An Architecture for the Digital Grid

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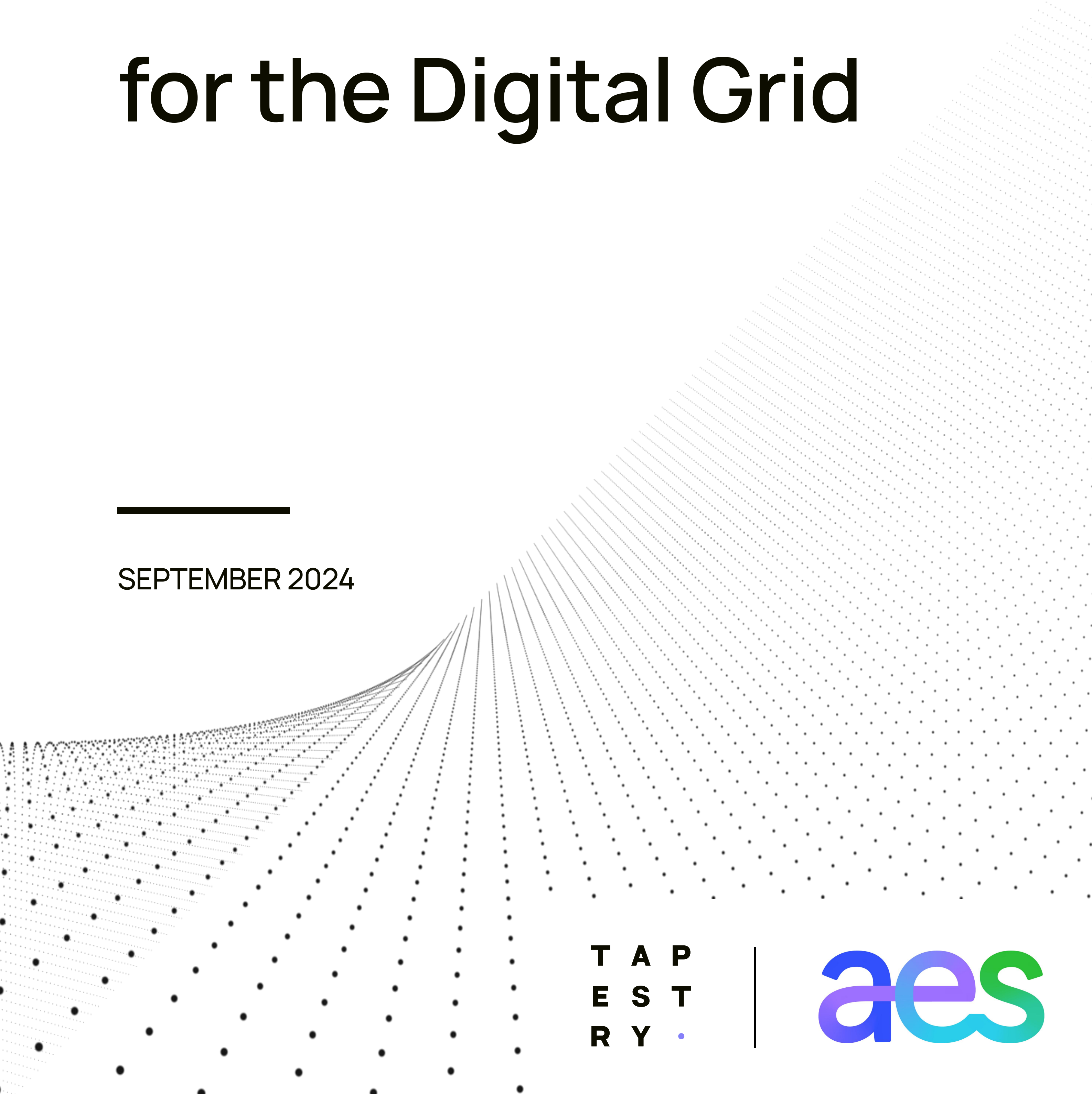

Executive Summary

The transformation of the power grid from analog to digital is inevitable and already underway. The increasing integration of digital energy assets allows for enhanced visualization and control, offering opportunities for improved intelligence, operations, planning and management. The shift to a digital grid requires collaboration and proactive planning to minimize potential disruptions. An accelerated yet orderly transition can unlock numerous benefits for stakeholders, including improved safety, reliability, affordability, equitable access, and resilience in the face of climate change.

Central to this transformation is the establishment of a widely accepted Digital Grid Architecture. This document proposes such an architecture, inspired by the Internet and divided into three categories: Structure, focusing on governing frameworks and market mechanisms; Interaction, focusing on open standards and software systems; and Infrastructure, focusing on the increasingly digital physical assets of the grid. We invite comments on this proposal, its evolution, and its benefits, to accelerate the development of a Digital Grid Architecture.

An Architecture for the Digital Grid

The transformation of the grid from an analog system into a digital system is underway and has momentum—it is not a matter of *if it will* change, but *how fast*. More and more digital energy assets are connected to the grid, whether as electrified consumer assets, sensors on lines, renewable inverter-based energy assets or any of the myriad other emerging smart assets. A digital energy asset is one where the keyfunctionality, control or coordination are digital. Inherently digital assets can be visualized and controlled at a level of precision that is not possible with analog resources. A digitally enabled grid presents an opportunity for unlimited change, including improved forecasting, enhanced collaboration and transformatively, the possibility of moving away from ensuring reliability through worst-case scenario planning and operations. Instead, a digital grid can use a system of standards and protocols to coordinate operations and ensure reliability across multiple time horizons. A digital grid is one where most of its key functionality, including its communications, control and coordination, are digital.

But unlike a switch that turns on or off electricity in our homes and businesses, changing the grid from its century-old analog form to a modern digital form will take time, investment and focused collaboration. A reactive approach will risk the safe, reliable and affordable grid to which we have become accustomed. Alternatively, an accelerated but orderly transformation will unlock benefits for stakeholders throughout the system — not only safety, reliability and affordability, but with equitable access and an opportunity to participate in benefits, including resilience in the face of climate change, and reduced emissions.

Key to the digital grid is defining a widely-accepted architecture that merges communications-based data architecture with the physical elements of the electric grid and will anticipate the evolving needs of the system through flexibility and openness. Despite considerable progress toward identifying the control structures, protocols, data formats and applications for individual digital technologies and components, there is still no widely adopted architecture that ensures reliable, safe and efficient interoperability of all digital grid elements in an increasingly distributed system. This paper puts forward a high-level draft architecture and its evolution to elicit feedback and encourage the near-term definition of such an architecture.

Numerous benefits will accrue to the energy system by embracing and accelerating a Digital Grid Architecture. A digital grid will be capable of understanding the evolving needs of the system and stakeholders and deliver flexible solutions to a dynamic system.

It will accommodate increasing grid complexity through distributed coordination; common and open data schema and protocols; and the ability to engage the numerous grid assets and participants to solve the needs of the system – including by absorbing stress that would otherwise diminish system performance.

These grid mechanisms will enhance transparency in information and enable broader participation in the grid. Through data-rich and AI-enabled changes to grid planning and operations, a more modern, cost effective and efficient grid will emerge. Reliability and security will be foundational operational building blocks. Ultimately, the digital grid will ensure that rapidly growing and evolving customer needs are met, and that the electricity-powered expectations of 21st century society are unlocked.

The Emerging Digital Grid

The electrical grid is evolving from a data-sparse and static analog system to an information-enriched and dynamic digital system – one where most of its key elements, as well as its communications and coordination, are digital. The current grid is filled with assets that are past their planned life, and we could spend $10 billion per year to simply like-for-like replace aging transmission lines without building anything new.[1] But we need new lines to meet increasing demand for energy and the integration of variable renewable assets.[2] The surging demand for energy — often renewable — from step-change loads like data centers and manufacturing accelerates the urgency of this transformation.[3] The electrification of vehicles, buildings and the assets within them will solidify the overall demand for new energy and the grid that delivers it.[4] Finally, these customer and commercial interests are supported by policy pushes from many relevant Federal and State entities.[5]

[1] The Brattle Group. Transmission Investment Needs and Challenges (June 2021) accessed at https://www.brattle.com/wp-content/uploads/2021/10/Transmission-Investment-Needs-and-Challenges.pdf. and The Brattle Group. Annual US Transmission Investments 1996-2023 (June 2024) accessed at https://www.brattle.com/insights-events/publications/annual-us-transmission-investments-1996-2023/.

[2] Jenkins, J.D., et al. Electricity Transmission is Key to Unlock the Full Potential of the Inflation Reduction Act, REPEAT Project (September 2022) accessed at https://repeatproject.org/docs/REPEAT_IRA_Transmission_2022-09-22.pdf.

[3] Crooks, Ed. Wood Mackenzie. Demand growth creates new challenges for the power industry (March 2024) accessed at https://www.woodmac.com/blogs/energy-pulse/demand-growth-creates-new-challenges-for-power-industry/.

[4] Hevia-Koch, P., et al. The clean energy economy demands massive integration investments now. (January 2024) accessed at https://www.iea.org/commentaries/the-clean-energy-economy-demands-massive-integration-investments-now and IRENA. Electrification with Renewables: Driving the transformation of energy services (2019) accessed at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/IRENA_RE-Electrification_SGCC_2019_preview.pdf.

[5] See, e.g., Rewiring America. Inflation Reduction Act fact sheets accessed at https://www.rewiringamerica.org/ira-fact-sheets and Department of Energy. New and Used Clean Vehicle Tax Credits accessed at https://www.energy.gov/energysaver/new-and-used-clean-vehicle-tax-credits and The White House. Fact Sheet regarding reshoring of manufacturing accessed at https://www.whitehouse.gov/briefing-room/statements-releases/2024/08/09/fact-sheet-two-years-after-the-chips-and-science-act-biden-%E2%81%A0harris-administration-celebrates-historic-achievements-in-bringing-semiconductor-supply-chains-home-creating-jobs-supporting-inn/ and Baker Tilly. What is the advanced manufacturing investment tax credit? accessed at https://www.bakertilly.com/insights/what-is-the-advanced-manufacturing-investment-tax-credit.

Technology will both enable and create a beneficial flywheel of incentives for grid and energy system transformation catalyzed by customer needs. These technologies include grid enhancing technologies, battery storage, virtual power plants and visualization and control platforms, which make the grid visible, flexible, efficient and capable of coordination.[6] They also include the diverse grid technologies that fundamentally rely on digital control and communication for their operation. These technologies, including smart meters, digital substations and transformers and EV charging infrastructure, as well as tools and systems such as DERMS, made up a $63 billion market in 2022.[7]

Power supply in the grid will change to be fundamentally digital as it becomes more renewable in response to customer demands, available technology and the numerous incentives aimed at decarbonization and climate resilience. The components of the digital grid will include numerous, distributed and diverse renewable generation assets (of various sizes, locations and types) and batteries, as well as inverters that need to be digitally programmed to provide grid stability.[8] The grid will accommodate two-way flow of electrons at scale and grid components that can and must be controlled and coordinated remotely, rapidly and with high precision.[9]

The scale of evolution needed to create a digital grid and respond to the referenced drivers of change requires proactive, head-on planning so we not only maintain a safe, reliable and affordable grid, but also maximize commercial and societal benefit—dragging our collective heels will only result in inefficiency and cost, limitations to economic growth and customer satisfaction and rigid methodologies for managing reliability in an increasingly dynamic ecosystem. In its worst form, an improperly planned future grid could lead to more frequent outages, higher costs for consumers and safety risks such as wildfires. Proactive plans will enable: (1) digital resources to maintain and enhance system reliability as an essential functionality; (2) coordinated flexibility at the distribution level; and (3) an open digital architecture that ensures reliability and flexibility while accelerating an orderly transition to the digital future.

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[6] Department of Energy. Pathways to Commercial Liftoff (April 2024) accessed at https://liftoff.energy.gov/innovative-grid-deployment/ and AES. Smarter use of the dynamic grid: Accessing transmission headroom through GETs deployment (April 2024) accessed at https://www.aes.com/sites/aes.com/files/2024-04/Smarter-Use-of-the-Dynamic-Grid-Whitepaper.pdf.

[7] IEA. Investment spending on electricity grids, 2015-2022 (2023) accessed at https://www.iea.org/data-and-statistics/charts/investment-spending-on-electricity-grids-2015-2022 License: CC BY 4.0. For additional context, $63 billion represented approximately 20% of all electrical grid spend in 2022.

[8] McKinsey. How grid operators can integrate the coming wave of renewable energy (February 2024) accessed at https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/how-grid-operators-can-integrate-the-coming-wave-of-renewable-energy.

[9] Boroyevich, D., et al. Intergrid: A Future Electronic Energy Network?, IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol 1, No 3 (September 2013) accessed at https://ieeexplore.ieee.org/abstract/document/6575114.

One clear step we can take toward this future energy system is to collaborate to define a Digital Grid Architecture, punctuated by clear standards and protocols and milestones marking the evolving path as the system transforms from analog-first to digital-first. This paper seeds some ideas of what an evolving Digital Grid Architecture might look like and its value to key stakeholder groups and the system more generally.

Our intention with this paper is not to be "right" or "exhaustive" about the details, but to spur discussion and collaborative action. We believe there is value to be captured for the ecosystem and negative externalities to be avoided if a coalition of ecosystem participants forms to tackle three next steps: (1) align around an architectural vision for the next generation grid; (2) identify the standards and protocols needed for reliable coordination of assets on the grid; and (3) develop and publish the standards and protocols for open use among grid participants. Each step will require certain expertise and leadership for success, and so a coalition of the willing is needed. This paper provides an initial framework for the architectural vision.

An Evolving Digital Grid Architecture

Before diving into a representation of the Digital Grid Architecture, it is helpful to describe what characterizes an analog, or "legacy," grid as compared to a digital, "transformed" grid. Essential characteristics of a legacy system are a preponderance of analog resources as well as processes that use identifiable, largely static criteria to plan and operate the grid and to send predictable quantities of power from large generation assets to load centers that have relatively consistent consumption profiles. In contrast, a digital grid is one where most of its key elements, as well as its control and coordination, are digital.[10] The sufficient presence of digital resources unlocks: (1) the ability to delegate decisions to smart assets throughout the grid and enable those assets through faster and distributed data processing and communication; (2) the material presence of resources with programmable rather than inherent grid stability capabilities; and (3) regulatory structures that recognize the potential for distributed resources to form a participatory, integrated and resilient grid.

The analog system does not become digital overnight—there is a period of transformation during which a credible digital system emerges and then scales in application. During the "emerging" time frame, early adopters of digital technology demonstrate functionality and corresponding value to other system participants. As digital assets become more widespread – and processes and people recognize and enable their benefits – "scaling" takes place and a transformed digital system emerges. These stages of evolution are not only practical to investment cycles, process redesign and culture change, but also deliver an orderly approach to transformation that maintains reliability and affordability.

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[10] Ibid. and Moorthy, Radha Sree Krishna and Chinthavali, Madhu. Building the Electric Power Grid One Unit at a Time, IEEE Power Electronics Magazine, pp. 26-33 (June 2024) accessed at https://ieeexplore.ieee.org/document/10574463. Note that a transformed, fully digital grid is conceptually distinct from a "digital-first grid", which may emerge much sooner and at a lower saturation of digital assets.

The Periods of Grid Evolution

Orderly change does not imply slowness. Indeed, this paper proposes an approximately 20-year timeline for digital transformation that is already well underway. Table 1 below describes four broad periods for the grid, the first “Legacy” being the largely analog period with limited digital systems in place. The next two periods of “Emerging” and “Scaling” describe an imprecise period of transition in which grid systems move from analog-first with disruptive levels of digital assets to digital-first with bridging quantities of analog[11] assets. The final period, to which different parts of the grid will arrive on different dates, is a “Transformed” digital grid in which analog assets are rare. It bears repeating that not all parts of the grid (e.g., communities, utilities, markets or regions) will transform at the same (or even consistent) rate. This does not reduce the value of the mental model presented because a digital system and its architecture should be resilient and flexible to different states and pace of change.

Table 1: Periods of Grid Evolution

Legacy	Pre-2020	• High-touch centralized control systems built to manage to least-cost distribution of energy in one direction from large, mainly fossil-fuel powered resources. • Planning and operations accomplished using deterministic modeling based on data inputs in separate models that are individually compiled and held by different grid participants. • Planning prioritizes redundancy against outage of large generation or loss of transmission line to ensure reliability. • Inherent characteristics of large resources determine both least-cost economic dispatch solutions and system stability.
Emerging	2020-2030	• Grids have a mix of legacy and digital assets, such as digital inverter-based resources, sensors and IoT devices. • The number, size, type and location of variable renewable inverter-based resources increase significantly. • Digital devices provide visibility throughout the grid, enabling new ways of planning, managing and operating an increasingly complex and bi-directional grid. • Access to quantities of high-quality data provides insight into the grid, connected assets and customer propensity. Paired with artificial intelligence, this allows for new optimization and coordination methods. • Legacy methods of modeling, planning and operating the grid persist for a time and struggle to accurately depict the behavior of digital assets. • An open Internet-style information architecture is eventually layered on top of the existing physical grid architecture, improving flexible connection and management of generation assets, demand-side optimization, and stacking asset use cases.
Scaling	2030-2040	• Major interconnections become digital-first as smart assets drive methods of planning, management, and operation. • Data-rich systems, advanced computing and AI-assisted coordination are key characteristics of how the complex energy system maintains reliability while allowing flexible access to and participation in the grid. • Grid assets (notably demand-side and energy storage) materially contribute to ensuring reliability and operational efficiency.
Transformed	2040+	• A distributed, dynamic and delegated grid operates at scale and is characterized by modernized digital grid assets, both known and still to be innovated. • Profound commercial and market transformations become possible, such as micro-transaction energy ledgers, continuously clearing wholesale markets and the obsolescence of traditional ancillary services. • Energy optimization decisions are bundled into the assets and services that consumers care about and understand, and these are enabled by digital electron buffers.

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[11] Indeed, this incremental transformation is analogous to the evolution of telephony. See, e.g., Downes, Larry, Harvard Business Review. The End of the Line for the Analog Phone Network (March 2014) accessed at https://hbr.org/2014/03/the-end-of-the-line-for-the-analog-phone-network.

There are a few observations about the Periods of Grid Evolution that warrant more detail here. First, during the Emerging period, the increase in variable renewables can be perceived to be disruptive to the Legacy system, and lead to potential sources of instability and reduced reliability. This concern is reinforced by the Legacy methods and tools of modeling, planning and operating the grid that lead to significant uncertainties. However, the increasing penetration of variable renewables seems to be an inevitability in response to the preferences of many grid customers, policy decisions that support decarbonization and increasingly competitive cost profiles.

Modernized digital tools and AI-based assistants, which emerge in the Scaling period, are required to address the challenges of variability. Given the characteristics of variable renewable resources – specifically the inverter-based and digital assets that are inherently controllable – modeling and planning with traditional N-1 reliability[12] as a fundamental construct creates a tendency to overbuild the grid for redundancy and negatively impact the bankability of renewable energy producing assets. Alternate methods for modeling and coordinating digital energy assets are warranted to enhance their operational capabilities and ability to respond and protect grid reliability. In addition, demand-side actions and assets remain modest in the Emerging period, and in the Scaling period these become material contributors to grid reliability and efficiency.

In the Transformed period, an established digital grid with robust integrations allows for innovative changes to how consumers interact with, contribute to and benefit from energy services. These integrations allow for changes to products, grid assets and markets. For example, customer products evolve to inherently include opportunities for energy choice, becoming “Electrified Digital Customer Assets” (EDCAs). These products include things like electric vehicles and Internet-connected heat pumps, and integrate a battery-based and software-enabled “electron buffer,”or a “Digital Electron Buffer (DEB)”, that coordinates consumption and grid access.

The value of DEBs is realized when the grid uses energy storage and responsive loads to solve network needs, in addition to the familiar battery use cases related to balancing of supply and demand. In the Emerging period, the buffer consists mainly of bulk storage assets that may provide full-time or part-time transmission service. As the digital grid scales, storage will be embedded in most buildings, vehicles and devices, which are empowered to contribute to the buffer through the Digital Grid Architecture. Further, these buffers will be fundamentally digital with the ability to be controlled via AI agents, and allow a fine-grained control over energy, i.e., to be Digital Electron Buffers. Finally, market changes in this period may include peer-to-peer and micro-transactions for energy arbitrage or grid services, or changes in behavior and consumption choices that optimize the path of energy flows and delivery of energy.

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[12] N-1 reliability is a power system concept that ensures normal operation of the grid in the event of a single unplanned event such as a loss of generator, transformer, or transmission line.

While these innovations are yet to be fully envisioned, one may take inspiration from the transformation seen in the mobile applications economy, with widespread and highly-valued services like ride share applications.

The Architectural Categories

The Digital Grid Architecture is a structure that supports and is resilient to the grid evolution described above and can be conceptually organized into three categories that take inspiration from the Internet.[13] The first "Architectural Category," reflected in Table 2 below, relates to the organizing frameworks, policies, mechanisms and methods governing interactions between participants in the ecosystem, referred to in this paper as "Structure." The second Category describes how communication and software systems engage with and amongst each other—the "Interaction" layer. A final Category brings the physical assets of the electrical grid into coordination and consideration under an "Infrastructure" layer. Additional details and the purpose of these Architectural Categories follows.

Table 2: Architectural Categories

	Purpose	Description
Structure	Provide the system governance, market mechanisms and interaction methods to support diverse industry forms, and to spur flexibility, rate of change, and competition, for the benefit of the various grid participants and stakeholders.	• Legal frameworks and regulatory policies, including for grid planning, operations and intelligence. • Market policies and mechanisms. • Methods to balance adoption of innovative technologies and approaches with grid reliability and security. • Control and coordination methods to ensure reliable interactions between system participants (e.g., centralized, delegated, distributed; and with granular information scale or aggregated scale).
Interaction	Ensure efficient end-to-end interoperability, reliability and affordability across multiple grid systems, and fostering competition by allowing multi-vendor and multi-technology solutions to be developed effectively.	• Openness and standardization as an organizational principle. • Applications for development, deployment, management, planning and operations of multiple, whole and partial grid systems. • Protocols for bidirectional, efficient, secure, fast and timely exchange of key grid information and commands. • Data and metadata formats and structures for universal representation of grid information and commands across wide ranges of time and physical granularity and flexible to innovation.
Infrastructure	Allow development, modernization, deployment and operation of physical technologies for intelligent production, storage, dispatch, flow control, sensing and consumption.	• Electronic and software control devices programmed to ensure reliability of the grid and optimal operation. • Electronic and software sensing and observing devices providing situational awareness of grid infrastructure. • Physical assets of the grid, including mechanical and electrical elements and systems, whether digital or analog. • Energy generation, storage and buffering elements.

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[13] The "Internet of the grid" is a well discussed, if not yet well defined, concept and the analogy to the Internet is apt. See, e.g., Huang, A.Q., et al. The Future Renewable Electric Energy Delivery and Management (FREEDM) System: The Energy Internet, in Proceedings of the IEEE, vol. 99, no. 1, pp. 133-148 (January 2011) accessed at https://ieeexplore.ieee.org/document/5634051 and Joseph, A. and Balachandra, P. Energy Internet, the Future Electricity System: Overview, Concept, Model Structure, and Mechanism, in Energies (August 20) accessed at https://www.semanticscholar.org/paper/Energy-Internet%2C-the-Future-Electricity-System%3A-and-Joseph-Balachandra/91f129b7cc8dc5b193f3e0101ffc37a7a15152cc. The Internet is a complex, coordinated system of distributed communication assets that had its own journey from analog-first systems to digital-first systems.

The Digital Grid Architecture

When Architectural Categories are characterized against the earlier posited Periods of Grid Evolution, an Evolving Digital Grid Architecture emerges. In Table 3 below, a high-level description of the Structure, Interaction and Infrastructure is provided by time period. Below the Table, slightly longer narratives are provided to explain how technical aspects of the Architecture support the grid and its participants in each period.

Table 3: Evolving Digital Grid Architecture

	LEGACY	EMERGING 2020-2030	SCALING 2030-2040	TRANSFORMED 2040+
STRUCTURE	Highly centralized and resistant to change, balancing monopolistic efficiency and competitive affordability for consumers	Increasing collaboration between participants, incentives emerge for change in areas of perceived high risk	Coordinated decisions are delegated into a dynamic, distributed and participatory system of flexible and responsive assets	Commercial and market innovations emerge on top of the energy system, enabled by rapid and continuous micro-market clearing
INTERACTION	System is dominated by a few proprietary and standard approaches that are then highly localized to each grid owner and operator	The value of data and AI insights and the need to manage increasing complexity drive open approaches backed by security	Coordination involves AI and agents, common APIs and data formats, and increased delegation of decision making to digital assets	Material parts of the system are managed by autonomous agents the provide and are provided continuously clearing information
INFRASTRUCTURE	Databases maintained through boots-on-the ground inform largely static and conservatively estimated view of assets	Individual grid areas are modernized, visible, and controllable with digital assets and coordinating software systems	Interconnections are modernized and digital-first, enabled by optimization that also coordinates reliability, stability	New assets emerge that bundle in energy elements such as stability maintenance, energy buffering, and dispatch strategies

The Architecture in the Emerging Period

In the Emerging Period of Grid Evolution, grid visibility and coordination is a dominant set of solutions for system needs. Visibility into grid assets and powerflow allows participants to make informed decisions about system planning, operations and management. The solutions open opportunities to (1) [14] become more aware of the dynamic capabilities of the grid through massive amounts of indexed and visualized data and (2) leverage the flexibility of renewable resources while managing the impact of their variability through their inherent ability to be controlled.

System participants also perceive the benefit of visibility and coordination and, therefore, adopt even more technologies that further enhance grid visibility. This beneficial flywheel of data supports changes to governing processes and methods of decision making and coordination.

- Customers lead the charge by demanding more influence over the type of energy they consume and better evidence that their actions lead to the supply of desirable energy to the grid. Adoption of technologies that electrify homes, transport and industry reinforce the customer desire to know that those electrified assets are fueled by an increasingly renewable energy mix.
- Utilities respond to customer needs (and policy requirements like FERC 2222) while maintaining grid reliability and resilience through advanced distributed energy resource management systems (DERMs) that provide improved visibility over customer distributed energy resources (DERs) and allow utilities to encourage certain coordinated behaviors to minimize disruption to the grid.
- At the same time, energy developers strive to meet increasing customer demand for energy in a timely and affordable way despite the stress that new project interconnection brings to both the transmission system and interconnection processes. Key to developer success and minimization of grid stress is improved transparency and visibility into what the existing system can sustain and how it can be upgraded affordably at speed.
- Finally, system operators embrace improvements in grid visualization, simulation and process coordination to enable–despite a constrained workforce–the technology desired by participants and the study volume and modernization required to integrate those new technologies.

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[14] Simplified, FERC 2222 requires utilities, in collaboration with system operators, to accommodate the participation of aggregations of distributed energy resources in wholesale electricity markets. See Federal Energy Regulatory Commission. FERC Order No. 2222 Fact Sheet, accessed at https://www.ferc.gov/media/ferc-order-no-2222-fact-sheet.

The Digital Grid Architecture enables visibility through higher fidelity and more frequently updated data streams and with fewer demarcations between data sets, whether within specific utility or operator footprints or even inter-regionally as collaborations between participants take place. Data becomes visible across parts of the grid that have traditionally been separated by technical, administrative and business boundaries, including (a) transmission and distribution, (b) operations and planning and (c) multiple grid participants or innovative businesses engaging in the ecosystem.

Visibility is enhanced through open-standard protocols and data formats that allow rapid and efficient coordination and interoperability across these traditional boundaries. Artificial Intelligence (AI) improves data quality through anomaly detection and surfaces insights that prove out the value of investing in data. Together with these transformations are robust technical mechanisms for ensuring privacy, security and governance. At the Infrastructure level, data comes from sensors, IoT devices and other smart digital elements, and is often combined with contextual data such as weather, vegetation and equipment statistics and customer propensity.

Because visibility improves across previously siloed functions and parts of the grid, collaboration and coordination is also unlocked through the Digital Grid Architecture. Collaboration may begin in subsections of the grid, or “collaboration islands”, or it may occur early in the Emerging Period within forward-leaning utilities or grid operators. Those early demonstrations of coordination and related benefits are the stepping stones for deeper and broader coordination throughout the grid. The precision of control enabled by digital assets and the ability to measure and quantify benefits offer compelling proof for the value of a digital grid and its corresponding architecture. Regulatory policies as well as industry best practices evolve to allow and support such collaboration and coordination so as to improve reliability and innovation, as well as affordability to end users.

The Architecture in the Scaling Period

In the Scaling Period of Grid Evolution, visibility leads to a deeper understanding of the grid through new abilities to conduct massive simulation and identify optimal planning and operational approaches to increasingly connected parts and processes of the grid. These combined insights inform decisions that are delegated for reliable coordination of the increasingly dynamic and complex energy system. Grid reliability and stability form a structural baseline for actions taken by distributed assets that participate in the system and are made possible through the flexibility and responsiveness of the digital elements.

In this period, system participants benefit from delegated coordination and the inherent reliability of the flexible digital grid. For example,

- Customers can apply personal optimizations related to the type of energy they consume (e.g., prioritizing type, source or price) and how it is delivered to them (e.g., prioritizing local energy, time of delivery or lowest total emission impact).
- Utilities take on an active coordination role within the distribution grid by balancing customer needs, actions taken by aggregators of energy resources and utility-instrumented distribution system assets to maintain grid safety, reliability and affordability. This role is facilitated by advanced software systems, targeted customer programs and price signals to distribution system participants.
- Energy developers benefit from improved grid visibility and efficiency of system operator processes, leading to increased project certainty. This enables developers to focus on creating differentiated product offerings to serve customers in new ways that leverage digital capabilities of the grid.
- Transmission system operators become more comfortable with the dynamic nature of the grid (production, consumption and delivery), and that digital assets are inherently controllable, flexible and capable of prioritizing grid reliability and stability as conditions of operation. This comfort, combined with enhanced planning, simulation and operational capabilities, allows operators to streamline interconnection processes and provide faster, secure connection to the grid. Finally, transmission system operators benefit from more predictable load profiles from the distribution system due to utility coordination.

The Digital Grid Architecture enables a reliable and stable grid through several methods. At the Infrastructure level, devices operate with greater autonomy based on increasingly sophisticated device software that are coordinated both at the grid edge and at a higher level and ensure reliability as a condition of interconnection. Relevant data, organized and shared via open data formats and protocols, allow advanced interoperability of devices and resources. This allows more sophisticated agents and AI applications to be developed, and common APIs[15] allow them to be portable across digital grid elements and subsystems that may be supplied by different vendors and built on diverse software and hardware stacks. Finally, grid-forming equipment and storage devices maintain grid stability as an essential result delivered by digital objectives and protocols.

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[15] API stands for Application Programming Interface and is a type of software that contains methods for different software applications to communicate with each other.

The Architecture in the Transformed Period

The Transformed Period arrives when the electrical grid is in a digital state at scale. Digital assets throughout the transmission and distribution systems coordinate and are coordinated to optimally deliver affordable, reliable and decarbonized energy. The grid is visible, efficiently used and planned with an informed understanding of the dynamic grid and the context in which it exists. Flexibility becomes a defining characteristic of the grid and grid operators leverage interconnected assets to deliver reliability and stability, not only through operational methods, but through protocols and standards that delegate to the asset behaviors that prioritize reliability and stability.

The visible and flexible digital grid, capable of coordination and optimization, allows for commercial and market innovations to emerge and use integrations into the digital grid platform to bundle energy services alongside electrified products. A new role emerges for each grid participant:

- Customer energy choices are bundled with the electrified, digital things that we care about, i.e., EDCAs.
- Utilities no longer rely solely on their investments and instrumented assets; rather, they engage third-parties, including customers, to help deliver a balanced and reliable grid with highly predictable load curves.
- The number and categories of companies that engage in energy development increases as electricity becomes a core component of more products (i.e., more products are EDCAs). These diverse energy developers actively integrate portfolios of EDCA to deliver services and products of increasing value to grid participants.
- Transmission system operators continue to monitor and coordinate wholesale markets, including inter-DSO energy transfers and delivery to the large “base” load curves that are more predictable and less variable.

The Transformed digital grid is enabled by rich data and dynamic models, computational power, artificial intelligence and standards and protocols for coordination. At the Infrastructure level, novel schemes for routing and buffering of electrons ensure a highly flexible and responsive grid. Interactions are facilitated by applications that support AI-based autonomous agents, and which in turn rest on continuous availability, exchange and brokerage of information. Finally, the governing structures of the grid allow for electron marketplaces that can (1) operate at a wide range of energy granularities, (2) allow real-time peer-to-peer trading of contracts and derivatives, including real-time auction-based mechanisms, and (3) support both simple and complex transactions that lead to efficient markets assisted by AI.

This section has boldly illustrated a Digital Grid Architecture that looks out past 2040. As with any predictions, the precise evolution of the digital grid may not match the details. Nonetheless, the principles described represent credible manifestations of a grid that is likely to emerge and an architecture that would support an organized and beneficial transformation.

Capturing the Benefits of a Digital Grid

The abundant benefits from adoption of a digital grid have been highlighted throughout this paper: the ability to accommodate an increasingly complex and dynamic grid; improved forecasting and decision making; more precise control and coordination; opportunities for collaboration and participation; transparency; and innovation, among others. A few additional benefits merit further elaboration in this section given the urgency of realizing their value to society and of facilitating an orderly grid evolution. They are: (1) sustaining global economic growth; (2) reliability through flexibility; (3) cybersecurity through standards and protocols; and (4) grid efficiency and equity.

Sustaining global economic growth

Stable and reliable electricity is a catalyst of technological innovation and economic growth.[16] For many years, customers connected to the grid with relative ease because the pace of transmission and generation build out and associated centralized control methods could meet the generally predictable demand growth.[17] But recent trends, including the electrification of "everything"[18] (including EDCAs), the uptake of AI across many different industries,[19] and adoption of renewable (and variable) energy sources,[20] mean that the need for new electricity resources far exceeds that of prior additions.[21] Energy developers, utilities and transmission operators all struggle to connect this new capacity fast enough to feed the engines of societal and economic growth.[22]

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[16] EIA. The link between growth in economic activity and electricity use is changing around the world (November 2017) accessed at https://www.eia.gov/todayinenergy/detail.php?id=33812.

[17] Federal Energy Regulatory Commission. Explainer on the Interconnection Final Rule, accessed at https://www.ferc.gov/explainer-interconnection-final-rule.

[18] IEA. Pathways for the Energy Mix, World Energy Outlook 2023, accessed at https://www.iea.org/reports/world-energy-outlook-2023/pathways-for-the-energy-mix.

[19] McKinsey & Company. Gen AI's Rapid Uptake (June 2024) accessed at https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-of-the-day/gen-ais-rapid-uptake.

[20] EIA. Annual Energy Outlook 2023, generally accessed at https://www.eia.gov/outlooks/aeo/ and specifically Table 9 (live link at https://www.eia.gov/outlooks/aeo/data/browser/#/?id=9-AEO2023&cases=ref2023&sourcekey=0) and source data file at https://www.eia.gov/outlooks/aeo/excel/aeotab9.xlsx.

[21] Ibid.

[22] Lawrence Berkeley National Laboratory. Queued Up: 2024 Edition (April 2024) accessed at https://live-lbl-eta-publications.pantheonsite.io/sites/default/files/queued_up_2024_edition_r2.pdf.

In short, the engines of economic growth have grown insatiable for energy in part because of their digital and data-rich nature. So perhaps it is no surprise that the source of stress to the electricity grid may also be the source of a solution. The data visibility, computational insights and inherent ability for control that are characteristic of digital systems allows the electricity system and sources of economic growth to be co-optimized. The Digital Grid Architecture coordinates the Structures, Interactions, and Infrastructure of the grid and the assets connected to it (both producing and consuming). This coordination, which prioritizes grid reliability and stability, will allow faster interconnection of new sources of energy and the load consuming assets that will push economic (and societal) growth through the next century.

Reliability through flexibility

As the electrical grid has been essential to resilient economic growth, so has reliability been essential to growth of a resilient electrical grid. But the way reliability is ensured in a dynamic and distributed digital grid is inherently different from the redundancy-driven methods of the analog system. The Digital Grid Architecture and related standards and protocols embody these differences, with flexibility being both a key input and output of the digital system.

Flexibility alone, without standards and protocols that enhance predictability and coordination, can be disruptive to a system. It is precisely this predictability and coordination that the Digital Grid Architecture brings to the dynamic and flexible digital grid. Once again, today's stressors to the electrical grid become its champions with an architecture in place. For example, the grid's current processes and modeling methods struggle to incorporate energy storage devices because of their need to charge from another source to then provide energy into the grid. Yet storage, strategically deployed throughout the grid, becomes a key element of the digital grid, forming a "buffer" of energy throughout the grid that is capable of optimizing and balancing network health, generation and demand.

To make the most of digital flexibility, AI and advanced computational capabilities enable scaling and resource coordination across the grid to maximize digital flexibility. However, these systems require standardized operating and communication protocols, emphasizing the value of a Digital Grid Architecture. Two key communications issues addressed by standards and protocols include (1) communication and processing latency (improved rapidly by focusing resources on improving a few key standard elements) and (2) variability (or jitter).

Standards, applied holistically, reduce latency and its variability and make for improved reliable communications and coordination over the current grid. With reduced communication latency and jitter, and AI and advanced computation making speed and scale of operation possible, grid stakeholders can benefit from collaboration platforms with a single source of truth. These platforms allow those who manage the grid and those who seek to connect to the grid to have a common understanding of hosting capacity and deliverability. These technical infrastructure components, interaction mechanisms and platforms, together with the structure and governance of the Digital Grid Architecture, will enhance both the reliability and flexibility of the grid.

Cybersecurity through standards and protocols

The proportion of digital assets on or connected to the electrical grid will continue to grow due to economic and industry trends. As the digital footprint expands, so does the potential risk of cyberattacks. Every EV, rooftop solar system, controllable thermostat and future EDCA is connected to the Internet and accessible via an app on your phone. This is why the Digital Grid Architecture must proactively address cybersecurity risk.

The solution to cyber risk is not to limit the growth of digital infrastructure, but to embrace digital systems and use standard and open protocols and data formats to provide verifiable, best-in-class, continuously updated mechanisms for secure connection.

Doing so will make the system less vulnerable, not more. Long experience in the industry shows that proprietary, closed, poorly-understood protocols are more vulnerable to determined attacks than open and standard protocols. Standardization reduces complexity and facilitates interoperability and security. With the Digital Grid Architecture as a framework, such standards are possible.

Grid efficiency and equity

A transformed digital grid can be planned and operated more efficiently, and therefore at lower cost than one that has neither embraced digitalization nor adopted the Digital Grid Architecture. Historically, the grid itself comprised only part of the cost of electricity to the customer, but trends toward renewable (and thus zero-marginal cost) energy mean that most of the cost of the future grid is the grid itself.[23] Therefore, a more efficient grid enables a more cost-effective electricity service to the consumer.

[23] Houghton, B., et al. Solving the rate puzzle: The future of electricity rate design, McKinsey (March 2019) accessed at https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/solving-the-rate-puzzle-the-future-of-electricity-rate-design and Wallace-Wells, D. What Will We Do With Our Free Power?, NY Times (August 2024) accessed at https://www.nytimes.com/2024/08/28/opinion/solar-power-free-energy.html?unlocked_article_code=1.Gk4.AjW4.h8uWCoZmprfG&smid=url-share.

This paper does not attempt to identify a tipping point for when the digital grid becomes more cost effective than maintaining a status-quo grid with mostly digital resources. However, it argues that operating a grid with significant digital and distributed assets penetration with today's planning and operating methods would be inefficient. Today's methods provide reliability through conservatism by building for the biggest spike in demand. This approach has created an underutilized grid, like a highway with too many lanes and full only once a year. In the future, this approach would necessitate even larger and less utilized electricity "highways", as there would be little ability to harness the flexibility of digital assets across all grid layers. The Digital Grid Architecture makes fuller use of the existing grid by coordination across digital assets embedded at all levels, such as grid enhancing technologies and the capabilities of DEBs.

Further, efficiency and affordability, as well as greenhouse gasses and other environmental pollutants, are borne unequally by the most vulnerable populations. By accelerating the orderly transformation to a digital grid, we futureproof the reliable transition to digital and distributed resources, supply more cost-effective electricity and enable a just and equitable transition.

This paper has enumerated many benefits that can be gained through a transition to a digital grid. It is notable that the factors that create challenges in the early Emerging period of grid transformation become the factors that enable benefits in a Transformed digital grid. The path from challenge to opportunity is stewarded by the Digital Grid Architecture, which ensures an orderly transformation that maximizes societal gain and minimizes negative externalities.

Conclusion

The electrical grid is a system under stress from foundational changes such as customer needs, deployed technology, aging infrastructure, climate extremes and outdated processes that govern access to the grid. We have presented a bold proposal for a path through this changing system to a future digital grid designed for the 21st century and beyond. The Digital Grid Architecture will not be perfect and details–like timelines–will certainly vary from those in the Architecture and from reality within and between individual grids. Despite variations, we believe that the principles of the Architecture and the manifestations of the digital grid are meaningful and actionable.

Fundamentally, we believe that the benefits of an electrical system preserved and unlocked by the digital grid and secured by the Digital Grid Architecture are numerous and accrue in relevant ways to all participants. But we will not achieve the benefits or the transformation at speed and scale without broad participation from the ecosystem of entities and experts who make our grid secure, reliable, innovative and meaningful for grid customers (i.e., all of us). Therefore, we invite comments to the Architecture and the concepts herein, and we request engagement to accelerate the future grid, together.

Please submit your comments via this form.

We look forward to your feedback and engagement.

About us

Tapestry is a project at X, Alphabet’s innovation lab, that is building AI-powered tools for a greener and more reliable future grid. AES is a global energy company that provides sustainable and innovative energy solutions. Since 2020, we’ve been working together to deploy new technologies that accelerate the transition to a cleaner energy future.