Greenhouse Gases Resulting from Grid-Connected Electricity Demand

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Abstract

Many governments and businesses would like to claim that their electricity use does not result in greenhouse gases. Because electricity cannot be traced from specific generators to purchasers, some regulators and users have proposed an approximation. Electricity purchasers would be credited with using clean power if they contract for electricity generated by particular zero-carbon suppliers to the grid or purchase certificates accompanying that zero-carbon generation, so long as those arrangements meet three conditions, or “pillars”: The associated clean power must be generated (1) nearby, (2) during the same hour, and (3) from newly constructed power plants. Even without those requirements, existing or planned newly constructed zero-carbon electricity generation is expected to account for 7 percent of US power in 2030. We show that with the requirements, this qualifying, already-planned power would be cleaner than average but not carbon-free. Electricity purchases meeting the restrictions will have average incremental emissions per megawatt-hour that range from 69 to 100 percent of unrestricted emissions. The three pillars do limit the amount of already-existing clean power that can be claimed, and so could have more climate benefits by reducing total electricity demand or encouraging construction of clean electricity capacity.

Acknowledgments

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1. Introduction: Emissions Resulting from Electricity Use

Many businesses, consumers, and governments around the world want to account for their effects on greenhouse gas emissions. Emissions resulting from purchased electricity—sometimes called "scope-two" emissions—are particularly difficult to calculate, especially when the electricity comes from a mix of generators connected to the electricity grid.

Amazon, Microsoft, and Google have announced aspirations to use only electricity "attributable to renewable energy sources."[1] A presidential executive order in 2021 required the US federal government to purchase "100 percent carbon pollution-free electricity" by 2030.[2] And the Inflation Reduction Act provided tax credits for producing goods responsible for less emissions, including emissions resulting from electricity purchases.

How can grid-connected customers claim their electricity purchases do not result in greenhouse gases? Some sign power purchase agreements with specific zero-carbon generators, such as solar farms or wind turbines. Others purchase renewable energy certificates issued by those zero-carbon generators.

In practice, however, which generator serves new demand depends on complex and changing considerations, including which ones are already operating, transmission capabilities, each generator's cost of production or construction, and the size and expected duration of the demand increase. When a business with a zero-carbon power contract or renewable energy certificates from wind turbines starts its daily operations, the wind turbines cannot respond by spinning faster. Instead, an electricity supplier somewhere on the same interconnected grid must increase output from existing generators, likely powered by fossil fuels. If demand grows meaningfully, utilities might need to construct new generators, some of which will be powered by natural gas.

Because tracking emissions caused by grid-connected electricity demand is difficult, users rely on approximations. A simple one used in many places, including the US greenhouse gas emissions inventory, assigns to each megawatt-hour (MWh) of electricity the *average* annual emissions intensity of the regional or national electricity grid.[3] Using grid averages is easy to implement, but has drawbacks. In particular, annual average emissions are typically lower than the short-run emissions resulting from small increases in electricity purchases, so grid averages understate the damages that result from increased electricity use (Holland et al. 2022a).

In lieu of averages, a relatively new approximation has gained support from big tech companies, various environmental groups, the US government, and the European Union. The

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[1] Amazon: https://sustainability.aboutamazon.com/climate-solutions/renewable-energy;
Microsoft: https://blogs.microsoft.com/on-the-issues/2023/08/16/apec-sustainability-decarbonization-fusion-energy/;
Google: https://www.google.com/about/datacenters/cleanenergy/.

[2] Executive Order 14057 (2021) "Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability."

[3] Inventory of U.S. Greenhouse Gas Emissions and Sinks | U.S. Environmental Protection Agency.

approach would credit grid-connected consumers with using carbon-free electricity if they sign contracts to purchase power from carbon-free generators or buy specially designed credits from generators of carbon-free power.[4] Some proponents of this solution argue that the credited clean power must be generated at the same time as the electricity use and nearby enough to be delivered over uncongested transmission lines. Others would add a third restriction that the credited clean power be from carbon-free generators that have been constructed recently. Together, these three conditions have come to be called the three pillars of crediting grid-connected clean electricity demand: nearby, hourly matched, and newly constructed.

The restriction that qualified clean power purchases be nearby prevents users in Massachusetts, say, from claiming credit for wind power in Texas. The restriction that purchases be hourly matched prevents purchasers from claiming credit when the wind is calm. And the restriction that credited generators be new prevents purchasers from claiming credit for power that had been serving the grid for decades.

Microsoft and Google have piloted programs to purchase grid-supplied renewable energy matched on an hourly basis to their electricity demand. The 2021 US presidential executive order defines carbon pollution–free electricity use as purchases from carbon-free sources matched with electricity consumption “on an hourly basis and produced within the same regional grid where the energy is consumed.” And a February 2023 rulemaking by the European Union adds the third pillar, requiring contracted clean electricity to be generated at a power plant that began operating during the preceding three years.

Supporters of these three conditions include the American Clean Power Association, a coalition of 14 environmental organizations including the Natural Resources Defense Council, Sierra Club, Environmental Defense Fund, and Union of Concerned Scientists, along with nonpartisan think tanks such as Energy Innovation and Princeton’s ZERO Lab.[5] As one proponent writes, “These ‘three pillars’—new supply, deliverability and hourly matching—can help ensure that fossil fuels do not provide the additional electricity” (Jenkins 2023).

As the supporters sometimes recognize, however, the three pillars are imperfect proxies for truly carbon-free electricity. Because zero-carbon generators often have the lowest marginal costs, they are typically the first deployed. When sun, wind, hydropower, or geothermal sources are available, they are used. In most places and times, those low-cost, zero-carbon sources are insufficient to cover all electricity purchases, and the remaining electricity demand will be supplied by generators with higher marginal costs, typically natural gas or coal. Crediting new electricity use with generation from existing or already planned new clean sources just means the existing electricity use must be met by other generators, which for the near future will come at least in part from fossil fuels.

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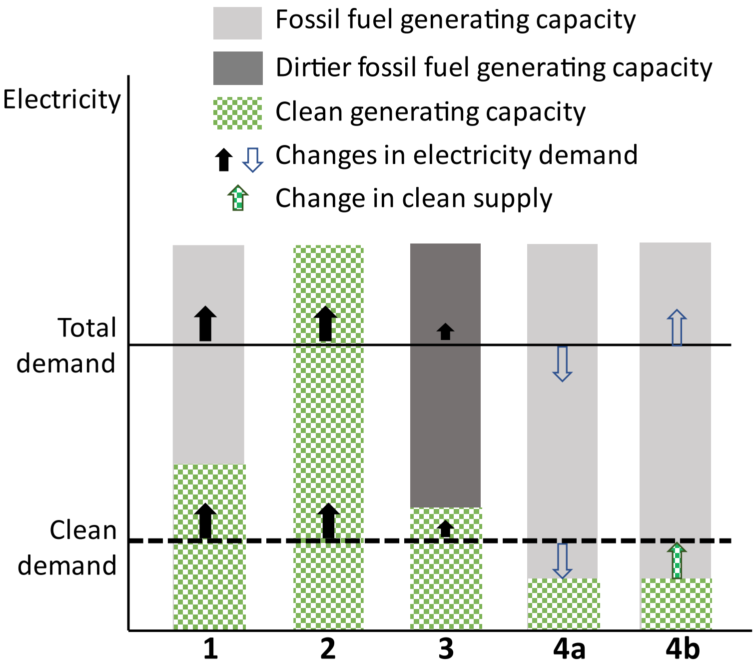
[4] We use “clean,” “zero-carbon,” or “carbon-free” to mean electricity from sources that result in low emissions, principally wind, solar, hydro, nuclear, and geothermal.

[5] American Clean Power (2023); EDF (2023); Fakhry (2023); Esposito et al. (2023); Ricks et al. (2023).

Four possible circumstances determine how the three pillars might affect carbon emissions. Each column of Figure 1 depicts one of those situations. Each describes a snapshot of the electricity market during a particular hour and at a particular location. In the first column, total demand (top line) is met first by all the available low-cost, clean power (diagonal lines) and then by higher-cost fossil fuels. Think of column 1 as a simple, short-run supply curve for one hour in one place. If electricity users want credit for using clean power (bottom dashed line), there's plenty of clean capacity from which they can purchase power or credits. An increase in clean demand increases total demand by that same amount (the two solid up arrows), causing more fossil fuels to be used. Electricity use credited with using existing clean sources will be no cleaner than uncredited electricity use.

Column 2 depicts a different situation, in which extra zero-carbon capacity is available beyond the capacity serving current demand, a situation called curtailment. Any new demand, whether wanting credit for being clean or not, will be supplied by the unused, low-cost, zero-carbon generators, resulting in no new carbon pollution. In those currently rare cases, clean energy crediting systems are unnecessary. Electricity use credited with using existing clean sources will be just as clean as uncredited electricity use.

Figure 1. Clean Electricity Demand and Carbon Emissions



One way that a clean crediting system like the three pillars might affect emissions would be if qualifying clean power was more abundant in places where increases in electricity demand are met by relatively less polluting fossil fuel powered generators. The contrast between columns1 and 3 in Figure 1 illustrate that possibility. Column 3 has relatively less abundant clean supply and relatively polluting fossil fuel capacity. If the restrictions cause some electricity customers to shift their power purchases from times and places like 3 to times and places like 1, emissions will decline. That doesn't mean the shifted power demand would result in zero emissions. Unless clean power is curtailed in those new places and times (shifting from 3 to 2), extra demand there will still be met by whichever generator is next in line to serve incremental purchases, typically natural gas or coal. However, if the incremental emissions from new power supply results in less greenhouse gases in places where more power is credited as clean, then shifting demand can result in lower emissions.

The final way clean energy crediting systems like the three pillars could limit greenhouse gases would be if they result in supply of qualifying clean power falling short of demand. Columns 4a and 4b of Figure 1 depict that scenario: the dashed line denoting clean demand exceeds the clean capacity. That situation could arise because more electricity customers seek to claim their use causes no greenhouse gases, or because the restrictions reduce *already qualifying* clean supply. Either way, the excess demand could result in two outcomes, one counterproductive and one hopeful.

The counterproductive way the three pillars could reduce greenhouse gases, depicted in column 4a, is by reducing electricity demand. If some consumers want electricity only if they can claim it is clean and would use less electricity if they could not, any restrictions on power that qualifies as clean also restricts total electricity demand and the accompanying emissions (the two hollow down arrows in column 4a of Figure 1). That emission decline has nothing to do with the actual emissions per MWh resulting from the power purchases. It reduces total emissions by reducing total electricity use. Any policy that reduced total power demand would similarly reduce emissions. A system that credited power as being clean only if it is purchased on Tuesdays would similarly reduce emissions.

More hopefully, if demand for clean electricity exceeds the supply of existing qualifying power, investors might find it worthwhile to construct even more new zero-carbon power plants than are already planned (the up arrow with diagonal lines in column 4b). If the new power serves customers who want electricity only if it is clean, the new clean demand would cause no carbon emissions.

Our analysis assesses the degree to which the three pillars change the amount of qualifying zero-carbon power forecast to be supplied, regardless of whether electricity purchasers intend for their demand to be clean. We compare the incremental emissions caused by new power demand in places where that qualifying power is scarce or abundant, under various configurations of the three pillars, today and in the future. And we evaluate ways that restrictions on what qualifies as zero-carbon power might increase the probability that clean supply falls short of demand, causing a reduction in total electricity demand or incentivizing new clean supply.

To answer those questions, we use the Cambium model developed by the Department of Energy's National Renewable Energy Laboratory (NREL) to show that a meaningful quantity of electricity meeting the three restrictions is already forecast to be part of the US generation mix, even without three-pillar crediting arrangements in place. Newly constructed zero-carbon generation—built within the prior two years—is expected to account for 7.2 percent of US electricity in 2030. Unless demand for clean power exceeds available qualifying clean power, or relocates to times and places with lower marginal emissions, crediting a tech company or government agency with using clean electricity because it contracts with nearby, hourly-matched, newly built, clean generators won't result in less pollution than if it ignores climate concerns.

As a consequence, even under restrictive versions of the three-pillars crediting schemes, the first megawatt-hours of grid-connected power demand in the United States that would be credited as carbon-free are projected to result in significant greenhouse gas emissions. We use Cambium to show that incremental electricity demand matched to carbon-free sources of electricity generated nearby, during the same hour as the demand, and from newly constructed sources would lead to incremental electricity supply with emissions intensities—carbon dioxide equivalent (CO_2e) per MWh—between 69 and 100 percent of the national unrestricted average.

In recent years, multiple research teams have examined crediting schemes that employ subsets of the three pillars, evaluating the emissions resulting from electricity demand credited by those schemes as being carbon-free. The studies' results differ widely based in part on assumptions they make about whether clean or polluting power plants are built to serve new demand. Giovanniello et al. (2024) illustrate one of the major points of confusion in this area, which they call "different interpretations of additionality" (p. 199).

The word *additionality*, as used in economics, refers to behavior that would not have occurred otherwise. Additional clean power would not have been generated without the users who purchase it. If electricity users purchase clean power that is not additional, their use must be supplied by additional generation that is likely to be from fossil fuels. Evaluating whether purchased clean power is additional requires estimating whether it would have been generated even without the use credited with purchasing it, a conceptually difficult task.

As an alternative to additionality, therefore, the third of the three pillars requires merely that credited clean electricity be generated by newly constructed sources, even though a lot of new sources are being constructed even without clean demand and are therefore not additional. Electricity use that contracts with additional clean sources causes zero carbon emissions; electricity demand that contracts with new clean sources that would have been built anyway causes the same carbon emissions as any electricity use. Regrettably, some research on this topic confuses the issue by treating the words *new* and *additional* as synonyms. When researchers assume new power is additional, they find—not surprisingly—that electricity use contracting with new clean power plants results in zero emissions.

Studies of clean crediting proposals typically deploy cost-minimization models of the electricity sector, such as the Electric Power Research Institute's US-REGEN or MIT and Princeton's GenX , to consider how the grid would expand if clean power demand increased.[6] We won't survey all the work here, but one early and prominent paper exemplifies the

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[6] https://esca.epri.com/models.html; https://energy.mit.edu/genx/.

approaches.[7] Ricks et al. (2023) use the GenX model of electricity dispatch and system expansion. They study the western US electric grid, projected to have substantial amounts of carbon-free electricity generation in 2030. They consider a very large increase in demand for clean power, approximately equal to current total industrial electricity use. If that clean power demand were matched on an hourly basis with carbon-free generation, Ricks et al. predict that it would result in zero emissions in California and the Pacific Northwest. In those areas, increasing three-pillars power demand causes large increases in clean power supply. In other parts of the western US, Ricks et al. estimate that a large fraction of demand that could claim to be using hourly-matched renewable resources would actually be met by fossil generation.

Our approach is simpler. We don't try to model how the electricity grid would respond to incremental demand for clean power under different crediting restrictions. Nor do we estimate the effect of different electricity procurement strategies by consumers. Instead, we calculate emissions intensities for electricity use matched to the supply of qualifying electricity currently predicted to be available in future years. All we do is report summaries of the Cambium model's forecast of electricity generation meeting the three pillars in each location and hour, along with the average marginal emissions weighted by the amount of forecast qualifying clean power.

The Cambium model's output estimates the emissions resulting from increases in electricity demand, for 133 regions around the US, for every hour of the year in 2025, and for future years out to 2050. It provides short-run estimates based on forecasts of future grid characteristics, as well as long-run estimates allowing for changes to grid characteristics resulting from increased demand. We use those outputs to calculate weighted averages of incremental emissions per MWh, weighting by the amount of carbon-free electricity already projected to be generated in each of those locations and hours that would meet various combinations of the three pillars: nearby, hourly matched, and new. The calculations approximate the average marginal emissions intensities for electricity demand meeting the three-pillars restrictions to qualify as zero-carbon. Our estimates are best thought of as summaries of the short and long-run marginal effects. For large changes, like those considered by Ricks et al., the results may differ.

In the short run, small increases in power demand meeting all three restrictions would result in average carbon emissions 0 to 18 percent lower than the national average for all unrestricted power demand today and in the near future. In the long run, allowing for construction of new power plants, increased electricity use meeting all three pillars results in 5 to 31 percent less carbon than without the restrictions. A small increase in electricity use meeting all three restrictions results in less carbon than without the restrictions, but is by no means carbon-free.

Crucially, however, we find that the restrictions have the potential to make a difference by limiting the amount of already-existing qualified clean power. If customers want credit for more clean electricity than qualifies under the restrictions, they must either reduce their

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[7] Bergman (2023) and EPRI (2023) nicely summarize and compare many of these papers. Also see Zeyen et al. (2023), Haley and Hargreaves (2023), Fell et al. (2023), and Xu et al. (2024).

electricity use or pay sufficiently higher prices to spur construction of new clean powerplants. Details of all these calculations are discussed in section 3, but we begin by briefly summarizing the underlying Cambium model.

2. NREL's Cambium Model

NREL's Cambium model produces a set of publicly available datasets, each describing the US electricity grid for a future year (Gagnon et al. 2023). Here we describe the Cambium 2024 datasets, for which 2025 is a future projection, and our calculations using that data. In Appendix A, we detail how NREL developed the model's projections.

Each Cambium output includes projected electricity demand for a particular year, for each of the 8,760 hours of the year and in each of 133 US electricity balancing areas in the 48 contiguous US states plus the District of Columbia.[8] Projections are available every five years from 2025 through 2050. Each includes projected demand, generation by various sources, costs, and carbon emissions. Amazon, the largest corporate purchaser of renewable power every year since 2020, recently announced plans to collaborate with NREL to use Cambium to estimate the emissions resulting from its own electricity use (O'Neil 2023).

For each hour in each balancing area, Cambium projects total generation, including from storage and distributed solar, as well as imports and exports from other balancing areas and Canada. To consider clean sources of electricity, we focus on a subset of that total, including energy generated from biomass, biomass with carbon capture, distributed and utility-scale solar power, onshore and offshore wind, geothermal, hydro, nuclear, and renewable-based combustion turbines. We exclude storage and imports from Canada.

The Cambium datasets include eight scenarios for future energy demand and supply. We focus on what NREL calls the "Mid-case" scenario, a case that includes midrange fossil fuel prices and in which the Inflation Reduction Act's tax credits for clean electricity production and investments do not phase out.[9] Other Cambium scenarios phase out the tax credits, use different assumed renewable energy and battery costs, project different natural gas prices and electricity demand growth, and force decarbonization by predetermined future dates. Although we focus on the mid-case scenario, we don't intend to put too much weight on any particular scenario. Rather, we use Cambium to highlight that three-pillars claims using clean power already forecast to be available will still generate meaningful carbon emissions, and that the three-pillars restrictions can significantly reduce the pool of that already-existing electricity.

In addition to the model results posted on the Cambium website, we also acquired from NREL staff a table of projected capacity additions and retirements in the Mid-case scenario that we use to estimate the portion of projected clean energy generation that will come from new sources in each hour and balancing area. We interpolate between the periodic Cambium datasets to get annual capacity changes and then apportion that new capacity to calculate the share of

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[8] Cambium's 133 balancing areas are considerably smaller than the current 66 balancing authorities that coordinate supply. https://www.eia.gov/electricity/gridmonitor/about.

[9] Bracci et al. (2023) also base their analysis on the Cambium Mid-case scenario.

demand in each hour served by new capacity (see Appendix A for details). We consider capacity to be new if it begins operations in the two years prior to the demand. For example, a solar plant that began operations in 2024 or 2025 would count as new capacity for electricity demanded during 2025.

Our implementation of the three pillars is relatively strict. For the nearby criterion, by using Cambium's 133 balancing areas, we require closer geographic matching than real-world implementations are likely to require. For the newness criterion, our definition accounts only for when power is demanded, not when the source of demand began operations. Many proposals would credit generators as being new if they were constructed shortly before the demand began, regardless of when the power is used. A data center that begins operations in 2025 could receive credit for clean power contracted in 2030 from a wind turbine built in 2024. Our simple definition of new disqualifies that six-year-old turbine.

Finally, we use two types of marginal greenhouse gas emissions that Cambium reports. The first is short-run emissions, the kilograms (kg) of CO_2e that would result from 1 MWh of increased electricity demand supplied by existing power plants. Each balancing area is presumed to have a single marginal generation type—solar, gas, etc.—and associated emissions in each hour. These short-run marginal emissions capture the operational response from the projected future power grid, not how investments in grid expansion might respond to changes in projected future demand.

The second type of marginal emissions Cambium estimates considers the long run, accounting for investments in expanded grid capacity. NREL calculates long-run marginal emissions by solving the models underlying Cambium twice for each modeled year: once for the projected conditions and a second time with a small percent increase in electricity demand in each balancing area in each hour of the year (Gagnon and Cole 2022). The resulting increased electricity supply, and hence emissions, includes short-term changes using the existing grid and long-term additions to the grid, both chosen to minimize costs of meeting the increased demand.

To assess the short-run effect of the three pillars, we calculate weighted averages of marginal short-run emissions with and without various combinations of restrictions. We can only partially assess the long-run effect. The Cambium long-run projections describe how increases in demand that result in new generators being constructed will affect emissions. They do not project how increases in demand *caused by the restrictions* will differ from increases in demand unencumbered by restrictions. Whether the short- or long-run estimates are most appropriate depends on the context, but for clarity of exposition, we begin with the short-run.

As with any model, Cambium comes with caveats. It calculates cost-minimizing investment and generation decisions, which may not reflect real-world decision-making. It does not model demand responses or flexible load shifting. The marginal emissions calculations, particularly for the long-run, assume a specific, uniform pattern of demand increases. Other patterns, such as increases that only occur during daytime, would create different emissions estimates. Finally, the weather data used to model regional hourly demand come from a single year, 2012.

Despite the inherent challenges of predicting electricity generation decades into the future, the Cambium datasets provide one well-developed estimate as to how changes in future US electricity demand will affect carbon emissions. It has been used by other researchers to study greenhouse gas emissions resulting from US electricity demand (Bracci et al. 2023) and is being used by major global corporations to evaluate their carbon footprints. We use it to add our own assessment as to how restricting increased demand for clean power to new, nearby, and hourly matched clean electricity sources will affect greenhouse gas emissions.

3. Short- and Long-Run Emissions Intensities

We start with the short-run emissions from incremental electricity demand using existing generation capacity, postponing until section 3.2 the discussion of long-run emissions from capacity expansion.[10] Each of these calculations, both short- and long-run, estimates emissions intensities for electricity that Cambium predicts will be generated without regard to demand by consumers for clean power.

3.1. Short-Run Emissions Intensities

The first, darkest-shaded columns for each year in Figure 2 report the weighted average short-run marginal emissions intensities for all generation:

$$\boldsymbol{z1} = \frac{\sum_i \sum_t z_{it} q_{it}}{\sum_i \sum_t q_{it}} \tag{1}$$

where z_{it} is the short-run marginal emissions intensity (kg of CO_2e/MWh) in balancing area *i* in hour *t*. The weights q_{it} are the MWh of total electricity generated in each balancing area *i* in hour *t*. The calculation in equation (1) can be thought of as the expected emissions resulting from 1 MWh of extra electricity demand occurring sometime and somewhere in the United States, with probability proportional to total generation in each time and place.

Equation (1) can be explained using Figure 1. Suppose columns 1, 2, and 3 represent three different hours and places. And suppose marginal emissions–the $\boldsymbol{z}$*s*–are 500 kg CO_{2e}/MWh in column 1, zero in column 2, and 1,000 in column 3. The weights, total demand, are the same in each hour and place in this example. So the calculation ***z1*** is just $\frac{500}{3} + \frac{0}{3} + \frac{1{,}000}{3} = 500.$

In practice, there are many more than three places and hours, and the resulting number for 2025 is $\boldsymbol{z1}$ = 774 kg/MWh, shown in the first column of Figure 2. For comparison, Cambium's projected *average* US carbon emissions resulting from electricity use in 2025 were less than half of that, 368 kg/MWh. The difference is to be expected because incremental emissions from existing generators come almost exclusively from fossil fuel sources (Holland et al. 2022). Average 2023 US combustion emissions from natural gas were 437 kg CO_2/MWh and

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[10] The short run is simpler to explain, and makes expositional sense as a starting point. For policies and long-term investments, the long-run measure will be more appropriate. Gagnon and Cole (2022) discuss when each measure is most appropriate. See also Gagnon et al. (2022) for an argument against using the short run estimates, and Holland et al. (2022b) for a reply.

from coal were 1,050 kg/MWh.[11] So the 774 kg/MWh shown in Figure 2's first column represents mostly a mix of coal and natural gas sources that would serve short-run demand increases.

In the second column of Figure 2, we examine carbon emissions resulting from incremental electricity purchases that could meet our restrictive version of the three-pillar guidelines for clean power: the power must be generated and used in the same balancing area, during the same hour, and from newly constructed sources. This means that we calculate the same weighted average of emissions intensities (z_{it}) as in equation (1), using the same emissions intensities (the z's) but where the weights are new clean power (q_{it}^{cn}) instead of all generation (q_{it}):

$$\boldsymbol{z2} = \frac{\sum_i \sum_t z_{it} q_{it}^{cn}}{\sum_i \sum_t q_{it}^{cn}} \tag{2}$$

The resulting number, $\boldsymbol{z2}$ = 775 kg/MWh, estimates how much CO_2e would result from a one-MWh short-run increase in electricity demand, on average across the contiguous US, when that demand could claim to be met only by newly constructed, nearby, hourly matched, carbon-free generators that Cambium forecasts as expected to be built.

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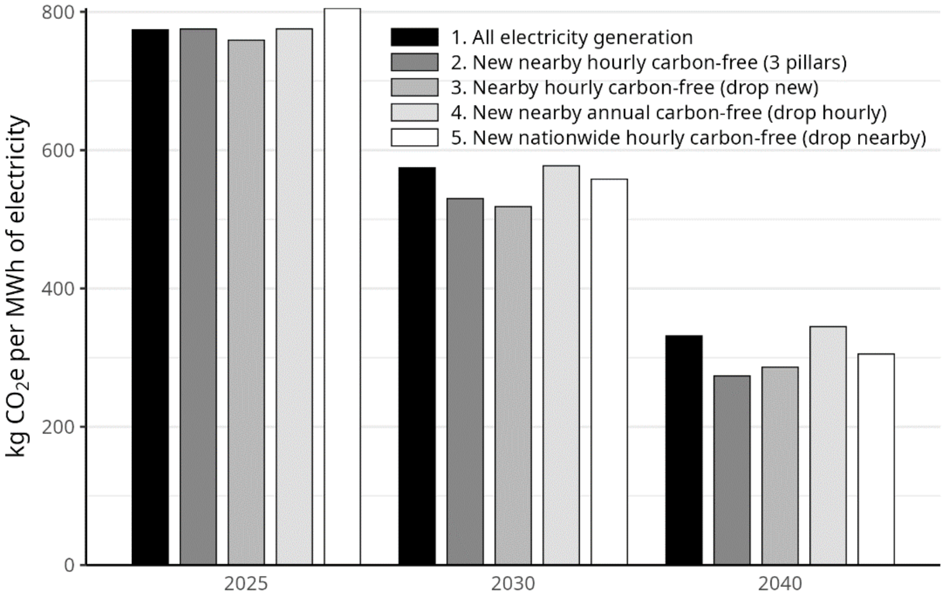
[11] https://www.eia.gov/tools/faqs/faq.php?id=74&t=11. These numbers are average combustion CO_{2e} emissions. Cambium includes other types of emissions; see Appendix A for details.

Figure 2. Short-Run Marginal Emissions Intensities



Source: Authors’ calculations from NREL Cambium model.
Note: Averages for existing and planned generation only. Details in Table 1.
Values and percentage differences in Table B.1.

In places and times when new clean energy was available, emissions resulting from incremental electricity demand in 2025 were projected to be the same as the national average from all sources. These diverge a bit in later years. In 2030 the difference between the grid’s overall marginal emissions rate (574 kg/MWh) and the marginal emissions rate in the times and places where Cambium projects qualifying clean energy to be available (530 kg/MWh) is 8 percent. In 2040 the difference grows to 18 percent. Electricity demand matched with three-pillars-eligible generation tends to be slightly cleaner, on average, but would still result in significant emissions.

The reason is simple. New clean capacity that the Cambium model projects will be added to the grid is not, in this example, caused by the incremental demand being added. We’ll turn to that possibility next. Here in Figure 2, that new clean capacity is projected to be built to serve expected demand growth and replace retiring generators. Any extra short-run incremental demand above expected growth would need to be met by extra generation from the existing grid, and that would come largely from fossil fuels.

Two assumptions need to be discussed before our calculations can be interpreted as the short-run marginal emissions resulting from purchased electricity. First, we focus on the case where existing or projected qualifying clean supply exceeds demand for clean power, as depicted in column A of Figure 1. As a result, when electricity consumers contract with zero-carbon suppliers or purchase zero-carbon electricity credits, they do not cause the capacity of renewable energy generation to increase any more than if they had purchased power without regard for the source. We view this case as realistic. Currently, for example, nationwide renewable electricity production far exceeds that required by state renewables requirements (Galen 2023). In the future, whether qualified clean supply will exceed demand for clean power will depend importantly on the restrictions placed on what generation qualifies as clean.

Second, we initially assume that the demand for clean electricity can easily follow the time pattern of zero-carbon generation—for example, growing when the wind is blowing or the sun is shining and shrinking at other times. Later, we consider more realistic patterns of clean electricity demand that might lead demand for clean power to exceed supply at particular places and times.

Returning to Figure 2, the third, fourth, and fifth columns examine the importance of each of the three restrictions for short-run emissions profiles from clean power claims by dropping them one at time. Column 3 drops the requirement that credited clean power come from newly constructed generators. We calculate the same weighted average incremental short-run emissions intensity as before, but instead of using all generation as in equation (1) or new hourly matched nearby clean generation as in equation (2), we use as weights the total amount of carbon-free generation—new and existing—in each hour and location, q_{it}^{c}.

$$\boldsymbol{z3} = \frac{\sum_i \sum_t z_{it} q_{it}^{c}}{\sum_i \sum_t q_{it}^{c}} \tag{3}$$

The resulting number, $\boldsymbol{z3}$ = 759 kg/MWh for 2025, projects how much CO_2e would result from an extra MWh of electricity demand, on average, when customers could claim that it is met by clean electricity generated during the same hour in the same balancing area.

Without the newness restriction, requiring credited clean energy to be hourly matched and nearby results in electricity use that is just as carbon-intensive as the unrestricted national average. The gain from the two restrictions, without newness, grows to 10 percent for 2030 and 14 percent 2040, similar to all three restrictions. Worse, as we show in section 4, without newness, a much larger quantity of existing generation will be credited as clean, increasing the potential for electricity customers to claim to be using clean power while actually resulting in significant greenhouse gas emissions. Without newness, the three pillars are especially ineffective.

Column 4 drops the hourly matching requirement. That requirement is implicit in columns 2 and 3 because each of those columns attaches different local marginal emissions rates to each specific hour and location. If hourly matching were not required, an electricity user could contract with a new nearby clean electricity supplier to pay for electricity generated during any hour of the year, even though physics requires that electricity demand equals supply at every moment.

In column 4, instead of using average hourly emissions intensities weighted by the generation in each hour, we use the simple average for each balancing area, $\overline{z}_i$, averaged over all 8,760 hours of the year.

$$\overline{z}_i = \frac{\sum_t z_{it}}{8{,}760} \tag{4}$$

This average can be viewed as the expected value of marginal emissions in a randomly drawn hour for region i. Equivalently, $\overline{z}_i$ can be thought of as the average emissions resulting from an increase of 1 MWh of demand every hour of the year.[12]

We then calculate the total amount of new clean electricity across all hours in location i: $q_i^{cn} = \sum_t q_{it}^{cn}$. Finally, we take the weighted average of the local average emissions intensities, $\overline{z}_i$, weighted by the amount of new clean electricity in each location.

$$\boldsymbol{z4} = \frac{\sum_i \overline{z}_i q_i^{cn}}{\sum_i q_i^{cn}} \tag{5}$$

Note that because this drops the hourly matching requirement, $\boldsymbol{z4}$ is a weighted average across the 133 balancing areas, which are subscripted by i. The three previous calculations all involved averages across two dimensions: 133 balancing areas and 8,760 hours.

The resulting number, $\boldsymbol{z4}$ = 775 kg/MWh in 2025, is again about the same emissions intensity as in column 1 and with all three restrictions in column 2. In 2030 and 2040, the column remains close to, but slightly dirtier than, the unrestricted column 1. This simply means that in 2040, for the average balancing area, incremental short-run emissions during hours when abundant clean energy is available will be no different than the average incremental emissions over all hours of the year. In either year, 2030 or 2040, the Cambium model predicts that requiring credited clean energy to be new and nearby, but not hourly matched, will have little or no effect on short-run marginal emissions.

Finally, column 5 drops the geographic matching requirement. That requirement is also implicit in columns 2, 3, and 4. The idea would be that an electricity user could contract for new clean electricity generated during the same hour as the demand, but generated anywhere in the United States.

Instead of using weighted average emissions intensities, weighted by the amount in each balancing area, we use a simple average for each of the 8,760 hours of the year, $\overline{z}_t$, averaged over the 133 balancing areas. Analogous to those in column 4, the numbers in column 5 represent the weighted average over the year of the expected value of marginal emissions that occur in one of the 133 balancing areas that is randomly drawn, weighted by total nationwide MWh of new clean power generation during that hour.

First, we calculate each hour's (unweighted) average emissions rate across balancing areas.

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[12] Different consumption patterns—where consumption in one hour is more likely than another—would yield different averages for $\overline{z}_i$.

$$\overline{z}_t = \frac{\sum_i z_{it}}{133} \tag{6}$$

Then we calculate the total nationwide amount of new clean electricity in hour *t*: $q_t^{cn} = \sum_i q_{it}^{cn}$. Finally, we take the weighted average of the hourly emissions intensities, $\overline{z}_t$, weighted by the amount of new clean electricity in each hour.

$$\boldsymbol{z5} = \frac{\sum_t \overline{z}_t q_t^{cn}}{\sum_t q_t^{cn}} \tag{7}$$

The resulting number, $\boldsymbol{z5}$ = 805 kg per MWh in 2025, projects the CO_2e that would result from an extra MWh of electricity generation, on average across the 8,760 hours of the year, when the region of demand is chosen at random from among the 133 balancing areas and when the hourly demand profile over the year follows the pattern of total nationwide generation from newly constructed clean electricity sources.[13]

Without the geographic matching requirement, the other two pillars are projected to have little or no effect on the short-run emissions rate caused by electricity demand that would already qualify as clean. Places in the contiguous United States projected to have more new clean power as part of their generation mix have roughly the same short-run incremental emissions intensities as places with less new clean power.

Taken together, columns 2, 3, 4 and 5 suggest that for short-term emissions intensities, the constraints change little relative to emissions intensities with no constraints at all. In the later years, the gap grows slightly, with short-run emissions intensities 18 percent lower than the unrestricted intensity in 2040.

Figure 2 describes emissions intensities, as opposed to total emissions. As we show in section 4, the restrictions have even more important effects on the quantity of qualifying electricity.

Figure 2 also describes only those intensities resulting from short-term incremental demand being served by *existing* generators. Some new demand, especially large increases that are expected to be permanent, will be met by investment in *new* generating capacity. The NREL Cambium model calls the resulting changes in CO_2e "long-run" incremental emissions.

3.2. Long-Run Emissions Intensities

Figure 3 presents the same set of calculations as Figure 2, but instead of reporting Cambium's projections for short-run emissions from existing capacity, Figure 3 reports the incremental emissions from a mix of existing capacity and newly constructed generators, whichever is projected to minimize the cost of meeting new demand.

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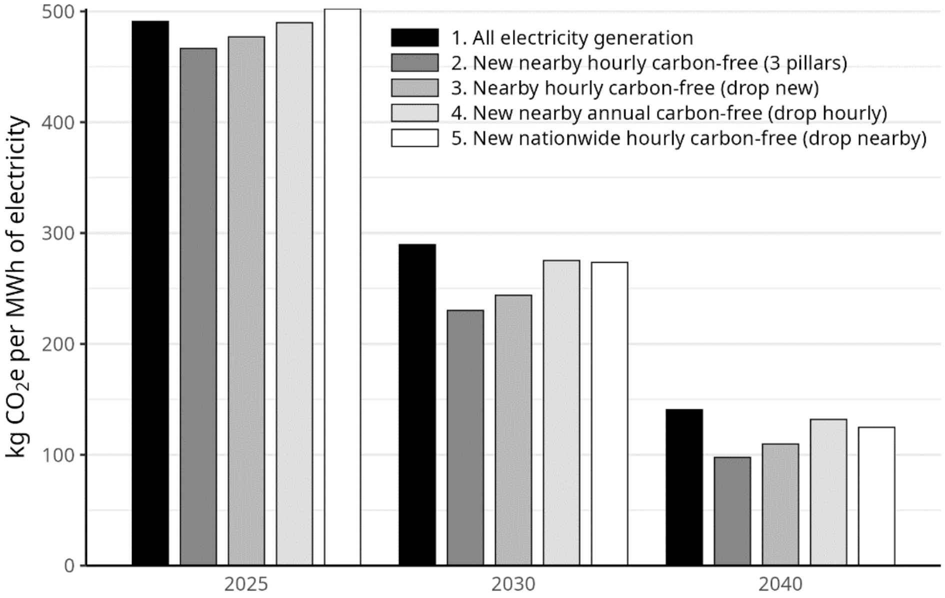
[13] As above, different consumption patterns—where consumption is more likely in one balancing area than another—would yield different averages for $\overline{z}_t$ and $z5$.

Figure 3. Long-Run Marginal Emissions Intensities



Source: Authors' calculations from NREL Cambium model.
Note: Averages for existing and planned generation only. Details in Table 1. Values and percentage differences in Table B.2.

The most obvious difference from Figure 2 is that the long-run incremental emissions intensities reported in Figure 3 are smaller. Cambium projected that the average short-run incremental emissions intensity would be 774 kg of CO_2e per MWh in 2025, in the first column of Figure 2, and the average long-run incremental emissions intensity would be 491 kg/MWh, in the first column of Figure 3. The long run is cleaner because newly added capacity is more likely to use zero-carbon sources. Most short-run incremental electricity from existing generators comes from a mix of natural gas and coal, but when new generators are built to serve demand, some fraction will be renewables with zero emissions.

Both figures show that even the most restrictive three-pillar versions of clean electricity credits do not reduce marginal emissions intensities by even one-third for electricity use claiming new, nearby, and hourly matched clean power already forecast. Electricity demand added to the grid when there is new, nearby, and hourly matched clean generation available has short-run emissions intensities between 0 and 18 percent below unconstrained demand, in Figure 2, and long-run emissions intensities between 5 and 31 percent below unconstrained demand, in Figure 3.

Columns 4 and 5 of both figures also show that by 2040, without the hourly or location restrictions, the other constraints change relatively little. Column 3 of Figure 3 suggests that without newness, the other two restrictions reduce long-run emissions intensity by around two thirds relative to all three together. And column 2 of both figures suggests that one new MWh of electricity demand meeting the three-part restriction will result in similar emissions as one new MWh without the restrictions today, and somewhat lower emissions in 2030 and 2040. Across all three years, electricity use claiming to use already-existing carbon-free power meeting the three-pillar restrictions would result in significant greenhouse gas emissions.

4. Explanations: Regional Variation and Limits on Total Clean Electricity

The patterns depicted Figure 2 and Figure 3 raise several questions. First, why are emissions intensities resulting from three-pillar eligible power demand today no less carbon-intensive than from unrestricted demand? Second, why will incremental emissions intensities from three-pillar eligible power be lower in in the future? And third, by how much might the three-pillar restrictions reduce emissions by limiting the amount of existing power qualified to serve clean demand, as opposed to its emissions intensity?

4.1. Reasons Short-Run Emissions Might be the Same

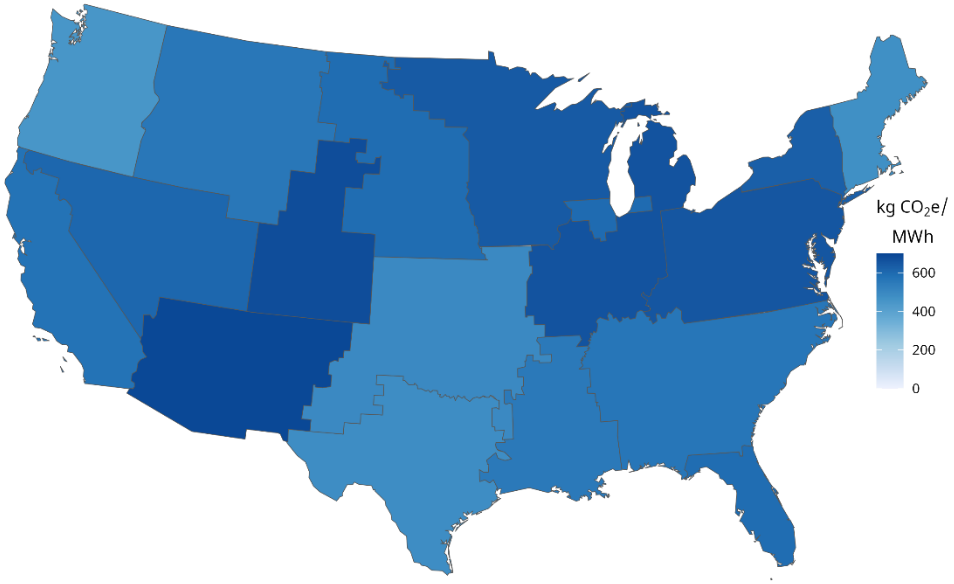
Some readers might find it surprising that the restrictions have so little relation to emissions intensities. The first column of Figure 1 provided one explanation. In most places and times, available clean power is insufficient to supply the entirety of electricity demand. As a result, any demand increase will likely be powered by fossil fuels. For 90 percent of balancing area hours in 2025, demand increases are projected to be served by coal and natural gas plants, with resulting greenhouse gas emissions. The weighted averages z1–z5 produce different values by changing the relative weights on places and times with different marginal emissions rates.

4.2. Reasons for the Lower Emissions: Regional Variation

In future years, why might three-pillar qualifying electricity demand have lower emissions intensities than unrestricted electricity demand? The obvious explanation would be that places and times in the US with more available clean power happen to have lower marginal emissions rates. Some regions have more zero-carbon electricity already being generated or planned, and some have more zero-carbon electricity that is the incremental source of any generation, whether contracted on a restricted three-pillar basis or not.

Figure 4 maps the regional variation in short-run emissions intensities of incremental electricity demand across the 133 balancing areas in the Cambium model for 2030. It depicts regional version in what the darkly shaded middle column of Figure 2 summarizes for the nation. Short-run emissions intensities range from a low of 418 kg of CO_2e per MWh of electricity generated in Texas to nearly 700 in Arizona and New Mexico. If, on average, regions of the country with lower marginal emissions rates (lighter shaded in Figure 4) have proportionally more available three-pillar qualifying power, then the weighted average of three-pillar qualifying generation would have lower marginal emissions.

Figure 4. Regional Variation: Short-Run Emissions Intensities in 2030



Source: Authors' calculations from NREL Cambium model. Values and percentage differences in Appendix Table B.3.

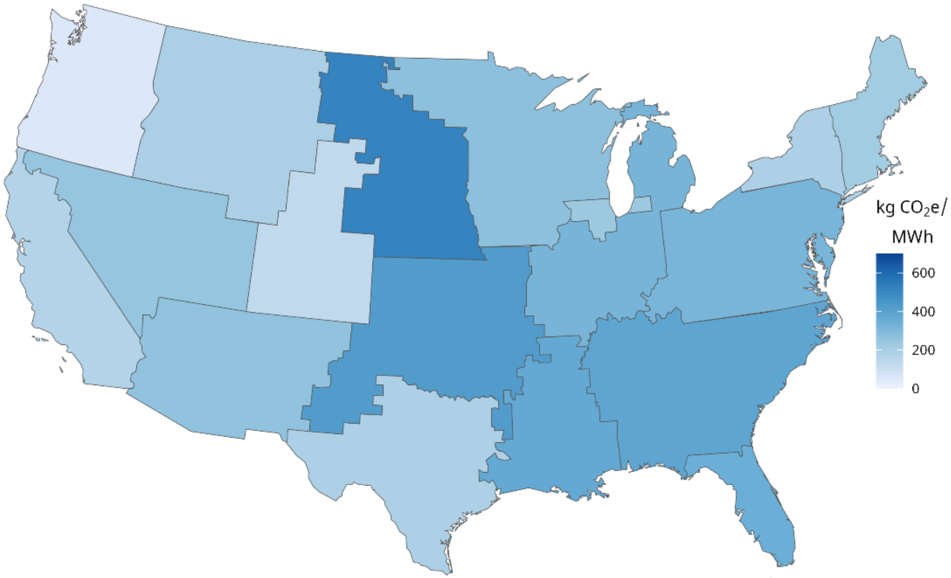
A similar pattern is evident for long-run emissions, depicted in Figure 5. The Pacific northwest, rather than Texas, is the place where incremental demand causes the lowest long-run emissions from expanding capacity. Locating in Washington rather than the Dakotas results in long-run emissions that are lower by more than 90 percent. In none of the 18 zones do the three-pillar restrictions yield larger reductions in emissions intensities—GHG emissions per MWh—for existing generation.

4.3. Reductions in Qualifying Clean Electricity Supply

What matters for climate change is not emissions intensities but total emissions, and total emissions depend in part on the total amount of electricity generated. Recall from the introductory discussion and Figure 1 that one way crediting restrictions might reduce greenhouse gases would be by increasing the likelihood that demand for clean electricity exceeds existing or projected qualifying clean power. In that case, unless suppliers respond by building more qualifying power, consumers wanting to use only clean power will either need to use less electricity, thereby requiring less generation and emissions, or cause new sources of zero-carbon power to be constructed.

Column 1 of Table 1 shows total projected US generation growing from 4.3 thousand terawatt hours (TWh) in 2025 to 5.9 thousand TWh in 2040. Column 3 shows the fraction of that power expected to be from zero-carbon sources: 51 percent in 2025, growing to 80 percent in 2040. And column 5 shows that 5.2 percent of all power in 2025 was expected to be clean and new—built in the prior two years—growing to 7.2 percent in 2030 then falling back to 5.3 percent in 2040.

Figure 5. Regional Variation: Long-Run Emissions Intensities in 2030



Source: Authors' calculations from NREL Cambium model. Values and percentage differences in Appendix Table B.3.

If businesses wanting to claim credit for using new clean power could purchase electricity generated anywhere and anytime, they would have 5 to 7 percent of US power generation as potential suppliers without any change to clean generation beyond what is already projected. So long as clean power demand didn't exceed 5 to 7 percent of existing clean supply, any additions to total electricity demand, whether credited as clean or not, would result in marginal emissions no different from uncredited electricity purchases occurring in the same hours and locations. The nearby and hourly matching restrictions prevent such anywhere-anytime purchases.

Even under all three restrictions, however, if businesses could easily locate anywhere at any scale and easily switch their demand on and off depending on whether local clean power is available, they could claim credit for that same 5 to 7 percent of projected generation as their source of clean supply. Their additions to demand would have marginal emissions intensities as in Figure 2 and Figure 3. Accordingly, to examine the effectiveness of the three-pillar restrictions on demand, we must make assumptions about businesses' ability to switch electricity use on and off.

Table 1. Existing and Planned Zero-Carbon Electricity

						Demand meeting three pillars			
	All generation	All zero-carbon generation		New zero-carbon generation		25% capacity needed		75% capacity needed	
Year	TWh (1)	TWh (2)	% of (1) (3)	TWh (4)	% of (1) (5)	TWh (6)	% of (1) (7)	TWh (8)	% of (1) (9)
2025	4,307	2,208	51%	222	5.2%	197	4.6%	74	1.7%
2030	4,682	2,950	63%	337	7.2%	301	6.4%	107	2.3%
2040	5,877	4,729	80%	309	5.3%	274	4.7%	98	1.7%

Source: Author's calculations using Cambium forecasts for the contiguous United States. Columns 6–9 assume electricity consumers must operate at least 25 and 75 percent of the time, capping demand during hours when available credited clean electricity exceeds the local amount that could run that share of the year's hours.

We start by assuming that to make capital-intensive investments profitable, plants must operate at full capacity during a minimum number of hours per year. In columns 6 and 7 of Table 1, we assume that the minimum is 25 percent of the annual hours, while in columns 8 and 9 we assume the minimum is 75 percent. We present these as a range of possibilities, not to take a stand on factories' electricity use patterns. Note that a factory running at full capacity 25 percent of the year and at less than full capacity during other hours would have an annual average capacity factor above 25 percent. We assume the hourly pattern is fully flexible, with no constraints on hour-to-hour changes.[14]

Recall from section 2 that our implementations of the geographic and newness pillars are stricter than most real-world versions. The 133 Cambium balancing areas are small, and our definition of newness limits credit to generators built during the previous two years. This extra constraint adds one more limitation. It means electricity customers will have no use for some of the qualifying clean power generated during the 25 percent of a year's hours in any balancing area when qualifying power is most abundant.

Figure 6 depicts the assumption for a typical balancing area in 2030. Hours of the year are sorted along the *x*-axis by decreasing projected generation of clean electricity. The *y*-axis depicts the amount of clean generation projected in each hour, and the top dashed line denotes the maximum electricity demand capable of using clean energy during 25 percent of the year's 8,760 hours, the amount available in the 2,190th hour ranked by clean generation.

We assume that when clean electricity supply exceeds that in the 2,190th hour, businesses use only the amount for which they have built capacity, leaving the rest of the generated clean electricity uncredited. And we assume that when clean electricity supply falls short of the amount in the 2,190th hour, businesses desiring clean power operate at less than full

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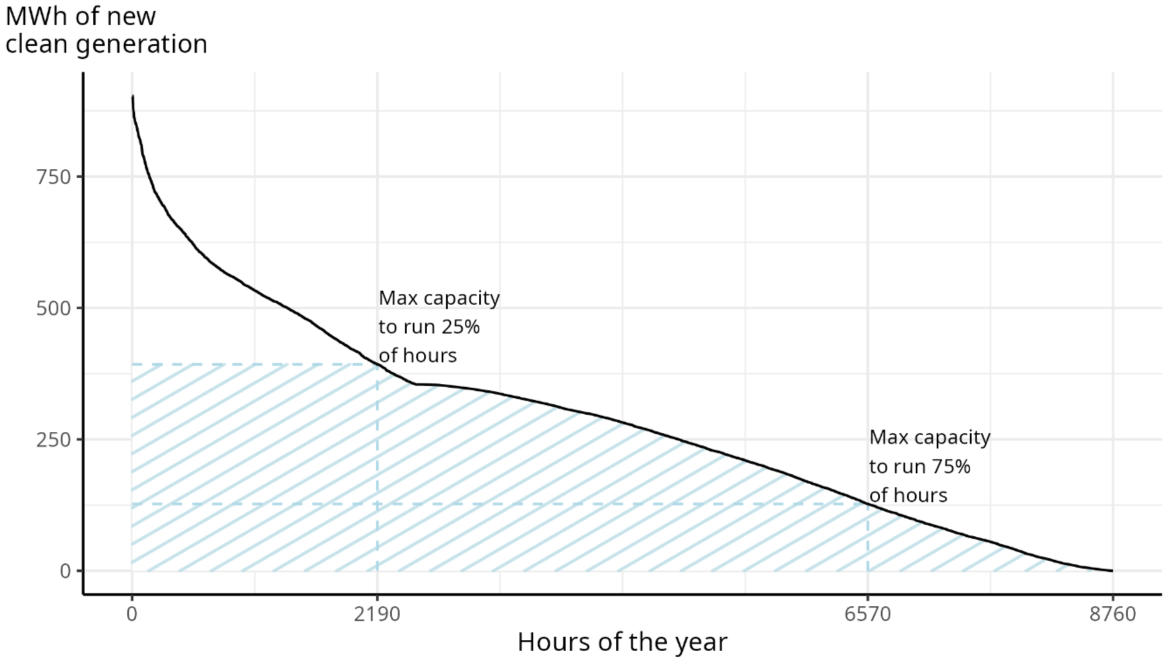
[14] Requiring clean electricity users to operate at 100 percent of capacity 100 percent of the time would be unrealistic. In that scenario, the sum of demand across all regions in 2030 would be 7.5 TWh, or 0.16% of all generation. Also, Norris et al. (2025) describe multiple ways data centers can shift demand across hours and locations.

capacity, using only the available zero-carbon electricity generated.[15] In 2030, that would yield a capacity factor of 63 percent in the typical balancing area shown in Figure 6. The area shaded with diagonal lines depicts the total clean energy that would be demanded by businesses needing to operate at full capacity at least 25 percent of the year.

Figure 6. Hypothetical Constraints on Clean Electricity Demand



Note: The shaded area represents the quantity of clean electricity that would meet the local three-pillars restriction for an example balancing area if electricity users wanting credit for clean power need to operate at full capacity during at least 25 percent of the hours. This area (Cambium region p125, the state of Delaware) has the closest-to-average total amount of new clean generation available in 2030. See summaries in Table 1, column 6.

To describe the results another way, if electricity users were completely flexible, with no capacity concerns, the entire area under the black line could be consumed before the restrictions became binding, 2.5 TWh in the example area depicted. That 2.5 TWh would be this area's contribution to the national total of 337 TWh of "new zero-carbon generation" listed in column 4 of Table 1. However, if users need to operate at full capacity for at least 25 percent of the annual hours, only 2.2 TWh of the 2.5 TWh of clean power in Figure 7 could be credited before the restriction on what counts as clean power became binding. That would correspond to one part of the 301 TWh total for 2030 listed in column 6 of Table 1.

If businesses seeking credit for using clean energy must operate at full capacity during 25 percent of annual hours, the three-pillars restrictions would reduce the amount of qualifying

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[15] For the calculations in Figure 7 and Table 1, it does not matter whether businesses decrease output in hours where clean electricity supply is low or instead buy electricity from other sources. The amount of demand for generation qualifying as clean claimed would be the same.

power that could be sold as clean. Without the 25 percent capacity need, 7.2 percent of US power generation in 2030 could serve clean energy demand (column 5) and meet the three-pillar restrictions. With the 25 percent capacity need, that share drops to 6.4 percent (column 7).

The difference, 0.8 percent of US electricity generation, slightly reduces the likelihood that existing or planned clean power will exceed the amount demanded by users wanting credit for using clean electricity. As discussed in the introduction and depicted in Figure 1, that could result in lower national electricity demand if users wanting credit for clean electricity would require more than 6.4 percent of total generation in 2030 and if clean energy seekers who cannot obtain credit would otherwise not use the electricity. That would reduce carbon emissions, if only by reducing total electricity generation. Alternatively, the difference could cause investments in zero-carbon power generation to meet that extra demand for clean electricity.

In the 2040 Cambium projections, our assumption that factories must operate at full capacity at least 25 percent of the time would have similar effects. It lowers the available clean supply that could meet that demand from 5.3 percent of all supply to 4.7 percent.

Columns 8 and 9 of Table 1 describe the situation if we assume factories requiring credit for using zero-carbon electricity must operate at full capacity during 75 percent of the year's hours, rather than 25 percent. The capacity factor for the typical region shown in Figure 6 would be 86 percent, rather than 63 percent. More importantly, the amount of available clean power that could meet that demand falls to 107 TWh in 2030, or 2.3 percent of total generation.

For reference, the 2024 United States Data Center Energy Usage Report projected that total US data center electricity demand growth from 2027 to 2028 was likely to be between 45 and 95 TWh (Shehabi et al. 2024). That range represents between half and all of the already-planned zero-carbon generation shown in column 8 of Table 1.

In either case—the 25 percent or 75 percent requirement—Cambium projects that all the zero-carbon generation in columns 6 and 8 will be available without being constructed specifically to serve clean energy demand, so its use would result in the marginal emissions reflected in Figure 2 and Figure 3 (with the caveat that Cambium's marginal emissions rates become less applicable as modeled demand changes become large). The three pillars would reduce carbon emissions primarily by reducing the supply of existing qualifying electricity that could be used by customers wanting credit for using clean power. But the three pillars would not ensure that the remaining qualifying electricity demand actually is clean. The qualifying electricity use in each case, 301 or 107 TWh in 2030, would not be zero-carbon.

The main mechanism by which the three pillars would have climate benefits is by restricting the amount of existing or already-planned clean power available to electricity users wanting to claim they cause no carbon emissions. Users wanting more credited clean power than is available would need to either reduce their electricity use and associated pollution or provide incentives to produce more clean power, either of which would benefit the climate. This mechanism isn't unique to the three-pillars proposal. Any systems placing sufficient restrictions on what power qualifies as clean would have the same features—but would vary in effectiveness and cost.

5. Conclusion and Policy Discussion

Electricity generation accounts for a quarter of US greenhouse gases, and many solutions to climate change involve electrifying even more activities, like transportation, cooking, and space heating. Decarbonizing the country as a whole requires decarbonizing the electricity grid and shifting demand for electricity away from times and places where new sources of demand will result in the most emissions. Toward that end, many governments and private business are requiring or incentivizing the awarding of credits for purchasing carbon-free electricity. As we hope our analysis has demonstrated, how purchases obtain those credits is key, at least until clean generation is more often the source for incremental electricity demand.

Buying electricity that was generated from new, nearby, clean sources during the same hour as its use can result in significant greenhouse gases. In many parts of the US, during many hours of the day, a large and growing amount of new clean power is expected without any incentives provided by clean demand. Crediting an electricity buyer with using clean electricity because it contracts for clean power that is already expected to be generated wouldn't result in less pollution than if the electricity buyer had ignored climate concerns.

One view of the three pillars is as a proxy for preventing electricity users from claiming credit for clean electricity that would been generated regardless. Without the restrictions, 63 percent of already-existing power in 2030 would come from clean sources, but well under 10 percent, perhaps as low as 1–5 percent, would be usable by businesses wanting credit for not causing emissions. If the policy sufficiently restricts credited power, electricity users wanting to claim they are not causing greenhouse gases will need to either reduce demand or cause new clean power generators to be built.

On the other hand, the restrictions have only modest consequences for the emissions intensity of electricity use when purchasers claim credit for already-existing clean power. For the foreseeable future, in most parts of the contiguous US, clean electricity purchases in times and places where clean power is available from newly built sources will still result in 60 to 100 percent as much carbon as if the purchaser ignored the restrictions. The three pillars have a larger effect by disqualifying some electricity purchases from being credited as clean than they do on the actual emissions caused by purchases that do qualify.

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Appendix A. The Cambium Model

Each of NREL's public Cambium 2024 datasets projects the US electricity grid for a future year—every five years from 2025 through 2050. Each set of results includes projected electricity demand, generation by various sources, costs, and carbon emissions for each hour of the year and in each of 133 US electricity balancing areas.

NREL compiles the Cambium spreadsheets based on the output of two underlying models. The first is the Regional Energy Deployment System (ReEDS) model. It estimates changes in the US electricity sector from estimates of least-cost responses to different future changes (Ho et al. 2021). The model was developed at NREL and is also available publicly. Users input assumptions about fuel costs, technology costs, and policies, and ReEDS solves a linear program to make decisions about investments and operations to deliver electricity while minimizing overall system costs. Cambium 2024 uses NREL's Annual Technology Baseline 2024 projections. ReEDS starts with existing generation capacity plus announced future construction, then adds decisions about whether to build new capacity or retire existing capacity. Cambium accounts for many existing state mandates and climate policies. Therefore, our analysis includes these policies to the extent they shape Cambium's figures.

The second model underlying Cambium is a commercial tool called PLEXOS (Energy Exemplar 2019). NREL uses it to simulate the hourly operations for future electric systems projected by the ReEDS model. PLEXOS estimates least-cost hourly dispatch of electricity from a given set of generators, network nodes, and transmission lines. It incorporates unit-commitment decisions and operating reserves, including details about operating constraints such as ramping rates and capacity maximums.

To create the Cambium datasets, NREL converts the ReEDS solution into a PLEXOS database and simulates hourly dispatch. The resulting datasets cover the lower 48 US States plus the District of Columbia.[16] The smallest geographic units for grid operations are the 133 balancing areas. These are the nodes for balancing supply and demand in the ReEDS and PLEXOS models. Data can also be reported by 18 generation and emissions assessment regions.

Cambium projections come with caveats, as noted above and in Cambium's documentation. They model cost-minimizing investment and dispatch decisions, which may not reflect real-world decision-making. The model derives marginal costs, but these are not necessarily equal to wholesale prices and certainly not retail prices, which are typically set by regulators. Cambium may not capture the full range of uncertainty, outages, or transmission constraints. It does not model demand responses or flexible load shifting. And the data PLEXOS uses to model hourly weather patterns comes from a single year, 2012.

Key assumptions include the following:

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[16] Projections about the supply of behind-the-meter solar electric supply come from NREL's Distributed Generation Market Demand Model (Sigrin et al. 2016).

- Projected electricity demand growth to 2050 averages 1.8 percent per year, “with conservative assumptions about the impact of demand-side provisions in IRA.”
- Fuel prices come from the *Annual Energy Outlook*. Natural gas prices are assumed to respond to natural gas demand in the electricity sector. Coal prices vary regionally but are demand-inelastic. Uranium prices are assumed to be uniform nationally and inelastic.
- Technology costs and capabilities for newly built electricity generators come from NREL’s 2024 “Annual Technology Baseline” (NREL 2024). Capabilities of existing generators come from EIA’s National Energy Modeling System.
- Generators have assumed lifetimes of 30 years for wind, solar, and geothermal; 50 for natural gas turbines; 60 for combined cycle; 75 for coal; 80 for nuclear; and 100 for hydropower. The model retires generators (except nuclear) before those ages if their value is less than half of ongoing fixed maintenance and operating costs or if they have announced an earlier retirement date.
- Cambium allocates generation to hours in a balancing area by assuming perfect mixing. The model includes some trading frictions between regions, but notes that “these are approximations: the nature and magnitude of coordination frictions in practice is diverse.”
- Cambium includes major national and state policies, including state renewable portfolio policies and GHG caps, but does not include every detail of every policy.

For each hour in each balancing area, Cambium projects total megawatt-hours of generation, including generation from storage and behind-the-meter solar and excluding any curtailed energy and net imports or exports. To examine clean energy, we use a subset of that total, including energy generated from biomass, biomass with carbon capture, concentrated solar power, distributed photovoltaic, geothermal, hydro, nuclear, renewable-based combustion turbine, utility-scale photovoltaic, onshore wind, and offshore wind. This excludes storage and imports from Canada.

As noted in section 2 of the text, Cambium reports two types of marginal greenhouse gas emissions that we use. Short-run emissions result from a 1 MWh increase in electricity demand, holding the capital assets of the grid fixed. The value comes from the emissions rate for whichever generator Cambium predicts would serve that demand increase, using the PLEXOS model and accounting for transmission, distribution, and efficiency losses. Each balancing area is presumed to have a single marginal generator and energy source in each hour. These short-run marginal emissions capture the operational response of the projected existing power grid, not how the grid structure might respond to changes in demand.

Long-run marginal CO_2e does not hold the assets of the grid fixed. Long-run emissions are calculated by solving both the ReEDS and PLEXOS models twice for each modeled year: once for the projected conditions and a second time with a nationwide increase in electricity demand. The sources of increased electricity supply include both short-term changes on the existing grid and long-term additions to the grid, both chosen to minimize the costs of meeting demand.

The Cambium user's manual describes multiple known limitations of these long-run emissions calculations. They result from increasing national electricity demand and then disaggregating the results into regions, not local demand increases. The models treat each hour as independent, whereas decisions to add capacity will depend on the likely load in preceding or ensuing hours. Power is assumed to mix freely across nodes, without state restrictions on imports and without specialized power purchase agreements.

Throughout, we focus on what NREL calls the "Mid-case" scenario, in which the Inflation Reduction Act's tax credits for clean electricity production and investments do not phase out. Other available Cambium datasets are (1) High demand growth (2) use lower and higher assumed renewable energy and battery costs; (3) project lower and higher natural gas prices; and (4) combinations of (2) and (3) with high natural gas prices and low renewables prices or high renewables prices and low natural gas prices. For both short- and long-run emissions, we use the measure that includes precombustion emissions (e.g., methane leaks from the natural gas supplied to plants) and non-CO_2 combustion emissions (e.g. small quantities of N_2O created during combustion).

A.1. New Generation

We also acquired from NREL staff a table of capacity changes that we use to define new clean energy generation, one of the advocated three pillars of clean electricity attribution. We interpolate between the periodic Cambium datasets to get annual capacity changes. We then assign that new capacity to meet demand. To estimate the amount of incremental generation provided by new capacity, we need to make assumptions about what capacity generates electricity in each hour and location. We do that using the following procedure. First, for each generation technology *g* (e.g., coal, utility-scale solar) in balancing area *i* in hour *t*, we estimate the generation from newly constructed generators in two ways: proportionally and by assigning new capacity first.

1. Proportional. This is simplest: We assume generation from each technology is proportional to capacity of each technology.

$$q_{itg}^{n} = q_{itg}\left(\frac{new\ capacity_{ig}}{total\ capacity_{ig}}\right) \tag{A.1}$$

   where q_{itg}^{n} is estimated generation from new sources of type *g* during hour *t*, q_{itg} is generation from all sources of type *g* during hour *t*, and the quotient in brackets is the fraction of type *g* capacity that is new in region *i*.
2. New capacity first. As an alternative assumption, we assume new capacity has a cost advantage and gets dispatched first. In this calculation, we assign 100 percent of the new capacity of each type to generation.

$$q_{itg}^{n} = min\left(q_{itg}, new\ capacity_{ig}\right) \tag{A.2}$$

We use a combination of those two terms to forecast the shares of each technology that come from new sources. For clean technologies like solar and wind, which do not have a heat rate, meaning they do not involve combustion of fossil fuels or steam heat, we use the proportional value in equation (A.1). For those technologies, new capacity has less of a marginal cost advantage, and there’s little reason to expect that new solar and wind generators will be dispatched before existing solar and wind generators in the same region. If 10 percent of solar capacity is new, we assume 10 percent of solar generation will be provided by newly built solar. For technologies that do have heat rates (bioenergy with carbon capture, biomass combustion, and nuclear power), we use the midpoint of estimates (A.1) and (A.2). The midpoint compromises between assuming new capacity is always dispatched before existing technology and taking the simple proportion.

Consider a simple example: a balancing area with 1 GW of nuclear power, 10 percent of which is new. If 100 MWh of nuclear power is generated in a given hour, we assume 55 MWh (55 percent) will come from newly built nuclear generators—that is, halfway between 10 MWh (proportional) and 100 MWh (new capacity first).

Appendix B. Tables

Table B.1. Short-Run Marginal Emissions Intensities

	No restrictions	Three pillars		Two pillars					
Year	All electricity	New nearby hourly carbon-free		Nearby hourly carbon-free (drop “new”)		New nearby annual carbon-free (drop “hourly”)		New nationwide hourly carbon-free (drop “nearby”)	
	(1)	(2)		(3)		(4)		(5)	
	kg of CO_2e per MWh and percentage decline relative to all electricity in column (1)								
2025	774	775	+0%	759	–2%	775	+0%	805	+4%
2030	574	530	–8%	518	–10%	577	+1%	558	–3%
2040	331	273	–18%	286	–14%	345	+4%	305	–8%

Source: Author’s calculations using Cambium forecasts.

Table B.2. Long-Run Marginal Emissions Intensities

	No restrictions	Three pillars		Two pillars					
Year	All electricity	New nearby hourly carbon-free		Nearby hourly carbon-free (drop “new”)		New nearby annual carbon-free (drop “hourly”)		New nationwide hourly carbon-free (drop “nearby”)	
	(1)	(2)		(3)		(4)		(5)	
	kg of CO_2e per MWh and percentage decline relative to all electricity in column (1)								
2025	491	467	–5%	477	–3%	490	–0%	502	+2%
2030	290	230	–20%	244	–16%	275	–5%	274	–6%
2040	141	98	–31%	110	–22%	132	–6%	125	–11%

Source: Author’s calculations using Cambium forecasts.

Table B.3. Projected Regional Marginal Emissions in 2030

	Weighted average emissions intensities (kg of CO_2e per MWh)			
	Short-run marginal kg of CO_2e per MWh		Long-run marginal kg of CO_2e per MWh	
Generation and emission assessment regions	All hours	Three pillars reduction	All hours	Three pillars reduction
	(1)	(2)	(3)	(4)
CAISO (CA)	565	−7%	146	−17%
ERCOT (TX)	418	−16%	191	−19%
FRCC (FL)	600	+2%	336	−48%
ISONE (New England)	479	+2%	250	−21%
MISO Central (IN, MI, MO)	658	−7%	319	−10%
MISO North (IA, MN, WI)	597	−7%	288	−8%
MISO South (AR, LA, MS)	570	−13%	358	−41%
NYISO (NY)	638	−14%	194	−21%
NorthernGrid East (ID, MT, WY)	535	−14%	189	−23%
NorthernGrid South (NV, UT)	617	−12%	229	−47%
NorthernGrid West (OR, WA)	453	−1%	47	+25%
PJM East (DC, DE, KY, MD, NJ, OH, PA, VA, WV)	663	−6%	336	−15%
PJM West (IL)	617	−12%	243	−29%
SERTP (AL, GA, NC, SC, TN)	570	+13%	394	+1%
SPP North (ND, NE, SD)	578	−11%	524	−6%
SPP South (KS, OK)	459	+4%	419	+0.3%
WestConnect North (CO)	606	−6%	131	−4%
WestConnect South (AZ, NM)	681	−5%	255	−18%

Sources: Authors' calculations from NREL Cambium model. Forty-eight contiguous US states plus Washington, DC. State postal codes are listed for guidance when generation and emission assessment region names are not descriptive, but state boundaries do not match precisely with zones. See map in the Cambium documentation (Gagnon et al. 2025, Figure 5).

Table B.4. Regional Differences: Available Electricity in 2030

	All generation	All zero-carbon generation		New zero-carbon generation		Three pillars			
						25% capacity needed		75% capacity needed	
Generation and emissions assessment regions	TWh (1)	TWh (2)	% of total (3)	TWh (4)	% (5)	TWh (6)	% (7)	TWh (8)	% (9)
CAISO (CA)	316	219	69%	25.0	7.9%	23.4	7.4%	13.4	4.2%
ERCOT (TX)	474	370	78%	43.6	9.2%	39.5	8.3%	17.6	3.7%
FRCC (FL)	295	72	25%	5.8	2.0%	5.0	1.7%	0.3	0.1%
ISONE (New England)	128	94	74%	17.1	13.4%	16.2	12.7%	5.2	4.1%
MISO Central (IN, MI, MO)	325	214	66%	38.2	11.7%	33.4	10.3%	13.4	4.1%
MISO North (IA, MN, WI)	244	182	74%	27.9	11.4%	23.9	9.8%	7.9	3.2%
MISO South (AR, LA, MS)	220	116	53%	26.6	12.1%	21.9	10.0%	1.2	0.5%
NYISO (NY)	161	125	78%	15.8	9.8%	14.7	9.1%	6.7	4.2%
NorthernGrid East (ID, MT, WY)	63	58	92%	7.6	12.1%	7.1	11.2%	2.8	4.4%
NorthernGrid South (NV, UT)	92	53	58%	5.7	6.2%	5.0	5.4%	0.5	0.6%
NorthernGrid West (OR, WA)	191	184	96%	10.7	5.6%	9.8	5.1%	5.1	2.7%
PJM East (DC, DE, KY, MD, NJ, OH, PA, VA, WV)	773	328	42%	29.6	3.8%	26.7	3.5%	8.7	1.1%
PJM West (IL)	141	118	84%	7.2	5.1%	6.6	4.7%	3.2	2.3%
SERTP (AL, GA, NC, SC, TN)	696	344	49%	15.7	2.3%	13.7	2.0%	5.2	0.7%
SPP North (ND, NE, SD)	73	66	90%	5.5	7.5%	5.0	6.8%	2.0	2.8%
SPP South (KS, OK)	253	213	84%	24.2	9.6%	20.4	8.1%	4.1	1.6%
WestConnect North (CO)	88	77	87%	8.5	9.6%	7.8	8.9%	3.4	3.8%
WestConnect South (AZ, NM)	149	117	79%	22.4	15.1%	20.4	13.7%	6.7	4.5%

Source: See Appendix Table B.3.