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From Operational Byproduct to System Production Factor: The Evolving Role of Power Data in Future Power Systems

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Among the growing complexity of power systems, power data has emerged as an increasingly critical yet historically undervalued resource. Traditionally regarded as a byproduct of system operation, collected primarily for monitoring and basic operational functions, power data was assigned secondary value relative to physical assets such as generation capacity, network infrastructure, and flexibility resources. However, as power systems transition toward high penetrations of distributed energy resources, electrified end uses, and decentralized decision-making, the primary system bottleneck is shifting from energy availability to system observability, coordination, and controllability. In this context, power data is no longer merely descriptive information, but a foundational input that affects whether distributed resources can be effectively perceived, coordinated, and utilized. This paper provides a system-level perspective on the evolving role of power data. Rather than focusing only on the technical use of data in specific digital functions, it argues that power data should be understood as a system-wide production factor rather than an operational byproduct, and discusses how future power systems can be reconfigured around data under practical technical and institutional constraints.

POWER DATA AS A CRITICAL SYSTEM RESOURCE

Traditionally, the core bottleneck of power systems lay in the physical layer, specifically in the limited availability of generation capacity and transmission capacity,[1] which can be viewed as "capacity scarcity". System planning and operation were therefore designed to overcome this physical constraint through infrastructure reinforcement and redundancy. However, the rapid proliferation of a diverse and heterogeneous array of energy resources is fundamentally reshaping this scarcity logic.[2] Future power systems are not only constrained by generation and transmission capacity, but increasingly challenged by the real-time observability and control of decentralized resources.

This structural transition is described in this paper as "cognitive scarcity", in which system limitations arise not only from insufficient physical capacity, but also from insufficient system awareness, coordination capability, and actionable information. As the system evolves from a centralized structure to a massive, heterogeneous network, the physical complexity has outpaced informational awareness, creating significant "blind zones" in system operation,[3] such as limited visibility of behind-the-meter DERs, EV charging behavior, user-side storage, flexible loads, and low-voltage feeder-end conditions. Power systems have ample regulation resources, such as storage and demand response, but increasingly lack the critical data regarding "when and where" to activate them efficiently.

Consequently, the role of power data must be reconsidered in the future. In an environment characterized by cognitive scarcity, data is no longer merely an auxiliary byproduct for monitoring and basic operational functions, but a foundational input for reliable system operation. Power data increasingly functions as a critical production factor, standing alongside physical assets such as generation resources and transmission resources in determining whether system resources can be effectively utilized at all.

INFORMATIONAL BOTTLENECKS IN POWER SYSTEMS

The shift from "capacity scarcity" to "cognitive scarcity" is driven by the need to transform fragmented information into actionable data assets. The shift from "capacity scarcity" to "cognitive scarcity" is driven by the need to transform fragmented information into actionable data assets. In this paper, data assets refer to historical, operational, and behavioral power-system data that can support planning, operation, coordination, and control. As illustrated in Figure 1, the growing integration of diverse resources necessitates a data-centric architecture to enhance system intelligence at both the planning and operational levels.

Planning redundancy under growing uncertainty. Planning decisions historically rely on general forecasts and safety margins to manage uncertainty.[4] Due to the lack of detailed data, physical redundancy is utilized as the primary hedge against demand fluctuations. As future power systems integrate diverse stochastic resources, this informational gap results in over-investment. Without deep mining of power data to characterize stochastic resources, planners must maintain conservative margins, proving that the true scarcity lies not merely in physical capacity, but in the accurate data required for efficient deployment.

From passive loads to multi-agent ecosystems. The power systems are undergoing a fundamental shift from highly centralized architectures to complex, multi-agent ecosystems.[5] The rapid integration of diverse resources and user-side resources means that the system's physical state is no longer determined by a few centralized plants, but by a large number of autonomous decision-makers. This physical decentralization fragments the "control capability" of the networks, making data the key medium capable of re-aggregating these decentralized resources.

Growing blind spots at the edge. While physical complexity at the grid edge has exploded, the observability provided by traditional infrastructure remains insufficient.[6] The SCADA systems, designed for top-down monitoring, often stop at the substation level and fail to provide granular visibility into millions of end-nodes. This leads to an "incomplete information system" where resources, such as EVs and user-side storage, are physically present but operationally "invisible".

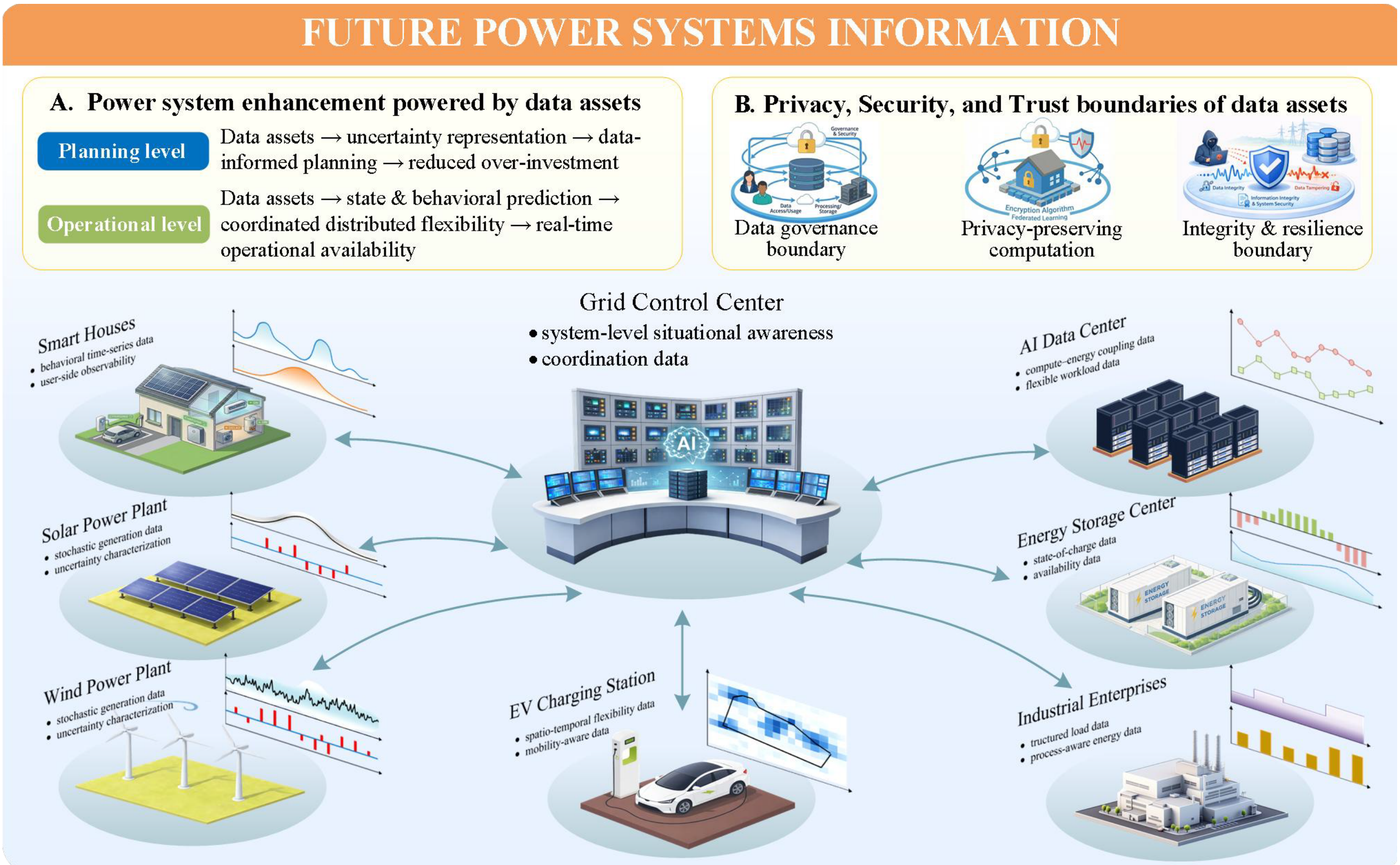

Figure 1. Conceptual framework of power data as a production factor in future power systems

SYSTEM ENHANCEMENT POWERED BY DATA ASSETS

By alleviating cognitive scarcity, data assets unlock latent value across the modern power system, shifting the operational paradigm from hardware-centric to information-centric operation, as partly illustrated in Figure 1B.

Reducing physical investment with data assets. At the planning level, data assets reshape decision-making by changing how uncertainty is represented and managed. When high-resolution historical, operational, and behavioral data are treated as data assets, uncertainty can be decomposed into identifiable patterns and statistically bounded risks. This enables planners to move from static, margin-based design toward probabilistic and scenario-aware planning methods. As a result, planning decisions can shift from over-investment toward targeted, data-informed investment, allowing conservative capacity margins and structural redundancy used to manage uncertainty to be partially reduced through improved information.

Activating operational flexibility through data assets. At the operational level, the primary limitation of highly distributed power systems lies not in the absence of flexibility, but in the difficulty of coordinating decentralized resources at scale. Although DERs and user-side resources are physically available, their utilization depends on timely state perception and behavioral prediction. Data assets support system operation by bringing together heterogeneous and distributed data streams into a clear and actionable representation of system conditions, allowing decentralized resources that were previously fragmented to be quantified and coordinated for real-time balancing and congestion management. In this way, data assets transform distributed flexibility from a passive and uncertain presence into a predictable and utilizable resource that can be reliably mobilized at scale.

PRIVACY, SECURITY, AND TRUST BOUNDARIES OF DATA ASSETS

The transition to a data-asset-driven paradigm depends not on technical feasibility alone, but on the ability to use data safely within clear trust and security boundaries. As illustrated in Figure 1C, these boundaries define the key system conditions for data utilization.

Data governance among entities. The unlocking of power data as a production factor is fundamentally limited by a "trust boundary" that exists between consumers, utilities, and third-party aggregators. Unlike physical assets, data assets lose their value if their ownership and usage rights remain ambiguous. Without clear rules governing data ownership, access, and benefit sharing, participants tend to withhold information rather than share it, causing the logic of data as a production factor to break down.

Privacy-preserving on the user-side. High-resolution power data is essential for future power system operation, yet it exposes sensitive patterns of private life, creating a tension between observability and digital sovereignty.[7] To address this, the system must move from centralized data collection toward privacy-preserving computing frameworks. By utilizing technologies such as federated learning and differential privacy, useful information can be extracted at the edge without the raw data ever leaving the user's premises, ensuring that privacy is a functional constraint rather than a barrier to the acquisition of data assets.

Information integrity and system security. By elevating data from an auxiliary signal to a critical production factor, the system's physical stability becomes inextricably linked to its informational integrity. A data-driven network is uniquely vulnerable to data poisoning and signal manipulation, where tampered information can lead to a chain of physical failures.[8] In this paradigm, security is no longer a secondary IT concern but a core component of power system reliability. Grid resilience must include the ability to remain stable even when some information is incorrect or distorted.

TOWARD DATA-CENTRIC POWER SYSTEMS

In the future, power systems should be understood not merely as physical networks with digital support, but as data-centric systems in which data assets increasingly shape system architecture, value creation, and long-term evolution.

Data-centric system design. Traditionally, grid infrastructure has been designed around security constraints, with data introduced as an auxiliary function. A data-centric power system shifts this logic by considering information requirements and physical constraints at the design stage. This implies the coordinated design of physical and digital layers, where hardware, such as smart inverters and transformers, is selected not only for power conversion, but also for sensing resolution and control responsiveness.

Valuation and pricing of data assets. Treating data as a production factor requires consistent principles for data valuation and pricing. Beyond basic data access fees, this involves recognizing the contribution of data to system operation and decision-making. By assessing how specific data assets improve system reliability, flexibility utilization, or cost efficiency, the value of power data can be quantified according to its marginal contribution to system performance, for example through value-of-information-based evaluation.[9] Such valuation and pricing methods can provide economic incentives for decentralized data holders and encourage higher-quality data sharing across multi-agent systems.

Data-enabled autonomous evolution. Rather than relying on fixed rules and operating assumptions, data-centric power systems update planning models, coordination strategies, and control actions based on observed system data. In this sense, data assets support not only adaptive operation, but a form of autonomous system evolution that enhances reliability under uncertainty, as well as changing resource and network conditions.

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AUTHOR CONTRIBUTIONS

Lun Xu: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Visualization, Writing original draft. Haitao Liu: Conceptualization, Resources, Funding acquisition, Supervision, Writing - review & editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.