

From Internet of Energy to Energy Physical Internet: A Paradigm Shift

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Abstract

The transformation of the global energy sector is often narrated through the fast and continuous digitalisation of network operations and asset management, while only partially capturing the deeper structural phenomenon that is taking place underneath the visible surface. The most relevant shift in the coming decade will be less about isolated digital tools and more about the emergence of interoperable, packet-based and cognitive infrastructures that redefine how energy flows are designed, orchestrated, monitored and governed. The concept of the Internet of Energy has progressively opened the space for distributed intelligence and advanced sensing; however, its architecture has remained primarily centralised, limited by vertically integrated data pipelines and constrained interoperability. Energy Physical Internet represents a discontinuity, conceptualised as a structural re-architecting of energy networks as distributed ecosystems in which flows are no longer the exclusive domain of traditional grid operations, but become interoperable services governed by multi-stakeholder coordination and explainable Human-AI models. This paradigm implies a layered rethinking of energy infrastructure, moving from mere automation to cognitive decision flows that can adaptively route, prioritise and optimise flows similarly to packet-based networks, while maintaining human supervision and accountability. Such transition brings strategic implications for utilities, regulators and policy makers, driven by European frameworks, ENTSO-E positions on digitalisation and infrastructural resilience challenges, forcing organisations to integrate human-centric design principles capable of embedding transparency, explainability and governance.

Keywords: Internet of Energy, Energy Physical Internet, Distributed Infrastructure, Cognitive Routing, Digital Utilities, Human-AI Collaboration, Interoperability, Energy Transition

Abbreviations

AI - Artificial Intelligence

DER - Distributed Energy Resources

DSO - Distribution System Operator

ENTSO-E - European Network of Transmission System Operators for Electricity

EPI - Energy Physical Internet

Human-AI - Human-Artificial Intelligence Collaboration

IEA - International Energy Agency

IoE - Internet of Energy

IoT - Internet of Things

TSO - Transmission System Operator

XAI - Explainable Artificial Intelligence

1. Introduction and Context

Digitalisation has become an almost universal label to describe transformation in the energy industry, from smart meters to advanced distribution management, from flexibility markets to automated forecasting. Yet the widespread use of the term risks trivialising the nature of the transition that is taking shape. The shift is progressively moving from digital-enabled processes to cognitive infrastructures in which the core logic of the energy

system is structurally re-interpreted. Digitalisation, originally understood as a tool to automate metering processes or optimise grid topology, is now evolving into a foundation for interoperable operations and intelligent decision-making where Human-AI collaboration plays a decisive role. The Internet of Energy appeared as a natural extension of the conventional power grid, enriched by sensing, Internet of Things technologies, analytics and flexible control mechanisms. Its dominant logic relied on collecting distributed information and re-centralising intelligence in command centers. While revolutionary in many early studies, the Internet of Energy has struggled to overcome architectural fragmentation and has often remained dependent on traditional operational silos that limit systemic coordination and adaptive response capabilities.

The most advanced utility organisations have progressively recognised the structural limitations of such models, especially in contexts characterised by high penetration of distributed energy resources, cyber-physical exposure, systemic risk propagation and new regulatory paradigms demanding transparency and accountability. Energy Physical Internet introduces a more radical standpoint that goes beyond incremental improvements. Rather than being the mere digital continuation of existing networks, it proposes a redesign that treats energy flows as packet-based digital services, orchestrated through interoperable platforms and governed through explainable intelligent mechanisms that enable human supervision without constraining system autonomy. In a context increasingly dominated by distributed decision points, the ability to embed transparency, accountability and ethical supervision becomes not only a design requirement but a prerequisite for trust and system acceptability among stakeholders, regulators and society at large. Recent regulatory positions highlight that digital infrastructures are converging with critical infrastructure policy frameworks. According to ENTSO-E and the European Commission digital energy agenda, the capacity to govern distributed intelligence will directly influence risk management and resilience strategies for the entire energy ecosystem [1-3].

As energy networks become data systems with computational capabilities embedded at multiple layers, the boundaries between operational technologies and information architectures increasingly disappear, producing hybrid ecosystems in which the traditional operational language proves insufficient for governance and strategic oversight. This introduction prepares the ground for a conceptual transition that is not merely technological but profoundly organisational, affecting industrial strategy, business models, governance frameworks and organisational competencies. The following sections examine the conceptual background, frame the business methodology required to understand the implications of the Energy Physical Internet, and present comparative evidence that illustrates the paradigm shift from centralised to distributed cognitive architectures.

2. Light Literature and Practice Review

The academic and industrial literature around the Internet of Energy has grown significantly in the last decade, with multiple studies

presenting IoE architectures as layers of sensing, communication and grid operations, largely inspired by Internet of Things and cyber-physical system paradigms. Most research converges on the idea that distributed sensing, analytics and control create the foundation for smarter energy infrastructures able to deliver flexibility and resilience in increasingly complex operational environments. However, the original Internet of Energy concept generally assumes a hierarchical logic, where distributed data flows towards centralised intelligence platforms and decisions are dispatched downward through command structures that replicate traditional utility operations. Early IoE architecture studies emphasised the potential of data-driven operations but often underestimated the organisational and governance challenges associated with truly distributed decision-making frameworks [4-6].

More advanced industrial publications have progressively suggested that centralised intelligence might not be sustainable in scenarios characterised by volatile distributed resources, dynamic network topologies and coordination between autonomous actors operating under different regulatory and commercial frameworks. ENTSO-E reports on digitalisation emphasise the need for interoperable infrastructures capable of supporting multi-party operations, especially in the context of flexibility markets, cross-border balancing, cybersecurity frameworks and evolving consumer participation mechanisms. Meanwhile, International Energy Agency publications repeatedly emphasise that digitalisation will transform energy systems into complex socio-technical ecosystems, where transparency, human involvement and governance are essential to maintain system reliability, social acceptance and regulatory compliance [7]. These institutional perspectives reveal a growing recognition that technical capabilities alone cannot deliver the transformation required by energy transition objectives.

In parallel, the Physical Internet concept originally emerged in the logistics sector as a proposal to treat goods and logistics services in a packet-based manner, enabling interoperability between independent operators through standardised interfaces and cooperative protocols [8]. Its gradual extension into energy literature reveals the conceptual analogy that becomes increasingly relevant as distributed generation proliferates: treating energy as packets enables granular routing, decentralised optimisation, multi-stakeholder orchestration and cognitive decision-making frameworks that can adapt to real-time conditions. Several academic analyses have explored the possibility of modelling energy flows not as continuous analog processes but as discrete computational entities, enabling advanced orchestration mechanisms and human-centric explainability that traditional control systems cannot provide. Whitepapers issued by technology providers emphasise the necessity of Human-AI collaboration in operational decision flows, recognising that the diffusion of distributed generation, prosumer participation, storage services and electric mobility introduces new operational logics which cannot be fully automated in a purely algorithmic manner without human oversight and ethical supervision [9,10].

What emerges from the most recent literature is a clear movement from digital automation to cognitive governance that transcends technological capabilities. The Internet of Energy has certainly opened the technological space for distributed sensing and analytics, enabling unprecedented visibility into grid operations and resource availability. However, Energy Physical Internet is opening the organisational and human space for distributed responsibility and decision authority, allowing multiple stakeholders to participate in system coordination while maintaining accountability and transparency. This conceptual evolution is not simply incremental or additive; it reshapes the underlying logic on which energy systems have been designed for more than a century, moving from centralised command structures to distributed cooperative frameworks that require new governance models, regulatory approaches and organisational capabilities.

3. Business Methodology & Framework

The methodological structure for understanding Energy Physical Internet should not be regarded as a procedural methodology in a conventional academic sense, focused on empirical hypothesis testing or statistical validation [11]. Instead, it constitutes a conceptual business framework that enables utilities and energy organisations to map their current positioning along the evolution from Internet of Energy to Energy Physical Internet, identifying capability gaps, investment priorities and transformation pathways. The framework must consider at least four dimensions that interact dynamically: technological architecture, interoperability maturity, decision intelligence, and human-centric governance. Each dimension represents a critical capability domain that determines organisational readiness for the paradigm shift, and their interaction creates the complete picture of transformation requirements that extend far beyond technology deployment.

The technological architecture dimension reflects the evolution from sensor-based digitalisation focused on data acquisition to packet-based distributed infrastructures capable of supporting dynamic decision routing and adaptive resource allocation. Under Internet of Energy paradigms, technology is predominantly framed as enabler of analytics and centralised optimisation, providing visibility and control from command centers. Under Energy Physical Internet, technology becomes the substrate for distributed decision intelligence, where computational capabilities are embedded at multiple network layers and coordination emerges through interoperable protocols rather than hierarchical commands. This architectural shift requires organisations to evaluate whether their technology stack supports open protocols, distributed edge analytics, explainable artificial intelligence frameworks and human-supervised decision flows that can operate autonomously while remaining accountable to governance frameworks and regulatory requirements [10,12,13,].

Interoperability maturity must be conceptualised beyond simple protocol compatibility or data exchange standards. Internet of Energy literature has often emphasised the need for common communication standards and application programming interfaces, but Energy Physical Internet introduces the necessity

of multi-stakeholder coordination in which distribution system operators, transmission operators, energy suppliers, aggregators and prosumers adopt shared decision interfaces that enable cooperative operations. The rapid emergence of flexibility markets and distributed grid services demonstrates that decision authority is progressively shifting towards distributed actors who must be capable of interacting through transparent, monitored and auditable processes. Maturity in interoperability therefore requires governance agreements, operational transparency frameworks, and supervisory mechanisms that are consistent with regulation, particularly regarding cross-border balancing, real-time security coordination and market coupling mechanisms that enable efficient resource utilisation across jurisdictions [14-16].

Decision intelligence represents the dimension in which most organisations encounter complexity and uncertainty. Internet of Energy analytics typically rely on predictive models that optimise load management, voltage control and distributed generation forecasting through centralised algorithms that operators monitor but rarely question or override. Energy Physical Internet requires not only predictive capacity but explainable decision routing that can be supervised by human operators who understand the reasoning behind algorithmic recommendations and can intervene when necessary [17]. This paradigm introduces cognitive layers that are capable of interpreting system signals, detecting anomalies, coordinating risk mitigation strategies and ensuring that algorithmic decisions remain aligned with regulatory principles, ethical standards and operational objectives. The presence of human oversight does not diminish the role of automated intelligence or slow down operations; instead, it integrates ethical supervision and operational accountability into decision flows, reinforcing trust among stakeholders and system resilience in unexpected situations.

Governance maturity constitutes the dimension in which regulatory, ethical and organisational factors converge to shape operational viability and stakeholder acceptance. Under Internet of Energy frameworks, governance structures were frequently discussed as afterthoughts or compliance layers added after technical deployment, resulting in misalignments between technological capabilities and regulatory expectations. Energy Physical Internet imposes governance as a strategic design principle that must be embedded in architectural logic from the outset [9], ensuring that data ownership, cybersecurity compliance, operational risk delegation and human accountability are considered integral components rather than external constraints. Utilities and energy institutions must therefore evaluate their organisational models, competencies, procurement strategies and regulatory relationships, ensuring alignment with evolving expectations on transparency, explainability and human-centric oversight that characterise modern critical infrastructure governance frameworks.

4. Insights and Evidence

Energy infrastructures designed under Internet of Energy principles have delivered significant improvements in digitalisation, automation and system visibility, enabling utilities to monitor

distributed resources and respond to operational challenges more effectively than traditional systems. However, most Internet of Energy deployments remain dependent on traditional operational structures and centralised intelligence models that limit their capacity to scale in increasingly complex environments. By contrast, Energy Physical Internet introduces distributed decision autonomy, packet-based routing and cognitive intelligence integrated with human supervision, creating fundamentally different operational capabilities. The comparative analysis presented below aims to clarify these structural differences and highlight the managerial implications that determine whether organisations are equipped to evolve from Internet of Energy architectures to Energy Physical

Internet frameworks.

Table 1 presents a systematic comparison across eight critical dimensions that differentiate Internet of Energy from Energy Physical Internet. The dimensions span architectural design, data management, operational control mechanisms, intelligence frameworks, human roles, governance approaches, interoperability capabilities and resilience strategies. Understanding these differences enables organisations to identify transformation requirements and investment priorities that go beyond technology upgrades to encompass organisational change, skill development and regulatory alignment.

Dimension	Internet of Energy (IoE)	Energy Physical Internet (EPI)
Architecture	Mainly centralised intelligence with distributed sensing	Distributed packet-based decision and routing
Data Models	Monolithic pipelines and vertical aggregation	Distributed data exchange and interoperable routing
Operational Control	Central command with partial automation	Multi-agent orchestration and adaptive routing
Intelligence	Predictive analytics and automated optimisation	Cognitive decision-making and Explainable AI
Human Role	Human oversight mainly reactive	Human-AI supervision embedded and proactive
Governance	Technology-driven, limited policy integration	Governance-by-design with transparency and accountability
Interoperability	Protocol-level integration	System-level interoperability across actors
Resilience	Vulnerable to central bottlenecks	Distributed resilience and autonomous risk mitigation

Sources: Review papers on Internet of Energy, European reports on digital power systems, Physical Internet conceptual literature

Table 1: Internet of Energy vs Energy Physical Internet

This comparison highlights that the transition from Internet of Energy to Energy Physical Internet involves more than incremental technological improvements or feature additions. The shift is conceptual, architectural and organisational, requiring fundamental rethinking of how energy systems are designed, operated and governed. Under Internet of Energy frameworks, the logic of digitalisation adds intelligence to traditional networks without fundamentally altering control structures or decision hierarchies. Under Energy Physical Internet, the network transforms into a distributed digital ecosystem in which multi-agent orchestration allows energy flows to be managed through dynamic routing mechanisms that adapt to real-time conditions. Instead of simply collecting and processing data centrally, Energy Physical Internet architectures distribute the decision workload across multiple layers and actors, enabling the system to respond to local conditions and optimise decisions based on contextual information that centralised systems cannot capture or process quickly enough [18,19].

The role of human actors also changes substantially between the two paradigms. Internet of Energy implementations frequently position human operators as monitors of automated systems, intervening

primarily when exceptions occur or when manual overrides become necessary. Energy Physical Internet elevates human actors as cognitive supervisors responsible for supervising algorithmic decisions and ensuring explainability across distributed operations [20]. Governance shifts from a technology-centric stance focused on deploying digital tools to a human-centric and policy-integrated logic that reflects regulatory momentum encouraging transparency and accountability in digital infrastructures. This transformation requires organisations to develop new competencies, establish new governance frameworks and fundamentally rethink operational models that have remained relatively stable for decades.

The transition to Energy Physical Internet affects different categories of stakeholders across the energy value chain, each experiencing distinct benefits and challenges. Table 2 presents a stakeholder-centric analysis that identifies expected benefits for utilities, regulators, customers, aggregators, grid operators and policy makers. Understanding these differentiated benefits enables organisations to build coalitions, align incentives and coordinate transformation initiatives that deliver value across the ecosystem rather than optimising isolated components at the expense of system-wide performance.

Stakeholder	Expected Benefit	Description
Utilities	Distributed resilience	Enhanced ability to manage distributed resources and mitigate operational risks
Regulators	Transparency and explainability	Policy-aligned oversight of decision processes and algorithmic accountability

Customers	Service reliability and flexibility	Improved system stability and flexible energy services tailored to usage profiles
Aggregators	Market interoperability	Seamless participation in flexibility markets with real-time integration
Grid Operators	Autonomous coordination	Adaptive routing and real-time control across distributed systems
Policy Makers	Governance-by-design	Structural embedding of policy objectives in digital architectures
<i>Sources: ENTSO-E digitalisation reports, IEA digital energy assessments, smart grid industrial reports</i>		

Table 2: Benefits of Energy Physical Internet for Stakeholders

The benefits outlined above demonstrate that Energy Physical Internet extends operational logic across multiple dimensions of the energy ecosystem rather than optimising isolated components. Utilities gain distributed decision autonomy which helps mitigate the risks associated with centralised intelligence bottlenecks, particularly under conditions of high renewable penetration and increased cyber-physical exposure that characterise modern energy systems. Regulators obtain more direct insight into algorithmic decision models and are better positioned to assess compliance, supervise risks and align technological deployments with broader societal objectives including energy security, climate targets and consumer protection. Customers experience improved service reliability as distributed coordination reduces vulnerability to single points of failure, while aggregators and grid operators gain operational flexibility which expands opportunities in emerging market structures including distributed flexibility services, cross-border balancing and local energy communities [21,22].

Policy makers benefit from governance frameworks that are embedded in architectural design rather than implemented retroactively as compliance layers that constrain innovation.

Instead of reacting to digitalisation after deployment and attempting to regulate technologies that are already widely adopted, Energy Physical Internet invites policy frameworks to become foundational, shaping digital infrastructures from the outset and ensuring that regulatory objectives regarding transparency, accountability and stakeholder protection are inherent in system design rather than added as external requirements. This proactive governance approach reduces regulatory friction, accelerates deployment and enhances societal acceptance of advanced digital technologies in critical infrastructure contexts.

The evolution from Internet of Energy to Energy Physical Internet can be conceptualised as a five-phase transformation journey that organisations must navigate strategically. Figure 1 presents this evolutionary timeline, illustrating how capabilities progressively build upon each other while introducing qualitative shifts in operational logic. The timeline demonstrates that Internet of Energy represents an essential but incomplete stage of digital evolution, providing the foundation upon which more advanced capabilities must be constructed through deliberate transformation initiatives.

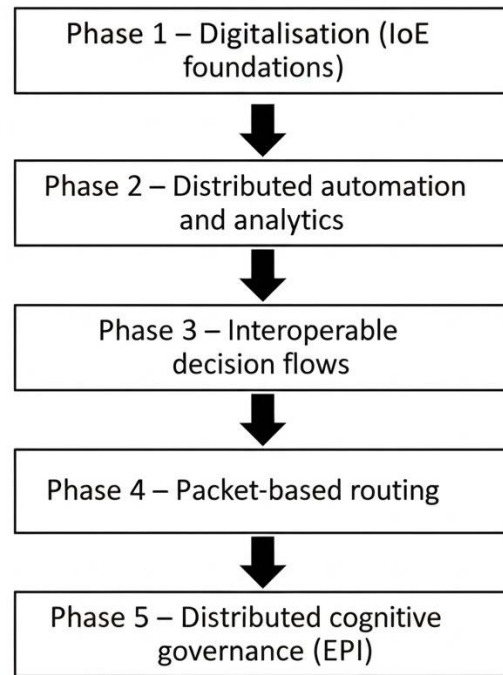


Figure 1: Evolution Timeline from IoE to EPI

Source: Conceptual synthesis based on IoE literature and Physical Internet frameworks

This timeline illustrates that Internet of Energy constitutes an essential but incomplete stage of digital evolution. The first phase introduced data flows, automation and distributed sensing capabilities that enabled the first wave of intelligent energy operations, moving utilities beyond manual processes and analog control systems. However, Internet of Energy lacked the integrated interoperability and cognitive governance required to manage distributed systems at scale, particularly as renewable penetration increases and coordination requirements become more complex. The second phase saw the introduction of distributed analytics and partial automation, enabling more sophisticated forecasting and optimisation, but centralised intelligence still represented a limiting factor that constrained system responsiveness and stakeholder participation.

The subsequent phases introduce interoperable decision flows that allow distributed actors to coordinate through shared operational logic rather than hierarchical commands. Packet-based routing marks a turning point as energy flows become programmable and adaptive, enabling dynamic resource allocation and congestion management that traditional systems cannot achieve. The final phase introduces distributed cognitive governance, where explainable artificial intelligence and human-centric supervision are embedded into operational logic rather than added as afterthoughts [23]. This stage defines the Energy Physical Internet and allows organisations to coordinate distributed decision points without compromising resilience, transparency or regulatory compliance. Organisations must recognise that each phase builds upon previous capabilities while introducing qualitative changes that require new competencies, governance frameworks and organisational structures.

5. Managerial and Societal Implications

The shift from Internet of Energy architectures to Energy Physical Internet has profound consequences that extend well beyond technology deployment or infrastructural design. What becomes increasingly evident is that organisations operating within energy ecosystems are moving from implicit digitalisation to explicit governance-by-design. At managerial level, this transition implies the need to actively integrate human-centric supervision, explainable intelligence and distributed roles into the organisational structure. Under Internet of Energy paradigms, digitalisation helped utilities enhance visibility and forecasting capabilities, but strategic decisions, budget allocations, talent acquisition and risk governance generally remained rooted in traditional operational models that assumed centralised control and hierarchical authority. Energy Physical Internet forces a reframing in which human expertise is not simply supported by automation but embedded inside algorithmic logic, thus demanding new competencies and organisational mechanisms that allow transparency and oversight at every decision node across the distributed network.

For senior management, the challenge does not reside only in recognising the necessity of cognitive infrastructures, but in ensuring organisational alignment between technological transformation and human-centric governance principles [24]. While distributed

energy resources, electrification, flexibility markets, storage integration and cross-sector coupling become pillars of industrial strategy, the capacity to oversee distributed intelligence becomes a fundamental capability that differentiates successful organisations from those that struggle with complexity. This capability requires investment in skills, recruitment and partnerships that give enterprises sufficient control over algorithmic processes without inhibiting innovation or slowing operational response times. Management must balance autonomy with accountability, enabling distributed decisions while maintaining strategic coherence and regulatory compliance across the organisation.

Societal implications begin with the role of energy systems as critical infrastructures upon which economic activity and social welfare fundamentally depend. Digitalisation amplifies systemic interdependencies between data flows, automation mechanisms and cyber-physical control systems, creating new vulnerabilities alongside new capabilities. As distributed intelligence increases, societies demand transparency, explainability and ethical accountability from systems that make decisions affecting energy access, pricing and reliability [25]. The Energy Physical Internet responds to these expectations by embedding human supervision into architectural logic, thus ensuring that technology does not undermine societal trust through opaque decision processes. In contexts where energy systems increasingly intersect with mobility, heating, industrial automation and urban planning, the capacity to justify automated decisions becomes a foundational requirement for maintaining social license to operate and regulatory legitimacy.

Policy frameworks reinforce this viewpoint through increasingly explicit requirements. European initiatives, including energy digitalisation guidelines and cybersecurity directives, progressively converge towards requirements that combine operational efficiency with ethical and human-centric priorities. These priorities include fairness of decision processes, explainability of algorithmic recommendations and accountability for distributed decisions that affect multiple stakeholders. As energy infrastructures evolve into socio-technical ecosystems, the boundary between technical design and public policy becomes blurred. Energy Physical Internet represents an approach that formalises this integration, translating normative expectations into architectural foundations that guide system behaviour rather than constraining it externally through compliance requirements. The organisational implications also concern cyber-physical resilience in an environment where digital attacks can have immediate physical consequences [26].

Internet of Energy infrastructures remain exposed to cyber threats that exploit centralised control and vertical data models, creating single points of failure that attackers can target to disrupt large portions of the network. In contrast, Energy Physical Internet introduces distributed resilience mechanisms that limit attack propagation and support autonomous mitigation strategies [10], reducing vulnerability to coordinated attacks. Nevertheless, autonomy without governance would create new risks by enabling uncoordinated responses that could amplify rather than contain disruptions. The human-centric nature of Energy Physical Internet

ensures that resilience is balanced with accountability, allowing systems to respond autonomously while maintaining oversight mechanisms that detect anomalies and coordinate responses across distributed components. Cybersecurity thus becomes not only a matter of defence but an integrated aspect of cognitive design.

The next implication relates to the social dimension of energy justice and equitable access to advanced energy services. Distributed intelligence, if governed transparently and inclusively, enhances access to flexibility services, gives consumers more participation opportunities and promotes equitable distribution of energy resources across different geographic and socioeconomic contexts. When governed improperly or designed without considering distributional impacts, automation risks reinforcing inequalities by prioritising sophisticated actors who can afford advanced technologies while excluding vulnerable populations. Human-supervised cognitive infrastructures ensure that decision processes reflect societal values and regulatory mandates rather than purely algorithmic optimisation that may overlook fairness considerations. This alignment between technological capability and social objectives becomes essential for maintaining public support and ensuring that energy transition benefits society broadly rather than concentrating advantages among privileged groups.

Finally, on an industrial scale, the shift towards Energy Physical Internet transforms how markets operate and how value is created and distributed across the energy value chain. Aggregators, prosumers and multi-sector actors become active participants in decision processes traditionally controlled by central grid operators and large utilities, creating new business models and revenue streams. This evolution requires governance frameworks that maintain operational stability while enabling market innovation, balancing competition with coordination. The Energy Physical Internet, through its cognitive architecture, represents a viable solution that integrates market innovation with operational security under transparent human supervision, allowing multiple actors to compete and cooperate simultaneously through well-defined interfaces and accountability mechanisms that protect system integrity while encouraging entrepreneurial activity.

6. Consulting Pill / Executive Takeaways

Distributed cognitive infrastructures require organisations to evaluate their governance maturity and alignment with evolving regulatory expectations. The transition from Internet of Energy to Energy Physical Internet is not merely a technological upgrade but an organisational transformation that affects strategic planning, investment priorities, competency development and regulatory relationships. Organisations must assess their current positioning across the four dimensions of technological architecture, interoperability maturity, decision intelligence and governance maturity, identifying capability gaps and transformation pathways that align with regulatory requirements and market opportunities. Human-AI collaboration must be embedded at architectural level to ensure that decision flows remain transparent and explainable in distributed environments [27,28].

This embedding cannot be achieved through superficial interfaces

or dashboard tools that present algorithmic outputs without context. Instead, organisations must integrate human oversight directly into decision logic, ensuring that algorithms provide explanations that human operators can understand, validate and override when necessary. This integration requires investments in explainable artificial intelligence frameworks, operator training programs and governance mechanisms that define responsibilities clearly. Interoperability represents a structural prerequisite of future energy models, demanding ecosystem-level coordination and multi-stakeholder alignment that extends beyond technical standards. Organisations must participate actively in developing interoperability frameworks, contributing to standardisation efforts and establishing operational agreements with other actors in the energy value chain. This participation requires engagement with regulatory bodies, technology providers and industry associations, investing resources in collaborative initiatives that may not deliver immediate returns but establish foundations for long-term competitiveness.

Cyber-physical resilience depends increasingly on distributed autonomy balanced with human-centric accountability, rather than central defences alone. Organisations must redesign security strategies to embrace distributed architectures, implementing defence-in-depth approaches that combine autonomous responses with coordinated oversight. This redesign requires integrating cybersecurity considerations into every layer of the technological stack and ensuring that security mechanisms do not compromise operational responsiveness or inhibit innovation. Organisational competencies must evolve from traditional operational skills focused on physical asset management to cognitive supervisory roles capable of managing distributed intelligence. This evolution requires recruitment strategies that attract professionals with hybrid competencies combining energy domain knowledge with data science, artificial intelligence expertise and governance understanding. Training programs must prepare existing workforce to transition from reactive monitoring roles to proactive supervisory functions, developing capabilities in algorithmic interpretation, ethical decision-making and multi-stakeholder coordination that characterise cognitive energy systems.

7. Conclusions and Future Directions

The evolution from Internet of Energy to Energy Physical Internet expresses a structural paradigm shift in how energy infrastructures are conceptualised, operated and governed. The Internet of Energy initiated digitalisation of power systems, introducing data flows and automated controls that improved operational efficiency and system visibility. However, its architectural logic remained anchored to hierarchies that centralised intelligence and limited interoperability across organisational boundaries. As distributed energy resources proliferate and renewable penetration increases, those foundational assumptions are increasingly challenged by operational realities that demand more flexible, adaptive and responsive coordination mechanisms.

Energy Physical Internet addresses such limitations by embedding interoperability, distributed autonomy and human-centric

governance as intrinsic architectural principles rather than external requirements. The central conclusion is that the cognitive paradigm does not replace human operators or eliminate their responsibilities; instead, it elevates them to supervisory functions that ensure algorithmic transparency and regulatory alignment. Unlike traditional automation narratives that emphasise efficiency gains through human displacement, Energy Physical Internet integrates explainability, ethical design and governance-by-design as fundamental components of system architecture. Energy infrastructures therefore become socio-technical ecosystems where technological progress and human-centric oversight evolve together, supporting each other rather than competing for primacy.

Another conclusion concerns strategic implications for enterprises, regulators and society. Energy Physical Internet introduces new operational logic that requires organisational reform, regulatory collaboration and continuous investment in competency development across multiple domains. The benefits extend beyond efficiency improvements, encompassing resilience enhancement, market flexibility expansion and societal trust reinforcement. In a world where energy systems represent critical digital infrastructures upon which economic activity and social welfare depend, the ability to justify decision processes becomes an indispensable component of strategic legitimacy. Organisations that fail to develop this capability risk losing regulatory approval, market position and stakeholder confidence as transparency expectations continue to rise.

Future developments of the Energy Physical Internet will likely concern deeper integration between energy infrastructures and cross-sector ecosystems including mobility, industry, heating and data-driven services. As urban infrastructures become increasingly interconnected through digital platforms, Energy Physical Internet architectures will provide the foundational logic through which distributed decisions can be coordinated, supervised and justified across sectoral boundaries. One direction of advancement concerns regulatory frameworks that embed algorithmic transparency and supervisory obligations within system design requirements. Policy initiatives will progressively formalise governance-by-design requirements that ensure cognitive infrastructures remain accountable to societal expectations regarding fairness, transparency and stakeholder protection.

In parallel, technological research will continue exploring explainable models capable of supporting human interpretation across increasingly complex decision spaces, developing interfaces that present algorithmic reasoning in forms that domain experts can understand and validate. Another path involves multi-actor participation as aggregators, prosumers and industrial actors participate more extensively in market mechanisms enabled by interoperability and packet-based routing capabilities that reduce coordination costs. A further direction involves cyber-physical convergence as cyber and physical infrastructures become inseparable, requiring adaptive cybersecurity mechanisms governed by human-centric supervisory frameworks rather than static control policies. Finally, future research and industrial innovation

will increasingly emphasise socio-technical implications as energy infrastructures continue evolving as cognitive ecosystems where ethical governance, trust and accountability drive acceptance and long-term sustainability.

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