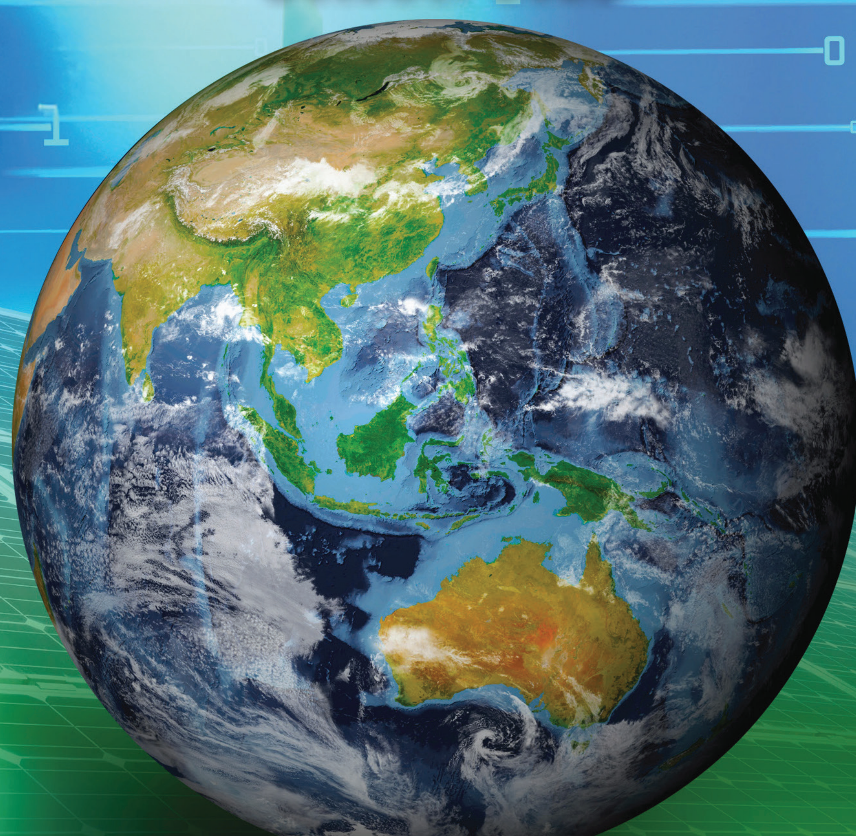
SUSTAINABLE DATA CENTERS ROADMAP

CHAPTER 3.2

Power Supply Greenhouse Gas Emissions (Scope 2)

Colin McCormick

October 2025



Innovation for Cool Earth Forum

3.2 Power Supply Greenhouse Gas Emissions (Scope 2)

Colin McCormick

A. Overview

Modern data centers consume large amounts of electricity. The International Energy Agency (IEA) estimates that electricity consumption by data centers produced 180 million tons of carbon dioxide ($MtCO_2$) emissions in 2024 (roughly 0.5% of global CO_2 emissions). In the IEA Base Case Scenario, these CO_2 emissions roughly double by 2030. (See Chapter 1 of this Roadmap.)

Most electricity for data centers is purchased from the electric grid ("in front of the meter" or "FTM"). The resulting greenhouse gas emissions are included under Scope 2 of the Greenhouse Gas Protocol Corporate Standard.[1] This chapter discusses the greenhouse gas emissions implications of data centers' reliance on the grid, current debates on revising Scope 2 methodology, approaches to mitigating Scope 2 emissions for data centers, and related issues that arise with respect to greenhouse gas emissions from on-site generation ("behind the meter" or "BTM"). The chapter concludes with Recommendations.

B. Scope 2 Location-Based Emissions for Data Centers

The Greenhouse Gas Protocol provides two separate methods for calculating emissions from the use of grid-supplied electricity. These methods are known as "location-based" and "market-based," and they can produce significantly different results.[2] Thus, the best practice for corporate emissions disclosure is to report both.

The location-based method considers electricity emissions from an engineering perspective. Because of the nature of electric power flow, the grid's electricity comes from many different power plants (the "grid mix"). Because the power plants on a grid typically use different types of technologies (e.g., gas, coal, wind, solar, etc.), they have very different CO_2 emissions per unit of electricity generated. Determining location-based emissions of grid-supplied electric power therefore requires averaging the emissions of all power plants on the relevant grid.

Typically, the "relevant" grid is considered to be the balancing area (or control area) over which a single grid operator is responsible for ensuring that electricity generation and supply are continually matched. This can be at the national, sub-national or super-national level. Grids with large amounts of low-carbon power generation, such as renewables or nuclear, have very low average greenhouse gas emissions per unit of energy generated ("carbon intensity"). For example, hydro-rich Sweden averages 8 g of CO_2 equivalent (gCO_2e)/kWh and nuclear-rich France averages 48 gCO_2e/kWh.[3] In contrast, grids with large amounts of coal have very high values (e.g., 623 gCO_2/kWh for Indonesia[4]). The global average grid carbon intensity in 2024 was 473 gCO_2/kWh[5]; IEA expects this figure to fall by approximately 4% per year through 2026[6] as grids add more low-emitting power generation and as high-emitting power plants are retired.

Because of the large range in grid carbon intensities in different regions, Scope 2 location-based emissions for data centers are heavily influenced by their location. Identical data centers located in different regions could have Scope 2 location-based emissions that differ by almost 100x. For example, a hypothetical 100 MW data center with a PUE of 1.2 that operates at 80% capacity would have Scope 2 location-based emissions of 6727 tCO_2e/year in Sweden and 523,918 tCO_2e/year in Indonesia[a].

As noted above, IEA estimates that data centers accounted for 180 Mt of CO_2 emissions in 2024.[7] Under the IEA Base Case Scenario, data center energy consumption will grow to 945 TWh/year by 2030. If this power were supplied by electricity with the 2024 global average emissions intensity, it would result in 447 $MtCO_2$ of Scope 2 location-based emissions. However, if average grid carbon intensity falls as projected by IEA, the 2030 global average grid carbon intensity will be 370 gCO_2/kWh, and emissions from data centers in the IEA Base Case would be 350 $MtCO_2$. Data center growth will likely be concentrated in particular countries and regions, so a more detailed analysis of electricity emissions for these specific grids (rather than the global average) would be needed to improve these estimates.

While calculation of Scope 2 location-based emissions currently uses annual average grid emissions intensity, the hour-to-hour emissions intensity of some grids can vary by large amounts. This is particularly true for grids with high solar and wind penetration. They can experience some hours with essentially zero emissions (during sunny and/or windy conditions when power is mostly supplied by solar and wind) followed by other hours with high emissions (when power is mostly supplied by gas or coal). Emissions intensity on some grids can also change substantially from season to season, for similar reasons. While this variability can pose challenges for maintaining grid reliability (e.g., the solar "duck curve" in the US,[8] Australia,[9] India[10] and elsewhere), it also means that shifting electricity consumption to low-emissions hours can significantly reduce actual emissions from electricity use.[11] This has led to proposals for reforming the Scope 2 location-based methodology (see below). It has also helped motivate some data centers to use load flexibility (see Chapter 4 of this Roadmap).

a This is calculated as follows. By convention, the 100 MW data center with PUE of 1.2 would draw 120 MW of power from the electric grid. Operating at 80% capacity, it would consume 840,960 MWh of grid power during a single year. Multiplying by the average carbon intensity of the grids in Sweden and Indonesia gives 6,727 tCO_2e and 523,918 tCO_2e, respectively. However, the amounts are usually negligible.

C. Scope 2 Market-Based Emissions for Data Centers

The Scope 2 "market-based" method considers electricity emissions from a market perspective. This method begins with the location-based emissions amount and then replaces grid-supplied energy with any renewable energy that was procured through market-based instruments, such as power purchase agreements (PPAs), on an energy basis (i.e., on a MWh-for-MWh basis, see Box 3.2-1). Under this method, the greenhouse gas emissions from procured renewable energy are effectively zero,[b] meaning that Scope 2 market-based emissions can be significantly reduced or even brought all the way to zero by procuring a sufficient amount of renewable energy. Many data center operators procure large amounts of renewable energy through PPAs for this purpose. The four large hyperscalers (Amazon, Google, Meta and Microsoft) are the largest corporate buyers of renewable energy globally, having collectively procured more than 84 GW via PPAs as of early 2025.[12] Thus, they report far lower Scope 2 market-based emissions than location-based emissions. (Not all hyperscalers report both location-based and market-based emissions, making this comparison difficult in some cases.)

The Greenhouse Gas Protocol Scope 2 guidance is under revision in 2025, with a final version expected in 2027. While the general concepts of separate location- and market-based emissions reporting will likely remain, the methods used to determine

b In some cases, procured renewable energy may be deemed to have a small amount of greenhouse gas emissions for the purposes of the Scope 2 market-based method. However, this is not typical, and the amounts are usually negligible.

the actual amount of emissions offsets will change. Several alternative approaches have been proposed, with the intention of more closely matching the physical nature of renewable power supply (such as time-variation in the grid mix) and/or more closely addressing overall impacts of power generation[13] on CO_2 emissions. The revisions will likely focus on more regional- and time-based matching requirements, limiting the ability to “replace” grid-supplied electricity with procured renewable energy on grids that are not where a company consumes power (e.g., through virtual PPAs (VPPAs), see Box 3.2-1) or with procured renewable energy that does not match the time profile of a company’s power consumption.[14]

Box 3.2-1

Market-based instruments for renewable power procurement

Corporate procurement of renewable electricity using market-based instruments is widespread, but the different types of instruments can lead to confusion. Power purchase agreements (PPAs) are the primary type of contract used in corporate procurement of renewable energy. PPAs can be either “physical” or “virtual” (also known as VPPAs).[15] Under physical PPAs, the buyer is located on the same grid as the supplier and takes ownership of the actual generated energy, “bundled” with its renewable attributes in the form of energy attribute certificates (EACs, see below). In a small number of cases, the buyer and seller are physically co-located, and the generated energy can be directly delivered behind the meter; this is known as a “direct PPA.” However, in most cases the buyer is not physically co-located with the seller’s power plant (despite being on the same grid). In these cases, the PPA is “sleeved,” with the generated energy supplied to the relevant utility, which then provides the equivalent amount of energy to the PPA buyer’s facilities. This may be supplied at different times of day from when the energy is physically generated, meaning that the utility must provide balancing services (for a “sleeving fee”).[16,17]

Because direct and physical PPAs require a buyer to find a renewable generator on the same grid, the possible supply is limited. To address this, many companies use VPPAs, which are purely financial transactions. Under a VPPA, the buyer guarantees a long-term fixed price for renewable energy generated by a power plant, and the seller sells the energy into its local grid (essentially a contract-for-differences). In return, the buyer takes title to the EACs. VPPAs allow buyers to secure EACs from renewable energy generation on grids that are far away from their physical location, greatly increasing the available supply of PPAs.[18] Direct and physical PPAs are usually regulated under different legal frameworks than VPPAs.[19] While VPPAs have dominated corporate renewable energy purchasing in the United States,[20] physical PPAs are more prevalent in Europe.[21]

Electricity EACs that are "bundled" with PPAs and VPPAs are denominated in MWh of generation. Specific examples of electricity EACs include renewable energy certificates (RECs)[22] in North America, Guarantees of Origin (GOs)[23] in Europe and Green Electricity Certificates (GECs) in Japan[24] and China.[25] Guidelines for EAC quality published by RE100 are used by many corporate procurers of renewable energy.[25] Many electricity EACs can also be procured "unbundled," which is essentially a direct purchase of the certificates themselves (from a renewable power generator or an intermediary broker) without any consideration of the underlying electricity. Typically, this is the lowest-cost way to obtain EACs, but it has the least direct and demonstrable linkage to accelerating deployment of renewable energy generation.

PPA buyers "retire" EACs to reduce their Scope 2 market-based emissions. This is done on a MWh-for-MWh basis, meaning that, in calculating emissions, each MWh of retired EACs replaces a MWh of electricity purchased from a grid, with the EAC typically carrying a zero (or sometimes near-zero) greenhouse gas emissions value. By procuring and retiring enough MWh of EACs to match or exceed the actual total procured MWh of electricity, companies can reduce their Scope 2 market-based emissions to zero.

While the use of PPAs has provided large amounts of capital to the renewable energy industry and has supported its rapid growth in many markets, it has also attracted criticism for enabling corporate emitters to "deem" emissions to be lower under the Scope 2 market-based method (by retiring the bundled EACs).[26,27] The use of unbundled EACs has attracted even more criticism.[28]

D. Mitigation Strategies for Scope 2 Location-Based Emissions

A variety of strategies can be used to reduce Scope 2 location-based emissions for data centers. In general, the strategies that will have the largest impact depend on the nature of the electric grid where the data center is located.

I. **Energy efficiency.** Ensuring maximum energy efficiency at both existing and new data centers by adopting the use of advanced cooling methods, increasing algorithmic efficiency, and implementing related techniques is highly impactful for reducing emissions on high-emissions grids. It also has numerous additional benefits even on relatively low-emissions grids (see Chapter 2 of this Roadmap). Energy efficiency reduces the total amount of high-emissions power generation required to serve a data center and minimizes additional impacts like land and water use for power production.

II. **Siting.** Physically siting new data centers in regions with low-emissions grids can have a large impact on ensuring Scope 2 emissions are low, given the large difference in average grid emissions intensity. However, this strategy does not apply to existing data centers that are located in high-emissions grid regions, and many planned data centers have other siting constraints that outweigh emissions considerations. Large new data centers may also require more additional power than low-emissions grids can supply.

III. **Load flexibility.** Implementing data center load flexibility by using on-site clean generation and storage and actively managing the timing of power consumption from the grid is highly impactful for reducing emissions on grids with large daily variation in their emissions intensity, such as those experiencing the "duck curve." Load flexibility can help ensure that data centers reduce their electricity demand during periods of peak grid demand, reducing the need to run the highest-emitting generators (typically gas-fired peaker plants). It can also be used to charge on-site storage during periods of high renewable generation, potentially avoiding the need to curtail solar and wind.[29,30] However, for grids that do not experience significant emissions variation throughout the day, load flexibility does not have a significant short-term impact on reducing emissions. In the longer term, load flexibility can reduce the amount of new generation capacity that a utility will build since utilities typically build new capacity to meet the projected future peak load. Particularly in cases when new gas-fired power plants are being planned for capacity addition, reducing the forecasted peak load can limit the construction of these plants and minimize potential “lock-in” of future emissions. (See Chapter 4 of this Roadmap.)

In addition to these strategies for individual data centers, utilities and grid operators can add low-carbon power generation to existing grids to serve new data center load. Adding power generation to existing grids (“expanding capacity”) is primarily under the control of utilities and grid operators, who respond to forecasted power demand from a wide range of power users. However, in a growing number of high-profile cases, the projected additional power demand from a data center is so large that the data center operator (typically a hyperscaler) has become directly involved with the utility planning process and tariff design.[31,32]

Data center operators can also seek to secure dedicated (BTM) on-site/co-located power to supplement or entirely replace grid-supplied power, often for the purpose of moving more quickly than utility planning processes allow. This can be challenging for several reasons, including limited physical space available for on-site generation, backlogged supply chains for key equipment, and operational reliability challenges (see below).

Several factors influence which types of generation technology are optimal for a given grid region and data center, including the following. These factors guide which types of generation technologies utilities plan to add to serve new load from data centers and other end users and also influence potential selection of on-site/BTM generation options.

i. **Dispatchability.** Generators that can be fully controlled, or “dispatched,” are relatively simple to integrate into an existing grid. Grid operators can directly ramp this generation up and down to match changes in power demand and to balance variable power supply from other generators. They can also incorporate this predictable generation into near-term power markets (e.g., day-ahead) to ensure adequate supply in advance. Dispatchable generation technologies include gas, coal, hydroelectric, geothermal and nuclear.

   Notably, while all of these generators can be dispatched, some can only adjust their generation output (“ramp”) relatively slowly (particularly nuclear and coal), while others can ramp more quickly, such as hydroelectric and gas. Open-cycle gas turbines (OCGTs) are typically the fastest-ramping generators and are dispatched by grid operators to respond to rapid changes in load or generation. A related but separate issue is the “cold start” time for different generators, which is the time it takes to turn back on from a full shutdown. This can be many hours or longer in the case of coal and nuclear.[33]

Solar and wind (“intermittent” renewables) are non-dispatchable generation technologies because grid operators cannot always turn them on at a specified time. However, their generation is predictable, meaning that grid operators can use weather models to reliably forecast how much power these technologies will generate over the next several hours to days.[34] Increasingly, AI-based weather forecasting is improving these predictions and extending them farther into the future.[35] Using these forecasting methods, in combination with load forecasting methods, allows grid operators to predict how much additional generation will be needed in future hours and to plan accordingly. A growing number of grids are installing large-scale energy storage (typically batteries) to shift when the energy generated by intermittent renewables is delivered to load. This improves reliability and allows the grid to better match time profiles of energy usage.[36] Batteries can also be integrated with solar and wind generation facilities, “firming” the combined facility and making it dispatchable, within some constraints.[37,38] Unfortunately, some grid operators are facing challenges in approving variable renewables for interconnection because of the need to implement accelerated processes to study the impact of intermittent generation.[39,40]

ii. **Technology readiness.** While some generation technologies are fully mature and well-proven commercially, others are in the early stages of development and lack established performance records at scale. In general, only mature technologies can be integrated into commercial power grids at scale, while emerging ones require phased scale-up and testing (with some exceptions).[41] Notably, data center hyperscalers have been willing to employ early PPAs to support development of some emerging power generation technologies for connection to the grid to the grid.[42,43] In addition to providing small amounts of additional low-emissions power, this practice can have important benefits for accelerating these technologies into the market. (See Chapter 4 of this Roadmap.)

iii. **Location flexibility.** All power generation technologies have constraints on where they can be built and operated. Some of these constraints are driven by regulatory or commercial factors, while others depend on technology and infrastructure. Solar and wind rely on natural resources that are unevenly distributed globally, hydroelectric relies on water resources and appropriate terrain, and geothermal depends on appropriate subsurface characteristics. Natural gas relies on gas pipeline infrastructure (including availability of additional transmission capacity), and adding carbon capture and storage (CCS) to natural gas requires appropriate geological storage and/or CO_2 transport. Coal relies on coal availability and transport infrastructure, and nuclear relies on fuel supply chains and waste disposal. The physical footprint of each technology also influences location flexibility, particularly in the context of on-site/co-location strategies for which space may be limited. In general, gas, coal and nuclear have small footprints that are more compatible with constrained existing data center locations, while solar and wind require large land areas that may not be available at these sites.

iv. **Costs.** Cost is central to decisions about which type of power to procure for data centers. Many data center developers prioritize least-cost power options, but this is by no means universal. Some hyperscalers have shown a significant willingness to pay for low-carbon power, even if cheaper high–carbon emitting options are available (including willingness to support emerging and developing technologies as noted above). Cost is influenced by many factors, including the scale and maturity of relevant supply chains, labor expertise and availability, commodity prices and financing.[44]

V. **Low-carbon on-site power generation strategies.** On-site, BTM power generation can in theory provide some or all of the electricity requirements for data centers during normal (non-emergency) operations. This approach has been rare, due to a combination of high-power requirements, high costs and limited onsite space, but some data center developers are now seriously exploring this option at some sites.[45,46] On-site generation can reduce or potentially eliminate the need for grid-supplied power, although completely "off grid" data centers must fully manage power supply reliability without help from the primary electric grid, a major technical challenge. A key consideration for selecting on-site power generation technologies is the need for a generator (usually in combination with some form of energy storage) to provide continuous power over long durations (i.e., a high-capacity factor) to match high data center uptime rates.

In some locations, variable renewable energy (solar and wind) backed by storage systems (e.g., lithium-ion batteries) can provide this power, resulting in very low life-cycle greenhouse gas emissions.[47] Dispatchable renewable generation, particularly geothermal and hydroelectric (both of which require no or minimal additional energy storage) can also provide decarbonized power if sufficient resources are available at or near the data center site.[48] Enhanced geothermal systems (EGS) may be particularly suited for decarbonized data center power due to their greatly expanded geographic reach and their dispatchability,[49] recent examples include Google's agreement with Fervo[50] and Meta's agreements with Sage Geosystems[51] and XGS Energy.[52]

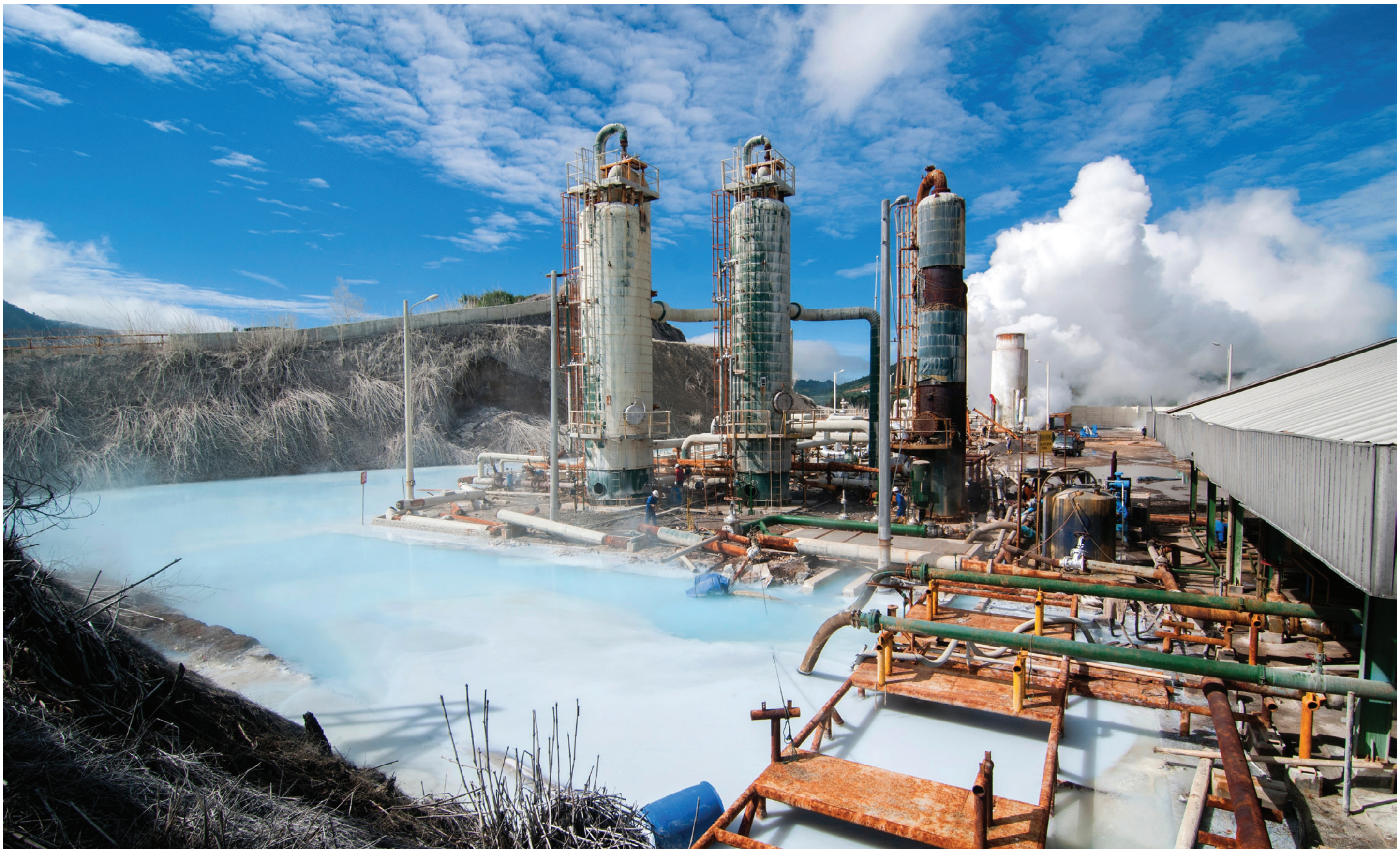
Gas-fired generation with CCS can provide low-carbon power at data center sites, with a relatively small physical footprint and high-capacity factor. The location constraints of this technology are driven primarily by access to CO_2 transport and storage rather than hydrological resources, subsurface heat or weather patterns.[53] Prominent examples of gas-fired generation with CCS include the announced[54] Crusoe/Tallgrass data center and the announced Frontier/Baker Hughes Sweetwater project,[55] both in Wyoming, United States.

Solid oxide fuel cells (SOFCs) are emerging as a source of on-site power generation.[56] These systems will mostly run on natural gas initially but are intended to switch to low-emissions hydrogen at a future date. SOFCs can be highly energy efficient in converting natural gas to electricity. They are particularly energy efficient when they are paired with district heat or other uses for their high-temperature waste heat, further reducing the intensity of greenhouse gas emissions compared to gas-fired generation.[57] However, the commercially deployed scale of SOFCs remains far lower than power generation systems based on gas-fired turbines, suggesting that scaling to multi-hundred-megawatt deployments may be a challenge.[58] SOFCs can be integrated with CCS to reduce emissions, although this approach has not been deployed commercially at scale.

Conventional nuclear power—both full-scale reactors and small modular reactors (SMRs)—is a potential source of decarbonized power for data centers with a compact footprint.[59] It has no inherent locational constraints, but it has substantial cooling requirements and relies on a nuclear fuel cycle supply chain that is highly limited in many relevant jurisdictions.[60] Recent high-profile examples, all of which are in the United States, include the planned restart of the 835-MW Unit 1 at the Three Mile Island nuclear power plant (scheduled for 2027)[61]; the planned construction of several SMRs, ranging from 50 MW to 320 MW in several locations (scheduled for 2030[62] and later[63]); and the planned construction of up to four GW-scale new AP1000 nuclear reactors (scheduled for 2032[64]).

There has also been significant interest in emerging nuclear fusion power technology for data centers, although this technology remains relatively early-stage and lacks an established supply chain for fuel and components.[65] A recent high-profile example is the planned construction of a 400-MW fusion power plant in the United States (scheduled for the early 2030s).[66]

Regardless of generation technology, BTM power requires careful integration with on-site backup power systems and energy storage, as well as potential coordination with grid supplied power, if the site maintains a grid tie. This places substantial reliability and coordination requirements on the BTM power generation.



E. Mitigation Strategies for Scope 2 Market-Based Emissions

All strategies for reducing Scope 2 location-based emissions are also relevant for reducing market-based emissions because the calculation of market-based emissions begins with the location-based total. Data center operators can further reduce market-based emissions by purchasing and retiring electricity EACs (see Box 3.2-1). The highest impact for this approach is by procuring renewable energy through PPAs bundled with EACs. As noted, the major hyperscalers have used this approach for well over a decade,[67] providing a revenue stream that supports many renewable energy projects around the world. The largest market remains North America,[12] but renewable PPAs are growing in Europe[68] and Asia.[69] This strategy will continue to be highly relevant, with hyperscalers expanding their renewable energy procurement in 2025.[70]

However, the growing use of electricity EACs to reduce market-based emissions has been controversial, with criticisms falling into two major categories. The first is based on the observation that the renewable energy represented by an EAC may not match the time profile of the electricity consumed by the buyer, potentially exacerbating grid balancing challenges. Similarly, if EACs come from renewable generation that is not on the same grid as the buyer (or is from a portion of the grid that is transmission-constrained), it may be unreasonable to claim this electricity is "consumed" by the buyer's facilities. These concerns have led to proposals such as the "three pillars" of time-matching, additionality[71] and location/regional constraints and "24/7 Carbon Free Energy."[72] In general, these principles would decrease the ability of buyers to use VPPAs and time-agnostic EACs in reducing Scope 2 market-based emissions.

The second broad category of criticism for using electricity EACs to reduce market-based emissions is based on the observation that renewable energy generation has dramatically different impacts on the marginal greenhouse gas emissions of grids in different locations. For grids with fossil fuel (such as open-cycle gas turbines) on the margin, additional renewable generation avoids a large amount of greenhouse gas emissions. However, for grids with renewables, such as hydroelectric, curtailed solar or wind, or even battery storage on the margin, additional renewable generation does not avoid any greenhouse gas emissions. This has led to proposals focused on marginal emissions, which would decrease the ability of buyers to use EACs from low-marginal-emissions grids to reduce Scope 2 market-based emissions.[73,74]

As the Greenhouse Gas Protocol Scope 2 guidance undergoes revision during 2025, the final direction of the Scope 2 market-based emissions method remains unclear. However, the revision will likely have a significant impact on the strategies used by data center operators for renewable energy procurement to reduce market-based emissions.

F. Recommendations

- *Data center operators should **maximize energy efficiency**, including using advanced cooling and other highly efficient equipment and implementing algorithmic efficiency whenever possible.*

- *Data center operators should consider implementing **load flexibility and on-site storage**, particularly for grids with highly variable emissions intensity.*

- *Data center operators should **include grid carbon intensity as a key siting consideration** and seek to site data centers in the lowest-emitting grid regions as much as possible.*

- *Data center operators and utilities should work together to **identify the optimal mix of new low-carbon power generation technologies to add to the grid to meet rising data center load**. This should include consideration of data center load flexibility when determining the amount of new generation required.*

- *Data center operators considering on-site/BTM power generation solutions should seek to **minimize emissions when selecting generation technologies**.*

- *Data center operators should continue to **support emerging/developing low-carbon power generation technology**.*

- *In addition to the above strategies, data center operators should continue to **procure renewable energy through PPAs**. They should also anticipate potential changes to the Greenhouse Gas Protocol Scope 2 guidance and plan accordingly when determining the necessary amount and type of procurement.*

- *Grid operators should work closely with data centers to **understand the appropriate amount of new capacity to add to meet rising load and should seek to maximize low-carbon generation technologies for new capacity additions as much as possible**.*

- *Grid operators should continue to **reform and accelerate the interconnection process for intermittent renewable generation** in order to provide new low-carbon capacity to meet data center and other demand.*

G. References

1. Mary Sotos. GHG Protocol Scope 2 Guidance: An amendment to the GHG Protocol Corporate Standard; World Resources Institute (WRI) Greenhouse Gas Protocol, Washington, DC, https://ghgprotocol.org/scope-2-guidance (2023).

2. Unique Karki, Vedant Sinha, Muhammad Ali Qamar, Ovais Khan, John Kissock & Prakash Rao. Understanding Scope 2 Emissions – Tipsheet 8; Lawrence Berkeley National Laboratory (LBNL), US Department of Energy (DOE) Office of Manufacturing and Energy Supply Chains (MESC), DOE Industrial Assessment Center, and University of California (UC) Davis, Berkeley, California, https://industrialapplications.lbl.gov/tip-sheet-understanding-scope-2 (Accessed August 2025).

3. European Union (EU) European Environment Agency (EEA). Greenhouse gas emission intensity of electricity generation in Europe; EEA, Copenhagen, Denmark, https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1 (2025).

4. Malgorzata Wiatros-Motyka, Dave Jones, Hannah Broadbent, Nicolas Fulghum, Chelsea Bruce-Lockhart, Reynaldo Dizon, Phil MacDonald, Charles Moore, Alison Candlin, Uni Lee, Libby Copsey, Sam Hawkins, Matt Ewen et al. Chapter 6: Country and Region Deep Dives in Global Electricity Review 2023 (Ember, London, United Kingdom, 2023, https://ember-energy.org/latest-insights/global-electricity-review-2023/country-and-region-deep-dives/).

5. Euan Graham, Nicolas Fulghum & Katye Altieri. Global Electricity Review 2025; Ember, London, United Kingdom, https://ember-energy.org/app/uploads/2025/04/Report-Global-Electricity-Review-2025.pdf (2025).

6. International Energy Agency (IEA). Executive summary in Electricity 2024 (IEA, Paris, France, 2024, https://www.iea.org/reports/electricity-2024/executive-summary).

7. International Energy Agency (IEA). Energy demand from AI in Energy and AI (IEA, Paris, France, 2025, https://www.iea.org/reports/energy-and-ai/energy-demand-from-ai).

8. Sean Wolfe. With rapid solar additions, the 'duck curve' begins to emerge in Texas; Factor This Power Engineering, Shelton, Connecticut, https://www.power-eng.com/renewables/solar-energy/with-rapid-solar-additions-the-duck-curve-begins-to-emerge-in-texas/ (2024).

9. Asma Aziz. Big batteries are solving a longstanding problem with solar power in California. Can they do the same for Australia?; The Conversation UN, Inc., Waltham, Massachusetts, https://theconversation.com/big-batteries-are-solving-a-longstanding-problem-with-solar-power-in-california-can-they-do-the-same-for-australia-231063 (2024).

10. Neshwin Rodrigues & Aditya Lolla. Solar adoption in India entering "accelerating growth" phase; Ember, London, United Kingdom, https://ember-energy.org/app/uploads/2024/09/India-solar-uptake.pdf (2024).

11. Akshaya Jagannadharao, Nicole Beckage, Dawn Nafus & Scott Chamberlin. Timeshifting strategies for carbon-efficient long-running large language model training. Innovations in Systems and Software Engineering 21, 517-531 (2025). https://doi.org/10.1007/s11334-023-00546-x.

12. Tony Lenoir. Nuclear bolsters top US hyperscalers' clean energy portfolio, now over 84 GW; S&P Global, New York, New York, https://www.spglobal.com/market-intelligence/en/news-insights/research/nuclear-bolsters-top-us-hyperscalers-clean-energy-portfolio-now-over-84-gw (2025).

13. World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD). Standards Development and Governance Repository; WRI and WBCSD, Washington, DC and Geneva, Switzerland, https://ghgprotocol.org/standards-development-and-governance-repository (Accessed August 2025).

14. Sarah Huckins. Scope 2 Standard Advances: ISB Approves Consultation on Market- and Location-Based Revisions; Signals Cross-Sectoral Work Ahead on Avoided Emissions; World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD), Washington, DC and Geneva, Switzerland, https://ghgprotocol.org/blog/scope-2-standard-advances-isb-approves-consultation-market-and-location-based-revisions (2025).

15. Rachit Kansal. Introduction to the Virtual Power Purchase Agreement; Rocky Mountain Institute (RMI) Business Renewables Center (BRC), Basalt, Colorado, https://rmi.org/insight/virtual-power-purchase-agreement/ (2018).

16. Chris Bowden. Understanding the evolution of the PPA market; Squeaky Clean Energy Group Ltd., London, United Kingdom, https://www.squeaky.energy/blog/understanding-the-evolution-of-the-ppa-market (2023).

17. Plàcido Ostos. The Role of Balancing in Virtual and Physical PPAs; LevelTen Energy, Seattle, Washington, https://www.leveltenenergy.com/post/balancing-in-vppas (2024).

18. Rob Collier. 4 Questions to Ask Before Choosing a Physical or Virtual Power Purchase Agreement; LevelTen Energy, Seattle, Washington, https://www.leveltenenergy.com/post/physical-power-purchase-agreement-or-virtual-ppa (2019).

19. Jordan Farrell. ESG, VPPAs and Dodd-Frank; Husch Blackwell LLP, Milwaukee, Wisconsin, https://www.climatesolutionslaw.com/2023/06/esg-and-renewable-energy/ (2023).

20. Benjamin Grayson. Corporate VPPAs: Risks and sensitivities; Norton Rose Fulbright US LLP, Houston, Texas, https://www.projectfinance.law/publications/2020/june/corporate-vppas-risks-and-sensitivities/ (2020).

21. Nicolas Briet. Virtual PPAs: State of Play in 2025; Pexapark, Zurich, Switzerland, https://pexapark.com/blog/prmc-virtual-ppas-state-of-play-in-2025/ (2025).

22. US Environmental Protection Agency (EPA). Renewable Energy Certificates (RECs); EPA, Washington, DC, https://www.epa.gov/green-power-markets/renewable-energy-certificates-recs (Accessed August 2025).

23. Association of Issuing Bodies (AIB). Renewable Energy Guarantees of Origin; AIB, Brussels, Belgium, https://www.aib-net.org/certification/certificates-supported/renewable-energy-guarantees-origin (Accessed August 2025).

24. Masaya Ishida. Electricity Certificate for Renewables: Comparison of Japanese and International Systems (English Edition); Renewable Energy Institute, Tokyo, Japan, https://www.renewable-ei.org/pdfdownload/activities/REI_RE-Certificates_EN.pdf (2022).

25. Daniel Kramb. China's energy market 'open for business' after support from RE100 on certificates; The Climate Group, London, United Kingdom, https://www.theclimategroup.org/our-work/press/chinas-energy-market-open-business-after-support-re100-certificates (2025).

26. Tina Freese. Virtual PPA Framework a Good First Step, but Regulatory Backing is Essential; Mercom Capital Group, LLC, Austin, Texas, https://www.mercomindia.com/vppas-in-india-not-gained-momentum-cerc-guidelines (2025).

27. Simone Accornero. Corporate renewable procurement: greenwashing or key driver of the EU's clean industrial deal?; European Climate, Infrastructure and Environment Executive Agency (CINEA), Brussels, Belgium, https://sustainable-energy-week.ec.europa.eu/news/corporate-renewable-procurement-greenwashing-or-key-driver-eus-clean-industrial-deal-2025-02-06_en (2025).

28. Anders Bjørn, Shannon M. Lloyd, Matthew Brander & H. Damon Matthews. Renewable energy certificates threaten the integrity of corporate science-based targets. Nature Climate Change 12, 539-546 (2022). https://doi.org/10.1038/s41558-022-01379-5.

29. John Fitzgerald Weaver. California solar curtailment down 12% on back of batteries; PV Magazine USA, Providence, Rhode Island, https://pv-magazine-usa.com/2025/07/22/california-solar-curtailment-down-12-on-back-of-batteries/ (2025).

30. Lucia Colaluce. Solar curtailment surges by 97% in Germany in 2024 despite lower operational costs; Strategic Energy Europe (Strategic Energy Corporation Business Unit), Bogota, Colombia, https://strategicenergy.eu/solar-curtailment-germany/ (2025).

31. Matthew Gooding. Google buys 115MW of geothermal energy to power Nevada data centers; Data Center Dynamics (DCD), London, United Kingdom, https://www.datacenterdynamics.com/en/news/google-buys-115mw-of-geothermal-energy-to-power-nevada-data-centers/ (2024).

32. Briana Kobor. Our first-of-its-kind partnership for clean energy has been approved in Nevada; Google Blog, Mountain View, California, https://blog.google/feed/nevada-clean-energy/ (2025).

33. Owen Comstock. Today in Energy: About 25% of U.S. power plants can start up within an hour; US Energy Information Administration (EIA), Washington, DC, https://www.eia.gov/todayinenergy/detail.php?id=45956 (2020).

34. Rui Yang. Solar and Wind Forecasting; National Renewable Energy Laboratory (NREL), Golden, Colorado, https://www.nrel.gov/grid/solar-wind-forecasting (Accessed August 2025).

35. Alessio Verdone, Massimo Panella, Enrico De Santis & Antonello Rizzi. A review of solar and wind energy forecasting: From single-site to multi-site paradigm. Applied Energy 392, 126016 (2025). https://doi.org/10.1016/j.apenergy.2025.126016.

36. Arcelia Martin. More Solar and Battery Storage Were Added to Texas' Grid Than Any Other Power Source Last Year; Inside Climate News, New York, New York, https://insideclimatenews.org/news/10022025/solar-battery-storage-texas-grid/ (2025).

37. Rob Clow. Australian firmed solar overtakes wind projects; Ion Analytics, New York, New York, https://ionanalytics.com/insights/infralogic/australian-firmed-solar-overtakes-wind-projects/ (2025).

38. Kostantsa Rangelova & Dave Jones. Solar electricity every hour of every day is here and it changes everything; Ember, London, United Kingdom, https://ember-energy.org/latest-insights/solar-electricity-every-hour-of-every-day-is-here-and-it-changes-everything/ (2025).

39. Joseph Rand, Nick Manderlink, Will Gorman, Ryan Wiser, Joachim Seel, Julie Mulvaney Kemp, Seongeun Jeong & Fritz Kahrl. Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection; Lawrence Berkeley National Laboratory (LBNL) Energy Technologies Area: Energy Markets & Policy, Berkeley, California, https://emp.lbl.gov/queues (2024).

40. Kaitlin Fung. 5 key questions about US grid interconnection answered; Wood Mackenzie, Edinburgh, United Kingdom, https://www.woodmac.com/news/opinion/5-key-questions-about-us-grid-interconnection-answered/ (2025).

41. Ally Copple. Fervo Energy Announces 320 MW Power Purchase Agreements with Southern California Edison; Fervo Energy, Houston, Texas, https://fervoenergy.com/fervo-energy-announces-320-mw-power-purchase-agreements-with-southern-california-edison/ (2024).

42. Helion Energy. Helion announces world's first fusion energy purchase agreement with Microsoft; Everett, Washington, https://www.helionenergy.com/articles/helion-announces-worlds-first-fusion-ppa-with-microsoft/ (2023).

43. Nuclear Newswire. Google announces power purchase agreement with Commonwealth Fusion; American Nuclear Society, Westmont, Illinois, https://www.ans.org/news/2025-07-02/article-7164/google-announces-power-purchase-agreement-with-commonwealth-fusion/ (2025).

44. Sascha Samadi. A Review of Factors Influencing the Cost Development of Electricity Generation Technologies. Energies 9, 970 (2016). https://doi.org/10.3390/en9110970.

45. Crusoe and Tallgrass. Crusoe and Tallgrass announce AI data center in Wyoming; Crusoe Energy Systems LLC, Denver, Colorado, https://www.crusoe.ai/resources/newsroom/crusoe-and-tallgrass-announce-ai-data-center-in-wyoming (2025).

46. Dylan Baddour & Arcelia Martin. Data centers are building their own gas power plants in Texas; The Texas Tribune, Austin, Texas, https://www.texastribune.org/2025/06/05/texas-data-centers-gas-power-plants-ai/ (2025).

47. DataBank Blog. Powering Data Centers With Renewable Energy For A Sustainable Future; DataBank Holding, Ltd., Dallas, Texas, https://www.databank.com/resources/blogs/powering-data-centers-with-renewable-energy-for-a-sustainable-future/ (2024).

48. Andrew Webber. How Hydro and Data Centers Are Pairing to Create Unique Value; National Hydropower Association, Washington, DC, https://www.hydro.org/powerhouse/article/how-hydro-and-data-centers-are-pairing-to-create-unique-value/ (2025).

49. Ben King, Wilson Ricks, Nathan Pastorek & John Larsen. The Potential for Geothermal Energy to Meet Growing Data Center Electricity Demand; Rhodium Group, LLC, New York, New York, https://rhg.com/research/geothermal-data-center-electricity-demand/ (2025).

50. Emma Penrod. NV Energy seeks new tariff to supply Google with 24/7 power from Fervo geothermal plant; Utility Dive (Informa TechTarget), Newton, Massachusetts, https://www.utilitydive.com/news/google-fervo-nv-energy-nevada-puc-clean-energy-tariff/719472/ (2024).

51. Dan McCarthy. Sage Geosystems and Meta sign 150MW geothermal power agreement; Canary Media, Asheville, North Carolina, https://www.canarymedia.com/articles/geothermal/sage-geosystems-and-meta-sign-150mw-geothermal-power-agreement (2024).

52. Lamar Johnson. Meta signs geothermal power deal for New Mexico data centers; Utility Dive (Informa TechTarget), Newton, Massachusetts, https://www.utilitydive.com/news/meta-xgs-energy-announce-geothermal-deal-new-mexico-data-centers-ai/750913/ (2025).

53. Nicki Stuckert, Patti Smith, Daniel Garcia & Jordan Alford. Meeting Data Center Electricity Demand: Mapping carbon capture potential for natural gas-fired generators in the US and Canada; Carbon Direct Inc., New York, New York, https://www.carbon-direct.com/research-and-reports/meeting-data-center-electricity-demand (2025).

54. Violet George. Wyoming Lands 1.8-Gigawatt AI Data Center Powered By Gas And Carbon Capture; Carbon Herald Inc., New York, New York, https://carbonherald.com/wyoming-lands-1-8-gigawatt-ai-data-center-powered-by-gas-and-carbon-capture/ (2025).

55. Baker Hughes. Baker Hughes, Frontier Infrastructure Announce Partnership to Accelerate Development of Carbon Capture and Storage, Data Center Projects in the U.S. (Press Release); Houston, Texas, https://investors.bakerhughes.com/news-releases/news-release-details/baker-hughes-frontier-infrastructure-announce-partnership

56. Bloom Energy. Bloom Energy Announces World's Largest Fuel Cell Installation in History; San Jose, California, https://www.bloomenergy.com/news/bloom-energy-announces-worlds-largest-fuel-cell-installation-in-history/ (2024).

57. Xiaotian Zhang, Zuwen Liu, Peng Qiu, Peixiang Wang, Kangwei Wei & Zhiguo Guo. Progress in methane-based solid oxide fuel cells: Challenges for clean and efficient utilization from natural gas. Fuel 395, 135211 (2025). https://doi.org/10.1016/j.fuel.2025.135211.

58. Erhan Eren. Fuel Cell Installations in Data Centers: Top 10 Projects & Companies; EnkiAI, San Francisco, California, https://enkiai.com/fuel-cell-installations-in-data-centers-top-10-projects-companies (2025).

59. US Department of Energy (DOE) Office of Nuclear Energy. Advantages and Challenges of Nuclear-Powered Data Centers (Blog); Washington, DC, https://www.energy.gov/ne/articles/advantages-and-challenges-nuclear-powered-data-centers (2025).

60. Jane Accomando. Nuclear-Powered Data Centers—What U.S. Developers Need to Know; Power Magazine, Rockville, Maryland, https://www.powermag.com/nuclear-powered-data-centers-what-u-s-developers-need-to-know/ (2025).

61. Amber Jackson. Microsoft & Constellation's Bid to Restart Three Mile Island; Data Centre Magazine, Norwich, Norfolk, United Kingdom, https://datacentremagazine.com/critical-environments/microsoft-constellation-restarting-a-nuclear-reactor (2025).

62. Amanda Peterson Corio. Our first advanced nuclear reactor project with Kairos Power and Tennessee Valley Authority (Blog); Google, Mountain View, California, https://blog.google/outreach-initiatives/sustainability/google-first-advanced-nuclear-reactor-project-with-kairos-power-and-tennessee-valley-authority/ (2025).

63. Amazon Staff. Amazon signs agreements for innovative nuclear energy projects to address growing energy demands; Amazon.com, Inc., Seattle, Washington, https://www.aboutamazon.com/news/sustainability/amazon-nuclear-small-modular-reactor-net-carbon-zero (2024).

64. World Nuclear News. Fermi America, Hyundai E&C team up for Texan reactors; World Nuclear Association, London, United Kingdom, https://www.world-nuclear-news.org/articles/fermi-america-hyundai-ec-team-up-for-texan-reactors (2025).

65. Digitalisation World. Fusion-powered data centres: Google purchases 200MW of fusion power from US$2 billion startup; Digitalisation World, Coventry, United Kingdom, https://digitalisationworld.com/news/70232/fusion-powered-data-centres-google-purchases-200mw-of-fusion-power-from-us-2-billion-startup (2025).

66. Sebastian Moss. Commonwealth Fusion Systems raises more than $1bn, backed by unnamed hyperscale data center developer - report; Data Center Dynamics (DCD), London, United Kingdom, https://www.datacenterdynamics.com/en/news/commonwealth-fusion-systems-raises-more-than-1bn-backed-by-unnamed-hyperscale-data-center-developer-report/ (2025).

67. Julia Komitova. Google Energy sings first wind farm PPA; Renewables Now, Sofia, Bulgaria, https://renewablesnow.com/news/google-energy-sings-first-wind-farm-ppa-84105/ (2010).

68. Mark Thomton, Hla Myat Mon, Chris Boba & Angélica Juárez. European renewable PPA market sees 19GW of new capacity contracted in 2024; Wood Mackenzie, Edinburgh, United Kingdom, https://www.woodmac.com/press-releases/european-renewable-ppa-market-sees-19gw-of-new-capacity-contracted-in-2024/ (2025).

69. You-Jie Cai. A Deep Dive into PPAs and VPPAs in East Asia; Apala Group, San Francisco, California, https://www.apalagroup.com/angles/wudgp1hcm054ccvow9mhu3waen8yl1 (2025).

70. Tony Lenoir. Corporate PPA leaderboard – Microsoft leap cuts into Amazon lead; S&P Global, New York, New York, https://www.spglobal.com/market-intelligence/en/news-insights/research/corporate-ppa-leaderboard-microsoft-leap-cuts-into-amazon-lead (2025).

71. American Clean Power. APC Framework: 3 Pillars for Building a Green Hydrogen Industry for Decarbonization; American Clean Power, Washington, DC, https://cleanpower.org/gateway.php?file=2023/06/ACP_GreenHydrogenFramework_OnePager.pdf (2023).

72. Google. 24/7 Carbon-Free Energy: Methodologies and Metrics; Mountain View, California, https://sustainability.google/reports/24x7-carbon-free-energy-methodologies-metrics/ (2021).

73. Emissions First Partnership (EFP). First Things First: Accelerating Grid Decarbonization (Homepage); https://www.emissionsfirst.com/ (Accessed August 2025).

74. Sam Koebrich, Joel Cofield, Gavin McCormick, Ishan Saraswat, Nat Steinsultz & Pierre Christian. Towards objective evaluation of the accuracy of marginal emissions factors. Renewable and Sustainable Energy Reviews 215, 115508 (2025). https://doi.org/10.1016/j.rser.2025.115508.