in the studies. The literature is also influenced by the scale benefit of integrated planning and rollout, although it may be less clear on evaluation baselines, so it is more difficult to make cross-study comparisons.

In South Asia, and especially in India, distribution losses, reduction of theft, modernization of meters, and reliability issues are usually the priorities of the studies^[86]. The green applicability of informatization is commonly manifested in the form of decreased wasted production and enhanced capacity management, and the more encompassing decarbonization is connected to the incorporation of renewable sources and the adaptation to the fast increase in demand. Since these factors, such as institutional capacity, tariff structure, and financial limitations, are so dominant, it is common in the literature to find that technical potential is contingent on governance, cost recovery, and practical enforceability of interventions based on analytics.

In Latin America, the evidence usually focuses on loss minimization, distributed solar integration, and resiliency to weather disruptions. The assessment of informatization is in the form of better visibility and manageability of distribution networks, such as feeder automation or targeted voltage control. The environmental gains may be high with fossil generation continuing to provide the margin in lots of hours, yet results in different countries are inconsistent as a result of various hydro shares, degrees of interconnection, and the structure of regulation^[87].

The literature in most African settings identifies informatization as a possible leapfrogging route by using mobile-enabled meters, modular control systems, and mini-grid or microgrid utilization^[88]. The environmental aspect often entails the minimization of the use of diesel production

in remote or erratic grid locales by facilitating hybrid renewable source production to work effectively and enhance the collection of revenue to maintain the businesses. The relative sparsity of evidence in peer-reviewed form relative to other areas and the situation-specific nature of findings are also evident, but the literature is consistent in its findings that connect the close relationship between informatization, operational sustainability, and emissions-intensive backup generation.

5.4. Determinants of Environmental Performance across Contexts

Across regions, several determinants repeatedly explain why the same class of informatization intervention yields different mitigation outcomes^[89]. The most influential determinant is the marginal emissions profile. Informatization changes operations at specific times and locations, so environmental outcomes depend on which units are displaced and on how dispatch responds to altered load, losses, or curtailment. Systems with fossil-heavy marginal generation typically show larger emissions reductions for a given energy-saving or curtailment-reducing intervention than systems where marginal generation is already low-carbon.

Network constraints and topology form a second determinant, particularly for distribution-level applications^[90]. Voltage constraints, thermal limits, and protection coordination can restrict the usable flexibility of DERs and electrified loads. Where distribution models are incomplete or topology is uncertain, operators may avoid active control, reducing realized benefits relative to theoretical potential. Informatization can mitigate this by improving network models and state estimation, but the quality of underlying asset data and the institutional processes for maintaining models become critical.

A third determinant is the market design and regulatory incentives^[91]. Flexibility and DER coordination frequently demand systems of compensation that are system-valuing and motivating to participate in. In the case of flat tariffs, weak incentives, and informatization can lead to better observability but not cause behavior change. In contrast, in markets that offer ancillary benefits to capacity, flexible demand, and ancillary services, informatization can scale the benefits of the environment through mobilizing the private assets in a manner beneficial to replacing the fossil balanc-

ing. Governance of data is also an issue as several developed applications demand data interchange among utilities, aggregators, and consumers; restrictive data regulations may reduce scalability, whereas lax privacy regulations may destroy trust and engagement.

The fourth determinant is institutional capacity, which influences the quality of implementation, cybersecurity posture, and capabilities to transform analytics into action^[60]. Under conditions of financial strains or the disintegration of utilities in the areas, informatization initiatives can be directed at metering and revenue defense as the antecedent to wider operational streamlining. Even without a higher-order specimen like DER or carbon-aware dispatch, this can cut environmental costs both in waste and in maintenance, and achieve higher-order specimens like DER orchestration or carbon-wise dispatch in time.

5.5. Transferability, Scalability, and the Gap between Potential and Realized Impacts

The literature distinguishes implicitly between technical potential and realized outcomes. Many modeling studies present high mitigation potential under assumptions of full adoption, perfect communication, and high controllability. Field evidence more often reveals the friction points that determine realized benefits: incomplete device enrollment, behavioral heterogeneity, telemetry gaps, delayed interoperability, and conservative operational practices driven by safety and liability. Scalability therefore depends on whether informatization architectures are designed for long-term integration rather than as isolated pilots^[92].

Transferability across regions requires careful attention to both physical and institutional similarity. Efficiency applications such as loss reduction and voltage optimization are comparatively transferable because they leverage universal physical principles, but even here, the magnitude depends on baseline conditions and device availability. Flexibility programs are less transferable because they rely on tariff structures, consumer behavior, and enabling technologies that vary widely. Renewable integration and congestion management results transfer most reliably when system characteristics are comparable, such as renewable penetration levels, interconnection strength, and market dispatch rules. DER coordination and VPP findings are among the least transferable without deep contextualization because they are

shaped by distribution constraints, interconnection rules, and the division of roles between utilities and third parties^[20,93].

Scalability also involves the lifecycle sustainability of digital infrastructure. As grids decarbonize, the operational emissions savings per unit of informatization may decline, increasing the relative importance of embodied impacts, device lifetimes, and circularity. Regions that deploy informatization at scale must therefore align technical roadmaps with procurement standards, upgrade cycles, and end-of-life management to preserve net environmental gains^[94].

Overall, global evidence supports the view that grid informatization can materially mitigate environmental impacts, but the strongest and most consistent benefits arise in applications where digital capability directly reduces waste, displaces high-emitting marginal resources, or increases utilization of low-carbon generation under real operational constraints. Variability in findings is largely explained by marginal emissions profiles, network constraints, market design, and institutional capacity, rather than by the informatization technologies alone^[94]. These insights motivate the focus of the next section on trade-offs, risks, and governance: the same factors that shape realized mitigation outcomes also determine whether informatization remains reliable, equitable, and environmentally net-positive when deployed at scale.

6. Trade-Offs, Risks, and Governance for Sustainable Informatization

It is the quality of grid informatization that is often introduced as an environmental enabler, as it can enhance efficiency, release flexibility, and expand the use of low-carbon resources^[67]. But informatization also brings with it new trade-offs, which determine the achievement of these benefits, and whether any of them are net environmental benefits in the entire system lifecycle. These trade-offs do not lie on the periphery. They include the material and energy imprints of digital infrastructure, the energy consumption of computing and communications, the allocation of costs and benefits throughout society, and the cyber-physical risks that come with greater connectivity and automation. It is through governance, policy, regulation, standards, and institutional practices that, to a large degree, dictate whether informa-

tization enhances system performance and environmental performance or generates weak dependencies and unfair results. This paragraph summarizes the significant trade-offs and risks that have been found in the literature and explains the governance terms that can facilitate environmentally sustainable grid informatization.

6.1. Embodied Impacts, Material Footprints, and Device Lifecycles

The environmental assessment of informatization often prioritizes operational emissions reductions, but the hardware required for digitalization has embodied impacts associated with material extraction, manufacturing, logistics, and end-of-life treatment. Smart meters, sensors, communications equipment, control devices, and supporting data infrastructure each carry embodied carbon and resource footprints, including metals, plastics, and in some cases, rare or critical materials embedded in electronics. These impacts can be modest compared with the operational emissions reductions achieved in carbon-intensive systems, but they become increasingly important as grids decarbonize and as operational emissions decline. In low-carbon systems, the net environmental advantage of informatization depends more strongly on extending device lifetimes, avoiding unnecessary replacement cycles, and ensuring that digital upgrades remain modular rather than requiring wholesale hardware refresh^[67].

One of the key sustainability concerns is therefore device lifecycle management. Mass implementation of meters and sensors generates synchronized pulses of end-of-life equipment after 10 years, particularly when communication standards change, or when firmware maintenance is discontinued. This invites threats of early obsolescence and lock-in, where owning proprietary ecosystems motivates us to upgrade instead of making repairs or upgrades. The literature postulates that these impacts can be mediated through procurement practices and technical specifications by focusing on interoperability, firmware, and long-term support commitments. Meanwhile, rapid innovation and long infrastructure lifetimes inherently conflict with each other: power system assets are generally decades long, whereas ICT cycles are years long. Green informatization needs governance systems that would balance these timescales and ensure that environmental loads are not pushed off the emission of operations

onto the fast track of material flows^[95].

6.2. ICT Operational Energy Use and the Carbon Footprint of Computation

Informatization increases electricity use within the grid's own digital nervous system. Communications networks, field devices, gateways, servers, and data centers consume energy continuously, and advanced analytics can introduce additional compute loads. While the energy intensity of grid ICT is typically small relative to total electricity delivered, its absolute magnitude grows as device populations scale and as more functions shift toward high-frequency data collection and real-time optimization. The environmental significance of ICT energy use depends on the carbon intensity of the electricity powering these systems and on whether computing resources are provisioned efficiently^[96].

Architectural choices affect this footprint. Cloud-centric designs can offer efficiency through shared infrastructure and modern cooling and power management, but they may increase data transport demands and create dependencies on remote services. Edge computing can reduce bandwidth and latency and improve resilience, but it can also increase the number of always-on devices and complicate lifecycle management. The sustainability challenge is not to choose a single architecture universally, but to align compute placement with operational needs and to avoid over-collecting and over-processing data when it does not improve control outcomes. As carbon-aware computing and procurement of low-carbon data center services become more common, governance can further reduce the footprint of informatization by aligning ICT operations with low-carbon electricity availability and by specifying efficiency requirements for vendors and service providers^[97].

6.3. E-Waste, Circularity, and End-of-Life Governance

Digitalization increases the volume and diversity of electronic waste in the power sector^[98]. Unlike traditional grid equipment, many informatization devices contain complex electronic assemblies that are difficult to refurbish or recycle, and the value of recovered materials may not justify collection and processing without a supportive policy. The risk is that large deployments of meters, sensors, and

communications devices create a growing stream of e-waste that is handled inconsistently across jurisdictions, potentially shifting environmental burdens to regions with weaker waste governance.

Circularity strategies make sustainable informatization take center stage. These plans involve the development of devices that can be disassembled, the standardization of parts among suppliers, repair and remodeling, and the development of reverse logistics to gather back the used devices. Neither do they need a lack of clarity on responsibility. Specifically, utilities, vendors and regulators have to decide who is responsible for taking care of end-of-life management and how to recoup expenses. The governance mechanisms that have often been discussed are the extended producer responsibility frameworks and the procurement requirements towards recyclability and take-back programs, although their implementation differs greatly. According to the literature, in the absence of explicit end-of-life policies, informatization may unwillingly contribute to environmental burdens despite causing a reduction in operational emissions, especially with the increase of deployment^[99].

6.4. Rebound Effects and Behavioral Responses That Erode Mitigation Benefits

Efficiency and flexibility programs that are made feasible by informatization may cause rebound effects, which decrease the net environmental benefits^[16]. An increase in efficiency reduces the expenditure of electricity, thus consumption can also rise to compensate for some of the energy saving. Dynamic tariffs and demand response can influence consumption in such a manner that minimizes costs without minimizing emissions because the load that is shifted will be in periods of greater carbon intensity. On the same note, offering close feedback to the customers regarding consumption can, at first, drop demand, but the impacts can diminish in the long term as they may reduce engagement or as households may introduce new electricity-saving appliances as savings are earned.

Environmental performance is thus related to behavior and socio-technical responses^[100]. Programs that operate voluntarily or customer focus or where tariffs are complicated to understand may be subject to participation decay and unequal reactions. Response can be stabilized by au-

tomation, though it creates barriers to its own adoption, and could concentrate benefits in the hands of individuals who can afford enabling devices. According to the literature, strong measurement and verification, well-considered incentives, and open communication have an impact on the persistence and fairness of program effects. In the case of environmental accounting, the implication is that the assumptions of static savings are often unrealistic; the credible accounting and assessment of the environment needs longitudinal assessment and the accounting of emissions over time, especially when the interventions do not reduce the load, but redistribute it.

6.5. Equity, Affordability, and Energy Justice in Digital Grid Transitions

The allocation of the informatization costs and benefits is not even^[79]. Dynamic pricing can make customers more vulnerable to volatility and can negatively affect households with limited flexibility, which can include medical equipment users, fixed work schedules, or poor building performance. There is a risk of the participation of demand response being biased to richer households (with smart appliances, EV, or flexible loads), and to customers with building automation systems. On the other hand, less-connected communities or communities with lower access to digital devices may not have access to new opportunities, and this forms a digital divide in who can enjoy the benefits of flexible markets, rebates, or lower bills.

These equity processes are important to the outcomes of the environment as they affect the level of adoption and political legitimacy. In case informatization policies are seen as unfair, involvement and control will be undermined, and the possibility of mitigation will be curtailed. On the other hand, the inclusive design can increase participation and make resources of flexibility more dependable. The literature highlights the fact that equity can be achieved by special subsidies for enabling technologies, anti-bill shock measures, designing default tariffs to create minimum harm, and designing programs to place a premium on non-energy benefits like comfort and health. Privacy protection and consent are also a part of governance and may be especially critical to vulnerable groups that might be more likely to become victims of data abuse^[101].

6.6. Cybersecurity and the Environmental Implications of Cyber-Physical Risk

One of the most significant threats posed by informatization is cybersecurity, since it may have a direct impact on reliability and operational efficiency^[102]. Cyber incidents may also impact the performance of the system negatively, drive the operator into conservative operation, and provoke an outage as the grid operation becomes increasingly dependent on data integrity and automated control. The environmental effects occur in a variety of ways, and they can include: outages can lead to greater dependence upon

diesel backup power; disruption can lead to redispatch to less efficient or higher-emitting units; and lack of control over DER coordination can lead to an increase in curtailment or decrease the availability of low-carbon flexibility. Conceived cybersecurity risk may inhibit data spreading and interoperability even in the absence of large-scale incidents, delaying the implementation of advanced applications with environmental advantages. **Figure 4** puts informatization into the net-benefit context, where the operational mitigation benefits received should outweigh the footprints and mitigation-based risks associated with lifecycles.

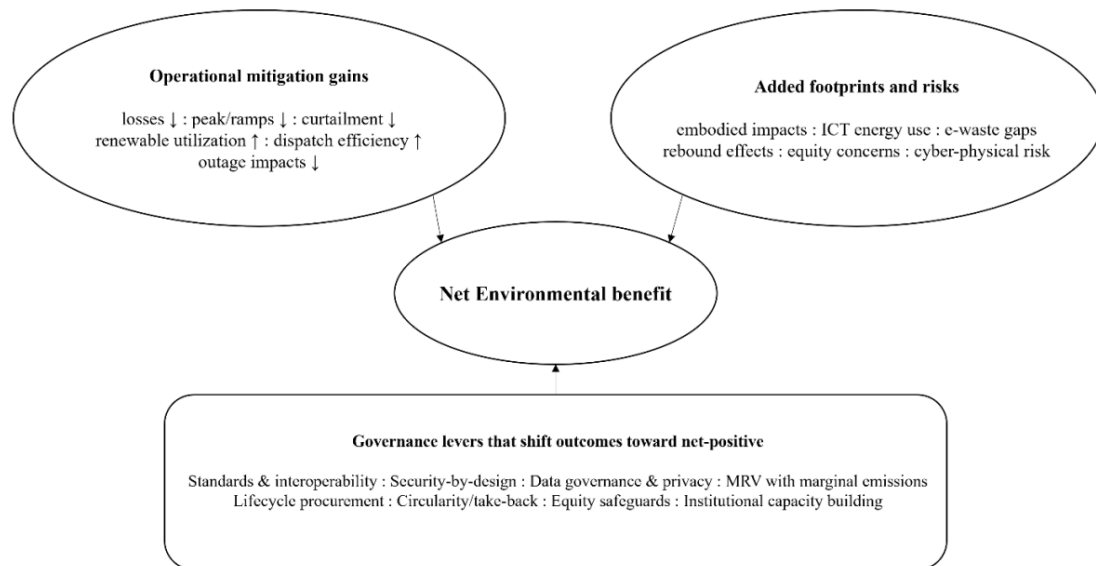


Figure 4. Net-benefit boundary and trade-off diagram for sustainable informatization.

The literature underscores that cybersecurity must be embedded into system architecture through defense-in-depth, secure authentication and authorization, robust patch management, segmentation of critical systems, and monitoring for anomalies^[47]. Cybersecurity also interacts with supply chain governance, as vulnerabilities in devices and software can propagate through the system. Because many informatization devices are deployed at scale and remain in the field for long periods, the ability to provide secure updates over time becomes a sustainability issue: insecure devices may be decommissioned prematurely, increasing e-waste and embodied impacts, or may remain in operation as persistent vulnerabilities. Governance frameworks that mandate security-by-design, require vendor transparency, and support coordinated vulnerability disclosure are therefore closely linked to both reliability and environmental sustainability.

6.7. Data Governance, Interoperability, and Institutional Coordination

Most of the most useful applications in informatization that can be helpful to the environment rely on the exchange of data beyond the organizational boundaries. DER coordination involves distributing operational constraints between the distribution utilities and aggregators^[103]. Carbon-conscious charging and optimization of flexibility can necessitate access to time- and location-dependent carbon signals. Planning integration needs information regarding the network assets, load profiles, and DER performance. These flows may be stalled by privacy, commercial sensitivities, or fragmented institutional responsibilities unless the data is managed coherently.

Good governance is a balanced governance that weighs

between being open and being secure^[104]. It establishes the ownership of data, the allowed use, and other standards of anonymization, aggregation, and consent. It also defines access controls that can enable innovation and not compromise security. Interoperability is an essential complement to governance, since the ability to access data is not of much use when it is stored in non-compatible formats or proprietary interfaces. According to them, standardized information models and protocols provide the ability to upgrade modularly, less vendor lock-in, and a wider range of analytics and control application ecosystem. The literature indicates that interoperability enhances faster rates of environmental gains, as it reduces integration expenses and also allows utilities to implement best-of-breed solutions instead of having to function within monolithic vendor ecosystems.

Institutional coordination is equally important^[104]. Informatization often spans transmission and distribution responsibilities, involves regulators and market operators, and depends on third-party service providers. Governance must therefore resolve role boundaries and accountability. For example, if an aggregator controls DERs that can affect distribution constraints, utilities need visibility and control safeguards; if utilities control customer devices, customers need transparency and protections. Clarifying accountability for performance, failures, and data misuse influences trust and adoption at scale.

6.8. Regulatory and Policy Mechanisms for Verifiable Net Environmental Benefits

Because informatization benefits can be diffuse and context-dependent, regulatory design strongly affects whether investments translate into environmental mitigation. Traditional cost-of-service regulation can discourage innovation if utilities are not rewarded for performance improvements or if benefits accrue outside the utility balance sheet. Performance-based regulation and incentive mechanisms that value loss reduction, peak reduction, reliability, and emissions mitigation can align utility incentives with environmental outcomes. Similarly, well-designed flexibility markets can remunerate demand response and DER services, increasing participation and enabling informatization platforms to operate at scale^[105].

Verification is central to credible policy. Measurement and verification protocols for demand response, energy savings,

and DER services determine whether reported environmental benefits are real. Where possible, verification should incorporate time-resolved emissions accounting, particularly for load-shifting applications, and should avoid reliance on static annual average emissions factors. Policymakers can also encourage lifecycle sustainability by incorporating embodied emissions, recyclability, and end-of-life obligations into procurement standards and regulatory approvals, ensuring that informatization does not create hidden environmental burdens^[106].

Lastly, there is governance that should deal with sequencing^[107]. What are given as basic steps in other contexts, including the quality of asset data, basic communications coverage, and reliable metering, are some preconditions to advanced applications. Any policy that drives high-complexity platforms without these underpinnings runs the risk of not performing and being publicly criticized. On the other hand, policies that regard the modernization of metering as the objective can overlook major mitigation prospects of the coordinated DER control and electrification management. Literature is also increasingly backing up incremental strategies of capability development that ensure interoperability and security at the very beginning. **Table 4** converts the discussion in the trade-off into a checklist that is based on governance-oriented and defines the mitigation measures that can be implemented in practice, the responsible stakeholders, and the monitoring indicators that can be applied to guarantee that the net-positive results are achieved.

6.9. Integrating Trade-Offs into Research and Deployment Decisions

The above-presented trade-offs suggest that it is not possible to assess sustainable informatization only in the context of its operational emission reduction potential. Net environmental benefit shows reliance on the impact of lifecycle, ICT operational footprint, resilience and cybersecurity posture, fairness, and legitimacy of programs, which are based on customer involvement and use of data. To researchers, this encourages more integrated approaches that combine power system models with time-resolved emissions estimation and life cycle evaluation, as well as include behavior dynamics and governance limitations. It implies that practitioners and policymakers need to incorporate environmental goals into informatization roadmaps by using performance metrics, interoperability and security specifics, and circularity-based

procurement and end-of-life policies^[108].

Overall, informatization brings about great mitigation opportunities and, at the same time, gives rise to new dependencies and risks that can undermine benefits if not managed. The governance models emphasizing security-by-design, interoperability, fair access, strict verification, and life-cycle

sustainability are essential to maintaining the fact that informatization becomes a net-positive contributor to environmental mitigation by scaling up smart grid deployments across the world. These lessons are summarized at the end and made into general lessons and specific priorities for utilities, regulators, and researchers.

Table 4. Trade-offs, risks, and governance checklist for net-positive informatization.

Issue Category	Risk to Net Environmental Benefit	Governance/Technical Mitigation	Primary Stakeholders	Suggested Monitoring Indicators
Embodied impacts	Hardware footprint offsets operational savings in low-carbon grids	Lifecycle procurement, modular upgrades, long support windows	Utilities, regulators, vendors	Device lifetime; embodied CO ₂ e reporting; replacement rates
ICT energy use	Computing/communications emissions grow with scale	Efficient architectures (edge/cloud balance), carbon-aware computing	Utilities, IT providers	ICT kWh/yr; data center carbon intensity; data volume per control benefit
E-waste/circularity	End-of-life burdens, informal disposal	Take-back programs, repair/refurbish, EPR policies	Regulators, vendors, waste sector	Collection rate; recycling yield; hazardous disposal compliance
Rebound effects	Savings erode due to behavior or load shifting to higher-carbon hours	Time-resolved MRV; program redesign; persistence studies	Utilities, regulators, researchers	Persistence of kWh/peak impacts; emissions by hour; participation decay
Equity & affordability	Benefits skew to digitally enabled customers; bill shocks	Protections, targeted subsidies, inclusive program design	Regulators, utilities	Participation by income/tenure; bill volatility; opt-out rates
Cybersecurity	Outages/redispach/curtailment from attacks or vulnerabilities	Security-by-design, patch governance, segmentation, audits	Utilities, vendors, regulators	Patch latency; incident frequency; critical asset exposure
Interoperability & lock-in	Proprietary ecosystems raise costs and shorten lifetimes	Open standards, interoperable interfaces, vendor-neutral procurement	Utilities, regulators	% assets standards-compliant; integration costs; multi-vendor operability
Verification (MRV)	Over-claiming impacts undermines credibility and policy	Standard MRV protocols; marginal emissions accounting	Regulators, utilities, ISO/RTOs	Verified vs. claimed savings; methodology transparency score

7. Conclusion

The informatization of grids is transforming the ability of electricity systems to assist in the mitigation of the environment. The informatization layer transforms data into operational flexibility and efficiency by making it observable at the distribution end, rather than the bulk power networks, and allowing more granular and faster control as well as more coordinated control. It is clear from the synthesis of the evidence across the world that the most reliable gains for the environment are achieved where informatization directly lowers waste or enhances the use of low-carbon resources in practice. Loss minimization, volt/VAR optimization, conservation voltage reduction, and automation of the distribution system demonstrate time and again significant gains in en-

ergy efficiency and operations in even systems with large baseline losses or outdated instrumentation. Digitally enabled flexibility (e.g., demand response and other forms) can provide significant mitigation in cases where it causes decreased peak-driven dispatch of units with high emissions, or in cases where it brings consumption levels into agreement with time-varying low-carbon supply; but its emissions effects are much more susceptible in the cases of margins of generation and load shifting evaluation with time-resolved carbon indicators instead of annual averages. Forecasting, congestion management, and reduction of curtailment become the high-leverage paths in high-renewable systems, particularly when informatization is coupled with flexible resources and market arrangements that make the resources valued and mobilized. DER interaction using DERMS and

virtual power plant architectures spreads the potential of mitigation by making distributed devices visible in the form of high constraint-aware system resources, but the resulting benefit highly relies on interoperability, quality of telemetry, visibility of the distribution network, and optimizations of incentives among the utilities, aggregators, and consumers. The rapidly expanding opportunities of managed EV charging and other electrification-facilitated (flexibility) can be considered based on carbon-conscious scheduling, distribution constraint management, and long-term engagement on a large scale.

One of the central ideas of the global comparison is that informatization is not a homogeneous solution that has homogeneous results. The fact that digital technologies are present does not influence environmental performance, but the environment where they are implemented does. The main factors influencing whether informatization will displace, curtailment will be reduced, or simply change energy use without producing a net effect are marginal emissions intensity, network constraints, market design, and institutional capacity. In lower- and middle-income environments where higher modernization and lower loss reduction, increased revenue protection, and better reliability may be conditional on environmental co-benefits may be vastly lower wastage and mitigated dependence on emissions-intensive backup power as informatization effects. Flexibility orchestration, carbon-conscious operation, and DERs and electrified loads increasingly feature in the focus of benefits in mature and lower-carbon systems, and the governance, access to data, and interoperability of these systems are giving a greater role in the determination of benefits.

It is also revealed in the review that net environmental benefit cannot be assumed. The process of informatization stepped into the aspects of material and energy footprint in meters, sensors, communications systems, and computer infrastructure; increased the rate of replacing electronics, exerted demands on e-waste and circularity, and posed cyber-physical risks capable of compromising reliability and even indirectly leading to increased emissions using flexible resources. Scalability is also conditional on social acceptance and equity issues, such as privacy, digital inclusion, cost, and benefits distributions in dynamic tariffs and flexibility programs. Such trade-offs ensure that governance is a determining factor in the continued informatization, being an

environmentally favorable shift. Environmental enablers are security-by-design, strong data governance, and interoperability standards, since they facilitate a durable, scalable implementation of the applications providing the mitigation.

It has a number of implications for practice and policy. To support the long-lived platforms, informatization should be ordered to align with the needs of systems, starting with foundational observability and data quality where they are lacking, and, at the same time, to be interoperable and designed to be long-lived. Second, time- and location-sensitive emissions accounting should be used to assess environmental performance whenever there is load shifting, integration of renewable, or flexibility; annual average emissions factors should not be relied on because they may misattribute and may hide the locations of the greatest benefits. Third, verification protocols must be reinforced in a way that allows the reported savings and flexibility effects to be represented as the effect of causal participation and behavioral dynamics in realistic participation and behavioral settings. Fourth, procurement and regulatory supervision ought to be supported by lifecycle sustainability by including upgradability, long-term security support, device repairability, and end-of-life take-back or recycling pathways, which will better prevent the operation emissions reductions from being neutralized by the increasing material burdens. Lastly, safeguards of equity, such as the protection of bills, the availability of enabling technologies, transparent consent processes, and the program design, should be perceived as a part of mitigation since they determine participation and the validity of digital grid transitions.

In the case of research, the results indicate that there should be a greater examination of integrated and comparable evaluation techniques. The next generation of work should engage more regularly in power system operational modeling, as well as the time-resolved marginal emissions estimation and the material and lifecycle assessment of digital infrastructure. There should also be more focus on large-scale empirical evaluation, reproducible datasets, and benchmarks that could compare the results between regions and applications. With the continuous development of AI-based analytics and automation, operational trustworthiness, resilience in the case of rare events, and auditable decision-making ought to be a primary research focus, especially when environmental goals are integrated into control loops.

On the whole, grid informatization can be described as a facilitating platform for environmentally optimal power systems, and not an individual climate solution. Informatization, through sound architecture, secure and interoperable data practices, plausible measurement and verification, and consideration of lifecycle, equity effects when applied can materially decrease environmental burdens by decreasing losses, peaking and balancing, which are carbon-intensive, curtailment, and coordination of the distributed and electrified resources that define modern grids. This multinational outlook of the present review emphasizes the fact that the greatest benefits will be received when informatization is adjusted to local limitations and is conditioned by those governance models that would turn digital potential into long-term and measurable environmental results.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or generated in this study. As this is a review, it is based on data and information from previously published sources, which are cited in the reference list.

Conflicts of Interest

The authors declare no conflict of interest.

References

- [1] McAllister, L.K., 2011. Adaptive Mitigation in the Electric Power Sector. *Brigham Young University Law Review*. 2011(6), 8.
- [2] Tian, X., An, C., Chen, Z., 2023. The Role of Clean Energy in Achieving Decarbonization of Electricity Generation, Transportation, and Heating Sectors by 2050: A Meta-Analysis Review. *Renewable and Sustainable Energy Reviews*. 182, 113404.
- [3] Akrami, A., Doostizadeh, M., Aminifar, F., 2019. Power System Flexibility: An Overview of Emergence to Evolution. *Journal of Modern Power Systems and Clean Energy*. 7(5), 987–1007.
- [4] Amin, S.M., 2011. Smart Grid: Overview, Issues and Opportunities. *Advances and Challenges in Sensing, Modeling, Simulation, Optimization and Control*. *European Journal of Control*. 17(5–6), 547–567.
- [5] Fang, X., Misra, S., Xue, G., et al., 2011. Smart Grid—The New and Improved Power Grid: A Survey. *IEEE Communications Surveys and Tutorials*. 14(4), 944–980.
- [6] Murino, T., Monaco, R., Nielsen, P.S., et al., 2023. Sustainable Energy Data Centres: A Holistic Conceptual Framework for Design and Operations. *Energies*. 16(15), 5764.
- [7] Williams, E., 2011. Environmental Effects of Information and Communications Technologies. *Nature*. 479(7373), 354–358.
- [8] Aziz, T., Lin, Z., Waseem, M., et al., 2021. Review on Optimization Methodologies in Transmission Network Reconfiguration of Power Systems for Grid Resilience. *International Transactions on Electrical Energy Systems*. 31(3), e12704.
- [9] Zhang, B., Chen, H., Liu, K., et al., 2023. Estimating the Environmental Impacts of Backup Generation After Power Outages: A Case Study of China. *Energy and Climate Change*. 4, 100114.
- [10] Farquharson, D., Jaramillo, P., Samaras, C., 2018. Sustainability Implications of Electricity Outages in Sub-Saharan Africa. *Nature Sustainability*. 1(10), 589–597.
- [11] O’Connell, N., Pinson, P., Madsen, H., et al., 2014. Benefits and Challenges of Electrical Demand Response: A Critical Review. *Renewable and Sustainable Energy Reviews*. 39, 686–699.
- [12] Liu, R., Bunke, D., Behrens, F., et al., 2024. Environmental Impacts of Digital Infrastructures and Digital Services: CO₂, Resource Consumption, Substances of Concern and More. In *Proceedings of the 2024 Electronics Goes Green 2024+ (EGG)*, Berlin, Germany, 18–20 June 2024; pp. 1–10.
- [13] Munonye, W.C., 2025. Circular Economy Meets Smart Energy Grids: Designing Systems for Resource Optimization and Carbon Reduction. *Frontiers in Sustainability*. 6, 1568254.
- [14] Aghahadi, M., Bosisio, A., Merlo, M., et al., 2024. Digitalization Processes in Distribution Grids: A Comprehensive Review of Strategies and Challenges. *Applied Sciences*. 14(11), 4528.
- [15] Rajendran, G., Raute, R., Caruana, C., 2025. The Brain behind the Grid: A Comprehensive Review on

- Advanced Control Strategies for Smart Energy Management Systems. *Energies*. 18(15), 3963.
- [16] Moretti, M., Djomo, S.N., Azadi, H., et al., 2017. A Systematic Review of Environmental and Economic Impacts of Smart Grids. *Renewable and Sustainable Energy Reviews*. 68, 888–898.
- [17] Moreno Escobar, J.J., Morales Matamoros, O., Tejeida Padilla, R., et al., 2021. A Comprehensive Review on Smart Grids: Challenges and Opportunities. *Sensors*. 21(21), 6978.
- [18] Al-Shetwi, A.Q., Hannan, M.A., Al-Masri, M.K., et al., 2025. Latest Advancements in Smart Grid Technologies and Their Transformative Role in Shaping the Power Systems of Tomorrow: An Overview. *Progress in Energy*. 7(1), 012004.
- [19] Ringler, P., Keles, D., Fichtner, W., 2016. Agent-Based Modelling and Simulation of Smart Electricity Grids and Markets—A Literature Review. *Renewable and Sustainable Energy Reviews*. 57, 205–215.
- [20] Smith, E.J., Robinson, D.A., Elphick, S., 2024. DER Control and Management Strategies for Distribution Networks: A Review of Current Practices and Future Directions. *Energies*. 17(11), 2636.
- [21] Nicolosi, M., 2012. The Economics of Renewable Electricity Market Integration: An Empirical and Model-Based Analysis of Regulatory Frameworks and Their Impacts on the Power Market [PhD Thesis]. Universität zu Köln: Cologne, Germany.
- [22] Vardon, M., Castaneda, J.-P., Nagy, M., et al., 2018. How the System of Environmental-Economic Accounting Can Improve Environmental Information Systems and Data Quality for Decision Making. *Environmental Science & Policy*. 89, 83–92.
- [23] Laimon, M., 2025. Renewable Energy Curtailment: A Problem or an Opportunity? *Results in Engineering*. 26, 104925.
- [24] Ma, H., Balthasar, F., Tait, N., et al., 2012. A New Comparison Between the Life Cycle Greenhouse Gas Emissions of Battery Electric Vehicles and Internal Combustion Vehicles. *Energy Policy*. 44, 160–173.
- [25] Borenstein, S., Jaske, M., Rosenfeld, A., 2002. Dynamic Pricing, Advanced Metering, and Demand Response in Electricity Markets. University of California Energy Institute: Berkeley, CA, USA.
- [26] Cavus, M., 2024. Integration Smart Grids, Distributed Generation, and Cybersecurity: Strategies for Securing and Optimizing Future Energy Systems. Preprints. DOI: <https://doi.org/10.20944/preprints202410.1225.v1>
- [27] Nurul, S.N., Biswas, A., Chowdhury, A.K., 2023. AI-Enabled Cyber-Physical Power Systems: Review of Smart Grid Security, Optimization, and Decision Support. *Applied IT and Engineering*. 1(1), 1–9.
- [28] Hojabri, M., Dersch, U., Papaemmanouil, A., et al., 2019. A Comprehensive Survey on Phasor Measurement Unit Applications in Distribution Systems. *Energies*. 12(23), 4552.
- [29] Biswal, C., Sahu, B.K., Mishra, M., et al., 2023. Real-Time Grid Monitoring and Protection: A Comprehensive Survey on the Advantages of Phasor Measurement Units. *Energies*. 16(10), 4054.
- [30] Boniface, U.E., Mayaki, C.S., 2024. High Voltage Engineering Innovations Enabling Efficient Transmission Reduced Losses Enhanced Reliability Sustainability across Modern Power Networks Worldwide Infrastructure. *International Journal of Materials and Engineering Technology*. 8(3), 296–311.
- [31] Hamilton, D., 2023. Optimization-Based Operation and Control Approaches for Improving the Resilience of Electric Power Systems [PhD Thesis]. Purdue University: West Lafayette, IN, USA.
- [32] Chhaya, L., Sharma, P., Kumar, A., et al., 2018. IoT-Based Implementation of Field Area Network Using Smart Grid Communication Infrastructure. *Smart Cities*. 1(1), 176–189.
- [33] Evangelopoulos, V.A., Avramidis, I.I., Georgilakis, P.S., 2020. Flexibility Services Management under Uncertainties for Power Distribution Systems: Stochastic Scheduling and Predictive Real-Time Dispatch. *IEEE Access*. 8, 38855–38871.
- [34] Cabrera-Tobar, A., Grimaccia, F., Leva, S., 2023. Energy Resilience in Telecommunication Networks: A Comprehensive Review of Strategies and Challenges. *Energies*. 16(18), 6633.
- [35] Said, D., 2022. A Survey on Information Communication Technologies in Modern Demand-Side Management for Smart Grids: Challenges, Solutions, and Opportunities. *IEEE Engineering Management Review*. 51(1), 76–107.
- [36] Bhattarai, B.P., Paudyal, S., Luo, Y., et al., 2019. Big Data Analytics in Smart Grids: State-of-the-Art, Challenges, Opportunities, and Future Directions. *IET Smart Grid*. 2(2), 141–154.
- [37] López Sáez de Argandoña, J., 2020. Virtual Power Plants Aggregating Distributed Energy Resources: A Tool for Integrating Large Shares of Variable Renewable Energy in a Flexible Power System [Master’s Thesis]. Universidad Politécnica de Madrid: Madrid, Spain.
- [38] Cheng, Q., Zhang, Z., Wang, Y., et al., 2025. A Review of Distributed Energy Systems: Technologies, Classification, and Applications. *Sustainability*. 17(4), 1346.
- [39] Pereira, S.L., 2024. Towards Fine-Grained, Holistic Energy Control in Large-Scale Computing Infrastructures [Master’s Thesis]. Universidade do Porto: Porto, Portugal.
- [40] Pradeep, Y., Seshuraju, P., Khaparde, S.A., et al., 2011. Flexible Open Architecture Design for Power System Control Centers. *International Journal of Electrical*

- Power and Energy Systems. 33(4), 976–982.
- [41] Shi, Y., Li, W., Fan, G., et al., 2024. Low-Carbon Dispatch of an Integrated Energy System Considering Confidence Intervals for Renewable Energy Generation. *Energy Engineering: Journal of the Association of Energy Engineers*. 121(2), 461–482.
- [42] Roy, S., Dhal, R., 2014. Situational Awareness for Dynamical Network Processes Using Incidental Measurements. *IEEE Journal of Selected Topics in Signal Processing*. 9(2), 304–316.
- [43] Omol, E., Mburu, L., Onyango, D., 2024. Anomaly Detection in IoT Sensor Data Using Machine Learning Techniques for Predictive Maintenance in Smart Grids. *International Journal of Science, Technology and Management*. 5(1), 201–210.
- [44] Sayed, K., Gabbar, H.A., 2017. SCADA and Smart Energy Grid Control Automation. In: Gabbar, H.A. (Ed.). *Smart Energy Grid Engineering*. Elsevier: Amsterdam, The Netherlands. pp. 481–514.
- [45] Refaat, S.S., Mohamed, A., 2019. Smart Management System for Improving the Reliability and Availability of Substations in Smart Grid with Distributed Generation. *The Journal of Engineering*. 2019(17), 4236–4240.
- [46] Tshering, C., Gyeltshen, T., 2024. Fault Location, Isolation and Service Restoration Through Advanced Distribution Management System. In *Proceedings of the TENCON 2024: IEEE Region 10 Conference*, Singapore, 1–4 December 2024; pp. 743–746.
- [47] Yaacoub, J.P.A., Noura, H.N., Salman, O., et al., 2025. Toward Secure Smart Grid Systems: Risks, Threats, Challenges, and Future Directions. *Future Internet*. 17(7), 318.
- [48] McKenna, E., Richardson, I., Thomson, M., 2012. Smart Meter Data: Balancing Consumer Privacy Concerns with Legitimate Applications. *Energy Policy*. 41, 807–814.
- [49] Wallis, T., 2023. How Can We Design a Socio-Technical, Interorganisational Response to Ensure Better Cybersecurity for Critical Infrastructure [PhD Thesis]. University of Strathclyde: Glasgow, UK.
- [50] Mock, D., Bush, J., Arbogast, S.V., 2024. DERs Role in a More Reliable, Sustainable, and Resilient Power System. UNC Energy Center, Kenan-Flagler Business School: Chapel Hill, NC, USA.
- [51] Ding, J., Qammar, A., Zhang, Z., et al., 2022. Cyber Threats to Smart Grids: Review, Taxonomy, Potential Solutions, and Future Directions. *Energies*. 15(18), 6799.
- [52] Schäfer, M., Cerdas, F., Herrmann, C., 2024. Towards Standardized Grid Emission Factors: Methodological Insights and Best Practices. *Energy and Environmental Science*. 17(8), 2776–2786.
- [53] Saeed, M.S., Mustafa, M.W., Hamadneh, N.N., et al., 2020. Detection of Non-Technical Losses in Power Utilities—A Comprehensive Systematic Review. *Energies*. 13(18), 4727.
- [54] El-Shahat, A., Haddad, R.J., Alba-Flores, R., et al., 2020. Conservation Voltage Reduction Case Study. *IEEE Access*. 8, 55383–55397.
- [55] Ahmed, M., Khan, M.R., 2025. Artificial Intelligence-Enabled Digital Twins for Energy Efficiency in Smart Grids. *Review of Applied Science and Technology*. 4(2), 580–615.
- [56] Nursimulu, A., 2016. Demand-Side Flexibility for Energy Transitions: Policy Recommendations for Developing Demand Response. Available from: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2831868 (cited 1 December 2025).
- [57] Zafar, U., Bayhan, S., Sanfilippo, A., 2020. Home Energy Management System Concepts, Configurations, and Technologies for the Smart Grid. *IEEE Access*. 8, 119271–119286.
- [58] Thunberg, C., Holström, M., 2024. Flexibility over Grid Expansion: Optimisation for Maximum Climate Value and Grid Utilisation: Qualitative and Quantitative Analysis of the Potential, Grid-and Climate Value of Transfer Capacity Flexibility. Available from: <https://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-533998> (cited 1 December 2025).
- [59] Bhattacharya, S., Chengoden, R., Srivastava, G., et al., 2022. Incentive Mechanisms for Smart Grid: State of the Art, Challenges, Open Issues, Future Directions. *Big Data and Cognitive Computing*. 6(2), 47.
- [60] Cavus, M., 2025. Advancing Power Systems with Renewable Energy and Intelligent Technologies: A Comprehensive Review on Grid Transformation and Integration. *Electronics*. 14(6), 1159.
- [61] Zang, T., Wang, S., Wang, Z., et al., 2024. Integrated Planning and Operation Dispatching of Source–Grid–Load–Storage in a New Power System: A Coupled Socio–Cyber–Physical Perspective. *Energies*. 17(12), 3013.
- [62] Olivella-Rosell, P., Lloret-Gallego, P., Munné-Collado, Í., et al., 2018. Local Flexibility Market Design for Aggregators Providing Multiple Flexibility Services at Distribution Network Level. *Energies*. 11(4), 822.
- [63] Hoummadi, M.A., Aroussi, H.A., Bossoufi, B., et al., 2024. A Review of Constraints and Adjustable Parameters in Microgrids for Cost and Carbon Dioxide Emission Reduction. *Heliyon*. 10(6), e27489.
- [64] Staudt, P., 2019. Transmission Congestion Management in Electricity Grids-Designing Markets and Mechanisms [PhD Thesis]. Karlsruhe Institut für Technologie: Karlsruhe, Germany.
- [65] Wang, J., 2025. Distributed Energy System. In *Carbon Neutral City*. Palgrave Macmillan: Singapore. pp. 231–260.
- [66] Samad, T., Annaswamy, A.M., 2017. Controls for

- Smart Grids: Architectures and Applications. *Proceedings of the IEEE*. 105(11), 2244–2261.
- [67] Moreno, R., Street, A., Arroyo, J.M., et al., 2017. Planning Low-Carbon Electricity Systems under Uncertainty Considering Operational Flexibility and Smart Grid Technologies. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. 375(2100), 20160305.
- [68] Mojumder, M.R.H., Ahmed Antara, F., Hasanuzzaman, M., et al., 2022. Electric Vehicle-to-Grid (V2G) Technologies: Impact on the Power Grid and Battery Sustainability. 14(21), 13856.
- [69] Ruggles, T.H., Caldeira, K., 2022. Wind and Solar Generation May Reduce the Inter-Annual Variability of Peak Residual Load in Certain Electricity Systems. *Applied Energy*. 305, 117773.
- [70] Shahidehpour, M., Fotuhi-Friuzabad, M., 2016. Grid Modernization for Enhancing the Resilience, Reliability, Economics, Sustainability, and Security of Electricity Grid in an Uncertain Environment. *Scientia Iranica*. 23(6), 2862–2873.
- [71] Paoletti, G., Herman, G., 2015. Monitoring of Electrical Equipment Failure Indicators and Zero-Planned Outages: Past, Present and Future Maintenance Practices. In *Proceedings of the 2015 61st IEEE Pulp and Paper Industry Conference (PPIC)*, Milwaukee, WI, USA, 14–18 June 2015; pp. 1–10.
- [72] Billanes, J.D., Jørgensen, B.N., Ma, Z., 2025. A Framework for Resilient Community Microgrids: Review of Operational Strategies and Performance Metrics. *Energies*. 18(2), 1–39.
- [73] Marrasso, E., Roselli, C., Sasso, M., 2019. Electric Efficiency Indicators and Carbon Dioxide Emission Factors for Power Generation by Fossil and Renewable Energy Sources on Hourly Basis. *Energy Conversion and Management*. 196, 1369–1384.
- [74] Fayiah, M., Kallon, M.K., 2025. Energy Efficiency and Smart Grid Technologies for Environmental Sustainability. In: Ogwu, M.C., Chibueze Izah, S. (Eds). *Evaluating Environmental Processes and Technologies*. Springer: Cham, Switzerland. pp. 439–462.
- [75] Frangopoulos, C.A., Caralis, Y.C., 1997. A Method for Taking into Account Environmental Impacts in the Economic Evaluation of Energy Systems. *Energy Conversion and Management*. 38(15–17), 1751–1763.
- [76] Samad, T., Koch, E., Stluka, P., 2016. Automated Demand Response for Smart Buildings and Microgrids: The State of the Practice and Research Challenges. *Proceedings of the IEEE*. 104(4), 726–744.
- [77] Taheri Hosseinkhani, N., 2025. Artificial Intelligence and Large Language Models in Energy Systems and Climate Strategies: Economic Pathways to Cost-Effective Emissions Reduction and Sustainable Growth. Available from: <https://ssrn.com/abstract=5385513> (cited 1 December 2025).
- [78] Wanapinit, N., 2023. Characterization of Operational Flexibility Resources and Evaluation of Potential Utilization in Distributed Energy Systems [PhD Thesis]. Universität Freiburg: Freiburg, Germany.
- [79] Nordling, A., Pädam, S., af Burén, C., et al., 2018. Social Costs and Benefits of Smart Grid Technologies. Available from: <https://iea-isan.org/wp-content/uploads/2019/01/Social-Costs-and-Benefits-of-Smart-Grid-Technologies.pdf> (cited 1 December 2025).
- [80] Adamo, A., Martín, H., de la Hoz, J., et al., 2025. A Review of Worldwide Strategies for Promoting High-Temperature Heat Pumps. *Applied Sciences*. 15(2), 839.
- [81] Stratigakos, A., 2023. Towards the Prescriptive Analytics Paradigm for Energy Forecasting and Power System Optimization [PhD Thesis]. Université Paris Sciences et Lettres: Paris, France.
- [82] Ratshitanga, M., Orumwense, E.F., Krishnamurthy, S., et al., 2023. A Review of Demand-Side Resources in Active Distribution Systems: Communication Protocols, Smart Metering, Control, Automation, and Optimization. *Applied Sciences*. 13(23), 12573.
- [83] Elkelay, M., Draz, A.M., Bastawissi, H.A.E., et al., 2025. Performance Characteristics of Diesel Engine Power Plants: Efficiency, Emissions, and Operational Flexibility. *Pharos Engineering Science Journal*. 2(1), 1–11.
- [84] Papakonstantinou, V., Kloza, D., 2015. Legal Protection of Personal Data in Smart Grid and Smart Metering Systems from the European Perspective. In *Smart Grid Security*. Springer: London, UK. pp. 41–129.
- [85] Wang, Y., Yan, W., Zhuang, S., et al., 2018. Does Grid-Connected Clean Power Promote Regional Energy Efficiency? An Empirical Analysis Based on the Upgrading Grid Infrastructure across China. *Journal of Cleaner Production*. 186, 736–747.
- [86] Khalid, Z., Kazmi, S.A.A., Hassan, M., et al., 2025. Socio-Economic Analysis for Adoption of Smart Metering System in SAARC Region: Current Challenges and Future Perspectives. *Sustainability*. 17(15), 6786.
- [87] Martínez-Conde del Campo, F.J., 2017. Electric Integration and Development of a Renewable Electric Grid in Latin America [Master’s Thesis]. Universidad de Chile: Santiago, Chile.
- [88] Onyeji-Nwogu, I., Bazilian, M., Moss, T., 2020. Big Data and the Electricity Sector in African Countries. *World Development Perspectives*. 17, 100170.
- [89] Zio, E., Aven, T., 2011. Uncertainties in Smart Grids Behavior and Modeling: What Are the Risks and Vulnerabilities? How to Analyze Them? *Energy Policy*. 39(10), 6308–6320.
- [90] Chen, J., Macauley, M., Marathe, A., 2009. Network Topology and Locational Market Power. *Computational Economics*. 34(1), 21–35.
- [91] Gwerder, Y.V., Figueiredo, N.C., Pereira da Silva, P.,

2019. Investing in Smart Grids: Assessing the Influence of Regulatory and Market Factors on Investment Level. *The Energy Journal*. 40(4), 25–44.
- [92] Nafi, N.S., Ahmed, K.E.U., Gregory, M.A., et al., 2016. A Survey of Smart Grid Architectures, Applications, Benefits and Standardization. *Journal of Network and Computer Applications*. 76, 23–36.
- [93] Yi, Z., Xu, Y., Wang, H., et al., 2021. Coordinated Operation Strategy for a Virtual Power Plant with Multiple DER Aggregators. *IEEE Transactions on Sustainable Energy*. 12(4), 2445–2458.
- [94] Palaparthi, H., Mahammad, Katari, P., et al. Environmental Alignment in IT Systems: Strategies for Sustainable Development. *Library Progress International*. 41(2), 161–175.
- [95] Jones, K.B., Zoppo, D., 2014. A Smarter, Greener Grid: Forging Environmental Progress Through Smart Energy Policies and Technologies. Praeger: Santa Barbara, CA, USA.
- [96] Uddin, M., Rahman, A.A., 2012. Energy Efficiency and Low Carbon Enabler Green IT Framework for Data Centers Considering Green Metrics. *Renewable and Sustainable Energy Reviews*. 16(6), 4078–4094.
- [97] Vora, H., 2025. Carbon Footprint of Digital Infrastructure: Data Centers, Cloud Computing, and the Path to Net Zero. *International Journal of Innovative Research of Science, Engineering and Technology*. 14(4), 5401–5413.
- [98] Turovets, J., Proskuryakova, L., Starodubtseva, A., et al., 2021. Green Digitalization in the Electric Power Industry. *Foresight and STI Governance*. 15(3), 35–51.
- [99] Mohamed, A.-M.O., Mohamed, D., Fayad, A., et al., 2024. Enhancing Decision Making and Decarbonation in Environmental Management: A Review on the Role of Digital Technologies. *Sustainability*. 16(16), 7156.
- [100] Dehdarian, M.A., 2017. Three Essays on Methodologies for Dynamic Modeling of Emerging Socio-Technical Systems: The Case of Smart Grid Development [PhD Thesis]. École Polytechnique Fédérale de Lausanne: Lausanne, Switzerland.
- [101] Cavoukian, A., Polonetsky, J., Wolf, C., 2010. Smart-Privacy for the Smart Grid: Embedding Privacy into the Design of Electricity Conservation. *Identity in the Information Society*. 3(2), 275–294.
- [102] Gunduz, M.Z., Das, R., 2020. Cyber-Security on Smart Grid: Threats and Potential Solutions. *Computer Networks*. 169, 107094.
- [103] Strezoski, L., Padullaparti, H., Ding, F., et al., 2022. Integration of Utility Distributed Energy Resource Management System and Aggregators for Evolving Distribution System Operators. *Journal of Modern Power Systems and Clean Energy*. 10(2), 277–285.
- [104] Kaiser, Z.R.M.A., 2024. Smart Governance for Smart Cities and Nations. *Journal of Economy and Technology*. 2, 216–234.
- [105] Dekkers, M., 2023. Smart Grid, Smart Rules or Smart Context? A Comparative Case Study of Smart Grid Implementation in Three (Experimental) Community Energy Projects [Master’s Thesis]. Delft University of Technology: Delft, The Netherlands.
- [106] Alcaraz, C., Lopez, J., Wolthusen, S., 2016. Policy Enforcement System for Secure Interoperable Control in Distributed Smart Grid Systems. *Journal of Network and Computer Applications*. 59, 301–314.
- [107] Flick, T., Morehouse, J., 2010. Securing the Smart Grid: Next Generation Power Grid Security. Syngress: Amsterdam, The Netherlands.
- [108] Gopstein, A., Nguyen, C., Byrnett, D.S., et al., 2020. Framework and Roadmap for Smart Grid Interoperability Standards Regional Roundtables Summary Report. US Department of Commerce, National Institute of Standards and Technology: Washington, DC, USA.