HOW AI'S DEMAND FOR ELECTRICITY CHALLENGES THE BULK POWER SYSTEM

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INTRODUCTION

The data centers that support artificial intelligence consume electricity at a scale rivaling cities.[1] Training OpenAI's ChatGPT-4 required roughly 50,000 megawatt-hours[2] of electricity.[3] That is enough to power San Francisco for three days.[4] As models grow more complex, training requirements and operational demands soar. ChatGPT-5 is estimated to use around 45,000 megawatt-hours of electricity each day, consuming the same amount of energy it takes to fully charge an iPhone battery for each of its 2.5 billion daily queries.[5]

The development of data centers in the U.S. is projected to increase electricity demand by hundreds of millions of megawatt-hours over the next decade.[6] Many recognize that the sheer volume of this demand threatens the reliability of the bulk power system. Clearly, if we do not have enough electricity due to AI-driven load growth, there will be a problem. Yet, few appreciate that *how* AI uses electricity, consuming huge and rapidly varying amounts of electricity, is challenging for an electrical system engineered to supply a steady frequency of alternating current. While this issue is secondary to meeting the volume of AI's energy needs, it could

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[1] Spencer Kimball, *Data Centers Powering AI Could Use More Electricity Than Entire Cities*, CNBC (Nov. 23, 2024), https://www.cnbc.com/2024/11/23/data-centers-powering-ai-could-use-more-electricity-than-entire-cities.html [https://perma.cc/X86M-RZDP].

[2] One megawatt-hour is approximately the amount of electricity that would be needed to power about 800 U.S. homes for one hour. *See How Much Electricity Does an American Home Use?*, U.S. ENERGY INFO. ADMIN. (Jan. 8, 2024), https://www.eia.gov/tools/faqs/faq.php?id=97&t=3 [https://perma.cc/FXX7-BE5A] (reporting average annual U.S. residential electricity consumption of 10,791 kWh, from which one megawatt-hour is sufficient to power approximately 800 homes for one hour).

[3] James O'Donnell & Casey Crownhart, *We Did the Math on AI's Energy Footprint. Here's the Story You Haven't Heard*, MIT TECH. REV. (May 20, 2025), https://www.technologyreview.com/2025/05/20/1116327/ai-energy-usage-climate-footprint-big-tech/ [https://perma.cc/JA64-TB2M].

[4] *Id.*

[5] *Id.*

[6] Arman Shehabi, Sarah J. Smith, Alex Hubbard, Alex Newkirk, Nuoa Lei, Md Abu Bakar Siddik, Billie Holecek, Jonathan Koomey, Eric Masanet & Dale Sartor, *2024 United States Data Center Energy Usage Report*, LAWRENCE BERKELEY NAT'L LAB., Dec. 20, 2024, at 5, https://doi.org/10.71468/P1WC7Q (projecting that data center growth will increase U.S. electricity demand by 174–394 TWh over the next decade); *see also id.* at 70 (describing how AI is a major accelerant of data center growth).

become increasingly important as AI-driven load takes up a larger share of demand. To understand this threat, this Tech Explainer will analyze the nature of electrical currents, examine the origins of our centralized bulk power system, and finally consider why the modern computing equipment at the heart of AI challenges reliability.

I. THE NATURE OF ELECTRICITY

Electrical currents are caused by the flow of electrons between atoms. Electrons carry a negative charge and orbit the positively charged nucleus of atoms in discrete energy shells.[7] In conductive materials, particularly metals, the sea of electrons in the atoms' outermost energy shells is only weakly bound and can be "delocalized," transferring energy by moving the electrons between atoms.[8]

Electrical currents propagate at a large fraction of the speed of light, moving energy around a circuit almost instantaneously.[9] However, this does not mean that electrons shoot instantly from a power source to a device. Instead, individual electrons "drift" slowly through conductive materials, causing a domino effect that pushes electrons in the circuit via electromagnetic force.[10] Just as water in a pipe can vary in pressure, electrical currents vary in voltage, the force of an electrical current.[11] Higher voltages move electrons with more force, and a change in voltage from positive to negative represents a reversal in the direction of the flow of electrons. When electrons move from one atom to another, the negatively charged movement creates an opposite, positively charged "conventional current," that can be used to power everything from lightbulbs to industrial motors.[12]

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[7] *The Science of Electricity*, U.S. ENERGY INFO. ADMIN., https://www.eia.gov/energyexplained/electricity/the-science-of-electricity.php [https://perma.cc/KAN8-Q5ZY].

[8] SAMUEL J. LING, JEFF SANNY & WILLIAM MOEBS, UNIVERSITY PHYSICS Volume 2 390–91 (OpenStax 2016), https://openstax.org/details/books/university-physics-volume-2 [https://perma.cc/Z4WD-FMMR].

[9] *Id.*

[10] *Id.* at 390.

[11] *Glossary: Voltage*, U.S. ENERGY INFO. ADMIN., https://www.eia.gov/tools/glossary/index.php?id=V [https://perma.cc/7E4Z-N4D3] ("The difference in electrical potential between any two conductors or between a conductor and ground. It is a measure of the electric energy per electron that electrons can acquire and/or give up as they move between the two conductors.").

[12] Ling *et al.*, *supra* note 8, at 389.

II. THE WAR OF THE CURRENTS

In 1831, Michael Faraday pioneered the mechanical creation of electric currents when he discovered that moving a magnet through a coil of conductive copper wire induces an electric current.[13] The mechanical motion of the magnet changed the magnetic field, exerting a force on electrons and causing them to shift, thus generating an electric current.[14] This discovery of electromagnetic induction remains the basis for the generators still used in power plants today.

Faraday's discovery enabled a wave of new electrical inventions, but early electrification efforts were constrained by a fundamental problem: many of these technologies relied on two incompatible forms of current, direct current (DC) and alternating current (AC).[15] Because DC flows in a single direction at a fixed voltage while AC reverses direction periodically, the two forms of current could not be easily interconnected across a common circuit, setting the stage for the "War of the Currents" that shaped the modern bulk power system.[16] The installation of electrical infrastructure was no small investment. As such, the promoters of electrification carried a significant burden to convince cities, industries, and homeowners to commit to installing devices of their respective electrical current.

On one side, Thomas Edison promoted DC electricity.[17] DC electricity flows through a circuit in one consistent direction.[18] This constant current occurs as negatively charged electrons are pushed one way, while the positively charged conventional current exists steadily in the opposite direction.[19] Since the direction of the negative charge and the direction of the positive charge remain constant, DC has a constant voltage polarity.

Edison promoted low-voltage DC because his lighting systems, meters, and underground networks were engineered for it.[20] Edison favored his more straightforward DC technology and feared that poorly installed and designed AC systems would impede the

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[13] JILL JONNES, EMPIRES OF LIGHT: EDISON, TESLA, WESTINGHOUSE, AND THE RACE TO ELECTRIFY THE WORLD 41 (2003). [hereinafter JONNES, EMPIRES OF LIGHT].

[14] *Id.*

[15] *Id.* at 163–71.

[16] Jill Jonnes, *Empires of Light*, Elec. Persp., 2003, at 50. [hereinafter Jonnes, *Electric Perspectives Article*].

[17] *Id.*

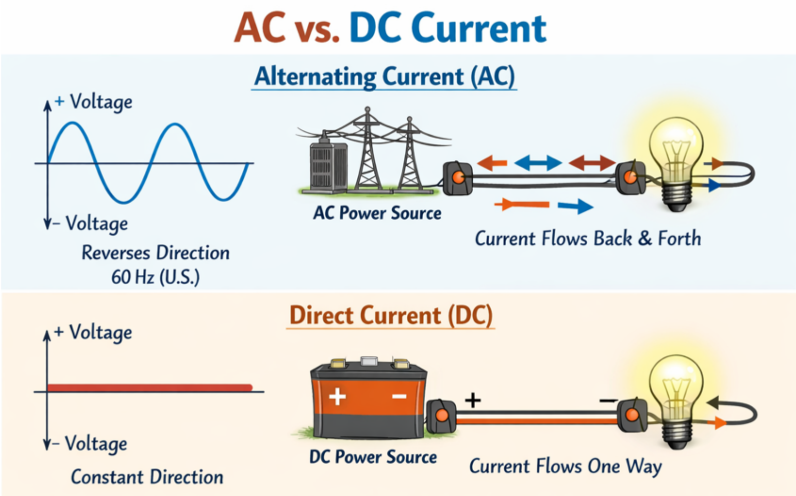
[18] PAUL ROSENBERG & ROBERT GORDON MIDDLETON, AUDEL PRACTICAL ELECTRICITY 12–14 (John Wiley & Sons, Inc. 2004).

[19] *Id.* at 14.

[20] Jonnes, *Electric Perspectives Article*, *supra* note 16, at 50.

adoption of electricity.[21] DC was also more apt for storage through the use of batteries.[22] Since batteries have a fixed positive and negative orientation, they require a current with constant voltage polarity to be charged and used on the same circuit.[23] Edison hoped to develop batteries for widespread use in local storage and electric cars.[24] However, DC was not well-suited to travel long distances along a circuit, so Edison envisioned electricity generated and distributed on a local basis.[25]

On the other hand, Nikola Tesla and George Westinghouse championed AC electricity.[26] AC electricity reverses the direction of the current back and forth on a regular cycle.[27] This happens as the voltage polarity changes from positive to negative, meaning that electrons are pushed backwards and forwards along the circuit as opposed to one constant direction.[28] While AC electricity reverses direction, it still delivers a consistent flow of energy. To understand this concept, it is useful to imagine a wood saw that moves back and forward along a log. The direction of the saw blade reverses from a forward cut to a backward cut, but the blade constantly exerts force on the wood, deepening the cut.



[21] JONNES, EMPIRES OF LIGHT, *supra* note 13, at 144–46.
[22] *Id.* at 44–46.
[23] ROSENBERG & MIDDLETON, *supra* note 18, at 20–26.
[24] JONNES, EMPIRES OF LIGHT, *supra* note 13, at 351.
[25] *Id.* at 142–44 (suggesting that Edison, as a businessman and inventor, was motivated by the patents and royalties tied to his DC-based inventions).
[26] Jonnes, *Electric Perspectives Article*, *supra* note 16, at 50.
[27] ROSENBERG & MIDDLETON, *supra* note 18, at 129.
[28] *Id.*

Figure 1: AC and DC voltages contrasted[29]

Unlike DC, AC can be stepped up to high voltage for efficient long-distance transmission and then stepped down for safe customer use. AC is suitable for transformation to different voltages because the alternating polarity of the current creates a constantly changing magnetic field that can be passed on in a transformer from one conductive coil to another without breaking the circuit.[30] By stepping electricity up to high voltages, AC electricity could be transmitted over much larger distances, allowing a few large generating stations to serve wide areas.

In addition to expanding transmission ranges, using AC electricity shaped what equipment could connect directly to the power system. AC is not directly compatible with batteries since the changing polarity does not align with a battery's fixed positive and negative orientation. However, AC was extremely well-suited for the rotary generators and motors that Tesla designed and patented.[31] As the rotor spins up along a conductive surface and down the other side, electrons are pushed backwards and forwards, experiencing a natural reversal in voltage polarity. Since many of the large implements of the early electric system used Tesla's AC rotor-based devices, including coal-powered generators and industrial motors, AC could be used directly across the system without requiring conversion of AC to DC.[32] Since the 19th Century it has been possible to convert AC to DC and vice versa; however, the devices required to do so add additional costs and create efficiency losses that even to this day remain sizeable, making compatibility without conversion desirable.[33] The benefits of AC electricity led many of Edison's early DC motors and generators to be exchanged for Tesla's AC devices.[34]

AC electricity's aptitude for transmission ultimately led Tesla and Westinghouse to win the "War of the Currents," establishing AC as the standard and shaping the modern bulk power system by allowing the centralization of generation.[35]

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[29] OpenAI, AI-Generated Image Depicting the Features of AC Current and DC Current (generated Mar. 4, 2026).

[30] ROSENBERG & MIDDLETON, *supra* note 18, at 143.

[31] JONNES, EMPIRES OF LIGHT, *supra* note 13, at 107.

[32] PHILLIP F. SCHEWE, THE GRID: A JOURNEY THROUGH THE HEART OF OUR ELECTRIFIED WORLD 53–55 (2007).

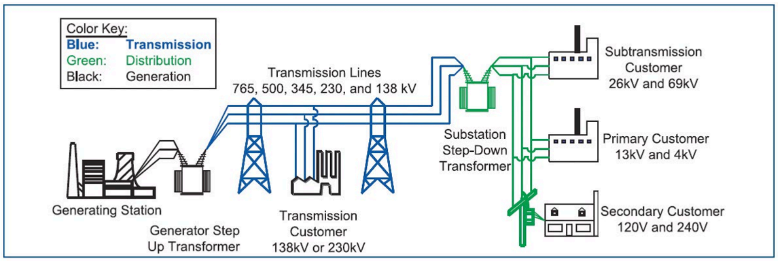
[33] Jim Sinopoli, *Using DC Power to Save Energy—and End the War on Currents*, TRELLIS (July 24, 2024), https://trellis.net/article/using-dc-power-save-energy-and-end-war-currents/ [https://perma.cc/4NNZ-QUYR].

[34] SCHEWE, *supra* note 32, at 77–80.

[35] *Id.* at 55.

III. THE MODERN BULK POWER SYSTEM

As more distribution systems committed to installing AC electricity infrastructure over the following century, the bulk power system was transformed from an array of small-scale generators and local consumers to a massively interconnected system with complex and professionally operated generation facilities.[36] Because transformers could effectively move high voltage AC electricity over great distances, centralized generation facilities could reach increasingly large consumer bases.[37] This growth helped enterprising providers like Samuel Insull cultivate new demand to support investment in larger infrastructure and assets while making electricity affordable to a broader public.[38] From harnessing the energy of Niagara Falls to unlocking the power of the atom through nuclear fission, growing consumer bases and advancing generation technologies promoted rapid expansion of the grid.



Source: NERC

Figure 2: Generation and transmission components and their associated control systems.[39]

Today, the US bulk power system extends all throughout the country so that access to reliable electricity is taken for granted. The bulk power system is organized into three AC-based interconnections: the Western interconnection, Eastern interconnection, and Electric Reliability Council of Texas (ERCOT).[40] Each system is synchronized at a frequency of 60 Hz, meaning the current reverses 60 times per second.[41] Since electrical current delivers energy essentially instantaneously across the system,

[36] *Id.* at 77–80.
[37] *Id.* at 45–51.
[38] *Id.* at 104–06.
[39] FED. ENERGY REGUL. COMM'N, *Reliability Primer* 10 (2020), https://www.govinfo.gov/content/pkg/GOVPUB-E2-PURL-gpo246326/pdf/GOVPUB-E2-PURL-gpo246326.pdf (image credited to NERC).
[40] *Id.* at 10.
[41] *Id.* at 23.

the supply of electricity must constantly be balanced with the demand.[42] If the supply of electricity fails, lights go out quickly, even hundreds of miles away.

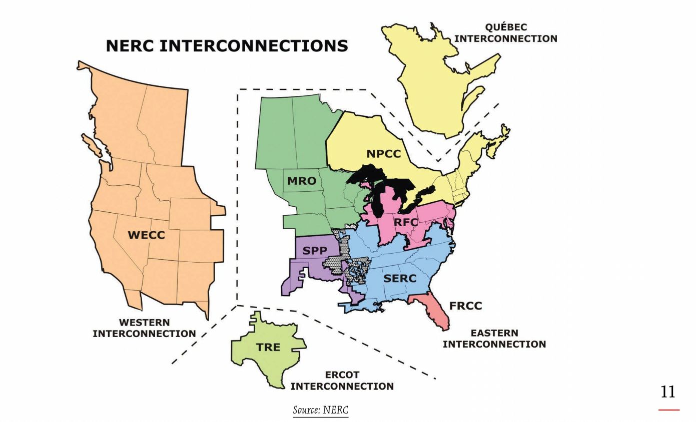


Figure 3: Map of North American Electric Reliability Corporation (NERC) electrical transmission network.[43]

A. THE 60-HERTZ HEARTBEAT

Frequency is the vital sign of this system.[44] Generation assets must stay synchronized on a common 60 Hz heartbeat to serve millions of connected devices. When supply and demand are in balance, frequency remains near its "nominal" value of 60 Hz. However, when demand exceeds supply, the system "slows" and frequency declines; when supply exceeds demand, the frequency increases.[45] If the frequency deviates too far from the nominal value of 60 Hz, protective relays can automatically trip equipment offline to prevent damage.[46] While this measure protects the equipment, the equipment going offline further disrupts balancing, potentially creating a cascade that could cause widespread blackouts.[47]

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[42] PJM INTERCONNECTION, L.L.C., *PJM Manual 12: Balancing Operations* § 3.1 (Oct. 1, 2025), https://www.pjm.com/-/media/DotCom/documents/manuals/m12.pdf [https://perma.cc/FWS8-2HHN].

[43] FED. ENERGY REGUL. COMM'N, *supra* note 39, at 11.

[44] N. AM. ELEC. RELIABILITY CORP., *Balancing and Frequency Control* 6 (May 11, 2021), https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/rs/reference_document_nerc_balancing_and_frequency_control.pdf [https://perma.cc/4AMZ-4UQM].

[45] *Id.* at 6.

[46] *Id.* at 8.

[47] *Id.*

To prevent deviations in frequency, balancing authorities operate throughout each interconnection to manage the real-time matching of resources and demand. They adjust generator outputs, deploy reserves, and reduce flexible demand. Balancing authorities constantly react to keep frequency movement within tolerances that protect equipment and prevent cascading outages.

AI's dependence on rapidly varying amounts of electricity is making the job of balancing authorities more difficult. Since the development of the first AC-based interconnections, balancing authorities have benefited from the rotational nature of many generators and motors used throughout the system. When instability occurs due to generation failures or rapid changes in load, the bulk power system's first line of defense is inertia, the kinetic energy stored in the rotating masses of online synchronous generators, which slows the rate of frequency change.[48] For example, if the supply of steam propelling a turbine suddenly stops, the mere weight of the equipment will continue to rotate the turbine, preventing a sudden and complete stop in electrical current. This buys valuable time for automated protections, such as governors, to kick in and correct the issue.[49] The stability of the bulk power system also benefits from frequency sensitive devices that smooth deviations by using more energy when frequency increase and less when it decreases.[50] For example, AC motors that directly use AC electricity from the bulk power system speed up with frequency increases and slow down with decreases, creating a natural smoothing effect.[51]

B. THE NEW "INERTIA-LESS" GIANT

Considering how AC-based devices can aid in smoothing frequency disruptions, the composition of load matters. DC-based systems like photovoltaic panels, batteries, and computer equipment, in contrast, are fundamentally different due to their lack of frequency.[52] These implements do not have inertia to buffer drop-offs or rotational components that can smooth frequency instability. When a DC-based device ramps up or down, changes are to demand are sudden. This can pose difficulties for balancing authorities.

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[48] *Id.* at 7.

[49] *Id.* at 8.

[50] Paul Denholm, Trieu Mai, Rick Wallace Kenyon, Ben Kroposki & Mark O'Malley, *Inertia and the Power Grid: A Guide Without the Spin*, NREL, May 2020, at 13, https://www.nrel.gov/docs/fy20osti/73856.pdf [https://perma.cc/Q26E-GQGC].

[51] *Id.* at 8.

[52] Sinopoli, *supra* note 33.

DC electricity is integral to computer processing because computers rely on precise variations in voltage to store and transmit information through binary language.[53] High voltage states are used to express ones, while low voltage states are used to express zeros.[54] A steady supply of DC electricity is crucial to maintain the stable voltage polarity necessary for binary language.[55]

Any reversal of voltage polarity, as found in AC electricity, would completely undermine the storage and exchange of computer information by disrupting the voltage values that the computer expects. Powering computer hardware directly with AC would be like trying to write a book while the pages are being flipped upside down 60 times each second. As a result, computers must convert AC power from the bulk power system to DC for use in CPUs, GPUs, and other computer components that transmit information through voltage manipulation. If you have ever felt the charging block of a computer, you have experienced this firsthand. These converters lose some of the energy from the AC current as heat when changing the current to DC as needed for the computer.

Computing hardware depends on stable DC voltage and does not "ride" frequency variation like motor-driven processes. Thus, data centers can amplify balancing challenges when electricity demands shift rapidly.[56] Since data centers convert AC from the bulk power system, a rapid ramp down in electricity demand for computation has a similar impact to a large AC load tripping offline. Balancing authorities are equipped to deal with these situations, yet the frequency and scale with which these swings occur in the context of AI data centers presents a legitimate reliability concern, as data centers can ramp back up just as quickly.

The volatility of traditional data centers has been limited by steady computational workloads, yet data centers powering AI are different. Traditional computing facilities were built primarily to store, process, and retrieve information, relying on conventional servers that draw power in steady, predictable rhythms.[57] An AI data center, however, operates less like a quiet archive and more like a heavy-industrial forge. AI workloads do not pull electricity in a

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[53] *Binary Numbers and the Binary Number System*, ELECS. TUTORIALS (Aug. 8, 2022), https://www.electronics-tutorials.ws/binary/bin_1.html [https://perma.cc/84JN-DLHM].

[54] *Id.*

[55] *Id.*

[56] N. AM. ELEC. RELIABILITY CORP., *Characteristics and Risks of Emerging Large Loads*, NERC 3 (July 2025), https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/whitepaper-characteristics-and-risks-of-emerging-large-loads.pdf [https://perma.cc/45GB-UJPC].

[57] *Id.* at 5.

smooth, continuous stream when training a model.[58] Sudden surges of hardware activity create massive, instantaneous fluctuations in power demand that occur as large numbers of computer chips draw DC electricity to process and record information using countless binary voltage manipulations.[59] Training necessitates unpredictable computer reactions to data, meaning that a facility's power draw can surge or plummet rapidly.[60] These inertia-less loads can shift in less than a second, which is faster than conventional generators can ramp.[61] Thus, ramps of substantial speed or magnitude can create serious frequency regulation problems. From the balancing authorities' perspectives, demand fluctuation events that were once rare occurrences due to outages, are now typical during AI training.

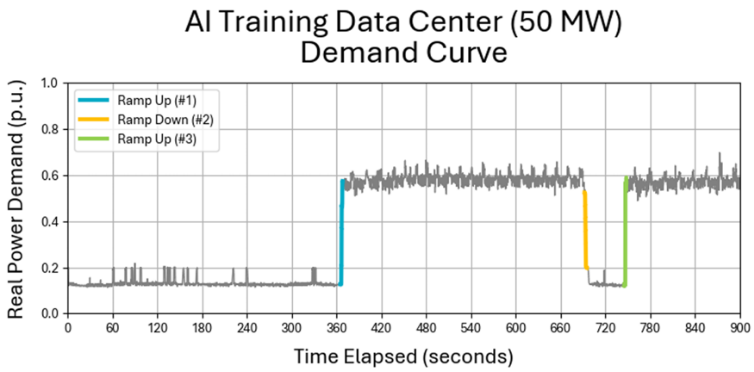

Figure 2.2: An AI Training Data Center Begins a Training Run (EdgeTunePower)

Figure 4: AI training data center demand curve.[62]

The scale of energy needed for training exacerbates the threat. Instead of standard processors, AI relies on massive, densely packed clusters of specialized graphics processing units (GPUs) working simultaneously to map connections across billions of parameters.[63] Because these specialized AI servers can demand up to ten times the power of standard equipment, the facilities operate at

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[58] N. AM. ELEC. RELIABILITY CORP., *supra* note 56, at 5–6.

[59] *Id.*

[60] *Id.*

[61] *Id.*

[62] *Id.* at 6 (citing EdgeTunePower, *Data Center Power Management*, https://www.etpower.ca/data-center-power-management [https://perma.cc/QKL3-3CSQ]).

[63] Divya Mahajan, *AI's Ballooning Energy Consumption Puts Spotlight on Data Center Efficiency*, THE CONVERSATION (Sept. 3, 2025), https://theconversation.com/ais-ballooning-energy-consumption-puts-spotlight-on-data-center-efficiency-254192 [https://perma.cc/6SDB-D9MJ].

extreme power densities.[64] This staggering concentration of electricity generates blistering heat, which in turn demands energy-intensive cooling systems to keep computer components operational.[65] To make matters worse, AI's electricty demand swings while training may become larger as model size increases. Larger models require more computations, meaning that more energy hungry GPUs must draw electricty.

Inference, which is the process of using a trained AI model to generate outputs, uses a significantly more stable electricity demand.[66] In 2022, Google stated that 40% of its AI energy use was for training while the other 60% went to inference.[67] Therefore, once models are trained reliablity risks can be reduced. Communication between balancing authroities and AI developers is important to prepare for fluctuations when training will occur.

CONCLUSION

The growing electricity demands and rapid fluctuations in electricity use of AI threaten reliability. While many policymakers are focusing on meeting growth, policy ensuring frequency regulation during AI training should not be overlooked. Fortunately, the inertia-less features of DC loads can also be used to improve reliability. The very features that make AI data centers challenging, digital control, telemetry, and fast response, make AI a promising candidate to improve reliability through the coordination of inverter-based generation assets like photovoltaics and batteries as well as flexible demand.[68] Through coordinated flexibility and delay-tolerant workloads, these massive facilities can support fast frequency response in low-inertia grid conditions. With the tremendous growth in AI-load, the bulk power system will need to evolve from a system that gradually ramps to a system that can rapidly meet changes in demand with inverter-based technologies that inject electricity instantly into the system.

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[64] *Id.*

[65] *Id.*

[66] N. AM. ELEC. RELIABILITY CORP., *supra* note 56, at 7.

[67] David Patterson, *Good News About the Carbon Footprint of Machine Learning Training*, GOOGLE RSCH. BLOG (Feb. 15, 2022), https://research.google/blog/good-news-about-the-carbon-footprint-of-machine-learning-training/ [https://perma.cc/XF2F-ELDH].

[68] Denholm et al., *supra* note 50.