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Autonomous Energy Systems Governance: A Multi-Layer Model for Technical Reliability, Legal Accountability, and Social Acceptance

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Abstract

Autonomous energy systems are increasingly reshaping grid operation, microgrid coordination, distributed restoration, peer-to-peer exchange, and transactive energy markets. While these systems may improve responsiveness, efficiency, and operational coordination, they also challenge governance approaches designed for infrastructures that remain primarily human-supervised. This article develops a multi-layer governance model for autonomous energy systems by integrating technical reliability, legal accountability, and social acceptance as mutually dependent conditions for responsible autonomy. The model is constructed through conceptual synthesis of literature on smart grid reliability, self-healing energy systems, artificial intelligence governance, legal responsibility, and socio-technical energy transitions. No experiments, datasets, simulations, legal case analyses, reliability measurements, or public acceptance surveys are reported. The proposed model identifies three interdependent governance layers: a Technical Reliability layer concerned with safe operation, fault tolerance, monitoring, recovery, and bounded control; a Legal Accountability layer concerned with responsibility attribution, auditability, liability allocation, evidentiary records, and regulatory oversight; and a Social Acceptance layer concerned with public trust, transparency, fairness, participation, legitimacy, and energy justice. The article further explains how these layers interact across the autonomous system lifecycle, showing that reliability evidence can strengthen accountability, legal clarity can support public trust, and participatory legitimacy can shape reliability priorities and autonomy boundaries. The model argues that autonomous energy systems cannot be governed responsibly through technical performance alone. Responsible autonomy requires systems that are operationally dependable, legally traceable, institutionally accountable, and socially legitimate. By linking engineering assurance, legal responsibility, and public acceptance in a unified governance framework, the article provides a conceptual foundation for policy design, regulatory review, system certification, and future empirical research on autonomous energy infrastructures.

Keywords Governance, Autonomous energy systems, Multi-layer model, Technical reliability, Legal accountability, Social acceptance

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Introduction

Energy systems are increasingly moving from digitally assisted operation toward more autonomous forms of coordination, including self-healing grids, automated microgrid control, peer-to-peer energy trading, and transactive energy platforms. Restoration and self-healing research shows how smart grids could increasingly identify disruptions and reorganize

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operation through distributed intelligence rather than centralized manual intervention [1]. Multiagent protection models and blockchain-based microgrid coordination further suggest that autonomy may become embedded in both physical control and institutional exchange architectures [2, 3]. As autonomy expands from technical optimization into market and governance functions, energy systems require governance models that can address reliability, responsibility, and legitimacy together.

The first governance deficit concerns technical reliability, because autonomous energy systems would require dependable sensing, decision-making, control execution, and recovery under uncertain operating conditions. Smart grid reliability studies emphasize that renewable integration, distributed assets, and control complexity create new challenges for maintaining system stability and operational assurance [4]. The second deficit concerns legal accountability, because autonomous decisions may complicate the attribution of responsibility when harms, service disruptions, or unfair outcomes occur. Legal scholarship on artificial intelligence has already identified difficulties in assigning personality, liability, and responsibility to autonomous software systems and their human or organizational designers [5, 6].

The third deficit concerns social acceptance, because energy infrastructures are essential services whose legitimacy depends on public trust, perceived fairness, and meaningful participation. Research on smart grids shows that social acceptance cannot be reduced to consumer adoption because automated infrastructures may alter control, privacy, equity, and institutional power relations [7, 8]. These deficits are interdependent rather than separate, since weak reliability may undermine trust, unclear liability may reduce acceptance, and public resistance may constrain technical deployment. A multi-layer governance model is therefore needed to conceptualize how technical reliability, legal accountability, and social acceptance could be structured as mutually reinforcing conditions for responsible autonomy.

This article contributes an original conceptual model for governing autonomous energy systems through three interacting layers. The model draws on technical literature on smart grid restoration, microgrid self-healing, and transactive energy design [1, 3, 9], while also integrating legal work on artificial intelligence liability and regulatory competition [10, 11]. It further incorporates socio-technical energy research showing that decentralization, community ownership, and institutional change shape whether advanced energy systems are trusted and accepted [12-14]. The article proceeds by defining autonomous energy systems, developing the conceptual foundation, specifying the three governance layers, and explaining how the model can inform policy and system design.

Background

Defining autonomy in energy systems

Autonomy in energy systems can be conceptualized as the capacity of digital agents, control architectures, or market platforms to sense conditions, evaluate alternatives, execute decisions, and adapt without continuous human instruction. In smart grids, such autonomy may appear through distributed restoration, self-healing protection, automated demand response, and local market coordination [1, 2]. In transactive energy systems, autonomy may extend into pricing, negotiation, settlement, and peer-to-peer exchange among distributed energy resources and prosumers [15, 16]. Autonomous energy systems therefore include not only self-optimizing technical infrastructures but also automated institutional arrangements that reshape how energy decisions are made.

Technical reliability of autonomous systems

Technical reliability in autonomous energy systems would require more than conventional equipment dependability because decision-making algorithms, communication networks, cyber-physical feedback, and human oversight boundaries become part of the reliability architecture. Research on smart grid control under renewable integration emphasizes that reliability problems emerge from variability, decentralization, and the need for adaptive control [4]. Self-healing smart grid designs similarly show that distributed fault detection and restoration require dependable coordination

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among sensing, diagnosis, and switching functions [17]. For autonomous systems, reliability governance should therefore cover failure anticipation, fault tolerance, recovery logic, explainable intervention points, and continuous monitoring.

Legal accountability for autonomous actions

Legal accountability for autonomous energy systems concerns how responsibility should be attributed when automated decisions produce physical, economic, or social consequences. Legal debates on artificial intelligence personality illustrate that treating autonomous software as a legal actor remains conceptually and institutionally contested [5]. Scholarship on the limits of legal personality further suggests that responsibility cannot simply be transferred to artificial agents without weakening accountability among developers, operators, owners, and regulators [6]. For autonomous energy systems, this means governance would require traceable decision records, defined responsibility chains, and liability allocation mechanisms that remain meaningful even when action is algorithmically mediated.

Social acceptance of automated and autonomous infrastructure

Social acceptance of autonomous energy infrastructure depends on whether affected publics perceive the system as trustworthy, fair, transparent, and aligned with broader energy values. Smart grid acceptance research indicates that moral values such as privacy, security, sustainability, and distributive fairness shape public responses to digital energy technologies [7]. Broader reviews of acceptance show that infrastructure legitimacy is not simply a matter of information provision but involves place-based concerns, institutional trust, and perceived procedural justice [18]. Autonomous energy systems would therefore require governance mechanisms that treat acceptance as an ongoing socio-political condition rather than a one-time deployment hurdle.

Existing governance fragmentation

Existing governance remains fragmented because technical, legal, and social questions are often handled by different institutions, professional communities, and evaluation routines. Energy transition scholarship shows that emerging systems are shaped by institutional change and organizational contestation rather than by technical optimization alone [12]. Responsible artificial intelligence research similarly argues that ethical principles, governance frameworks, and technical design practices often remain disconnected unless translated into operational accountability structures [19-21]. Autonomous energy governance should therefore move beyond siloed assurance and toward an integrated model in which reliability evidence, legal responsibility, and public legitimacy are designed to interact.

Conceptual Foundation

The tripartite nature of autonomous system governance

Autonomous energy system governance can be conceptualized as tripartite because technical, legal, and social conditions jointly determine whether autonomy is responsible. Technical reliability establishes whether autonomous action can be trusted operationally, but legal accountability determines whether responsibility remains assignable when action becomes machine-mediated [22]. Social acceptance determines whether communities, consumers, operators, and regulators regard autonomous energy decisions as legitimate within essential service contexts [8]. The tripartite model therefore treats autonomy not as a purely technical property but as a governed socio-technical condition.

Multi-layer models in governance and engineering

Multi-layer thinking is useful because autonomous energy systems combine physical infrastructure, software control, organizational decision-making, market coordination, and public legitimacy. Integrated transmission-distribution test systems for transactive energy demonstrate that technical and market designs must be evaluated across interconnected operational levels rather than isolated components [9]. Polycentric and decentralized energy transition research similarly suggests that governance authority may be distributed across local, regional, and system-level actors [13]. A multi-layer

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governance model could therefore provide a conceptual bridge between engineering assurance, institutional responsibility, and democratic legitimacy.

Layer interdependence and co-evolution

The three layers should be understood as interdependent and co-evolving because changes in one layer can strengthen or weaken the others. This tripartite framing finds empirical support in recent taxonomic research on energy autonomy in local flexibility markets, which demonstrates that autonomy must be understood across multiple dimensions including communication, control, physical infrastructure, and learning—each with distinct governance implications [23]. For example, blockchain-enabled energy systems may improve transaction traceability but can also introduce governance, scalability, and accountability challenges if institutional responsibilities are unclear [24]. Peer-to-peer energy trading may create new opportunities for local coordination, yet it can also intensify questions about consumer protection, market fairness, and regulatory oversight [25]. The model therefore assumes that reliability, accountability, and acceptance interact dynamically rather than functioning as separate compliance domains.

The Multi-Layer Governance Model: Layers and Components

Overview of the three layers

The proposed model organizes autonomous energy governance into three layers: Technical Reliability, Legal Accountability, and Social Acceptance. The Technical Reliability layer concerns whether autonomous functions can operate safely, recover from faults, and remain controllable under uncertainty, drawing on smart grid restoration and self-healing concepts [1, 17]. The Legal Accountability layer concerns whether responsibility for autonomous actions can be assigned, audited, and enforced, reflecting wider debates on artificial intelligence liability and governance [10]. The Social Acceptance layer concerns whether affected publics and institutions regard autonomous energy systems as transparent, fair, participatory, and aligned with public values [7, 18].

Figure 1 presents the Multi-Layer Accountability Model, showing how technical reliability, legal accountability, and social acceptance interact to support responsible autonomous energy governance.

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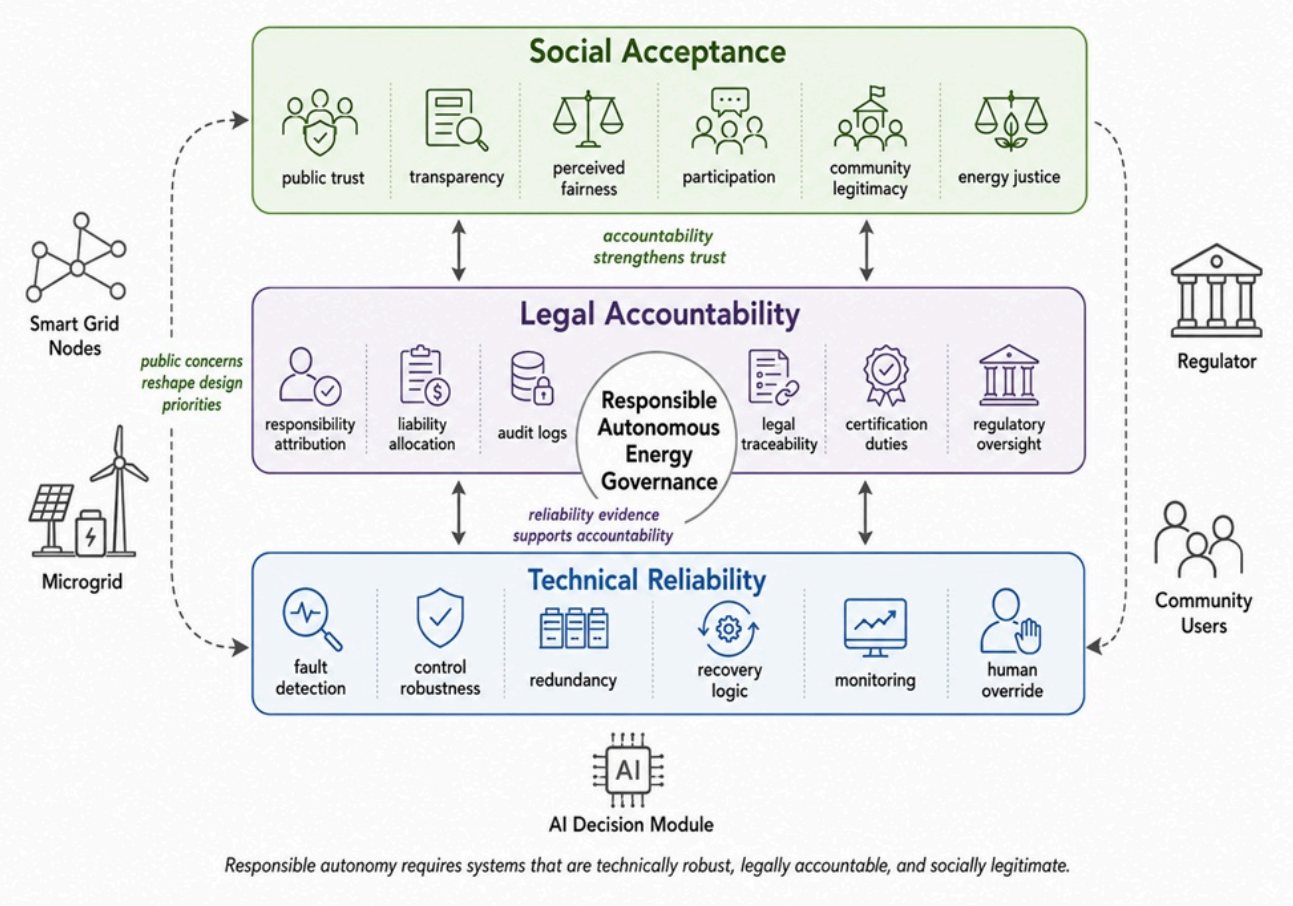


Figure 1. Multi-Layer Accountability Model for Autonomous Energy Systems

Layer-specific governance mechanisms

Each layer has distinct governance mechanisms that should not be collapsed into a single technical compliance checklist. Reliability mechanisms could include redundancy, verification, monitoring, fail-safe operation, and resilience-oriented design, especially where autonomous control affects critical infrastructure [2, 4]. Accountability mechanisms could include responsibility mapping, legal traceability, audit logs, certification duties, and regulator-accessible evidence, consistent with broader artificial intelligence governance concerns about responsibility and oversight [20, 22]. Acceptance mechanisms could include public explanation, stakeholder participation, community benefit design, and procedural justice, reflecting research on community energy and decentralization [13, 14].

Cross-layer interfaces

The model's distinctive contribution lies in its cross-layer interfaces, where reliability evidence supports legal accountability, legal accountability supports public trust, and social acceptance feeds back into design legitimacy. Technical audit trails, for instance, could connect operational reliability monitoring with legal evidentiary requirements, making autonomous decisions more accountable without requiring constant human control [22]. Legal transparency could also strengthen acceptance by clarifying who is responsible when automated energy decisions affect prices, access, or service continuity [10, 11]. At the same time, public concerns about fairness or risk could shape reliability priorities and system design criteria, consistent with socio-technical research on institutional change in smart energy transitions [12]. **Table 1** presents the three interdependent layers of the Autonomous Energy Systems Governance Model, outlining their core components, principal governance questions, and the primary mechanisms through which technical reliability, legal accountability, and social acceptance interact to support trustworthy autonomous energy governance.

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Table 1. Layers of the Autonomous Energy Systems Governance Model

Layer	Core Components	Key Governance Questions	Primary Mechanisms
Technical Reliability	Fault detection, control robustness, redundancy, recovery logic, cyber-physical monitoring, human override boundaries	Can the autonomous system remain safe, dependable, and recoverable when operating conditions change or faults occur?	Fail-safe architecture, resilience engineering, formal verification, operational monitoring, stress testing, incident learning, escalation protocols
Legal Accountability	Responsibility attribution, liability allocation, auditability, evidentiary records, regulatory duties, institutional oversight	Who is accountable for autonomous actions, and what evidence is available when decisions cause harm, disruption, unfairness, or regulatory breach?	Responsibility mapping, audit logs, legal traceability, certification duties, regulator access, contractual allocation, compliance documentation
Social Acceptance	Public trust, transparency, perceived fairness, participation, community legitimacy, energy justice	Why should affected publics accept autonomous energy decisions, especially when they affect essential services, prices, access, or local control?	Explainability practices, participatory governance, stakeholder review, fairness assessment, community benefit mechanisms, procedural justice forums

Technical Reliability Layer

Safety engineering for autonomous energy systems

The Technical Reliability layer begins with safety engineering because autonomous energy operations may act faster than human intervention and may affect grid stability, energy access, or market coordination. Self-healing and restoration research indicates that autonomous systems should be designed to detect faults, isolate affected components, and restore service through dependable control logic [1, 17]. Multiagent smart grid protection suggests that distributed decision-making may improve responsiveness but would require careful coordination to avoid conflicting autonomous actions [2]. A governance model should therefore treat fail-safe design, redundancy, verification, and controlled degradation as public-interest requirements rather than optional engineering enhancements.

Reliability metrics and monitoring

Reliability monitoring in autonomous energy systems should be conceptualized as a governance function rather than a purely technical dashboard. Although this article does not report numerical reliability metrics, governance-oriented monitoring could track whether autonomous actions remain explainable, reversible, bounded, and consistent with approved operational objectives [4]. Secure self-healing microgrid research shows that reliability may also depend on the integrity of communication, coordination, and transaction layers, especially when digital infrastructure mediates autonomous operation [3]. Monitoring should therefore connect technical performance evidence with accountability records and public assurance processes.

Certification and standards

Certification for autonomous energy systems would require evaluating not only component performance but also the governance adequacy of autonomous decision architectures. Technical assurance should consider how distributed control, transactive energy mechanisms, and peer-to-peer energy trading alter the boundaries of responsibility and operational risk [9, 15, 16]. Artificial intelligence governance scholarship indicates that trust requires more than ethical

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principles because oversight must be embedded into design, documentation, and institutional review [20, 21]. Certification should therefore be structured as a layered process that verifies reliability controls, accountability evidence, and acceptance-relevant transparency before autonomy is expanded.

Legal Accountability Layer

Allocating responsibility for autonomous decisions

The Legal Accountability layer addresses how responsibility could be allocated when autonomous energy systems make or execute decisions that affect grid operation, market participation, consumer access, or service continuity. Legal scholarship on artificial intelligence warns that autonomous software should not be treated as a substitute for human or organizational responsibility because doing so could create accountability gaps rather than resolve them [5]. The limits of legal personality suggest that accountability should remain distributed among designers, operators, asset owners, platform providers, regulators, and institutional decision-makers according to their role in enabling autonomous action [6]. In autonomous energy systems, responsibility allocation should therefore be structured around decision authority, system design control, operational supervision, and capacity to prevent or correct harm.

Regulatory frameworks and legal personality

Regulatory frameworks for autonomous energy systems would need to clarify whether existing energy, product liability, consumer protection, and digital governance rules are sufficient for autonomous decision-making. Critical legal assessments of artificial intelligence liability show that emerging regulatory proposals must address not only harm compensation but also documentation, foreseeability, risk allocation, and institutional responsibility before deployment [10]. Debates on regulatory competition in artificial intelligence further indicate that fragmented jurisdictions may produce uneven accountability expectations for developers and operators [11]. Autonomous energy governance should therefore avoid relying on artificial legal personality as the primary solution and should instead specify legally accountable human and organizational actors across the autonomy lifecycle.

Auditability and evidentiary requirements

Auditability is the practical bridge between autonomous technical operation and legal accountability because responsibility cannot be meaningfully assigned without records of what the system perceived, predicted, decided, and executed. Ethical governance research on artificial intelligence and robotics emphasizes that trust requires oversight structures capable of documenting autonomous behavior and enabling review after consequential actions [22]. In energy systems, auditability could be structured through decision logs, model-version records, override histories, control authorization records, incident reconstruction tools, and regulator-accessible documentation. These mechanisms should be designed before deployment because evidentiary gaps after system failure would weaken both legal accountability and public confidence. **Table 2** illustrates the reciprocal interactions among technical reliability, legal accountability, and social acceptance, showing how strengths or weaknesses in one governance layer can reinforce or undermine the effectiveness and legitimacy of the others within autonomous energy systems.

Table 2. Layer Interaction Matrix

Influencing Layer	Effect on Technical Reliability	Effect on Legal Accountability	Effect on Social Acceptance

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Technical Reliability	Strong reliability enables controlled autonomy, bounded failure, and recoverable operation; weak reliability increases cascading operational risk.	Reliable monitoring and decision records strengthen evidence for responsibility attribution; opaque failures weaken legal traceability.	Demonstrable safety and recoverability increase trust; repeated faults, unexplained disruptions, or uncontrolled automation reduce legitimacy.
Legal Accountability	Clear duties encourage reliability-by-design, certification, and continuous monitoring; unclear liability may reduce incentives for assurance.	Strong accountability clarifies institutional roles; weak accountability creates responsibility gaps across developers, operators, and regulators.	Transparent responsibility structures increase confidence that harms can be addressed; unclear liability produces distrust and resistance.
Social Acceptance	Public concerns can redirect reliability priorities toward safety, fairness, and service continuity; ignored concerns may create deployment constraints.	Participatory scrutiny can strengthen accountability expectations; exclusion of stakeholders may hide harms or weaken legitimacy.	Inclusive governance reinforces trust and legitimacy; perceived unfairness, opacity, or loss of control undermines acceptance.

International and cross-border legal challenges

Autonomous energy systems may operate across interconnected grids, digital platforms, multinational technology providers, and cross-border electricity markets, creating jurisdictional complexity. Transactive energy and peer-to-peer exchange research shows that decentralized market designs can connect actors and assets in ways that challenge traditional regulatory boundaries [15, 25]. Blockchain-based energy applications further illustrate how automated settlement, distributed ledgers, and platform governance may complicate responsibility when infrastructure, data, and transactions cross institutional borders [24]. Cross-border governance would therefore require interoperable accountability principles, regulator cooperation, and clear rules for platform operators whose autonomous systems affect multiple energy jurisdictions.

Social Acceptance Layer

Public trust and perceived risk

The Social Acceptance layer focuses on whether autonomous energy systems are perceived as trustworthy, fair, understandable, and compatible with public expectations for essential infrastructure. Smart grid acceptance research indicates that publics may evaluate digital energy systems through moral values such as privacy, autonomy, sustainability, and distributive fairness rather than through technical efficiency alone [7]. Studies of smart grid acceptance also suggest that public support can remain fragile when promised benefits are unclear or when governance arrangements fail to address risk, control, and institutional trust [8]. Autonomous energy systems should therefore be governed through public assurance mechanisms that respond to perceived risk rather than treating acceptance as passive consent.

Transparency and explainability for social legitimacy

Transparency and explainability are central to social legitimacy because affected users and communities need understandable reasons for autonomous decisions that influence prices, access, reliability, or local energy control. General artificial intelligence ethics research identifies transparency, accountability, fairness, and human oversight as recurring principles in global AI governance debates [20]. However, critiques of principle-based ethics warn that principles alone cannot guarantee responsible artificial intelligence unless they are translated into institutional practices and

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enforceable mechanisms [21]. For autonomous energy systems, explainability should therefore connect technical explanations, legal traceability, and public-facing communication in ways that are understandable without oversimplifying operational complexity.

Participatory governance and co-design

Participatory governance is necessary because autonomous energy systems may redistribute control among utilities, platforms, aggregators, prosumers, regulators, and communities. Research on decentralization shows that energy transitions can shift governance authority away from centralized institutions, but such shifts may remain incomplete or contested if institutional arrangements do not support meaningful local agency [13]. Community-owned renewable energy studies further indicate that local impacts, ownership structures, and participatory processes shape how energy innovations are understood and accepted [14]. Autonomous energy governance should therefore include co-design processes, stakeholder review forums, and participatory evaluation of autonomy boundaries before automated decision authority is expanded.

Addressing energy justice and equity

Social acceptance also depends on whether autonomous energy systems advance or undermine energy justice. Automated market coordination, peer-to-peer trading, and transactive energy could enable new forms of flexibility and participation, but they could also disadvantage users with limited digital access, low bargaining power, or constrained ability to respond to automated price signals [16, 25]. Energy transition scholarship emphasizes that the next phase of transition requires attention to institutional, social, and policy dimensions rather than technical deployment alone [26]. A socially acceptable autonomous energy system should therefore include fairness review, consumer protection, accessibility safeguards, and procedures for identifying groups that may bear disproportionate risks.

Interaction, Synergies, and Trade-offs

Synergies across layers

The three layers can reinforce one another when governance is designed as an integrated architecture rather than a sequence of separate checks. Strong technical reliability can generate evidence for legal accountability, while clear legal responsibilities can incentivize reliability-by-design and continuous monitoring [10, 22]. Public trust can also strengthen the legitimacy of technical and legal governance when stakeholders see that autonomous systems are explainable, contestable, and aligned with public values [7, 19]. In this sense, responsible autonomy can be conceptualized as a co-produced condition in which safe operation, accountable institutions, and social legitimacy mutually support each other.

Managing trade-offs

The same layers may also generate tensions that require explicit governance. For example, highly automated control may improve speed and efficiency but reduce human interpretability, while extensive legal documentation may improve accountability but slow innovation or create compliance burdens [11, 21]. Community participation may increase legitimacy but complicate technical optimization when local values conflict with centralized efficiency objectives [14, 18]. Managing these trade-offs would require transparent decision rules, proportional oversight, public-interest criteria, and mechanisms for revising autonomy levels when reliability, accountability, or acceptance concerns intensify.

Governance Integration and Implementation

Operationalizing the multi-layer model

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Operationalizing the multi-layer model would require embedding governance checkpoints into the lifecycle of autonomous energy systems, from design and procurement to deployment, monitoring, incident review, and revision. Technical development should define autonomy boundaries, fail-safe procedures, and monitoring duties before deployment, drawing on the logic of self-healing and distributed smart grid control [1, 17]. Legal implementation should map responsible actors, evidentiary duties, audit access, and liability arrangements before autonomous functions are activated [5, 10]. Social implementation should involve stakeholder engagement, fairness assessment, and public explanation processes that clarify why autonomy is being introduced and how affected parties can contest or influence it.

Institutional and regulatory implications

Institutionally, autonomous energy governance would require closer coordination among energy regulators, system operators, technology providers, consumer protection bodies, and community stakeholders. The governance of smart energy transitions already involves institutional contestation among organizations, suggesting that autonomy may intensify conflicts over authority, responsibility, and control [12]. Artificial intelligence governance research similarly indicates that ethical and legal oversight should be embedded in institutions rather than left to voluntary principle statements [19, 20]. Regulators may therefore need sandbox mechanisms, certification pathways, audit powers, and cross-sector expertise to evaluate autonomous energy systems before and after deployment.

Monitoring and adaptive governance

Adaptive governance is necessary because autonomous energy systems will change over time through software updates, learning processes, market redesign, and evolving social expectations. Blockchain and transactive energy studies show that digitally mediated energy systems may introduce new governance challenges as participation, automation, and platform functions expand [15, 24]. Continuous monitoring should therefore cover not only operational reliability but also accountability records, user complaints, fairness concerns, participation quality, and institutional learning. The model requires further validation through future conceptual refinement, comparative legal analysis, and carefully designed pilot governance processes.

Limitations

Conceptual abstraction and need for empirical testing

This article is limited by its conceptual design and does not test the proposed model through empirical cases, simulations, reliability metrics, legal outcomes, or public acceptance data. The model draws on smart grid reliability, artificial intelligence governance, legal accountability, and socio-technical acceptance literature to construct an integrated framework [4, 6, 19]. Because it does not evaluate actual autonomous energy deployments, its claims should be understood as model-building propositions rather than demonstrated findings. Future research would need to examine how the layers operate in real technical, legal, and social settings.

Contextual variability and transferability

The model may also vary across legal systems, market designs, infrastructure ownership models, and cultural expectations about automation and energy governance. Social acceptance research shows that public responses to energy infrastructure depend on place, trust, values, and institutional history [18]. Similarly, legal and regulatory debates on artificial intelligence suggest that accountability arrangements may differ substantially across jurisdictions and governance traditions [11]. The model should therefore be adapted contextually rather than applied as a universal template without attention to institutional and cultural variation.

Conclusion

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Autonomous energy systems require a governance model that treats autonomy as more than a technical capability. This article has proposed a multi-layer model that integrates technical reliability, legal accountability, and social acceptance as interdependent foundations of responsible autonomous energy governance.

The central argument is that no single layer can secure responsible autonomy on its own. Technical reliability without legal accountability may leave harms unresolved, legal accountability without technical evidence may be unenforceable, and both may fail if affected publics perceive autonomous energy systems as opaque, unfair, or illegitimate.

Future research should develop interdisciplinary methods for testing and refining the model in real-world governance settings. Pilot implementation, comparative legal analysis, participatory design, and operational assurance research could help determine how autonomous energy systems can become technically dependable, legally responsible, and socially legitimate.

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References

1. Fan D, Ren Y, Feng Q, Liu Y, Wang Z, Lin J. Restoration of smart grids: current status, challenges, and opportunities. Renew Sustain Energy Rev. 2021;143:110909. https://doi.org/10.1016/j.rser.2021.110909.

2. Shobole AA, Wadi M. Multiagent systems application for the smart grid protection. Renew Sustain Energy Rev. 2021;149:111352. https://doi.org/10.1016/j.rser.2021.111352.

3. Rath S, Nguyen LD, Sahoo S, Popovski P. Self-healing secure blockchain framework in microgrids. IEEE Trans Smart Grid. 2023;14(6):4729-40. https://doi.org/10.1109/TSG.2023.3253723.

4. Ourahou M, Ayrir W, Hassouni BE, Haddi A. Review on smart grid control and reliability in presence of renewable energies: challenges and prospects. Math Comput Simul. 2020;167:19-31.

5. Čerka P, Grigienė J, Sirbikytė G. Is it possible to grant legal personality to artificial intelligence software systems? Comput Law Secur Rev. 2017;33(5):685-99. https://doi.org/10.1016/j.clsr.2017.03.022.

6. Chesterman S. Artificial intelligence and the limits of legal personality. Int Comp Law Q. 2020;69(4):819-44.

7. Milchram C, van de Kaa G, Doorn N, Künneke R. Moral values as factors for social acceptance of smart grid technologies. Sustainability. 2018;10(8):2703. https://doi.org/10.3390/su10082703.

8. Bugden D, Stedman R. Unfulfilled promise: social acceptance of the smart grid. Environ Res Lett. 2021;16(3):034019.

9. Nguyen HT, Battula S, Takkala RR, Wang Z, Tesfatsion L. An integrated transmission and distribution test system for evaluation of transactive energy designs. Appl Energy. 2019;240:666-79. https://doi.org/10.1016/j.apenergy.2019.01.178.

10. Bertolini A, Episcopo F. The expert group's report on liability for artificial intelligence and other emerging digital technologies: a critical assessment. Eur J Risk Regul. 2021;12(3):644-59.

11. Smuha NA. From a 'race to AI' to a 'race to AI regulation': regulatory competition for artificial intelligence. Law Innov Technol. 2021;13(1):57-84.

12. Rohde F, Hielscher S. Smart grids and institutional change: emerging contestations between organisations over smart energy transitions. Energy Res Soc Sci. 2021;74:101974.

13. Judson E, Fitch-Roy O, Pownall T, Bray R, Poulter H, Soutar I, et al. The centre cannot (always) hold: examining pathways towards energy system de-centralisation. Renew Sustain Energy Rev. 2020;118:109499. https://doi.org/10.1016/j.rser.2019.109499.

14. Berka AL, Creamer E. Taking stock of the local impacts of community owned renewable energy: a review and research agenda. Renew Sustain Energy Rev. 2018;82(3):3400-19. https://doi.org/10.1016/j.rser.2017.10.050.

15. Capper T, Gorbatcheva A, Mustafa MA, Bahloul M, Schwidtal JM, Chitchyan R, et al. Peer-to-peer, community self-consumption, and transactive energy: a systematic literature review of local energy market models. Renew Sustain Energy Rev. 2022;162:112403. https://doi.org/10.1016/j.rser.2022.112403.

16. Nizami S, Tushar W, Hossain MJ, Yuen C, Saha T, Poor HV. Transactive energy for low voltage residential networks: a review. Appl Energy. 2022;323:119556.

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https://doi.org/10.1016/j.apenergy.2022.119556.

17. Torres BS, Ferreira LR, Aoki AR. Distributed intelligent system for self-healing in smart grids. IEEE Trans Power Deliv. 2018;33(5):2394-403.

18. Wolsink M. Social acceptance revisited: gaps, questionable trends, and an auspicious perspective. Energy Res Soc Sci. 2018;46:287-95.
https://doi.org/10.1016/j.erss.2018.07.034.

19. Floridi L, Cowls J. A unified framework of five principles for AI in society. In: Carta S, editor. Machine learning and the city: applications in architecture and urban design. Hoboken (NJ): Wiley; 2022. p.535-45.

20. Jobin A, Ienca M, Vayena E. The global landscape of AI ethics guidelines. Nat Mach Intell. 2019;1(9):389-99.

21. Mittelstadt B. Principles alone cannot guarantee ethical AI. Nat Mach Intell. 2019;1(11):501-7.

22. Winfield AF, Jirotka M. Ethical governance is essential to building trust in robotics and artificial intelligence systems. Philos Trans R Soc A Math Phys Eng Sci. 2018;376(2133):20180085.
https://doi.org/10.1098/rsta.2018.0085.

23. Foroughi M, Bagherpour M, Eliassen F, Poudineh R. Autonomy as empowerment: a taxonomic framework for analyzing energy autonomy in local flexibility markets. Appl Energy. 2025;389:125777.
https://doi.org/10.1016/j.apenergy.2025.125777.

24. Andoni M, Robu V, Flynn D, Abram S, Geach D, Jenkins D, et al. Blockchain technology in the energy sector: a systematic review of challenges and opportunities. Renew Sustain Energy Rev. 2019;100:143-74.

25. Soto EA, Bosman LB, Wollega E, Leon-Salas WD. Peer-to-peer energy trading: a review of the literature. Appl Energy. 2021;283:116268.
https://doi.org/10.1016/j.apenergy.2020.116268.

26. Markard J. The next phase of the energy transition and its implications for research and policy. Nat Energy. 2018;3(8):628-33.
https://doi.org/10.1038/s41560-018-0171-7.

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