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Artificial Intelligence in Energy Systems: Conceptual Gaps, Governance Challenges, and Theory-Building Opportunities

João Silva[1*], Pedro Costa[1], Ana Beatriz[2]

Abstract

Artificial intelligence is increasingly embedded in energy systems through forecasting, optimization, control, demand response, smart-grid analytics, market coordination, and renewable-energy integration. Although this literature has expanded rapidly, it remains conceptually fragmented, with many studies emphasizing technical performance while giving less attention to governance, institutional responsibility, energy justice, accountability, and theory development. This review critically examines articles published to identify conceptual gaps, governance challenges, and theory-building opportunities in AI-enabled energy systems. Rather than treating AI only as a computational instrument, the review conceptualizes it as a socio-technical force operating within infrastructures, markets, regulatory systems, organizational routines, and energy-transition politics. The synthesis shows that current research lacks unified frameworks for explaining how AI interacts with decentralization, flexibility, resilience, market complexity, and public legitimacy. It also reveals persistent silos between engineering, computer science, policy, ethics, and energy social science, resulting in limited attention to human-AI relationships, consumer vulnerability, algorithmic accountability, and institutional embedding. The review argues that future energy-AI scholarship should move beyond application taxonomies and performance-driven model evaluation toward interdisciplinary theory-building that links technical design choices with governance outcomes. Socio-technical transition theory, institutional theory, responsible innovation, anticipatory governance, energy justice, and human-AI interaction research offer useful foundations for explaining when AI supports just and resilient energy transitions and when it may reinforce inequality, opacity, or accountability gaps. The article concludes that responsible energy AI requires not only better algorithms but also stronger conceptual frameworks, explainability provisions, regulatory oversight, public accountability, and mechanisms for democratic legitimacy.

Keywords Theory-building, Artificial intelligence, Energy systems, Conceptual gaps, Governance challenges, Review

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Introduction

Artificial intelligence has become a prominent feature of contemporary energy research, appearing across studies of sustainable energy systems, smart grids, renewable forecasting, demand response, and market coordination. Reviews of AI in sustainable energy describe a broad field in which machine learning, deep learning, and optimization methods are increasingly used to improve planning, prediction, and operational decision-making [1]. Similar surveys of machine

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learning in energy systems show that AI is no longer confined to isolated technical tasks but is increasingly positioned as a general-purpose infrastructure for energy-system transformation [2, 3]. This proliferation makes a critical review timely, because the central question is no longer whether AI can be applied to energy systems, but how the field should conceptualize, govern, and theorize its expanding role.

Despite this rapid growth, the literature remains uneven in its conceptual development. Many studies organize knowledge around application areas, algorithms, or performance tasks, as seen in reviews of building energy prediction, solar forecasting, and smart-grid analytics [4-6]. These contributions are valuable, yet they often leave implicit the broader assumptions through which AI is understood as a form of energy intelligence, decision authority, or infrastructure governance. The result is a voluminous but fragmented literature in which technical advancement often outpaces conceptual consolidation and policy relevance.

This review focuses on conceptual gaps, governance challenges, and theory-building opportunities in the literature on AI in energy systems. It differs from bibliographic and mapping studies that primarily classify publications, keywords, or methodological clusters, although such work has helped reveal the growing scale and diversity of the field [2, 7]. Rather than conducting a statistical synthesis, the review reads the literature critically to identify what remains undertheorized in discussions of AI-enabled energy forecasting, control, demand-side response, digitalization, and energy justice. The aim is to examine how existing work frames AI, where those framings fall short, and what conceptual resources could support a more mature interdisciplinary research agenda.

The article proceeds by first defining the review's scope and situating AI within the broader landscape of energy-system transformation. It then maps dominant AI paradigms and examines how system boundaries, techno-centric assumptions, and governance deficits shape the literature. Subsequent sections identify gaps in conceptual frameworks, human-AI relationships, energy justice, regulatory oversight, accountability, and legitimacy, drawing on technical reviews as well as socio-technical and ethical scholarship [8-12]. The contribution is a synthetic research agenda that positions conceptual and governance-oriented work as central to the next generation of energy-AI scholarship.

Background and Scope

The expanding landscape of AI in energy systems

The literature reveals that AI has diffused across nearly every segment of energy systems, including generation forecasting, building energy prediction, grid monitoring, demand-side response, electricity markets, and renewable integration. Solar radiation forecasting reviews illustrate how machine learning has been used to address variability in renewable generation, while building-energy studies show similar interest in prediction, benchmarking, and operational optimization [4, 5]. Smart-grid surveys extend this landscape to big data analytics, fault detection, autonomous decision support, and distributed control [6, 13, 14]. Energy economics and finance research further expands the field by showing how machine learning is applied to prices, markets, risk, and investment decisions [15].

Previous reviews and their limitations

Previous reviews have provided important overviews of AI techniques, application domains, and methodological advances, but they often remain organized around technical functionality rather than conceptual or governance questions. Systematic reviews of machine learning in energy systems catalogue algorithms and use cases, while demand-response reviews classify reinforcement learning and optimization approaches according to modeling strategies and operational objectives [3, 16, 17]. These studies help consolidate a technically diverse field, yet they rarely ask how AI changes energy governance, institutional responsibility, or the relationship between automation and public accountability. This review therefore adds a critical and synthetic layer by examining what kinds of theory the field lacks and what governance problems are obscured when AI is treated mainly as an optimization instrument.

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Conceptual foundations of energy systems and AI

Energy systems are not merely technical networks but socio-technical infrastructures shaped by physical constraints, markets, regulation, user behavior, and institutional coordination. AI research in smart grids often emphasizes prediction, classification, and control, but these computational functions operate within infrastructures characterized by uncertainty, interdependence, and high reliability requirements [13, 18]. Big-data studies in smart grids show that data availability, system observability, and computational scalability are central to AI deployment, yet they also reveal unresolved questions about how data-driven intelligence relates to physical system models and operational expertise [7, 14]. A conceptual foundation for energy AI must therefore connect algorithmic capabilities with system boundaries, decision authority, infrastructure risk, and institutional context.

Governance and institutional dimensions of energy AI

Governance in this review refers to the rules, institutions, accountability mechanisms, ethical norms, and organizational practices that shape how AI is designed, deployed, monitored, and contested in energy systems. General AI ethics scholarship has shown that principles such as transparency, fairness, accountability, and human oversight are widely invoked but often difficult to operationalize in sector-specific settings [11, 12]. In energy systems, the governance problem is intensified because AI may affect critical infrastructure, consumer access, market coordination, and the allocation of flexibility burdens across households and communities [9, 10]. The field therefore requires governance analysis that is attentive not only to algorithmic ethics but also to energy regulation, infrastructural resilience, and public legitimacy.

Recent scholarship further emphasizes that governance problems in AI-enabled energy systems extend beyond technical reliability toward explainability, institutional accountability, and multi-level coordination. Reviews of AI governance in smart energy systems demonstrate that explainability, trustworthiness, and transparency remain fragmented across operational and regulatory domains, limiting stakeholder confidence in automated decision-making [19]. Research on decentralized electricity governance similarly argues that emerging digital and distributed energy systems require new accountability structures capable of coordinating actors across multiple institutional scales [20]. In parallel, studies of cross-sectoral accountability metrics show that increasingly digitalized energy infrastructures require integrated governance indicators capable of tracking transparency, data responsibility, and institutional performance during energy transitions [21].

Theory-building in interdisciplinary fields

Theory-building is necessary when a field accumulates empirical and technical studies faster than it develops shared concepts, explanatory mechanisms, and middle-level propositions. AI-in-energy research now contains extensive application-oriented work, but bibliographic and review studies indicate that the field remains dispersed across engineering, computer science, economics, and sustainability domains [1, 2, 22]. Energy social science and digitalization research suggest that interdisciplinary fields mature when they move beyond cataloguing technologies and begin explaining how technologies interact with institutions, users, and transition pathways [8, 9, 23]. For energy AI, theory-building means clarifying how algorithmic prediction, adaptivity, autonomy, and explainability shape energy-system outcomes under specific governance and socio-technical conditions.

Conceptual Mapping of AI in Energy Systems

Dominant AI paradigms in energy research

The dominant AI paradigms in the energy literature include supervised learning for forecasting and classification, reinforcement learning for control and demand response, deep learning for complex pattern recognition, and data analytics for smart-grid monitoring. Reviews of machine learning in energy systems highlight the breadth of supervised and unsupervised methods, while reinforcement-learning studies show growing interest in adaptive control for demand response and building operations [3, 17]. Smart-grid and renewable-energy studies further show the emergence of AI as a coordination layer for complex, distributed, and data-intensive energy systems [6, 13, 18]. However, these paradigms

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are often presented as methodological toolkits rather than as distinct ways of knowing, governing, and intervening in energy systems.

System boundaries and levels of analysis

A recurring conceptual issue is that studies define energy-system boundaries at very different levels, from household devices and buildings to microgrids, smart grids, electricity markets, and national infrastructures. Building-energy prediction studies often focus on local consumption patterns, while smart-grid big-data reviews address system-wide monitoring, communication, and operational intelligence [4, 7, 17]. Energy-market research introduces another level of analysis, where AI is connected to pricing, trading, financial risk, and strategic decision-making [15, 24]. These boundary choices matter because they determine whether AI is conceptualized as a local efficiency tool, a grid-control mechanism, a market actor, or a governance technology.

The techno-centric bias and its consequences

Much of the literature treats AI as a technical optimization tool whose value is measured through improved prediction, automation, efficiency, or operational control. Demand-side response and reinforcement-learning reviews often emphasize algorithmic design and control performance, while paying comparatively less attention to user agency, institutional accountability, and social acceptance [16, 17]. Digitalization scholarship challenges this bias by showing that energy technologies are embedded in social inclusion, consumption patterns, and governance arrangements rather than existing as neutral technical upgrades [9, 23]. The consequence of techno-centrism is that the field risks overlooking how AI redistributes authority, responsibility, and risk among system operators, consumers, regulators, and technology providers.

Figure 1 synthesizes this argument by positioning AI in energy systems as a layered socio-technical governance phenomenon in which algorithmic capabilities, decision domains, institutional mechanisms, and societal outcomes are mutually connected.

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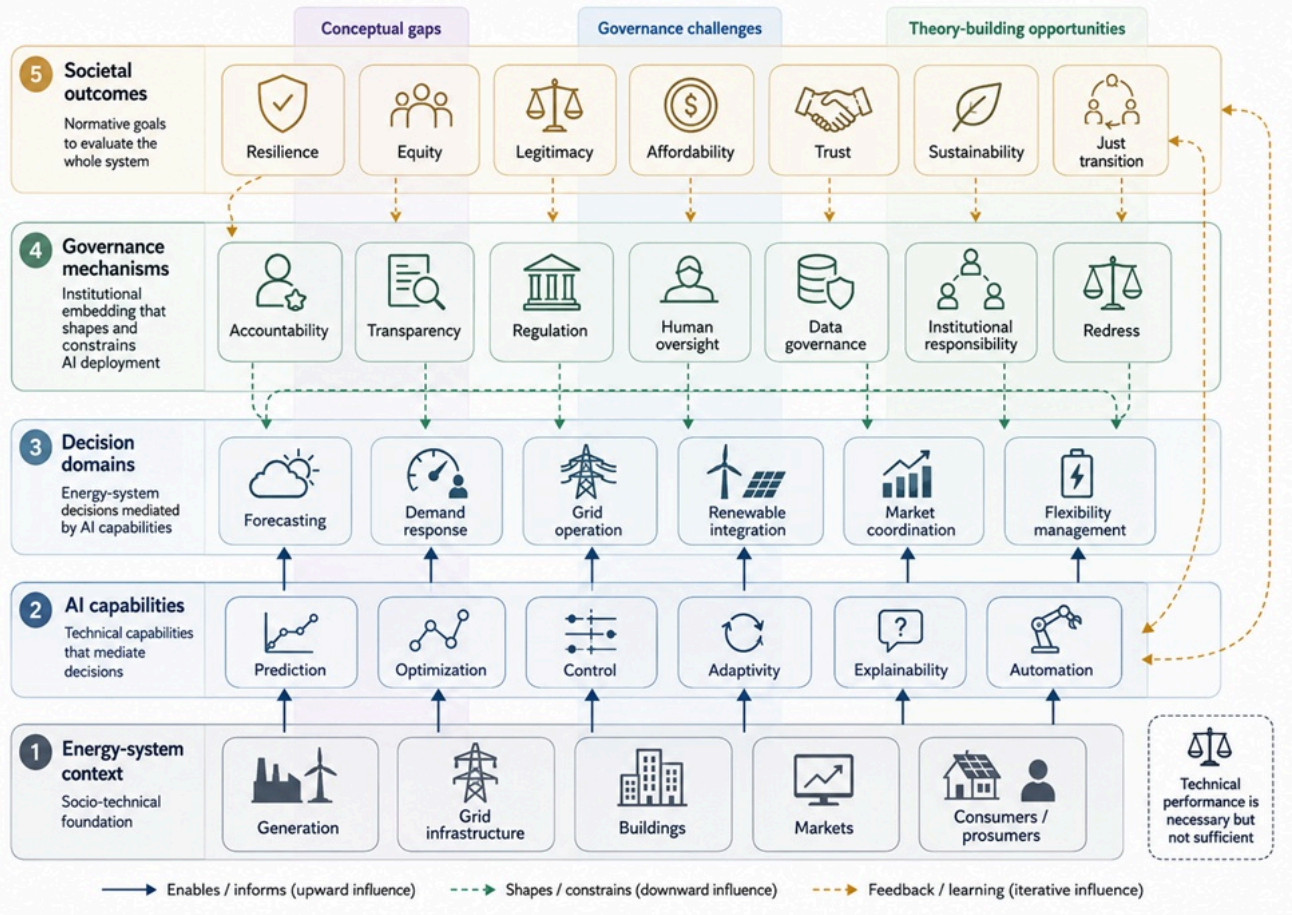

Figure 1. Socio-Technical Governance Framework for Artificial Intelligence in Energy Systems

Conceptual Gaps in the Literature

Lack of unified frameworks for AI-energy interaction

The literature lacks a unified conceptual framework for explaining how AI capabilities interact with energy-system properties such as intermittency, decentralization, flexibility, resilience, and market complexity. Broad reviews identify many applications and opportunities, but they often stop short of theorizing how AI changes the structure and governance of energy systems as systems [1, 22]. Smart-grid analytics studies show the importance of data infrastructures and computational intelligence, yet they rarely integrate these elements into a general theory of AI-enabled energy transformation [6, 7]. As a result, knowledge accumulates in separate application clusters rather than through cumulative conceptual development.

Table 1 consolidates the manuscript's conceptual contribution by showing how dominant technical framings of AI can be reframed as socio-technical roles with distinct theoretical and governance implications.

Table 1. Conceptual Reframing of AI in Energy Systems: From Technical Function to Socio-Technical Role

Dominant framing in existing literature	Typical analytical focus	Conceptual limitation	Proposed reframing	Added theoretical value

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AI as a forecasting tool	Accuracy, error reduction, prediction horizons, model comparison	Treats AI primarily as a technical improvement mechanism	AI as an epistemic system that shapes how energy futures are known, modeled, and acted upon	Links prediction to uncertainty, decision authority, and institutional trust
AI as an optimization instrument	Efficiency, cost minimization, load balancing, resource allocation	Assumes optimization goals are neutral or self-evident	AI as a value-laden allocation mechanism	Makes visible the distributional and justice implications of optimization objectives
AI as an autonomous control layer	Real-time operation, reinforcement learning, adaptive control, automation	Understates human oversight, contestability, and accountability	AI as a delegated decision system embedded in critical infrastructure	Connects autonomy to responsibility, reliability, and governance-by-design
AI as a smart-grid enabler	Data analytics, sensing, communication, distributed coordination	Focuses on digital capability while underdeveloping institutional context	AI as infrastructure intelligence operating across technical and organizational boundaries	Clarifies how data, platforms, utilities, regulators, and users jointly shape outcomes
AI as a market coordination device	Pricing, trading, risk analysis, peer-to-peer exchange, demand flexibility	Often treats markets as computational environments rather than governed institutions	AI as algorithmic intermediation within regulated energy markets	Connects market automation to legitimacy, oversight, and consumer protection
AI as a transition accelerator	Renewable integration, flexibility, decarbonization, system transformation	Risks assuming that AI automatically supports sustainable transitions	AI as a contingent transition actor that can reinforce or disrupt existing regimes	Links energy AI to socio-technical transition theory, institutional lock-in, and path dependency
AI as a responsible innovation challenge	Ethics principles, transparency, fairness, accountability	Principles may remain abstract without sector-specific mechanisms	AI as a governable socio-technical system requiring anticipatory oversight	Bridges AI ethics, energy justice, and practical governance mechanisms

Undertheorized human-AI relationships in energy

Human-AI relationships in energy systems remain insufficiently theorized, especially regarding how operators, consumers, prosumers, aggregators, regulators, and communities should interact with algorithmic systems. Demand-response studies frequently model users as flexible resources or controllable loads, while smart-grid and Internet-of-Things research emphasizes connectivity, automation, and system responsiveness [16, 25, 26]. Such perspectives are useful for technical design, but they often provide limited insight into trust, consent, comprehension, contestability, and the lived experience of algorithmically mediated energy services. Socio-technical digitalization research suggests that these human dimensions are central rather than peripheral to the legitimacy of AI-enabled energy transitions [8, 9].

Table 2 outlines the principal human-AI interaction challenges discussed in the energy-system literature.

Table 2. Human-AI Interaction Challenges in Energy Systems

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Human actor	AI-mediated interaction	Key challenge	Governance implication
Grid operators	Automated operational recommendations	Automation bias and overreliance	Need for human oversight protocols
Consumers	Dynamic pricing and smart-home control	Limited transparency and comprehension	Requirement for understandable AI explanations
Prosumers	AI-assisted flexibility coordination	Unequal bargaining power	Consumer protection and participation safeguards
Regulators	Monitoring AI-driven energy platforms	Technical complexity and limited expertise	Capacity-building and regulatory modernization
Energy communities	Platform-based coordination systems	Exclusion from algorithmic decision processes	Inclusive governance and participatory design
Utilities	Predictive optimization systems	Accountability diffusion across vendors and operators	Clear institutional responsibility allocation

Missing links between AI and energy justice

The connection between AI design and energy justice remains one of the most underdeveloped areas in the literature. Recent work on AI and energy justice argues that algorithmic systems may shape distributional, procedural, and recognition outcomes by influencing who receives benefits, who bears flexibility burdens, and whose needs are represented in data and decision rules [10]. Digital energy studies similarly show that inclusion and exclusion can emerge through access to data, platforms, automated services, and smart infrastructures [8, 9]. Yet most technical AI research in forecasting, control, and optimization does not explicitly analyze justice implications, leaving a gap between energy-AI innovation and the normative goals of equitable energy transitions.

Governance Challenges for AI in Energy

Regulatory fragmentation and institutional inertia

AI governance in energy systems faces regulatory fragmentation because responsibility is distributed across energy regulators, market operators, utilities, technology vendors, consumer protection agencies, and data-governance institutions. The smart-grid literature shows that AI and digital technologies operate across communication, control, and market layers, but governance arrangements often remain organized around older institutional categories [13, 14, 26]. This creates institutional inertia, where regulatory mandates evolve more slowly than algorithmic capabilities and platform-based energy services. The problem is especially significant for peer-to-peer trading and decentralized energy coordination, where new forms of algorithmic intermediation challenge existing assumptions about market participation and oversight [24, 27].

Accountability and transparency deficits

Accountability and transparency remain persistent deficits in the governance of AI-driven energy decision-making. General AI ethics scholarship warns that ethical principles can remain weak if they are not translated into enforceable responsibilities, institutional procedures, and mechanisms for redress [11, 12]. In energy contexts, this concern is heightened because AI may influence pricing, demand response, grid access, outage management, or the prioritization of flexibility resources [10, 16]. Although technical studies increasingly discuss explainability and data quality, the literature

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still offers limited guidance on who should be accountable when algorithmic energy decisions produce unfair, unsafe, or publicly contested outcomes.

Table 3 summarizes the major governance deficits and institutional risks identified in AI-enabled energy systems

Table 3. Governance Deficits and Institutional Risks in AI-Enabled Energy Systems

Governance dimension	Typical AI application area	Main institutional risk	Potential governance response
Transparency	Smart-grid analytics and automated control	Opaque algorithmic decision-making	Explainable AI standards and reporting protocols
Accountability	Demand response and grid optimization	Unclear responsibility for harmful outcomes	Defined liability frameworks and audit mechanisms
Data governance	Smart-metering and IoT-enabled systems	Data asymmetry and privacy concerns	Sector-specific data governance regulations
Market oversight	Peer-to-peer trading and pricing systems	Algorithmic market manipulation	Regulatory monitoring and compliance review
Public legitimacy	Automated infrastructure management	Reduced public trust and contestability	Participatory governance and stakeholder inclusion
Institutional coordination	Multi-actor energy platforms	Fragmented regulatory authority	Cross-sector governance coordination mechanisms

Ethics, public trust, and legitimacy

Ethical acceptability and public trust are not secondary concerns in energy AI, because energy systems are essential infrastructures tied to welfare, affordability, climate goals, and democratic accountability. Digitalization research shows that smart energy transitions can produce new forms of social inclusion but also new exclusions, particularly when digital systems are designed without attention to user diversity and institutional context [8, 9]. AI ethics studies further caution that high-level principles alone cannot secure legitimacy unless they are connected to sector-specific practices, governance mechanisms, and public accountability [11, 12]. The literature therefore needs a stronger account of democratic legitimacy in AI-enabled energy systems, especially where automated decisions affect consumers, communities, and critical infrastructure resilience.

Theory-Building Opportunities

Importing theories from socio-technical transitions

Socio-technical transition theory offers one of the clearest opportunities for deepening energy-AI research because it can explain how algorithmic systems interact with infrastructures, institutions, markets, and user practices. Current AI reviews often describe applications across smart grids, renewable forecasting, and sustainable energy management, but they rarely connect these applications to transition concepts such as regime stability, niche experimentation, institutional lock-in, or multi-level change [1, 2]. Digitalization studies show that energy technologies reshape social inclusion and consumption patterns, which suggests that AI should be analyzed as part of broader transition dynamics rather than as an isolated computational layer [8, 9]. Future research could therefore use socio-technical transition theory to explain when

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AI reinforces existing energy regimes, when it enables decentralization, and when it creates new dependencies on data infrastructures and platform actors.

Institutional theory and the governance of algorithmic systems

Institutional theory can help explain why AI governance in the energy sector develops slowly despite rapid technical innovation. Smart-grid and Internet-of-Things studies show that AI-enabled energy systems involve many actors, including utilities, grid operators, technology firms, regulators, consumers, and market intermediaries [25, 26]. Yet governance mechanisms often remain fragmented because institutions adapt through existing rules, professional norms, jurisdictional boundaries, and legacy regulatory assumptions. Institutional theory would allow scholars to examine how algorithmic accountability, transparency, and oversight become formalized, resisted, or translated into organizational routines within energy-sector institutions.

Responsible innovation and anticipatory governance

Responsible innovation and anticipatory governance provide useful resources for shifting energy-AI research from reactive risk management toward early-stage reflection on social purpose, ethical design, and institutional accountability. AI ethics scholarship has already shown that abstract principles can be insufficient unless they are linked to concrete governance arrangements, while energy justice research demonstrates the need to examine how algorithmic systems affect vulnerable consumers and communities [10-12]. These insights suggest that responsible innovation in energy AI should include anticipation of unintended consequences, inclusion of affected publics, reflexive evaluation of design assumptions, and responsiveness to emerging risks. Such an approach would move beyond asking whether AI improves system performance and toward asking whether AI development is socially desirable, governable, and aligned with just energy transitions.

Building mid-range theories for energy AI

A major theory-building opportunity lies in developing mid-range theories that connect specific AI capabilities to specific energy-system outcomes. For example, deep reinforcement learning is increasingly discussed as a method for smart-grid operation, but its conceptual implications for autonomy, resilience, and human oversight remain underdeveloped [28]. Similarly, flexible demand response and community energy scheduling studies show how AI can coordinate distributed resources, yet they do not always explain when adaptivity improves equity, reliability, or institutional legitimacy [16, 29]. Mid-range theories could bridge abstract governance principles and technical case studies by specifying how explainability, adaptivity, prediction, and automation produce different outcomes under different infrastructural and institutional conditions.

Table 4 presents a structured research agenda linking AI capabilities with governance-oriented research priorities.

Table 4. Future Research Priorities for Governance-Oriented AI in Energy Systems

Research priority	Core research question	Relevant disciplinary contribution	Expected scholarly contribution
Explainable energy AI	How can AI decisions become understandable for energy stakeholders?	Computer science and governance studies	Improved accountability and trust
AI and energy justice	How do algorithmic systems redistribute energy benefits and burdens?	Energy justice and social science	Greater equity in energy transitions
Institutional adaptation	How do regulators and utilities adapt to AI-enabled infrastructures?	Institutional theory and public policy	Better governance coordination

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Democratic legitimacy	Under what conditions are automated energy decisions socially acceptable?	Political science and ethics	Stronger public legitimacy frameworks
Data infrastructure governance	Who controls energy-system data and interoperability standards?	Information systems and law	More transparent data governance
Human-centered automation	How should humans collaborate with AI in critical infrastructures?	Human-AI interaction research	More resilient socio-technical systems

Table 5 translates the review's theoretical agenda into a structured matrix that links specific theory-building pathways to explanatory questions, governance challenges, and testable mid-range propositions for future energy-AI research.

Table 5. Theory-Building Matrix for Responsible AI in Energy Systems

Theory-building pathway	Core explanatory question	AI-energy phenomenon explained	Key governance problem addressed	Illustrative mid-range proposition
Socio-technical transition theory	How does AI interact with existing energy regimes, niches, infrastructures, and transition pathways?	AI-enabled forecasting, flexibility, smart grids, renewable integration, and decentralized coordination	Whether AI accelerates just transitions or reinforces incumbent power structures	AI supports transformative energy transitions only when algorithmic capabilities are aligned with institutional reform, user participation, and decarbonization goals.
Institutional theory	How do rules, norms, professional routines, and regulatory mandates shape the adoption and oversight of AI?	AI deployment by utilities, grid operators, aggregators, regulators, and market intermediaries	Regulatory fragmentation, institutional inertia, unclear responsibility	Accountability deficits emerge when AI capabilities evolve faster than the institutional routines needed to assign responsibility and provide redress.
Responsible innovation	How can ethical reflection, inclusion, anticipation, and responsiveness be embedded before AI harms become infrastructural?	AI design choices in demand response, smart buildings, market platforms, and grid automation	Late-stage ethics, weak public engagement, insufficient anticipatory governance	Energy-AI systems are more legitimate when affected publics and institutional stakeholders shape problem definition, data selection, deployment, and monitoring.
Energy justice theory	How does AI affect distributional, procedural, and recognition justice in energy transitions?	Algorithmic pricing, flexibility allocation, automated demand response, access to smart services	Unequal burdens, exclusion from data-driven services, invisibility of vulnerable users	AI-enabled energy optimization may deepen injustice when efficiency gains are achieved by shifting flexibility burdens onto users with limited agency or representation.
Human-AI interaction	How should operators, consumers, prosumers,	Human oversight, operator trust,	Automation bias, reduced agency,	Explainable AI improves governance only when

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theory	and regulators understand, contest, and collaborate with algorithmic systems?	consumer consent, explainability, contestability	lack of meaningful human control	explanations are actionable for the specific human actors expected to interpret or contest decisions.
Critical data infrastructure theory	How do data availability, quality, ownership, interoperability, and platform control shape energy-AI outcomes?	Smart-meter data, IoT systems, platform-based coordination, grid observability	Data asymmetry, surveillance risk, vendor dependency, platform power	AI becomes a form of infrastructure power when control over energy data determines who can predict, optimize, participate, and govern.
Democratic legitimacy theory	Under what conditions are AI-mediated energy decisions publicly acceptable and institutionally defensible?	Automated decisions affecting pricing, reliability, access, outages, and flexibility	Public trust, legitimacy, transparency, accountability	AI-mediated energy decisions gain legitimacy when affected actors can understand, challenge, and influence the rules through which decisions are made.

Toward A Research Agenda

Prioritizing conceptual work alongside technical advances

Future energy-AI research should give conceptual and theoretical work a status equal to technical model development. Existing reviews of machine learning, deep learning, smart-grid analytics, and sustainable energy applications reveal a strong emphasis on algorithms, performance objectives, and application taxonomies [3, 6, 13, 21]. This emphasis has advanced the field technically, but it has also left unresolved questions about what AI is becoming within energy systems: an optimization tool, a decision infrastructure, a governance mechanism, or a socio-technical actor. A more balanced research agenda would encourage conceptual articles, critical reviews, typologies, and theory-building studies that clarify the assumptions underlying energy-AI scholarship.

Fostering interdisciplinary collaboration

Interdisciplinary collaboration should move beyond the superficial combination of technical and social vocabulary and toward genuinely shared research questions. Energy economics and finance studies demonstrate that AI is already linked to markets, trading, risk, and investment behavior, while socio-technical digitalization studies show that energy technologies affect inclusion, social practice, and governance [8, 15, 23]. Legal scholars, ethicists, engineers, computer scientists, energy economists, and social scientists therefore need collaborative spaces where concepts such as optimization, fairness, reliability, flexibility, legitimacy, and accountability can be jointly defined. Such collaboration would help prevent the field from dividing into separate technical and critical literatures that rarely inform each other.

Embedding governance into AI design cycles

Governance should be embedded into AI design cycles rather than added after technical systems have already been developed. Peer-to-peer trading, demand response, and smart-grid automation all show that AI can reshape market participation, consumer roles, and operational authority [16, 24, 27]. Research should therefore examine how regulatory constraints, transparency requirements, accountability mechanisms, and consumer protections can be incorporated during problem formulation, data selection, model design, deployment, and monitoring. This direction would support governance-by-design approaches in which technical architecture and institutional responsibility are treated as co-produced rather than separate domains.

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Empirical studies of real-world AI governance in energy

The field also needs empirical studies of how AI governance is practiced in real energy organizations, including utilities, aggregators, grid operators, energy communities, and digital platform providers. Existing technical reviews identify extensive possibilities for AI-enabled forecasting, optimization, and control, but they provide limited evidence about how organizations actually assign responsibility, interpret algorithmic recommendations, or manage contestation in operational settings [13, 18, 28]. Studies of digitalization and AI governance suggest that real-world implementation can produce tensions between efficiency, inclusion, accountability, and institutional legitimacy [8, 9, 30]. Future research should therefore examine organizational routines, regulatory negotiations, procurement practices, and public engagement processes through which energy AI becomes governable or remains opaque.

Synthesis and Interdisciplinary Integration

Weaving together technical, social, and governance threads

This review identifies a field that is technically rich but conceptually uneven, with strong application literatures in forecasting, smart grids, building energy prediction, demand response, markets, and renewable integration [4, 5, 15, 17]. At the same time, digitalization, energy justice, and AI ethics scholarship reveal that technical systems cannot be separated from questions of inclusion, accountability, transparency, and public legitimacy [9-12]. The central synthesis is that AI in energy systems should be understood as a socio-technical governance phenomenon rather than only as a computational method. This framing allows the field to connect technical capacities with institutional arrangements, social consequences, and theoretical explanations of energy transition change. **Figure 2** illustrates the proposed socio-technical governance framing for AI in energy systems, showing how technical AI capabilities must be interpreted alongside social consequences, institutional arrangements, and governance mechanisms.

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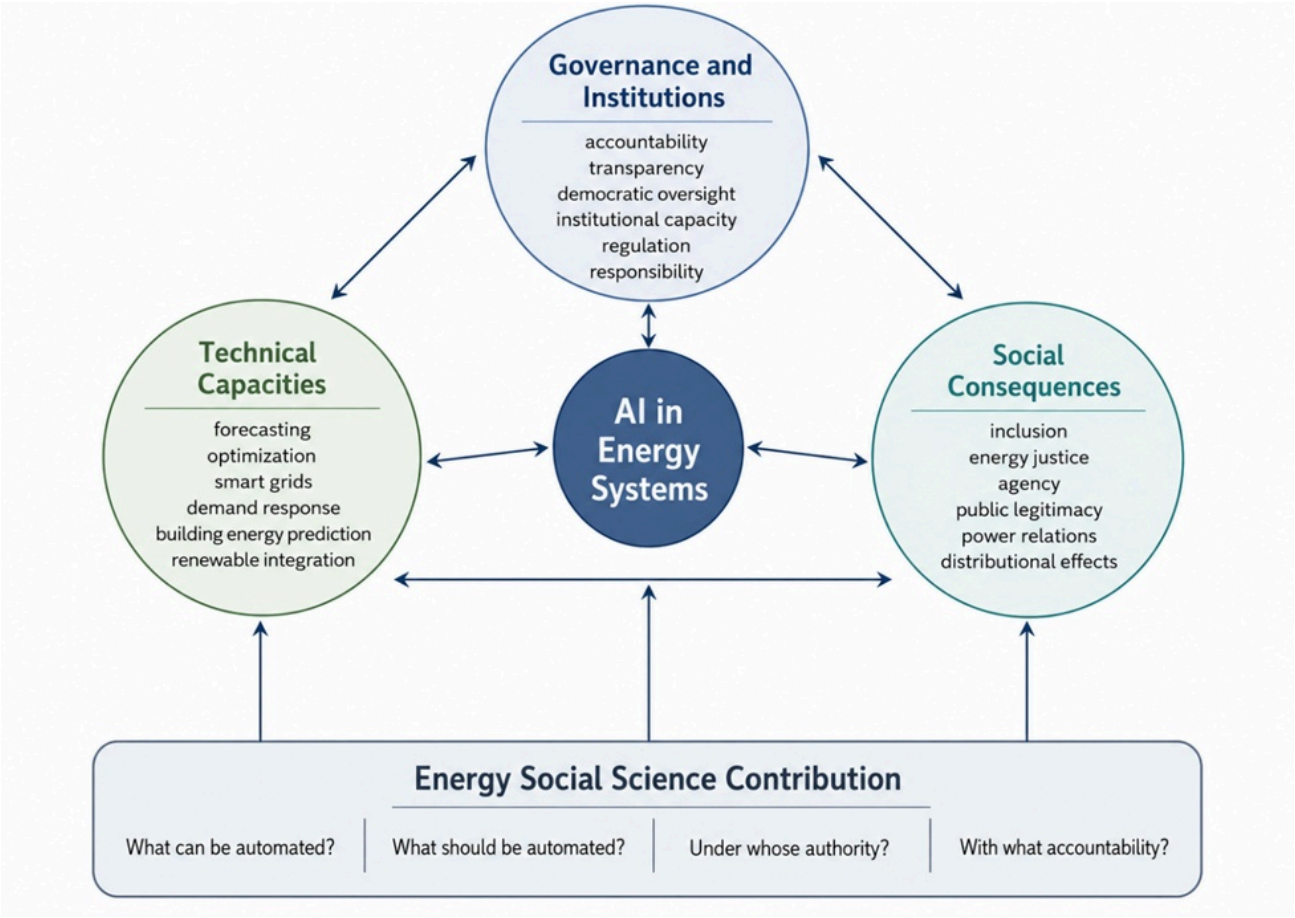

Figure 2. AI in Energy Systems as a Socio-Technical Governance Phenomenon

The role of energy social science in AI research

Energy social science has a crucial role in broadening the questions asked by AI-in-energy research. While engineering and computer science studies often focus on optimization, control, and predictive accuracy, socio-technical scholarship asks how digital systems reshape agency, responsibility, inclusion, and power in energy transitions [8, 9, 23]. This does not mean rejecting technical AI research; rather, it means situating technical design within wider debates about justice, governance, institutional capacity, and democratic legitimacy. A stronger role for energy social science would help ensure that AI research addresses not only what can be automated, but also what should be automated, under whose authority, and with what mechanisms for accountability.

Evaluation of the Review's Scope and Limitations

Coverage and selection bias

This review is a targeted synthesis rather than an exhaustive systematic review, and its coverage reflects deliberate selection across technical, governance, and socio-technical literatures. The included sources span broad AI-in-energy reviews, smart-grid analytics, demand response, digitalization, energy justice, electricity markets, and AI ethics, but the field is wider than any 29-source review can fully capture [1, 2, 10, 13]. Some areas, such as wave energy forecasting, electricity-market coordination, and renewable optimization, are represented through selected works rather than comprehensive subfield coverage [24, 31]. The review's value therefore lies in critical integration and gap identification, not in claiming complete coverage of all AI applications in energy systems.

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The challenge of a rapidly moving field

AI in energy systems is a rapidly moving field, which means that conceptual gaps and governance challenges may evolve as technologies, regulations, and infrastructures change. Recent work on deep reinforcement learning and smart-grid operation illustrates how quickly algorithmic approaches can move from experimental interest to proposed operational paradigms [28]. Similarly, newer reviews of smart-grid integration and optimization suggest that the application landscape continues to expand across energy conversion, grid operation, and distributed energy coordination [32]. Because of this pace, the review's findings should be read as a critical snapshot of the 2017–2023 literature window rather than a fixed map of the field's future boundaries.

Assessing the quality of conceptual contributions

Evaluating conceptual and theory-building contributions is methodologically different from evaluating model performance, forecast accuracy, or simulation outputs. Technical reviews can compare algorithms, datasets, and application areas, while conceptual reviews must assess clarity, explanatory value, scope, coherence, and capacity to open new research questions [3, 6, 22]. This review therefore evaluates the literature through critical argumentation rather than quantitative metrics, asking whether studies clarify AI's role in energy systems, connect technical design to governance, and support cumulative theory-building. Such an approach is appropriate for a review concerned with conceptual gaps and governance challenges rather than with empirical effect sizes or performance benchmarking.

Limitations of the Review

Inevitable selectivity and time-bound nature

The review's reliance on 29 sources and a 2017–2023 literature window imposes inevitable selectivity and temporal boundedness. Although the selected articles cover major technical, socio-technical, governance, and ethical themes, they cannot represent every subfield of AI in energy systems with equal depth [1, 10, 14, 16]. Important work published outside the selected journals, outside the time window, or after 2023 may refine or challenge some of the review's conclusions. Future reviews could extend the search strategy, include additional disciplinary databases, and compare pre- and post-2023 developments in AI governance and energy-system digitalization.

Limited empirical grounding of the critique

The critique developed in this review is grounded in published literature rather than in direct interviews, field observations, regulatory case studies, or practitioner engagement. This means that the analysis may not fully capture how utilities, regulators, aggregators, technology vendors, and energy communities actually experience AI governance in practice. Published studies of smart grids, demand response, digitalization, and AI ethics provide strong indications of conceptual and institutional challenges, but real-world implementation may reveal additional tensions, workarounds, and context-specific governance practices [8, 12, 13, 26]. Future research should therefore combine conceptual synthesis with empirical studies of AI deployment and oversight in operational energy settings.

Conclusion

The literature on AI in energy systems is rich in applications but comparatively poor in conceptual integration, governance analysis, and theoretical depth. Studies have expanded across forecasting, optimization, control, markets, digitalization, and smart-grid operation, yet the field still lacks shared concepts for explaining what AI becomes when embedded in critical energy infrastructures. This review has shown that many contributions remain organized around technical performance and application domains rather than around cumulative theory-building. As a result, the field risks becoming increasingly productive but insufficiently reflective.

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Addressing these gaps is not an academic luxury but a practical necessity for energy transitions. AI systems can influence access, affordability, flexibility, reliability, market participation, and institutional responsibility. If these systems are developed without strong conceptual and governance foundations, they may reinforce existing inequalities, obscure accountability, or weaken public trust in energy-system transformation. Responsible energy AI therefore requires more than better algorithms; it requires deeper understanding of the social, institutional, and normative conditions under which algorithms operate.

The review has identified several theory-building opportunities that can help the field mature. Socio-technical transition theory can connect AI to broader patterns of infrastructure change, while institutional theory can explain regulatory inertia and organizational adaptation. Responsible innovation and anticipatory governance can help researchers evaluate AI design choices before harms become embedded in infrastructure. Mid-range theories can further link specific AI capabilities, such as adaptivity and explainability, to outcomes such as resilience, equity, legitimacy, and accountability.

The next generation of energy-AI scholarship should treat critical, conceptual, and governance-oriented work as an integral part of the field rather than as a peripheral concern. Technical innovation will remain essential, but it should be accompanied by interdisciplinary inquiry into responsibility, justice, institutional design, and democratic legitimacy. A more mature field will ask not only how AI can optimize energy systems, but also how it should be governed, explained, constrained, and aligned with collective energy-transition goals. This is the direction in which AI research in energy systems must move if it is to support just, resilient, and publicly legitimate energy futures.

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Conflict of interest

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