

# Smart Grid Origins, Definitions, Technologies, and Emerging Trends: A Power Community Perspective

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**Abstract**—This paper captures an engaging—and at times heated—Power-Globe (PG) discussion of evolving definitions of smart grid technologies. The exchange took place between December 2024 and January 2025. The primary objective of this paper is to clarify some of the ambiguities surrounding the

term “smart grid” over the past two decades, as highlighted in the spirited PG debate. “Smart grid” has sometimes been advocated as a panacea to resolve the tension between competing objectives for the provision of electricity (specifically, making it reliable, clean, and affordable). This paper examines the term “smart grid” in terms of raw technical functionalities, applications, and use cases, some of which may get closer than others to meeting the aspirational promises. While smart technology should expand our menu of options, it will not absolve us of the need to make hard decisions.

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This work represents an extemporaneous exchange of debates that took place between December 2024 and January 2025. The list of authors includes the 23 members of the community who were most actively engaged in the editorial review.

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**Index Terms**—Smart grid, power system, definition, functionality, application, use case.

## I. INTRODUCTION

THE concept of “smart grid” has been widely advocated to describe a set of transformative solutions for modern power systems. However, despite the ubiquity of the term in operation, policy, and industry discourse, the precise definition of a “smart grid” remains ambiguous, with interpretations varying across technical, regulatory, and market-driven perspectives.

This paper was motivated by a lively Power-Globe (PG) debate, which reflected ongoing concerns and differing viewpoints regarding what constitutes a “smart grid”. With over 8300 subscribers worldwide, the PG e-mail forum (created by G. T. Heydt during his tenure at the National Science Foundation) includes academic researchers, teachers, students, industry professionals, and interested observers from diverse fields such as electric grid planning, engineering, operations, economics, and policy.

The debate emerged organically from an e-mail sent by one of the group members with the subject line: “Definitions of Smart Grids a Decade Ago—What Has Changed?” The ensuing discussion thread reflected a wide range of perspectives we aim to capture in this paper. It also highlighted the potential and limitations of smart technologies in mitigating existing power system constraints, emphasizing that while such advancements expand the range of solutions available, they do not eliminate the fundamental trade-offs that must be managed.

Accordingly, the objective of this paper is to examine the term “smart grid” from a technical perspective, focusing on its core functionalities rather than its aspirational promises.



By dissecting practical applications and constraints of smart grid technologies, this paper aims to contribute to a more nuanced understanding that can better inform policymakers, industry stakeholders, and the broader public.

Some key topics that generated discussion and even strong disagreements are the following:

- 1) Are “smart grid” definitions just vague buzzwords, or do they refer to real achievable things?
- 2) Have the objectives established for the “smart grid” been accomplished, and to what extent?
- 3) Have metrics and parameters been correctly selected and verified to validate conclusions?
- 4) Are the definitions and views from different sectors too fragmented for a common understanding?
- 5) To what extent has the energy trilemma of sustainable, cheap, and reliable electricity been solved, and what is the origin of discrepancies in performance?

## II. HISTORICAL CONTEXT FOR ELECTRIC GRID DESIGN AND OPERATIONAL PRACTICES

Power systems originated in the 1880s as localized, vertically integrated systems with generation, delivery infrastructure, and load designed and built by single companies. Isolated systems in major cities became interconnected to improve their load factor and to share generation reserves between areas, made possible by increasingly higher-voltage transmission and buoyed by economies of scale of increasingly efficient steam turbines.

Key advances in the early 1900s included the development of protective relays and electromechanical controls. By necessity, power systems were designed to be operable and robust with the minimal reliance on telecommunications. Crucially, system-wide supply and demand balance could be maintained using only locally measured variables.

Regulatory frameworks were established as investor-owned utilities emerged as major players. Guided by varying political and economic approaches across different countries, access to electricity eventually extended throughout the 20<sup>th</sup> century from urban centers to rural areas inherently more expensive and less profitable to serve.

The post-World War II period saw significant grid expansion and reliability improvements in industrialized nations, driven by rapid economic growth, rising electricity demand, and increasing societal dependence on electricity. Relying primarily on coal-fired, oil-based, hydroelectric, and nuclear power plants, electric grids evolved from fragmented local systems into highly interconnected national networks with centralized control.

Starting around 1973, vigorous growth in capacity gave way to other transformations of electric grid operations in response to increased volatility of oil prices encouraging shifts to other fuel types (see Fig. 1 from <https://visualizingenergy.org/world-electricity-generation-since-1900>), exhaustion of ever-improving economies of scale, and an increasing emphasis on sustainability. This era marked the emergence of early digital computing in power system analysis and planning, laying the groundwork for more information-intensive grid management technologies. The rise of solid-state electronics

revolutionized measurement, control, and communication, with the tools such as supervisory control and data acquisition (SCADA) systems that allow digital and remote monitoring of large-scale networks. Soon afterwards, the energy management system (EMS), with its associated suite of applications (state estimation,  $N-1$  security assessment, preventive, corrective, and optimal control, forecasting, etc.), became the cornerstone for the reliable operation of power systems, almost three decades before the “smart grid” notion was coined.

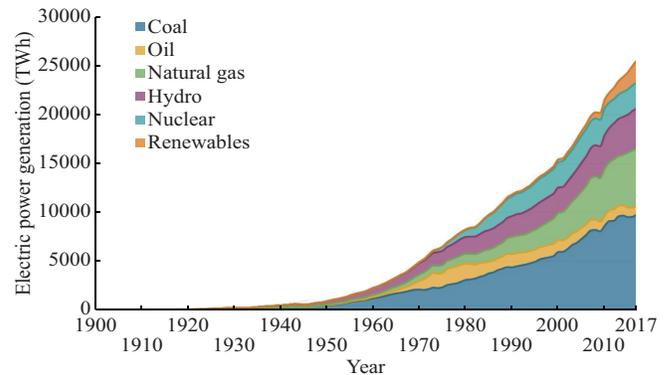


Fig. 1. Historical data depicting world electric power generation by fuel type (1900-2017).

The integration of renewable energy sources such as wind and solar also accelerated dramatically since 2000, supported by advancements in power electronics as well as energy storage and demand-side management. Meanwhile, the liberalization and deregulation of electricity markets in many regions around the turn of the millennium introduced new operational and economic dynamics, with increased competition and deployment of decentralized energy resources.

Until around the late 1990s, the electric grid was almost exclusively a one-way delivery system with centralized control. While utilities adopted SCADA/EMS systems for monitoring and control, these lacked real-time intelligence, adaptability, and automated recovery mechanisms. Large-scale blackouts exposed the vulnerabilities of a growing but rigid and aging power infrastructure.

Technological responses to these challenges included real-time data analytics, automated control systems, and distributed generation, which have seen different degrees of adoption across the industry. Most recently, new analytical tools such as artificial intelligence (AI), machine learning, and blockchain technology have been introduced to reshape grid operations with applications such as predictive maintenance, cybersecurity enhancements, and decentralized energy trading. The transition toward electrification of transport and digitalization is further reshaping demand patterns and grid flexibility as of the 2010s, with many voices calling for more resilient and adaptive energy systems.

Although engineers have been steadily working to improve power systems since their inception, it was from circa the late 1990s that information as such became the pivotal aspect for their evolution. Consider that electric grids pre-date computers, pocket calculators, and even telephone infra-

structure. To be tractable by pencil and slide rule, their design, analysis, and operation had to be based on many simplifying assumptions, along with generous overdesign to accommodate margins of uncertainty. Only recently has it been possible to contemplate a profoundly more detailed, yet comprehensive view of the largest technical systems ever built by humans.

The term “smart grid” emerged in public technical documents at the end of 1997 and was pioneered among other individuals by Dr. M. Amin, while he was at Electric Power Research Institute (EPRI), USA. This vision encompassed the integration of sensing, communication, control, automation, and cybersecurity across the entire energy system—from fuel source and generation to transmission, distribution, and end-use. The initiative developed several enabling technologies, including fast look-ahead modeling and simulation, self-healing networks, wide-area situational awareness with actionable intelligence via phasor measurement units (PMUs), fast state and topology estimation, reinforcement learning, and adaptive, automated control systems based on AI. These breakthroughs aimed to transform the grid from a reactive system into a predictive adaptive infrastructure.

A bibliometric analysis of use of the term “smart grid” in the context of “electric grid” from 1998 to 2024 is presented in Fig. 2 (constructed by Scopus).

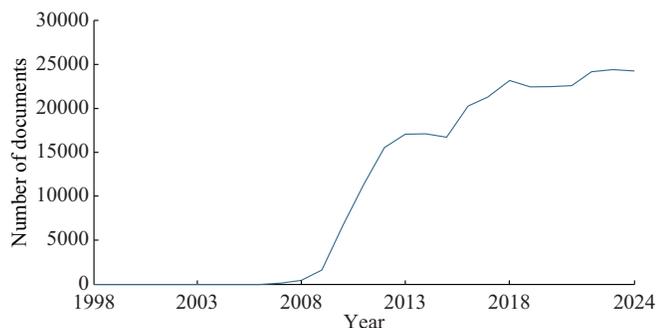


Fig. 2. Number of published documents featuring “smart grid” per year from 1998 to 2024.

### III. SMART GRID DEFINITIONS

The PG debate offered many possible definitions of “smart grids”. The most-cited definition was from the U.S. Energy Independence and Security Act (EISA) of 2007, which informally expressed this definition by means of application examples and policy objectives as follows:

- 1) Increased use of digital information and control technology to improve reliability, security, and efficiency of distribution grids.
- 2) Dynamic optimization of grid operations and resources, with full cybersecurity.
- 3) Deployment and integration of distributed resources and generation, including renewable energy sources.
- 4) Development and incorporation of demand response, demand-side resources, and energy-efficiency resources.
- 5) Deployment of “smart” technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering,

communications concerning grid operations and status, and distribution automation.

- 6) Integration of “smart” appliances and consumer devices.
- 7) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric vehicles (EVs) and hybrid EVs, and thermal-storage air conditioning.
- 8) Provision to consumers of timely information and control options.
- 9) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.
- 10) Identification and lowering of unreasonable or unnecessary barriers to the adoption of smart grid technologies, practices, and services.

One PG debate participant summarized this definition as “increased use of digital information technology to improve reliability, security, and efficiency of electric grid operations”.

The European Technology Platform SmartGrids, created in 2005, defined the smart grid as “a electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers, and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies”.

A 2011 U.S. Department of Energy document titled “What the Smart Grid Means to Americans” epitomized the aspirations in its subtitle: “The Smart Grid will save us energy, protect consumers, safeguard our environment and ultimately save money for all Americans.” Specifically, this report envisioned that a smart grid would: “enable active participation by consumers; optimize asset utilization and efficient operation; anticipate and respond to system disturbances; accommodate all generations and storage options; provide power quality for the digital economy; enable new products, markets, and services; and operate resiliently against attacks and natural disasters”.

PG debate participants expressed strong skepticism as to whether, nearly a quarter century later, these aspirations have materialized: “We were promised a revolution, and what we got (for the most part) were automated meter reads and remote connects/disconnects.” The discussion reflected significant disagreement regarding the extent to which the various objectives, visions, and implementations had been accomplished. Specifically, multiple participants agreed that there has been overpromise, although many also believed the high-level objectives remain valid.

More profoundly, there was skepticism about the usefulness of attempting to converge to a single coherent definition: “Every user of the term has their own individual understanding or interpretation and definition of the term according to the local needs and requirements. The meaning of the term smart grid varies according to the system requirements and conditions of each individual country.”

One participant pointed out that “smart grid” is a target concept. Systems will be in a diversity of degrees in assimilating the concept, so there is no system in a pure “smart”

state. Consistent with this view, another offered a simple yet comprehensive definition: “A smart grid is an electric grid that affords visibility and control at higher resolution in space and time.”

A short informal survey among PG debate participants asked which term related to the modernization of electric grids they considered is the most adequate. As shown in Fig. 3, the term “smart grid” continues to be the most popular.

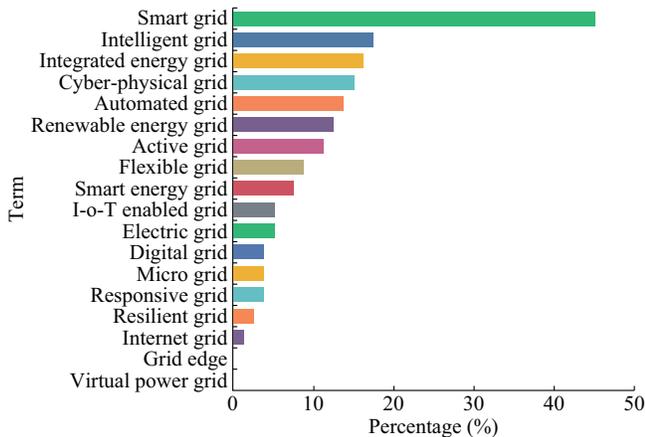


Fig. 3. PG participant survey results for preferred term to capture grid modernization.

#### IV. KEY QUESTIONS ARISING FROM PG DEBATE

As seen in Section III, the PG debate regarding the meaning of “smart grid” has raised the following important considerations:

- 1) Is “smart grid” the most appropriate term?
- 2) Are the promised features functioning as intended?
- 3) Has the public understanding of the term improved?
- 4) Has the integration of digital information and control technologies improved the reliability, security, and efficiency of electric grid operations?
- 5) Is “smart grid” a product, a service, or a framework?
- 6) How is it applied—does it exist as a single entity or as multiple interrelated components?

From the end-user standpoint, several practical questions emerged, such as:

- 1) Have “smart grid” developments reduced electricity costs, improved reliability, and increased resilience and flexibility?
- 2) Have energy storage solutions or advancements in electric mobility provided tangible benefits for participants in power systems?

The following additional questions were largely drawn from the PG open discussions:

- 1) What is the essence of an electric grid?
- 2) Is an electric grid just a physical network, or does it include other aspects such as the socio-technical systems and human interactions it supports?
- 3) Is an electric grid a unified entity, or is it an aggregation of interconnected but separately managed and operated systems?
- 4) What are the boundaries of an electric grid? Are they physical or conceptual? And by what means are these bound-

aries set and maintained?

5) How has the energy transition affected the reality and understanding of electric grids? Have changes in electric grids made them more dependent on digitalization, AI, and machine learning?

6) Is the primary purpose of an electric grid to ensure a flexible supply of electric power to meet customer power demands and grid reliability requirements, or does its role extend to enabling larger social goals such as a cleaner environment, societal progress, and societal connectivity?

7) How can utilities develop sustainable business models within the smart grid ecosystem?

8) What policies are needed to standardize “smart grid” technologies and ensure compatibility across regions?

9) How can regulators balance innovation with consumer protection and grid stability?

#### V. TECHNOLOGIES AND APPLICATIONS

“Smart grid” technologies include, on the one hand, enabling technologies such as digital communications, advanced metering infrastructure (AMI), controllability of devices, blockchain transactions, and big data processing capability for grid analytics. On the other hand, they also include technologies such as EVs, cryptocurrency mining, and data processing whose increasing use imposes new demands on electric grid performance. For each category, below, we briefly outline some of the major needs and opportunities (without claiming to be exhaustive).

##### A. Load

Modern electrical loads are evolving, driven by rapid advancements in power electronics that enable more responsive and flexible power demands and supplies, and by large increases in power usage due to EVs, electrolyzers, data centers, cryptocurrency mining, and switches from gas to electric heating. Some of this growing power usage, such as for EVs and electric heating, also presents opportunities for “smart grid” technologies. Because it is both large and intrinsically flexible, it can be coordinated with renewable supply to mitigate costs and carbon emissions.

##### B. Generation and Storage

Solar and wind generation as well as batteries present themselves to AC grids as inverter-based resources (IBRs) with different physics from traditional rotating machines. IBRs lack inherent inertia. However, using power electronics, IBRs can be controlled to provide synthetic inertia and fast frequency response. These controlled IBRs can help ensure voltage stability as well as angle or frequency stability.

Supply fluctuations due to resource variability can be mitigated to some extent by improved forecasting and by increased flexibility of grid operations. Energy storage systems (ESSs) such as batteries, pumped hydro, and flywheels are key to managing renewable variability. PG debate participants expressed support for the view that “smart grid” approaches to integrating storage with IBRs and rotating machines will be key for the future sustainability and reliability of grid operations.

### C. Infrastructure Hardware

Modern power systems rely on advanced infrastructure hardware to ensure efficient, stable, and reliable electricity transmission and distribution. Technologies such as high-voltage direct current (HVDC) systems play a crucial role in long-distance power transfer with minimal losses, especially for interconnecting asynchronous grids and integrating large-scale renewable energy sources. Power electronic converters enable the seamless transition between AC and DC power, facilitating the operation of HVDC systems and renewable energy integration.

Additionally, flexible AC transmission systems (FACTSs) can improve power flow control, voltage stability, and overall grid efficiency by dynamically adjusting transmission control parameters. Innovations such as superconducting transmission lines could further reduce losses and increase capacity, if economically viable.

Effective voltage control mechanisms are essential for maintaining grid stability, particularly with increasing IBR penetration. Robust protection systems safeguard electric grids against faults and disturbances, ensuring quick fault detection and isolation. Advanced sensor integration enhances real-time monitoring, enabling predictive maintenance and smarter grid management. Together, these technologies are envisioned to serve as the backbone of a resilient, efficient, and future-ready power infrastructure.

### D. Software and Communications

The modernization of power systems in the 21<sup>st</sup> century relies heavily on digital communication technologies that enable seamless data exchange across locations and applications. PG debate participants emphasized the crucial role of data availability “in terms of issues, volumes, and sampling frequencies that were not very clearly imagined before”.

Advanced metering and sensor measurements can provide real-time insights into power usage, system performance, and disturbances, supporting more efficient grid management. Modern control rooms integrate these data streams, enhancing operators’ ability to monitor, analyze, and respond to grid conditions in real time. Geographic information systems (GISs) provide the basis for locational cross-referencing of data in diverse planning and operational applications. Recently, the U.S. Department of Energy (DOE) has coined the term “grid-enhancing technologies”, which embrace new devices, sensors, and software intended to better exploit existing transmission and distribution (T&D) assets such as FACTS, dynamic line rating, and demand response.

Another use of digital technology involves facilitating economic transactions between and among different participants in grid operations, including new types of participants (e.g., aggregators of distributed energy resources or controllable loads) as well as traditional utilities and consumers.

The large amount of data potentially generated lends itself to AI-driven analytics that can enable predictive maintenance, demand forecasting, nowcasting, and operational optimization. Additionally, the blockchain technology has been advocated as a tool for securing transactions, improving transparency, and enabling decentralized energy trading.

As digitalization increases, cybersecurity becomes a critical concern. Cyber threats grow with both the sophistication of adversaries and the increasing attack surface. Beyond standard techniques for cyber-protection, grid-specific approaches include intrusion detection, anomaly prediction, and AI-based security monitoring.

### E. Sample Smart Grid Use Cases

“Smart grid” applications vary across countries, companies, locales, and voltage levels; they are too numerous to list exhaustively here. Three examples serve to illustrate the interdependence among technical components necessary to realize some of the more ambitious application objectives.

AMI or “smart metering” provided early support for real-time energy consumption monitoring and demand-side management, and a basis for faster automated demand response (ADR). Leveraging AMI data for operational purposes such as voltage management requires additional integration between utility departments and software.

Preventive responses to disturbances leverage predictive analytics and real-time data to mitigate potential failures before they occur, in the interest of improving system reliability and resiliency. Preventive responses depend on detailed and timely data delivered from diverse sources (e.g., the status of grid assets and weather conditions), validated algorithms to crunch these data, and devices that can be quickly actuated (e.g., isolating a circuit section or initiating demand response).

An important use case is to accelerate recovery from disruptions. The ultimate vision of self-healing networks implies that every step of the way is automated, from fault detection and identification to the use of algorithms for optimizing reconfiguration strategies and actuators for performing the reconfiguration almost instantly, while honoring the inherent hazards of field switching operations.

## VI. NEW ARCHITECTURES AND FRAMEWORKS

Beyond the individual components and participants, the structure or connectivity of an electric grid as a whole is of interest. As one PG debate participant pointed out, the paradigm change hinges on a massive parallel and bi-directional communication system, along with the presence of distributed intelligence—far exceeding the specifications of typical hardware and infrastructure in place today. For example, few distribution grid assets today are capable of identifying their neighbors or their location on a circuit. Increasing controllability, communication, and state awareness introduces new opportunities for system-wide coordination across all time and length scales. A key to designing a decentralized architecture is designing the control or price signals required for an architecture to deliver good whole-system outcomes. The space of possibilities can be characterized in terms of four dimensions as follows:

- 1) Available input data from sensors and communication infrastructures ranging across voltage and current sensors, detailed waveform measurements, and economic information such as real-time prices. All these come on a variety of timescales.

2) Available actuators, i.e., devices subject to intentional control, which now include demand-side distributed generation, smart appliances (e.g., water heaters), and storage as well as high-voltage transmission-level components. Combined with demand-side connectivity such as Wi-Fi and Bluetooth, this extends controllability and coordination to lower voltage levels.

3) Two-way networking and coordination between actuators and information sources essential for information processes (e.g., edge computing), and for design architectures intended to facilitate coordination among different parties. This two-way connectivity is foundational for various degrees of decentralized and distributed control.

4) Control logic, i.e., the collection of algorithms used for decision-making, which includes specification of the objectives to be optimized. New opportunities are emerging with the application of machine learning, AI, and associated computational techniques. While traditional approaches focus on achieving global optimality through centrally managed algorithms, alternative models involve decentralized or distributed decision-making. These may lead to sub-optimal results but offer greater robustness against failures, mistaken assumptions, and the challenges of managing complex systems.

These possibilities together enable a vast range of possible designs and functionalities, and the appropriate choices of these designs and functionalities will be highly situation-dependent. It also bears repeating that the envisioned deployments of these state-of-the-art digital technologies for electric grids are still far from the practical reality on the ground at many utilities.

The combination of new technologies for measurement, communication, and computation represents an entirely different paradigm from the earlier digital computing of the market liberalization era, never mind the pre-digital computing era in which interconnected systems originally developed. Thus, “smart grid” capabilities introduce countless new avenues for system coordination as well as different visions for their best and most economical use.

Arguably, the operative question for the attainment of “smarter grid operations” has now changed from “what can we do, given technical constraints” to “what do we want to do”. There is of course a need to balance costs, benefits, and uncertainties, including the risk profile of innovations, and to identify and consider which parties carry (or should carry) specific risks, costs, and benefits—but these are choices, not givens.

The definition of a “smart grid” based on detailed observability and controllability considerations might suggest that operating at greater granularity is “smarter” and thus “better”. However, new technologies can also introduce new failure modes, ranging from cyber security risks to the need for the system to fail gracefully after faults, which must be considered in system design.

Consequently, there are strategic decisions and trade-offs to be made, which will vary depending on historical, geographic, regulatory, and political context. From this perspective, smart grids are ultimately constrained by the smartness of the humans designing them.

## VII. POLICY AND REGULATION

Policy and regulatory frameworks play a critical role in shaping the evolution of power systems. The physical goals are to ensure grid security, reliability, resiliency, power quality, and environmental compatibility. Economic design and operational goals include incentive alignment, resource adequacy, efficiency, fairness, conceptual coherency and transparency, minimal administrative intervention, internalization of externalities, and minimal transitional disruption. In addition, most would also agree that the access to electric power should be affordable and equitable.

Physical and economic goals can be translated into performance metrics for “smart grids”, although quantifying them can be difficult and requires some comparative baseline. It is even more difficult to articulate trade-offs between and among objectives along these different dimensions of performance. Different countries and states employ different frameworks for implementing some combination of markets and governmental regulation toward these ends. These frameworks face significant challenges that transcend national, regional, or local jurisdictions.

For example, policymakers must craft regulations that foster continuing innovation without exposing power system participants to undue risk. Another major issue is the harmonization of regulatory standards across jurisdictions that are physically coupled within the same interconnection. The absence of unified policies can lead to inefficiencies, price volatility, and challenges in integrating clean energy sources effectively.

Equity and affordability remain central concerns. Policies should address the social and economic impact of regulatory decisions, ensuring that vulnerable communities are not disproportionately burdened by energy transitions, while still incentivizing investment in cleaner and more resilient power infrastructure.

Data governance and digitalization also present new regulatory frontiers for power systems. The increasing use of smart meters, AI-driven grid management, and decentralized electric power markets raises questions about privacy, cybersecurity, and market fairness—demanding policies that balance technological potential with participant protection, in the context of enabling use of data for more economic and resilient grid operations.

Finally, “smart grids” and their rapidly evolving technical capabilities, including the transition to new resources and participation models, bring to the fore several challenges in the management of electric grids as coupled physical and economic systems. A danger is that operational difficulties can continue to arise for grid-supported electric power markets when conceptually problematic physical or economic presumptions remain imbedded in core operational rules.

For example, the core design of current grid-supported U.S. electric power markets includes the presumption that grid-delivered energy  $E(n, T)$  conditional on grid delivery location  $n$  and delivery period  $T$  is a standardized commodity with perfectly substitutable units (MWh) that ought to be transacted at a uniform per-unit price  $LMP(n, T)$  (\$/MWh) equating marginal benefit (\$/MWh) to marginal cost (\$/MWh). However,

the MWh unit depends essentially on the passage of time, and multiple distinct dispatchable sequences of power (MW) injections and/or withdrawals will often be available to a system operator to achieve the grid-delivery of any “next” MWh at  $n$  during  $T$ . Typically, power producers, power users, and the system operator will not be indifferent regarding which power sequence is dispatched to achieve this “next unit” delivery; for example, they might care about the ramp-rate (MW/min) profile of this dispatched sequence at  $n$  during  $T$ . Consequently, “marginal benefit” and “marginal cost” are not well-defined concepts for grid-delivered energy  $E(n, T)$ .

Members of the PG e-mail forum represent a broad spectrum of views on specific policy solutions. However, most would presumably agree there is a need to develop conceptually-coherent policy and regulatory frameworks for power systems able to adapt rapidly and effectively to the evolving landscape for these systems. This development will require careful collaboration among governments, industry stakeholders, and research institutions, and between different research and professional disciplines.

### VIII. LOOKING FORWARD

The evolution of power systems is no longer driven solely by advances in hardware or incremental upgrades to existing infrastructures. What lies ahead is the deliberate design of architectures, control frameworks, and regulatory systems that integrate digital intelligence, bi-directional communication, and distributed decision-making across all levels of the electric grid. The challenge is not simply what can be done technologically, but what societies, utilities, and regulators choose to prioritize.

Future developments will depend on aligning four key dimensions—data availability, controllable assets, connectivity, and control logic—with broader economic and social objectives. This alignment will require balancing the promise of higher efficiency, resilience, and renewable energy integration against emerging vulnerabilities such as cybersecurity risks, cascading failure modes, and social inequities. The “smartness” of future electric grids will therefore be measured not only by their digital sophistication but also by the quality of the institutional, human, and ethical decisions that shape them.

For the next generation of researchers, this means shifting attention from questions of capability (“What can be built?”) to questions of purpose and impact (“What should be built, and why?”). Instead of simply developing ever more advanced control algorithms, the more urgent challenge is to determine which functions are most valuable for resilience, equity, and sustainability, and how these functions can be embedded in robust, scalable architectures. Key directions include:

1) Prioritizing resilience over optimality: investigating architectures and control logics that can absorb shocks and failures gracefully, rather than only optimizing steady-state performance.

2) Integrating social and technical dimensions: framing research questions that explicitly address equity, affordability,

and community impact, alongside engineering efficiency.

3) Clarifying trade-offs: developing methods to evaluate not just what is possible with digital and distributed intelligence, but what is advisable given risks, costs, and institutional constraints.

4) Embedding adaptability: focusing on designs and policies that allow systems to evolve as technologies, policies, and social expectations shift.

Looking forward, the integration of grid-forming inverters, advanced storage, and AI-enabled coordination presents unprecedented opportunities for decentralization and flexibility. At the same time, these technologies raise questions about who carries risk, how costs and benefits are shared, and what trade-offs should guide design and operation. Effective policies and regulations will need to adapt quickly, providing stability while fostering innovation, ensuring affordability, and protecting vulnerable communities.

Ultimately, the trajectory of power systems will hinge on more than technical breakthroughs. It will depend on the ability of researchers, practitioners, and policymakers to ask the right questions, balancing robustness, adaptability, and justice, so that the next generation of electric grids is not only smarter, but also more resilient and fair.

### IX. CONCLUSION

The PG debate highlighted the urgent need for deeper sustained dialogue among experts across all facets of the electric power sector, including generation, transmission, distribution, end-use applications, planning, operations, economics, market regulation, and more. While meaningful progress has been made in modernizing electric grids, the road ahead requires not only continued innovation but also bold strategic investments and cross-sector collaboration. Only through such coordinated efforts can we bridge the gap between visionary goals and actionable system-wide transformation.

To what extent has the tri-part goal for power systems—the achievement of sustainable, affordable, and reliable power delivery—been resolved, and what accounts for remaining discrepancies in performance? This key question poses a critical ongoing challenge as we continue to observe the evolution and uneven implementation of smart grid technologies.

Additionally, the ongoing debate over terminology reflects the evolving and multifaceted nature of key concepts in the field. While such discussions are a healthy sign of intellectual engagement, certain disagreements remain unsettled, signaling the need for continued exploration and consensus-building.

### X. EPILOGUE

The authors of this paper wish to express their appreciation for the PG e-mail forum and its significant contributions to the power engineering sector. None of us can claim complete impartiality, as we all speak from some position of expertise. The authors have aimed to do justice to the diverse views expressed in this discussion, and look forward to a continuing meaningful, Socratic dialogue: agreeing to disagree.

Special thanks to authors who participated in the general editing of this paper. They helped to reconcile the, at times, seemingly opposing views from leading experts, doing so without generating unnecessary controversy, while faithfully reflecting the depth and substance of the informed discussions that took place.

## XI. BIBLIOGRAPHY AND FURTHER READING

Since the text was primarily compiled from online discussions and offline comments contributed by the debaters and authors, no references have been explicitly cited in the text. However, a bibliography and suggested further reading, related to the topics discussed, is provided and categorized as follows:

- 1) Historical evolution of the electric grid: [1]-[5].
- 2) Deregulation, markets, and policy: [6]-[12].
- 3) Power system engineering and control: [13]-[18].
- 4) Energy policy, infrastructure, and resilience: [19]-[21].
- 5) Smart grid, communication, and cybersecurity: [22]-[29].

## REFERENCES

- [1] J. Cohn, *The Grid: Biography of an American Technology*. Cambridge: MIT Press, 2017.
- [2] P. F. Schewe, *The Grid: A Journey Through the Heart of Our Electrified World*. Washington, D.C.: Joseph Henry Press, 2007.
- [3] G. Bakke, *The Grid: The Fraying Wires Between Americans and Our Energy Future*. New York: Bloomsbury USA, 2016.
- [4] R. Hirsh, *Power Loss: The Origins of Deregulation and Restructuring in the American Electric Utility System*. Cambridge: MIT Press, 1999.
- [5] R. A. Dent, *The Foundations of Electricity: 125 Years of Electrification*. New York: IEEE Power & Energy Society, 2016.
- [6] P. L. Joskow and R. Schmalensee, *Markets for Power: An Analysis of Electrical Utility Deregulation*. Cambridge: MIT Press, 1983.
- [7] Federal Energy Regulatory Commission. (1996, May). Promoting wholesale competition through open access non-discriminatory transmission services by public utilities. [Online]. Available: <https://www.ferc.gov>
- [8] Federal Energy Regulatory Commission. (1999, Dec.). Regional transmission organizations. [Online]. Available: <https://www.ferc.gov>
- [9] J. Lin and F. H. Magnago, *Electricity Markets: Theories and Applications*. Hoboken: Wiley-IEEE Press, 2017.
- [10] M. Shahidehpour and M. Alomoush, *Restructured Electric Power Systems: Analysis of Electricity Markets with Equilibrium Models*. New York: Wiley-IEEE Press, 2001.
- [11] L. Tesfatsion, *Economics of Grid-supported Electric Power Markets: A Fundamental Reconsideration, Foundations and Trends in Electric Energy Systems 8:1*. Delft: NOW Publishers, 2024, pp. 1-123.
- [12] L. Tesfatsion, *A New Swing-contract Design for Wholesale Power Markets, IEEE Press Series on Power Engineering*. Hoboken: Wiley-IEEE Press, 2021, pp. 1-266.
- [13] P. Kundur, *Power System Stability and Control*. New York: McGraw-Hill, 1994.
- [14] B. Wollenberg and A. J. Wood, *Power Generation, Operation, and Control*, 3rd ed. Hoboken: Wiley-IEEE Press, 2013.
- [15] A. Mazer, *Electric Power Planning for Regulated and Deregulated Markets*. Hoboken: John Wiley & Sons, 2007.
- [16] J. Grainger and W. Stevenson, *Power System Analysis*. New York: McGraw-Hill, 1994.
- [17] J. Machowski, J. Bialek, and J. Bumby, *Power System Dynamics: Stability and Control*, 2nd ed. Hoboken: Wiley, 2008.
- [18] A. Abur and A. Gomez-Exposito, *Power System State Estimation: Theory and Implementation*. New York: CRC Press, 2004.
- [19] US Department of Energy. (2016, Nov.). Quadrennial energy review: energy transmission, storage, and distribution infrastructure. [Online]. Available: <https://www.energy.gov/sites/prod/files/2016/12/f34/QER%201.1%20Implementation%20Report%20Card.pdf#:~:text=The%20report%2C%20which%20examines%20transmission%2C%20storage%2C%20and%20distribution,Council%20and%20Office%20of%20Science%20and%20Technology%20Policy>
- [20] P. Fox-Penner, *Power After Carbon: Building a Clean, Resilient Grid*. Cambridge: Harvard University Press, 2020.
- [21] *DOE Technology Readiness Assessment Guide*, DOE G 413.3-4A, 2011.
- [22] K. Vu, M. M. Begovic, and D. Novosel, "Grids get smart protection and control," *IEEE Computer Applications in Power*, vol. 10, no. 4, pp. 40-44, Oct. 1997.
- [23] M. Shahidehpour and Y. Wang, *Communication and Control in Electric Power Systems: Applications of Emerging Technologies*. Hoboken: Wiley-IEEE Press, 2003.
- [24] J. Momoh, *Smart Grid: Fundamentals of Design and Analysis*. Hoboken: Wiley-IEEE Press, 2012.
- [25] S. M. Amin, "Smart grid: overview, issues and opportunities. Advances and challenges in sensing, modeling, simulation, optimization and control," *European Journal of Control*, vol. 17, no. 5, pp. 547-567, Sept. 2011.
- [26] M. Amin and B. Wollenberg, "Toward a smart grid," *IEEE Power and Energy Magazine*, vol. 3, no. 5, pp. 34-38, Sept./Oct. 2005.
- [27] M. Amin. (1998, Jan.). The self-healing grid: concepts and advancements. [Online]. Available: [https://massoud-amin.umn.edu/sites/massoud-amin.umn.edu/files/2020-03/cinsi\\_01-27-1998\\_rac.pdf](https://massoud-amin.umn.edu/sites/massoud-amin.umn.edu/files/2020-03/cinsi_01-27-1998_rac.pdf)
- [28] US Department of Energy. (2016, Dec.). Smart Grid Investment Grant Program Report. [Online]. Available: [https://www.energy.gov/sites/prod/files/2017/01/f34/Final%20SGIG%20Report%20-%202016-12-20\\_clean.pdf](https://www.energy.gov/sites/prod/files/2017/01/f34/Final%20SGIG%20Report%20-%202016-12-20_clean.pdf)
- [29] EC. (2022, Nov.). Smart grids in the European Union Report. [Online]. Available: [https://setis.ec.europa.eu/smart-grids-european-union\\_en](https://setis.ec.europa.eu/smart-grids-european-union_en)

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