Powering Artificial Intelligence: How Artificial Intelligence's Massive Energy Demands Are Reshaping the Future of Smart Grid

Bahman Zohuri[1], Farhang Mossavar-Rahmani[2] and Mehdi Abedi-Varaki[3]

1. Ageno School of Business, Golden Gate University, San Francisco 94105, California, USA

2. Finance School of Business Technology and Engineering, National University, San Diego 92110, California, USA

3. FTMC-Center for Physical Sciences and Technology, Savanoriu Ave. 231, LT-02300 Vilnius, Lithuania

Abstract: The rapid evolution and expanding scale of AI (artificial intelligence) technologies exert unprecedented energy demands on global electrical grids. Powering computationally intensive tasks such as large-scale AI model training and widespread real-time inference necessitates substantial electricity consumption, presenting a significant challenge to conventional power infrastructure. This paper examines the critical need for a fundamental shift towards smart energy grids in response to AI's growing energy footprint. It delves into the symbiotic relationship wherein AI acts as a significant energy consumer while offering the intelligence required for dynamic load management, efficient integration of renewable energy sources, and optimized grid operations. We posit that advanced smart grids are indispensable for facilitating AI's sustainable growth, underscoring this synergy as a pivotal advancement toward a resilient energy future.

Key words: AI, smart grid, energy demand, data centers, load balancing, renewable integration, grid modernization, deep learning power consumption, real-time monitoring, AI in energy systems.

1. Introduction

AI (artificial intelligence), no longer a theoretical pursuit, has firmly established itself as the bedrock of contemporary technological advancement. Its integration spans an ever-widening array of applications, from the seemingly ubiquitous intelligent voice assistants and increasingly sophisticated self-driving vehicles to groundbreaking advancements in medical diagnostics and personalized recommendation engines that shape our digital experiences. This pervasive integration means AI is now deeply woven into the fabric of our daily lives [1, 2].

These computational advancements come with significant energy requirements. Training a single state-of-the-art AI model such as a large language model can consume hundreds of megawatt-hours of electricity, equivalent to the annual consumption of dozens or even hundreds of homes. This high energy usage is further exacerbated by the continuous need for inference processing, particularly in real-time AI services like facial recognition, autonomous control, and large-scale recommendation systems [2].

This surge in energy consumption, particularly from densely concentrated AI workloads, introduces significant challenges for power grid infrastructure worldwide. Traditional electrical grids were largely designed for centralized power generation and relatively predictable consumption patterns from residential, commercial, and industrial users. However, the rise of AI-driven data centers presents a fundamentally different load profile.

Corresponding author: Bahman Zohuri, Ph.D., adjunct professor, research fields: artificial intelligence and machine learning.

AI workloads, especially the training of complex models and the execution of real-time inference result in dynamic and often unpredictable power demands. Unlike traditional, steady loads, AI processing can cause rapid, sharp increases or decreases in electricity over very short periods. These sudden power swings, or high "ramp rates", are difficult for the grid to anticipate and manage, straining generation, transmission, and distribution infrastructure (see Fig. 1).

Furthermore, the geographical concentration of AI workloads exacerbates these challenges. Clustering hyperscale data centers and AI training hubs in specific regions places immense localized stress on the regional power supply. This concentrated demand can push local grids to their limits, increasing the risk of grid instability, voltage and frequency fluctuations, and inefficiencies in power delivery. In extreme cases, this localized strain elevates the risk of brownouts or even blackouts, impacting the AI facilities, surrounding communities, and critical infrastructure. The current grid infrastructure in many areas is simply not equipped to handle these large, dynamic, and concentrated power demands. Modernizing the grid to be more flexible, resilient, and capable of handling these new load characteristics, potentially through advancements like smart grid technologies, improved energy storage solutions, and enhanced transmission capacity, becomes increasingly crucial to support the continued expansion of AI. The need to integrate more renewable and DERs (distributed energy resources) effectively also becomes more pressing to power these energy-intensive operations sustainably and reliably.

The global energy infrastructure must evolve to meet these new demands. Smart energy grids, which incorporate advanced communication networks, real-time analytics, and intelligent load-balancing mechanisms, provide a forward-looking solution. These modern grids can adapt in real-time to fluctuating demands, integrate renewable energy sources, and utilize AI-based systems to enhance their own performance [3].

Fig. 1   A Facebook data center in Luleå, Sweden.
Source: Jonathan Nackstrand/AFP/Getty.

This article explores the growing intersection between AI's expanding energy needs and the transformation of traditional power systems into adaptive smart grids. It highlights the challenges and opportunities when two of the most impactful technologies, AI and energy infrastructure, converge. Through this lens, we gain insight into how the future of innovation is fundamentally tied to the future of intelligent, sustainable energy systems [4, 5].

The burgeoning era of AI is inextricably linked to a significant and rapidly increasing demand for energy, particularly within environments characterized by intensive computation. The foundational process of creating cutting-edge AI models, including sophisticated architectures like large-scale transformer networks that boast billions or even trillions of parameters, necessitates immense hardware resources. GPUs (graphics processing units), TPUs (tensor processing units), and other specialized AI accelerators form the backbone of this computational power. By their very nature, these processors demand substantial electrical power to operate at peak performance and require advanced cooling systems to prevent overheating. As AI adoption permeates industries and applications globally, energy consumption patterns are fundamentally shifting from traditional, less intensive computing workloads towards AI-centric computations that are inherently resource-hungry.

The training phase of these advanced AI models stands out as a particularly energy intensive activity. A

prime example is training large generative models, such as those in the GPT (generative pre-trained transformer) series. This process can consume several megawatt-hours of electricity over weeks or even months, depending on the model size, dataset scale, and hardware efficiency. Quantifiable estimates highlight the environmental implications: training such models can produce dozens to hundreds of tons of carbon dioxide, particularly when the power sources are reliant on non-renewable fossil fuels. This significant carbon footprint underscores the urgent need for more sustainable energy solutions within the AI landscape.

While the energy consumed by a single inference task (using a trained AI model to make a prediction or generate an output) is considerably less than that required for training, the sheer scale and continuous nature of inference across many applications lead to substantial aggregate energy consumption. Real-time AI services embedded in web searches, recommendation systems, natural language processing applications, and automated systems collectively contribute significantly to energy demand.

Furthermore, the proliferation of AI in edge computing environments has introduced another significant dimension to its energy footprint. AI is increasingly being deployed on many devices at the network edge, including smartphones, sensors, autonomous vehicles, industrial IoT (internet of things) systems, and smart home devices. These systems leverage on- or near-device processing for critical reasons such as minimizing latency for real-time responses, enhancing data privacy by processing locally, and reducing bandwidth costs associated with transmitting large volumes of data to the cloud. Although the power consumption of individual edge AI systems is relatively low compared to a data center, the sheer scale of their deployment reaching billions of devices globally means that collectively, edge AI represents a significant and growing contributor to worldwide energy usage. This distributed energy demand, while different from concentrated data centers, presents its

own challenges for overall energy management and sustainability.

The geographical distribution of AI workloads is also a concern. High concentrations of AI data centers in specific regions such as Northern Virginia in the U.S. or Frankfurt in Germany create regional stress on electrical grids, often outpacing infrastructure upgrades. This imbalance leads to localized power bottlenecks, increased electricity prices, and environmental concerns when fossil-fuel-based peaked plants are used to meet spikes demand.

To address these growing concerns, there is a critical need to design energy-efficient AI systems, adopt green AI practices, and integrate AI workload scheduling with smart grid responsiveness. These steps are necessary not only for environmental sustainability but also for maintaining grid stability and avoiding blackouts as AI continues to scale [6, 7].

2. Why Traditional Grids Can Not Keep Up

Traditional electrical power grids, broadly conceived and constructed in the 20th century, were fundamentally designed to support a centralized, one-directional flow of electricity. This model generates power at large-scale plants (such as fossil fuel or nuclear facilities) and transmits it to many consumers. These systems were optimized for relatively predictable usage patterns and steady, often linear, increases or decreases in demand throughout the day and across seasons. Fig. 2 illustrates a traditional grid architecture with centralized generation and hierarchical distribution. However, the advent of an AI-driven and profoundly digitalized global infrastructure has rendered these foundational assumptions about energy consumption patterns obsolete.

The core reasons why traditional grids struggle to accommodate the energy demands of modern AI include.

2.1 Inflexible Architecture for Dynamic Loads

AI workloads introduce energy consumption patterns that are both highly irregular and intensely

demanding. Training complex AI models or executing high-frequency inference tasks generate power requirements that fluctuate dramatically and unpredictably. For instance, data centers dedicated to running large AI models can exhibit sudden, massive spikes in electricity draw as computational tasks scale up rapidly. This volatile and high-magnitude demand fundamentally differs from the more gradual and predictable load changes that traditional grid infrastructure was built to handle. The inherent lack of real-time adaptability and responsiveness in these legacy systems makes them vulnerable to instability when confronted with such erratic and intense demands. This can lead to operational inefficiencies, localized voltage reductions (brownouts), or even necessitate forced shutdowns to prevent system collapse, posing a significant challenge to maintaining a stable and reliable power supply. The envisioned AI-driven smart grid design (Fig. 3) highlights the need for a more dynamic, responsive, and potentially bi-directional energy flow to address these limitations.

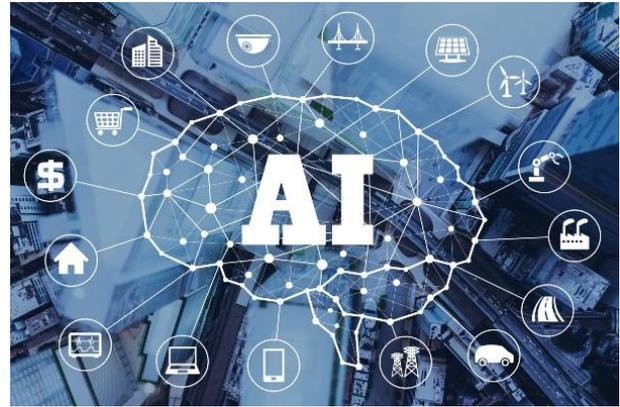**Fig. 2   Typical traditional power grid.**
Source: www.google.com.

Fig. 3   AI-driven and highly digitalized world.
Source: www.wkipedia.net.

2.2 Absence of Two-Way Communication

Traditional grids operate on outdated control architectures that lack digital intelligence and feedback mechanisms. This means the grid cannot "see" or react dynamically to what's happening in real-time whether its demand surges from an AI cluster, sudden drops due to renewable variability, or local generation from rooftop solar panels. There is no systematic integration of smart meters, sensors, or AI-based grid management, limiting its ability to balance demand and supply on the fly.

2.3 Inability to Support Decentralization

The modern energy ecosystem is becoming increasingly decentralized. AI edge computing deployed in electric vehicles, smart factories, and 5G networks requires power near the point of use, sometimes integrated with local energy sources like solar panels or microturbines. Legacy grids, built for centralized distribution, lack the topology and infrastructure to support microgrids, local storage systems, and DERs.

2.4 Poor Renewable Energy Integration

AI's energy demands could, in theory, be offset by renewables. However, traditional grids are not optimized for intermittent energy sources like wind and solar. Without advanced forecasting, grid-scale batteries, or AI-driven load balancing, the grid cannot efficiently absorb or distribute these renewable

inputs. Renewable energy is sometimes wasted (curtailed), or fossil fuel backup systems are used defeating sustainability goals.

2.5 Geographic Load Imbalances

AI data centers are often clustered in areas with favorable tax, connectivity, or climate conditions such as Northern Virginia or parts of Scandinavia. These localized concentrations of AI activity create heavy burdens on regional transmission and distribution systems, which may not have been designed for such dense consumption. Traditional grids cannot re-route power efficiently across regions without risking overloads or instability.

In summary, in essence, traditional grids lack the digital, flexible, and distributed capabilities needed to support the explosive and variable growth in AI-related electricity demands. They are fundamentally reactive systems in a world that now requires proactive, intelligent, and decentralized power management. Without modernization, digitization, automation, and AI-enhanced forecasting these legacy grids will remain a bottleneck to AI scalability and sustainable energy progress [8, 9].

3. The Smart Grid: A Modern Solution

The growing energy demand driven by AI, edge computing, and data centers has exposed the inflexibility and limitations of traditional electrical grids. As the need for real-time, localized, and high-density energy delivery grows, the power sector must evolve. Smart grids represent this evolution a convergence of electricity, communication, and digital intelligence.

3.1 What Is a Smart Grid?

A smart grid is an intelligent, adaptive energy network that uses advanced information and communication technologies to monitor, predict, and respond to changes in energy demand and supply in real time. Unlike legacy grids, smart grids are bidirectional,

meaning they allow for both centralized and decentralized energy generation and consumption.

They integrate:

• Digital sensors and smart meters for precise monitoring,

• IoT and communication networks for data flow and analytics,

• AI algorithms for demand forecasting and optimization, and

• Automated control systems to manage electricity distribution.

3.2 Why Smart Grids Are Essential for AI

AI systems especially large-scale training operations and real-time inference engines place dynamic, localized, and often unpredictable loads on the power infrastructure. Smart grids are purpose-built to handle this through the following key capabilities.

4. Real-Time Demand Response

Smart grids can adapt instantaneously to fluctuating energy consumption patterns. For example, when an AI data center suddenly spikes in demand during model training, the grid can:

• Automatically reroute electricity,

• Tap into local storage (like batteries), or

• Temporarily reduce non-critical loads elsewhere to maintain stability.

This elasticity is crucial for avoiding overloads and blackouts.

5. Dynamic Load Balancing and Optimization

Smart grids enable predictive analytics using AI and ML (machine learning) algorithms to forecast demand from energy-intensive users. These forecasts help balance loads across regions, minimize congestion in transmission lines, and reduce the reliance on costly backup power plants.

They also allow dynamic pricing, where electricity costs vary based on demand—encouraging more efficient energy use and lowering peak demand stress.

6. Integration of Renewable Energy

One of the most critical challenges in modern energy systems is integrating intermittent renewable sources like solar and wind. Smart grids can:

• Forecast renewable output using weather data,

• Smooth out fluctuations using AI-based control systems, and

• Automatically switch between renewable and traditional power sources.

This enables AI operations to be powered sustainably, reducing their carbon footprint.

7. Support for Decentralized Energy and Microgrids

As AI systems move toward edge computing, power demand becomes more distributed. Smart grids allow for the seamless integration of:

• Local energy generation (e.g., solar rooftops),

• On-site storage (e.g., lithium-ion or flow batteries), and

• Autonomous microgrids that can operate independently or in sync with the central grid.

This decentralization boosts resilience and lowers latency for energy delivery, which is especially important for mission-critical AI applications like autonomous vehicles or remote healthcare.

8. Resilience, Security, and Self-healing

Smart grids are designed with resilience in mind. They can detect faults, reroute power, isolate damaged sections, and even self-heal through automation. With cyber-physical integration, they also implement advanced cybersecurity protocols to protect both energy assets and sensitive AI workloads hosted in critical infrastructure [3].

In summary, smart grids are not just an upgrade, they are a paradigm shift in how electricity is generated, distributed, and consumed. They are the necessary backbone for a future where AI systems are deeply embedded in every aspect of society, from medicine and manufacturing to transportation and national

defense [2]. As Fig. 4 illustrates, AI is reshaping future, the future of grid toward AI-driven smart grid.

The synergy between smart grids and AI is also mutually reinforcing while smart grids enable AI to operate reliably and sustainably, AI enhances grid operations by providing smarter predictions, optimizations, and control [10, 11]. As we step into a future defined by data and intelligence, smart grids will be the energy foundation that makes it all possible.

9. AI for the Smart Grid—A Synergistic Loop

While smart grids are designed to support the needs of AI systems, AI also enhances the capabilities of smart grids themselves. This synergy creates a powerful feedback loop: AI enables the grid to be more adaptive, predictive, and efficient.

Here's how AI empowers smart grid functions.

9.1 Predictive Demand Forecasting

AI models particularly those using machine learning and time-series analysis can:

• Predict future energy demands at granular intervals (hourly, daily, seasonally),

• Learn user behavior patterns (e.g., EV charging at night, HVAC use at noon),

• Account for complex variables like weather, economic activity, and localized events.

Example: Google DeepMind helped the UK's National Grid reduce forecasting errors by over 50%, improving both reliability and efficiency.

Fig. 4   Paradigm of AI-driven smart grid.
Source: www.iot.eetimes.com.

**Powering Artificial Intelligence: How Artificial Intelligence's Massive Energy Demands
Are Reshaping the Future of Smart Grid**

97

10. Fault Detection and Self-healing

AI algorithms are trained to detect anomalies in voltage, frequency, or transmission signals that indicate system faults or cyber intrusions. These systems:

- Trigger alarms before failure,
- Automatically isolate affected segments,
- Enable real-time grid reconfiguration for uninterrupted service.

Example: IBM's AI platform uses neural networks to detect transformer failures before they happen, minimizing downtime and repair costs.

11. Renewable Energy Forecasting and Load Matching

AI enhances the integration of renewables by:

- Forecasting solar and wind output using satellite weather data,
- Matching generation with projected load curves,
- Optimizing storage and dispatch strategies.

Example: Siemens and NVIDIA are collaborating on digital twin models of grids that use AI to simulate and balance fluctuating renewable energy in real time.

12. Adaptive Energy Pricing and Consumer Engagement

AI supports dynamic pricing models that reflect real-time demand and supply conditions. Consumers can receive:

- Automated recommendations to shift usage,
- Smart appliance control via AI assistants,
- Incentives to conserve energy during peak periods.

This leads to demand-side flexibility, reducing stress on the grid during AI-intensive operations like model training or blockchain processing.

13. Grid Cybersecurity and Data Integrity

As smart grids become more connected, they are also more vulnerable. AI is used to:

- Monitor communication protocols for anomalies,
- Detect and mitigate DDoS (distributed denial-of-service) attacks,
- Secure edge nodes in decentralized networks.

Example: NREL (National Renewable Energy Laboratory) uses AI to detect cyber-physical anomalies in real-time across the U.S. power grid testbeds.

The drive toward smarter, more resilient, and AI-enabled grids is taking different forms around the world. Each region is leveraging its strengths (technological, regulatory, and infrastructural) to shape a unique smart grid evolution. Here's a comparison of major global efforts that is presented in Table 1 as global comparison: smart grid implementations and AI integration.

14. Policy and Infrastructure Considerations

As AI rapidly scales and exerts increasingly complex demands on energy systems, it is clear that technological innovation alone is not enough. The successful integration of AI into national power infrastructure requires comprehensive policy frameworks, regulatory modernization, and proactive investment in grid architecture. Without aligned policy and infrastructure, the promise of smart grids and sustainable AI becomes significantly harder to achieve.

Table 1 Comparison summary table.

Region	AI role in grid	Key use cases	Challenges
United States	Reliability, prediction	Wildfire risks, outage forecasting	Regulatory fragmentation
EU	Sustainability, demand mgmts.	Real-time balancing, smart billing	Policy harmonization
China	Centralized automation	Autonomous control, virtual power plants	Data privacy, over centralization
Japan/Korea	Resilience, local optimization	Earthquake prediction, microgrids	Space, cost, technological dependencies

15. Grid Modernization and Investment

Governments must prioritize grid modernization initiatives that include the digitization of transmission and distribution systems. This means upgrading substations with intelligent control systems, deploying smart sensors, and investing in real-time energy management platforms. Public-private partnerships, green infrastructure bonds, and incentive-based funding models are critical to ensuring that utilities and tech firms have the capital to build resilient, AI-ready grids.

16. Renewable Energy Mandates and AI Workload Alignment

AI's carbon footprint is a growing concern. Policymakers can address this by linking AI development incentives to renewable energy sources, such as mandating that data centers powering large AI models procure a minimum percentage of energy from clean sources. Time-of-use pricing policies can also encourage scheduling AI workloads during renewable surpluses, optimizing grid load while reducing emissions.

17. Zoning and Siting for AI Infrastructure

AI data centers are often deployed in clusters, leading to localized stress on regional grids. National and regional planning authorities must develop smart zoning policies that account for grid capacity, land use, and environmental impact. Proactive siting strategies—such as co-locating data centers near renewable farms or within microgrids—can ease infrastructure strain and improve grid efficiency.

18. Regulatory Frameworks for Grid Flexibility and AI Integration

Traditional regulatory environments are often rigid and not suited for real-time, AI-driven decision making. Policies must evolve to allow utilities and grid operators to use AI for autonomous dispatch, demand response, and pricing. This includes ensuring that AI-based systems comply with transparency, explainability, and cybersecurity standards to avoid regulatory pushback or public distrust.

19. Standards and Interoperability

With smart grid technologies sourced from global vendors, interoperability standards become essential. National energy commissions and international organizations (e.g., IEEE (Institute of Electrical and Electronics Engineers), IEC (International Electrotechnical Commission)) should develop unified standards for AI-in-the-loop control, data exchange formats, and grid interface protocols to enable seamless integration across regions and suppliers

In summary, effective AI integration into the energy sector requires coordinated policies, infrastructure modernization, and regulatory reform to ensure sustainable, resilient power delivery.

Strategic investments, renewable energy mandates, and flexible grid governance are essential to align AI growth with national energy goals.

20. Conclusion

AI's rapid and pervasive integration across virtually all sectors of the global economy marks a transformative era in computational capability. However, the swift and widespread adoption of AI in almost every area of the world economy heralds a revolution in computing power. But this remarkable scientific achievement requires energy, a crucial resource that is often overlooked. Training ever-larger AI models, supporting widespread real-time inference, and deploying AI on billions of edge devices is an escalating and substantial burden on existing power infrastructure. The dynamic, high-density, and frequently unpredictable power demands of contemporary AI workloads are becoming too much for traditional electrical grids, which were built for the centralized, predictable energy flow of the 20th century. There are real concerns to the stability, efficiency, and

dependability of the grid because of this mismatch between the energy profile of sophisticated AI and traditional energy systems.

To sustainably power the next wave of AI innovation and ensure grid resilience in an increasingly digitized world, a fundamental paradigm shift in energy infrastructure is not merely advantageous but essential. The foundation of this essential change is the development of intelligent, adaptive smart grids, which are distinguished by real-time monitoring, sophisticated automation, and embedded AI capabilities. These contemporary grids are naturally adaptable enough to handle the extreme fluctuations in AI-driven energy usage. More significantly, they facilitate a potent synergistic loop: smart grids give AI the stable and dynamic energy base it needs, while AI also provides the intelligence required to optimize grid operations, forecast demand variations, integrate intermittent renewable sources seamlessly, and improve overall system resilience.

However, a coordinated and cooperative effort that goes beyond technological advancement is required to realize the full potential of this synergy. It is imperative that policymakers, regulatory agencies, utility corporations, and AI researchers and developers collaborate together. To reduce AI's carbon footprint, this entails making major investments in updating grid infrastructure a top priority, putting in place progressive regulatory frameworks that support innovation while maintaining stability and security, and vigorously encouraging the integration of renewable energy sources. Important initiatives include strengthening the cybersecurity posture of interconnected energy and AI systems, establishing data interoperability standards for efficient grid management, and putting policies in place that encourage energy-efficient AI design and implementation.

In the end, the future of energy is closely tied to the development of AI in the twenty-first century. The scalability, accessibility, and sustainability of AI will depend on its capacity to handle complicated energy demands. We can create a resilient, effective, and sustainable energy future that can support AI's transformative potential for the good of society by strategically combining smart grid innovation with proactive policy, significant infrastructure investment, and the very intelligence that AI provides.

References

[1] Zohuri, B., and Zadeh, S. 2020. *Artificial Intelligence Driven by Machine Learning and Deep Learning*. Hauppauge: Nova Science Pub Inc.

[2] Mossavar-Rahmani, F., and Zohuri, B. "Forecasting the Future: How Artificial Intelligence Is Revolutionizing Global Energy Demand Prediction." (to be published)

[3] Zohuri, B. 2025. "The Looming Threat Blackout of the National Grid and Critical Infrastructure (A National Security Crises)." *Journal of Energy and Power Engineering* 19: 31-5.

[4] Jones, N. 2018. "How to Stop Data Centres from Gobbling Up the World's Electricity." *Nature* 561 (7722): 163-6. https://doi.org/10.1038/d41586-018-06610-y.

[5] Fang, X., Misra, S., Xue, G., and Yang, D. 2012. 2011. "Smart Grid—The New and Improved Power Grid: A Survey." *IEEE Communications Surveys & Tutorials* 14 (4): 944-80. https://doi.org/10.1109/SURV.2011.101911.00087.

[6] Patterson, D., Gonzalez, J., Le, Q., Liang, C., Munguia, L.-M., Rothchild, D., So, D., Texier, M., and Dean, J. 2021. "Carbon Emissions and Large Neural Network Training." https://arxiv.org/abs/2104.10350.

[7] Shankar, S., and Reuther, A. 2022. "Trends in Energy Estimates for Computing in AI/Machine Learning Accelerators, Supercomputers, and Compute-Intensive Applications." https://arxiv.org/abs/2210.17331.

[8] Dominion Energy. 2023. "Loudoun County Transmission Line Project Overview." https://www.dominionenergy.com/projects-and-facilities/electric-projects/power-lines/loudoun-county.

[9] U.S. Department of Energy (DOE), Office of Electricity. 2022. "Grid Modernization Multi-Year Program Plan (MYPP)." https://www.energy.gov/oe/grid-modernization.

[10] International Energy Agency (IEA). 2021. *Smart Grids—Tracking Report*. Courtice: IEA. https://www.iea.org/reports/smart-grids.

[11] World Economic Forum. 2020. "Cyber Resilience in the Electricity Ecosystem: Playbook for Boards and Cybersecurity Officers." https://www.weforum.org/reports.