From Smart Grid to Energy Physical Internet: Why the Future Will Be Packet-Based

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Abstract
The rapidly accelerating energy transition increasingly exposes the structural limitations of today's electric grids, even when enhanced through conventional smart-grid capabilities. While smart grids introduced advanced monitoring, automation, and limited bidirectional flows, they were not conceived to operate as distributed, interoperable, packet-based networks that can orchestrate highly granular energy exchanges across heterogeneous nodes. In this evolving scenario, digital infrastructures, Internet-inspired architectures, and distributed decision-making mechanisms become fundamental in order to manage flexibility, criticality, congestion, and resilience across ever more decentralized energy ecosystems. This article proposes reading the evolution of power systems through a transport-and-traffic-oriented lens, in line with the positioning of CRTTE, a journal strongly concerned with flows, routing, network capacity, congestion, and infrastructure planning. By conceptualizing electricity as a flow of packets rather than a bulk continuous commodity, a novel design approach emerges in which Distributed System Operators transition from asset-based managers into orchestrators of multi-actor energy traffic. The progression from smart grids toward what we refer to as the Energy Physical Internet reveals that electricity infrastructures, similarly to vehicular and data traffic, increasingly need routing capabilities, interoperable layers, explainable decision rules, and congestion-aware network intelligence, especially at the intersection of DER integration, electrification of mobility, and high-voltage grid interconnection. The analogy with road and data networks is neither simplistic nor merely metaphorical. It reflects the underlying architectural rethinking required as digital sensing, edge intelligence, artificial intelligence, and interoperable platform design converge into a new operational paradigm. Energy traffic becomes manageable similarly to packet flows on IP-based networks, enabling new forms of routing, prioritization, load balancing, and cyber-physical resilience across distributed infrastructures. This conceptual transition holds significant consequences for infrastructure planning, regulation, digital governance, and emerging business models in an increasingly electrified, digitalized, and renewable-based future.

Abbreviations

AI - Artificial Intelligence	for Electricity
DER - Distributed Energy Resources	**EPI** - Energy Physical Internet
DSO - Distribution System Operator	**EV** - Electric Vehicle
ENTSO-E - European Network of Transmission System Operators	**IoE** - Internet of Energy
	QoS - Quality of Service

TSO - Transmission System Operator
XAI - Explainable Artificial Intelligence

1. Introduction
Electricity has historically been interpreted as a one-directional flow transmitted through hierarchical infrastructures from centralized generation to passive loads. Over the last decade, however, grid modernization and renewable integration have challenged this paradigm. Not only have loads become distributed and dynamic, but generation itself has shifted closer to consumption through photovoltaics, prosumers, storage systems, electric vehicle fleets, and local energy communities. This profound and multi-dimensional transformation calls for a conceptual reframing that can accommodate the increasing complexity of energy flows on physical infrastructure. The strategic relevance of this transition goes well beyond generation mix. It concerns the architecture of the energy system, the governance of distributed assets, the management of cross-sector electrification, and the development of interoperable information frameworks capable of supporting bidirectional and multidirectional exchanges. These developments expose a critical question in terms of traffic management. Energy must be routed, prioritized, and balanced dynamically, under uncertain conditions, across heterogeneous network segments with varying degrees of controllability, sensing capability, and digital maturity [1-10].

This article, therefore, consistent with CRTTE's orientation, treats electricity as a flow on a network, adopting analogies familiar to transportation, data networking, and infrastructure planning. The central argument is that the future electric grid must evolve into an Energy Physical Internet, a conceptual domain in which energy flows behave in a packet-like manner, enabling routing strategies similar to data networks and traffic engineering. In this view, the Distributed System Operator becomes a traffic orchestrator rather than a traditional infrastructure operator. By adopting this framework, we position the article not merely as an energy technology discussion but as a business-strategic analysis aligned with the needs of infrastructure decision-makers, planners, regulators, and industrial stakeholders. The implications extend to investment strategies, digital governance, interoperability standards, resilience policies, and the design of next-generation industrial ecosystems [11-13].

Treating energy as a transport-and-traffic problem also introduces managerial questions related to congestion, routing optimization, access rights, prioritization policies, resilience enhancement, and explainability of automated network decisions. Not only does the distributed nature of renewable-based infrastructures require smarter capabilities, but the surge of electric mobility, electrified heating, and industrial electrification directly increase the density and variability of energy flows across networks. These changes intensify demand for advanced traffic engineering across substations, feeders, microgrids, and distributed resources. In other words, the energy system is no longer a static infrastructure but a dynamic cyber-physical environment whose operational reliability depends on distributed intelligence. This creates strategic opportunities for grid operators, equipment manufacturers, industrial utilities, and digital infrastructure players, while simultaneously demanding new regulatory models and governance frameworks to maintain fairness, security, and systemic resilience [14,15].

This introductory section lays the conceptual foundation for understanding why the traffic perspective is not optional but inevitable, especially under accelerating decarbonization, electrification, and digitalization trends. It also anticipates a methodological framework that will be further elaborated later, comparing vehicular, data, and energy traffic characteristics, highlighting their convergence and divergence, and providing first principles for a traffic-based interpretation of energy infrastructures.

2. Background and Literature and Practice Review
The concept of the smart grid emerged to address exactly the limitations of traditional top-down electrical infrastructures. Smart grids introduced sensing, automation, bidirectional flows, and demand response capabilities. International institutions such as the EU and ENTSO-E have defined multi-layer smart grid roadmaps addressing data integration, cybersecurity, and distributed intelligence, while industrial whitepapers from grid automation vendors have explored the architecture necessary for enhanced visibility, edge analytics, and interoperable control systems. Nevertheless, smart grid paradigms were primarily evolutive rather than disruptive. They largely extended existing infrastructures without redefining their architectural nature. As a result, the underlying operational paradigm remains tied to centralized planning, centralized supervisory control, and bulk load management. While this approach has improved efficiency, it still falls short of enabling a fully distributed operational model capable of granular orchestration and energy packet routing [16-18].

Recently, European regulatory bodies have emphasized the necessity for congestion management solutions that can operate across heterogeneous segments of the grid, while simultaneously addressing the increasing presence of distributed renewable generation and electrified mobility sectors. Several studies point out that congestion will become endemic in renewable-based networks unless managed with more advanced strategies inspired by traffic engineering. The notion of Energy Physical Internet emerges as a conceptual extension of the Physical Internet, originally formulated in the context of logistics networks. The Physical Internet aims to optimize logistics efficiency through modular containerization, open routing, and interoperability across multiple stakeholders. In this sense, EPI borrows many of its principles from logistics and applies them to distributed energy infrastructures. The transition from logistics to energy is not merely metaphorical but supported by evidence of shared challenges, including routing, prioritization, resource allocation, interoperability, and the need for distributed decision systems [19-21].

A number of academic and industrial publications have begun exploring the application of Physical Internet concepts to energy distribution networks, emphasizing distributed control, energy

packetization, and interoperability across multiple operators. The European Union has incorporated Physical-Internet-aligned strategies into its digital energy initiatives, especially concerning cross-border energy cooperation, smart grid interoperability, and new DSO responsibilities. Research on distributed systems and cyber-physical platforms contributes additional theoretical and practical insights on distributed control, edge intelligence, and platform-based energy services. Collectively, these bodies of literature highlight that the energy system is evolving toward a distributed control environment requiring multi-layer digital governance.

Congestion management reports from ENTSO-E emphasize the need for routing strategies, capacity balancing, priority-based allocation, and cross-border interoperability. Similarly, the European Commission's guidance on distributed grid operation points toward explainable automation, data sovereignty, and real-time coordination of distributed assets. Industrial practice is already moving in this direction. DSOs and TSOs in several European countries are piloting congestion-oriented traffic management techniques, often using AI-driven analytics and edge control to better allocate capacity and shift loads. These initiatives demonstrate not only the feasibility of energy traffic control but also its strategic importance for grid resilience and business continuity in a renewable-dominated future. Taken together, the literature and practice landscape suggest a fundamental shift. While smart grids improved instrumentation and automation, the next phase requires architectural redesign. This redesign should internalize traffic engineering principles, distributed digital capabilities, and Physical Internet paradigm elements, evolving toward an Energy Physical Internet that reflects the demands of contemporary electrification and resilience [22,23].

3. Business Methodology and Conceptual Framework

The conceptual foundation of Energy Physical Internet rests on drawing analogies between three types of traffic: vehicular traffic on road networks, data traffic on digital communication systems, and energy traffic on electrical infrastructures. Each of these systems faces similar challenges related to routing, congestion, capacity management, prioritization, and resilience. By examining these parallels, decision-makers can leverage established methodologies from transport and data engineering to address emerging challenges in energy distribution. The methodology employed in this article is not quantitative in the traditional sense but rather conceptual and comparative. It establishes a mapping between transport concepts and energy operations, creating a business-oriented framework that can guide strategic decisions related to infrastructure design, operational procedures, regulatory models, and technology investments.

The first dimension of this framework concerns network architecture. In vehicular traffic, road networks consist of nodes such as intersections, interchanges, and parking areas connected by roads of varying capacity. In data traffic, routers and switches interconnect through fiber optic cables, wireless links, and satellite connections. In energy traffic, substations, distributed resources, and consumption points interconnect through transmission lines and distribution feeders. All three systems exhibit hierarchical structures, with higher-level networks carrying bulk flows and lower-level networks managing local distribution. The second dimension relates to flow characteristics. Vehicular traffic consists of discrete vehicles moving along predetermined routes with varying speeds and priorities. Data traffic comprises packets transmitted across networks with specific protocols and quality-of-service requirements. Energy traffic involves electrons flowing through conductor's subject to physical laws governing voltage, current, and impedance. While energy flows differ fundamentally from vehicles and data packets in their continuous nature, the conceptualization of energy as discrete units transmitted across infrastructure enables traffic-inspired management strategies.

The third dimension concerns congestion management. In vehicular traffic, congestion arises when demand exceeds road capacity, leading to delays, queuing, and potential accidents. Traffic engineers address congestion through route optimization, signal coordination, access control, and capacity expansion. In data traffic, congestion occurs when packet arrival rates exceed router processing capacity, resulting in latency, packet loss, and service degradation. Network operators manage congestion through bandwidth allocation, priority queuing, load balancing, and traffic shaping. In energy traffic, congestion manifests as voltage deviations, thermal overloading of lines, and frequency instability. Grid operators traditionally addressed congestion through network reinforcement and centralized dispatch, but distributed generation and electrification trends demand more dynamic and localized management approaches. The analogy suggests that energy congestion can be managed through routing optimization, priority allocation, and distributed control mechanisms similar to those used in transport and data systems.

Table 1 systematically compares these three traffic domains across multiple dimensions, providing a structured framework for understanding how traffic engineering principles can inform energy system design and operation.

Dimension	Vehicular Traffic	Data Traffic	Dimension	Energy Traffic (EPI)
Network Infrastructure	Roads, intersections, highways with hierarchical structure	Routers, switches, fiber optic cables, wireless links	Network Infrastructure	Substations, distributed energy resources, transmission and distribution lines
Flow Unit	Individual vehicles with discrete origin-destination pairs	Data packets with headers, payloads, and routing information	Flow Unit	Conceptual energy packets with source, destination, and routing metadata

Congestion Mechanism	Demand exceeds road capacity, causing delays and queuing	Packet arrival rate exceeds processing capacity, causing latency	Congestion Mechanism	Power flow exceeds line capacity, causing voltage deviations and thermal overloads
Routing Strategy	Traffic signals, route guidance systems, dynamic lane assignment	Shortest path algorithms, quality-of-service policies, load balancing	Routing Strategy	Distributed optimization, demand response, dynamic topology reconfiguration
Priority Mechanisms	Emergency vehicles, high-occupancy lanes, bus rapid transit	Differentiated services, traffic classes, bandwidth reservation	Priority Mechanisms	Critical infrastructure prioritization, flexible load curtailment, storage dispatch
Resilience Approach	Alternative routes, incident management, redundant capacity	Redundant paths, automatic rerouting, network segmentation	Resilience Approach	Microgrids, distributed storage, automated reconfiguration, islanding capability

Table 1: Comparative Analysis of Traffic Domains

Table 1 demonstrates that while the three traffic domains differ in their physical manifestations and constraints, they share fundamental challenges and solution approaches. This convergence enables cross-domain learning and the application of proven traffic engineering methodologies to energy system design. The framework suggests that energy system operators should increasingly adopt traffic management mindsets, viewing their role not as passive infrastructure managers but as active orchestrators of dynamic flows subject to real-time optimization and coordination.

Building on this comparative framework, we can now examine specific routing decisions that characterize packet-based energy systems. In traditional power systems, energy routing was largely predetermined by network topology and centralized dispatch schedules. In contrast, EPI enables dynamic routing decisions based on real-time conditions, availability of distributed resources, and operational priorities. These routing decisions can be categorized across several operational scenarios, each presenting distinct challenges and opportunities for traffic-inspired management strategies. Table 2 illustrates representative routing scenarios in energy systems and their analogies to traditional traffic management decisions.

Operational Scenario	Routing Decision	Traffic Analogy
Localized congestion on distribution feeder during peak demand	Reroute energy through alternative feeder or activate local storage to reduce load	Traffic diversion to parallel road during rush hour congestion
High renewable generation in one region, deficit in adjacent region	Direct surplus energy to deficit region through interconnection, balancing supply and demand	Interstate highway balancing traffic between metropolitan areas
Emergency situation requiring power to critical facilities	Prioritize energy packets to hospitals, emergency services, infrastructure control systems	Emergency vehicle priority lanes and traffic signal preemption
Transmission line outage requiring reconfiguration	Automatically reconfigure network topology, activate distributed generation, establish microgrids	Road closure requiring dynamic route recalculation and detour signage
Electric vehicle charging coordination during evening peak	Schedule charging sessions based on grid capacity, renewable availability, and user preferences	Parking lot entry management based on available capacity and reservation priority
Cross-border energy exchange between interconnected grids	Coordinate flows based on bilateral agreements, market prices, and transmission capacity	International border crossing coordination for freight transport

Table 2: Energy Routing Decision Scenarios

Table 2 illustrates the diversity of routing decisions required in modern energy systems and demonstrates how traffic engineering concepts provide natural frameworks for addressing these challenges. Each scenario requires real-time information, decision algorithms, coordination mechanisms, and the ability to override default routing patterns when necessary. The packetization concept enables this flexibility by treating energy flows as managed entities subject to dynamic optimization rather than passive consequences of network physics. This shift from passive to active management represents a fundamental transformation in grid operations, demanding new organizational capabilities, technical infrastructure, and regulatory frameworks.

4. Insights and Evidence from Packet-Based Energy Perspectives

The transition from centralized bulk power systems to packet-based energy architectures generates multiple strategic insights with direct implications for infrastructure planning, operational procedures, and business models. The first insight concerns the fundamental shift in operational philosophy. Traditional grid operations focused on maintaining system-wide balance between total generation and total consumption, with operators exercising centralized control over large generating units and passive loads. Packet-based systems instead emphasize localized balance and distributed coordination, with operators orchestrating numerous small transactions between heterogeneous resources. This shift requires new thinking about what constitutes optimal grid operation and how to measure operational performance.

The second insight relates to the role of information infrastructure. In traditional systems, information systems primarily supported after-the-fact billing and periodic performance monitoring. In packet-based systems, information infrastructure becomes mission-critical operational infrastructure, enabling real-time routing decisions, automated coordination, and continuous optimization [14,21]. This elevates cybersecurity, data governance, and communication reliability to the same strategic importance as physical infrastructure resilience. Grid operators must therefore invest in digital capabilities with the same rigor previously reserved for physical assets, recognizing that operational success increasingly depends on information processing capacity rather than simply generation capacity.

The third insight addresses market structure and business models. Traditional electricity markets featured clear roles for generators, transmission operators, distribution operators, and retail suppliers, with well-defined interfaces between these actors. Packet-based systems blur these boundaries as prosumers simultaneously consume and generate, storage operators arbitrage across timescales, aggregators coordinate distributed resources, and platform operators facilitate peer-to-peer transactions. This complexity demands new market designs that can accommodate distributed transactions, dynamic pricing, and multi-sided platform economics. Traditional regulatory frameworks based on cost-of-service principles and vertically integrated utilities may prove inadequate for governing these decentralized market structures.

The fourth insight concerns the importance of explainability and transparency in automated decision-making [24]. As routing decisions become increasingly automated and complex, stakeholders demand understanding of why particular decisions were made, especially when those decisions affect their costs, reliability, or environmental preferences. Black-box optimization algorithms may achieve technical efficiency but fail to gain social acceptance if affected parties cannot understand or challenge their outcomes. This requirement for explainable AI extends beyond technical feasibility to encompass organizational accountability, regulatory compliance, and democratic legitimacy. Packet-based systems must therefore incorporate transparency mechanisms that make automated routing decisions comprehensible to human supervisors and affected stakeholders. Figure 1 provides a conceptual representation of a packet-based energy network showing the integration of distributed resources, routing intelligence, and coordination mechanisms across multiple hierarchical levels.
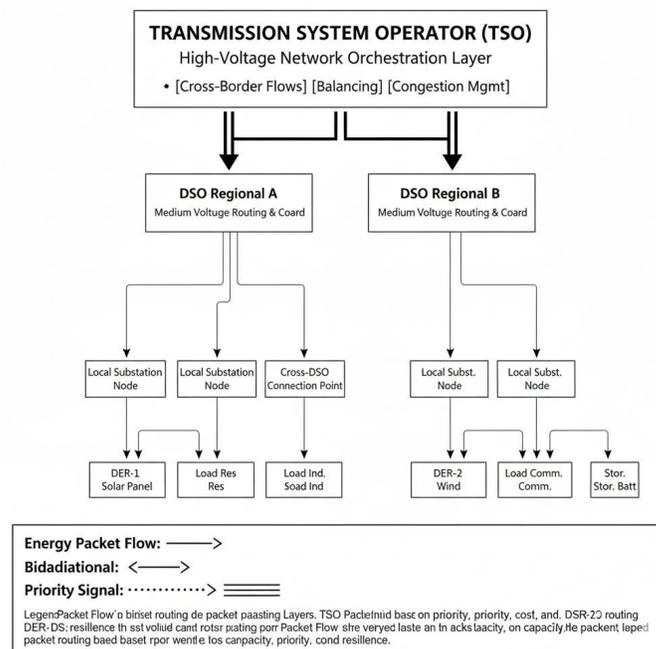

Figure 1: Conceptual Architecture of Energy Physical Internet

Figure 1 depicts the hierarchical structure of a packet-based energy system, showing how routing decisions cascade from transmission level through distribution networks to individual distributed resources and loads. The architecture emphasizes bidirectional flows, multiple interconnection points, and distributed decision-making capabilities at each level. This structure enables the flexible routing scenarios described in Table 2 while maintaining overall system coordination through information exchange and hierarchical optimization protocols.

The fifth insight concerns resilience characteristics of packet-based systems. Traditional grid resilience strategies relied on redundancy, backup generation, and rapid restoration after outages. Packet-based systems add a new dimension: resilience through reconfiguration and local autonomy. When portions of the network experience disruptions, packet-based architectures enable rapid formation of microgrids, rerouting of flows through alternative paths, and prioritization of critical loads through automated decision algorithms. This resilience-by-design approach reduces dependence on expensive redundant infrastructure while improving system response to both anticipated and unanticipated disruptions.

The sixth insight addresses the integration of electric mobility into grid operations. Electric vehicles represent both significant new loads and potential distributed storage resources. Packet-based architectures enable intelligent coordination of vehicle charging and discharging based on grid conditions, renewable availability, and individual user preferences. This coordination transforms electric vehicles from passive loads that threaten grid stability into active participants that enhance grid flexibility and support renewable integration. The economic value of this coordination capability may significantly offset the infrastructure costs required to support widespread electrification of transport.

The seventh insight concerns data governance and platform economics. Packet-based systems generate vast quantities of operational data regarding energy flows, routing decisions, resource availability, and consumption patterns. This data has strategic value for system optimization, market operations, and service innovation, but also raises concerns about privacy, commercial advantage, and regulatory oversight. Platform operators who control this data may acquire significant market power, potentially creating new forms of infrastructure monopoly. Regulatory frameworks must therefore address data ownership, access rights, and platform governance to prevent exploitation while enabling innovation. The architecture of packet-based systems should incorporate data governance principles from the outset rather than attempting to retrofit governance mechanisms after platforms become entrenched.

5. Managerial and Societal Implications

The transition toward packet-based energy infrastructures carries profound implications for organizational capabilities, business strategies, regulatory frameworks, and societal expectations. From a managerial perspective, grid operators must transform from asset-intensive utilities focused on infrastructure reliability into digital orchestrators managing complex multi-stakeholder ecosystems [24]. This transformation requires fundamentally different organizational competencies, including platform architecture design, algorithm development, real-time optimization, cybersecurity management, and stakeholder coordination [25]. Traditional engineering competencies remain essential but become necessary rather than sufficient conditions for operational success. Utilities must therefore invest in digital talent acquisition, organizational restructuring, and cultural change to enable this transition.

The business model implications extend beyond grid operators to encompass the entire energy value chain. Equipment manufacturers must evolve from selling physical assets to providing integrated solutions combining hardware, software, and ongoing services. Energy retailers must transition from simple commodity trading to offering sophisticated energy management services that optimize customer outcomes across multiple dimensions. Technology providers and platform operators may enter the energy sector from adjacent industries, bringing digital capabilities and business model innovation that challenge incumbent players. This convergence of energy and digital sectors creates opportunities for new market entrants while threatening established players who fail to adapt rapidly enough.

Regulatory frameworks must evolve to accommodate distributed decision-making while maintaining system reliability, market fairness, and consumer protection [26]. Traditional regulatory approaches based on rate-of-return regulation and vertically integrated monopolies prove inadequate for governing packet-based systems with multiple operators, distributed resources, and platform-mediated transactions. Regulators must develop new frameworks addressing market design, platform governance, data rights, interoperability standards, and performance-based incentives. This regulatory evolution must balance multiple objectives including innovation encouragement, investor confidence, consumer protection, and competitive market development.

The cybersecurity implications of packet-based systems demand particular attention. As energy infrastructure becomes increasingly dependent on digital information systems and automated decision-making, cyber threats pose growing risks to physical infrastructure and operational reliability [27]. Packet-based architectures distribute intelligence across numerous nodes, expanding the attack surface while potentially improving resilience through distributed redundancy. Security strategies must therefore address both centralized coordination systems and distributed edge devices, requiring comprehensive approaches spanning hardware security, software verification, network segmentation, and organizational security culture. Regulatory frameworks must mandate minimum cybersecurity standards while enabling operators to adopt innovative security approaches appropriate to their specific operational contexts.

Societal implications include questions of equity, participation, access rights, and the governance of shared infrastructures. If automated routing prioritizes industrial loads over residential communities during congestion events, societal acceptance may diminish. Academic and regulatory institutions will therefore need to address equity concerns and explicitly consider socio-economic impacts of automated prioritization policies. Global trends in transport electrification further reinforce the importance of packet-based infrastructures. Electric vehicle penetration is already increasing congestion risks in distribution networks. Without distributed flexibility, EV charging may create substantial load peaks, causing localized overload conditions and requiring costly infrastructure upgrades. Packetization supports dynamic load shifting, local balancing, and real-time charging coordination, enabling electric mobility to integrate into existing infrastructures without excessive reinforcement costs.

Managerial complexity also emerges in multi-energy systems. Packet-based electricity infrastructures may eventually interact with hydrogen networks, thermal grids, and vehicle-to-grid services. The integration of multiple energy vectors demands harmonized standards, interoperable communication interfaces, and coordinated planning strategies across energy sectors and regulatory frameworks. In such scenarios, DSOs may evolve into multi-energy coordinators responsible for distributed orchestration across sectors, further expanding their managerial responsibility. The increasing interconnection of European grids also magnifies the strategic relevance of packet-based infrastructures. Cross-border interconnections, pan-European transmission corridors, and interregional balancing mechanisms require harmonized routing strategies, standardized interfaces, and collaborative resilience frameworks.

In such a context, ENTSO-E initiatives encouraging cross-border coordination become central to EPI adoption. Packet-based infrastructures provide the digital foundation for balancing renewable flows across borders, improving decarbonization outcomes and energy sovereignty.

Resilience considerations acquire a new dimension. Distributed orchestration enables rapid reconfiguration of flows during extreme weather events, cyber incidents, or equipment failures. Rather than relying on centralized backup, packetization deploys flexibility resources locally, leveraging microgrids, distributed storage, and automated reconfiguration protocols to minimize outage durations. This approach increases resilience while reducing reliance on traditional redundancy investments. In summary, managerial and societal implications extend across organizational capabilities, regulatory frameworks, digital infrastructures, cybersecurity, interoperability, equity, and resilience. Packetization demands a rethinking of business models, regulatory instruments, and societal agreements governing access, prioritization, and automated decision-making.

6. Consulting Pill and Executive Takeaways
From a consulting standpoint, decision-makers should internalize the transformative nature of packet-based infrastructures and begin designing organizational strategies that accommodate the transition toward distributed orchestration and energy routing. While avoiding prescriptive language or direct marketing, several executive considerations naturally emerge from the conceptual framework introduced above. Firstly, managers must recognize that packetization is not a matter of adding smarter equipment but rather a strategic organizational shift toward dynamic orchestration capabilities. This requires internal alignment, interdisciplinary competence development, and digital transformation programs aimed at integrating edge intelligence, platform automation, and flexibility markets [28].

Secondly, infrastructure planning must increasingly incorporate flexibility-first principles, prioritizing investments in distributed orchestration, sensing networks, digital twins, and automated decision frameworks before resorting to physical reinforcement. By adopting flexibility-based strategies, organizations can minimize capital expenditure, accelerate renewable integration, and enhance resilience under variable conditions. Thirdly, governance mechanisms must be aligned to enable distributed decision-making and interoperability. DSOs should adopt platform-based architectures designed to host future orchestration algorithms, interoperability standards, cybersecurity controls, and data-sharing frameworks.

Fourthly, managers should anticipate increasing regulatory oversight concerning fairness, prioritization, explainability, and data governance. Organizations must develop transparent mechanisms demonstrating how automated routing decisions comply with regulatory principles and meet societal expectations. Finally, executive decision-making will benefit from adopting traffic-inspired analytics and performance indicators. Metrics derived from transport engineering, such as congestion propensity, flow reliability, and routing efficiency, can be adapted to energy systems, enabling data-driven decisions aligned with traffic engineering paradigms.

7. Conclusions and Future Directions
The evolution from smart grids to the Energy Physical Internet signifies a strategic and structural transformation in how electricity is generated, distributed, and managed. By interpreting electricity as a flow of packets, stakeholders unlock new opportunities for real-time orchestration, congestion mitigation, digital governance, and resilience enhancement. The managerial implications reach deep into organizational competencies, regulatory mandates, infrastructure planning, data governance, and societal expectations regarding fairness, transparency, and cybersecurity. Future directions involve strengthening interoperability frameworks, developing explainable routing algorithms, harmonizing regulatory structures, enabling cross-sector integration, and improving resilience through distributed orchestration. DSOs and TSOs will need to coordinate closely, adopting shared governance mechanisms capable of handling distributed decision-making and cross-border energy flows. Industrial players and digital infrastructure providers will also play a decisive role by developing

interoperable platforms, storage systems, and flexibility services aligned with EPI principles [29].

Packetization is not a technological detail but a systemic redefinition of energy infrastructures. In an increasingly electrified economy, where renewable integration, electric mobility, and distributed resources accelerate the demand for routing intelligence, packet-based architectures provide a conceptual and operational foundation for building resilient, sustainable, and inclusive energy ecosystems. The strategic imperative for decision-makers is clear: organizations that successfully navigate this transition toward traffic-inspired energy management will position themselves as leaders in the next phase of energy system evolution, while those that cling to centralized paradigms risk obsolescence in an increasingly distributed and dynamic operational environment [30].

References

1. Benelli, F., Maciariello, F., Marku, R., & Stile, V. (2025). Towards an Energy Physical Internet: Open Business Models and Platforms for Electricity Distribution Enabled by IoT, Blockchain, and Conditional Payments. In *Conference Book of Abstracts of the 4th International Conference Creativity And Innovation In Digital Economy* (*CIDE 2025*). Universitatea Petrol-Gaze (UPG).
2. Montreuil, B. (2011). Toward a Physical Internet: meeting the global logistics sustainability grand challenge. *Logistics Research, 3*(2), 71-87.
3. Benelli, F., Këlliçi, E., Maciariello, F., & Stile, V. (2025). Artificial Intelligence for Decentralized Orchestration in the Physical Internet: Opportunities, Business Trade-offs, and Risks in Road Freight Logistics. In *Conference Book of Abstract of the 4th International Conference Creativity And Innovation In Digital Economy* (*CIDE 2025*).
4. International Energy Agency. (2022). Grid Integration of Variable Renewables: Policy and Regulatory Aspects. Paris: IEA Publications. https://www.iea.org/reports
5. Rifkin, J. (2011). *The third industrial revolution: how lateral power is transforming energy, the economy, and the world.* Macmillan.
6. European Commission. (2023). Smart Grid Mandate: Standardization for Smart Grids. Brussels: EU Publications. https://ec.europa.eu/energy/topics/technology-and-innovation/smart-grids
7. Jindal, A., Kumar, N., & Aujla, G. S. (Eds.). (2021). *Internet of Energy for Smart Cities: Machine Learning Models and Techniques.* CRC Press.
8. European Commission. (2021). Digital Energy Action Plan. Brussels: Directorate-General for Energy. https://ec.europa.eu/energy/topics/digitalisation/digital-energy-action-plan
9. European Union Agency for Cooperation of Energy Regulators. (2023). Framework Guidelines on Congestion Management. Ljubljana: ACER. https://www.acer.europa.eu
10. Schneider Electric. (2022). EcoStruxure for Distribution System Operators: Digital Platform for Grid Edge Intelligence. Paris: Schneider Electric Whitepaper.
11. Siemens Energy. (2022). Grid Software Solutions: AI-Based Congestion Management and Forecasting. Munich: Siemens Energy Publications.
12. McKinsey & Company. (2022). The Future of Distribution Grids: From Passive Networks to Active Orchestrators. Energy Insights Report. https://www.mckinsey.com/industries/electric-power-and-natural-gas
13. Boston Consulting Group. (2022). The Distributed Energy Transition: Strategic Implications for Utilities. BCG Energy Practice Report.
14. Deloitte. (2023). Energy Management Reimagined: From Asset-Heavy to Platform-Based Business Models. London: Deloitte Insights.
15. Gartner Group. (2023). Hype Cycle for Utility Operations and Customer Engagement Technologies. Stamford: Gartner Research.
16. International Electrotechnical Commission. (2022). Smart Grid Interoperability Standards Roadmap. Geneva: IEC Publications. https://www.iec.ch/smartgrid
17. IEEE Standards Association. (2023). IEEE 2030 Standard for Smart Grid Interoperability. Piscataway: IEEE SA Publications. https://standards.ieee.org/standard/2030-2011.html
18. ENTSO-E. (2022). Digitalisation Roadmap for TSOs. Brussels: European Network of Transmission System Operators for Electricity. https://www.entsoe.eu/digital
19. ENTSO-E. (2023). Market Report: Congestion Management Practices Across European TSOs. Brussels: ENTSO-E Publications.
20. European Parliament. (2023). Directive on Common Rules for the Internal Market for Electricity (Recast). Official Journal of the European Union, L 158/125.
21. Maciariello, F., Benelli, F., Sangiuolo, G., Lorenzi, E., Caponio, C., & Salvadori, C. (2025, September). TrackOne: Smart Logistics for a Sustainable and Interoperable Agricultural Supply Chain in the Era of Digitization. In *2025 International Conference on Software, Telecommunications and Computer Networks* (*SoftCOM*) (pp. 1-7). IEEE.
22. World Economic Forum. (2023). Digital Transformation of the Energy System. Geneva: WEF White Paper Series.
23. Accenture. (2023). The Digital Grid: How AI and Data Analytics are Transforming Energy Distribution. Dublin: Accenture Strategy Report.
24. Benelli, F., Maciariello, F., Salvadori, C., Këlliçi, E., & Stile, V. (2025). Human-AI Collaboration in SMEs: A Role-Sensitive Framework for Cognitive Enterprise Hubs.
25. Benelli, F., Maciariello, F., Salvadori, C., Kelliçi, E., & Stile, V. (2025). Human-AI Collaboration in SMEs: A Role-Sensitive Framework for Cognitive Enterprise Hubs. In *Proceedings of the 22nd Conference of the Italian Chapter of the Association for Information Systems* (*ITAIS 2025*).
26. Benelli, F., Maciariello, F., & Salvadori, C. (2024). The influence of technologies on organizational culture in innovative SMEs.
27. Liberti, F., Avolio, F., Cicoira, V., Cosmo, N., Laudonia, A., Maciariello, F., & Stile, V. (2025). Distributed Artificial

Intelligence and Health Governance: A Multidimensional Analysis of the Tensions Between Rules, Ethics and Innovation.

28. European Network for Cyber Security. (2022). Cybersecurity Framework for Smart Energy Systems. Brussels: ENCS Report.

29. Benelli, F., Këlliçi, E., Maciariello, F., Salvadori, C., & Stile, V. (2025). Enhance Student Wellbeing and Digital Literacy with Machine Learning and Spatial Analysis. In *The 2nd Workshop on Education for Artificial Intelligence* (*EDU4AI 2025*).

30. Benelli, F., Caronna, M., Këlliçi, E., & Maciariello, F. (2025). Leveraging the urban physical internet for sustainable heritage management: Edge AI, federated learning, and digital twins. In *HERITAGE CAPITALISATION AND DEVELOPMENT-IDENTITY, INNOVATION, DIGITALISATION, ENVIRONMENT, AWARENESS AND SECURITY" HERITAGE–IIDEAS*.