Paths to Carbon Neutrality

A Comparison of Strategies for Tackling Corporate Scope II Carbon Emissions

Tabors Caramanis Rudkevich
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Primary Authors:

Hua He

Alex Derenchuk

Aleksandr Rudkevich

Richard Tabors

Tabors Caramanis Rudkevich
300 Washington Street
Newton, MA 02458
www.tcr-us.com

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EXECUTIVE SUMMARY

Global climate change has pushed carbon emissions to the forefront of public scrutiny and scientific inquiry. At center stage are industries producing carbon emissions by generating electric power (Scope 1 emissions), as well as corporations whose consumption of electricity drives much of that production (Scope 2 emissions).

At the same time, ongoing efforts to develop "clean energy" alternatives have lowered costs for sources that were once thought to be niche, such as solar and wind energy. Corporations that are large consumers of electricity — among them Amazon, Google, Microsoft, and Meta, which all have global networks of data centers— have increasingly turned to investment in these clean energy sources, striving to shrink their carbon footprints.

These companies have taken different approaches to investment in clean energy, such as the RE100 initiative, Google's 24/7 Carbon-Free Energy plan, Microsoft's 100/100/0 vision, and the Emissions First partnership led by Meta and Amazon. All these approaches involve investment in new clean energy projects to balance grid electricity consumption with clean energy generation.

In our study we explore the costs and impact of these different approaches, looking at three strategic questions facing large electricity consumers:

- What is the most effective clean energy procurement strategy in terms of total cost ($/MWh of customer load) and CO_2 abatement cost ($/metric ton of CO_2 displaced)?
- How do energy-matching strategies compare to an emissions-focused strategy in terms of avoided emissions and reaching carbon neutrality?
- How do customer location and load profile affect the impact and cost of each strategy?

To answer these questions, we look at four different clean energy procurement strategies being used by large electricity consumers and perform a detailed analysis of each strategy's costs and the results it delivers. If the intent is to maximize emission reductions per dollar of capital allocation, accelerating overall grid decarbonization, which strategy cuts the most carbon for the least expense?

Factors in the Analysis

We evaluated 10 different large electricity customers pursuing four different clean energy procurement strategies in the year 2025.

We compared two customer types with different load profiles:

- A load profile representing stand-alone, commercial retail buildings.
- A flat load profile representing the data centers or industrial installations.

In parallel, we studied customer load in five different balancing authorities (BAs), selected for geographical and regulatory diversity:

- The California Independent System Operator (CAISO)
- The PJM Interconnection (PJM)
- Duke Energy Carolinas (DUKE)
- Portland General Electric (PGE)
- The Los Angeles Department of Water and Power (LADWP).

CAISO and **PJM** are large system operators that cover broad geographic regions and operate wholesale power markets. **DUKE** is a vertically integrated electric utility (VIEU) region. **PGE** and **LADWP** are municipal areas each served by a vertically integrated electric utility.

Under some strategies, clean energy could also be procured in three additional ISO/RTO power markets: The Electricity Reliability Council of Texas (ERCOT), the Southwest Power Pool (SPP), and the Midcontinent Independent System Operator (MISO).

We evaluated four clean energy procurement strategies:

1. **Annual energy matching.** (The current industry standard.) The customer must match their load with generation from procured clean energy on an annual basis. Clean energy can be procured in the customer's local balancing authority or from any of the five ISO/RTO balancing authorities in this study: CAISO, PJM, MISO, ERCOT, or SPP. The annual energy matching strategy in this study meets the RE100 requirements.
2. **Local annual energy matching**. This is identical to annual energy matching, except that the customer must procure clean energy within the balancing authority where their load is located.
3. **Hourly energy matching**. The customer must match their load on an hourly basis with generation from clean energy procured within the balancing authority where their load is located. In addition, the customer may utilize battery storage to shift clean energy between usage hours. This strategy meets the 24/7 Carbon-Free Energy requirements.
4. **Carbon matching**. The customer must reach *carbon neutrality*, which is defined as having avoided emissions (carbon emissions displaced by incremental clean energy procurement) that equal or exceed the carbon emissions attributable to their load on an annual basis. Clean energy can be procured within the customer's local balancing authority, or from any of the five ISO/RTO balancing authorities in this study — CAISO, PJM, MISO, ERCOT, or SPP.

We calculated carbon emissions attributable to load ("load emissions") and carbon displacement attributable to generation ("avoided emissions") from procured clean energy by using Locational Marginal Emission Rates (LMERs) from the long-term Tabors Caramanis Rudkevich market forecast.[1]

LMERs provide an accurate, transparent measurement of the change in power system emissions created by a change in electricity supply, demand, or transmission at any specific location and time. The most reliable sources for marginal emission rates are balancing authorities. They have access to the most granular operating data, and they run the dispatch algorithms that identify marginal generators.

Currently LMERs are not widely available, but there is broad movement to provide increased access to this data for carbon accounting and carbon-aware operating decisions. For example, The Infrastructure Invest and Jobs Act (IIJA) specifically calls for the U.S. Energy Information Administration (EIA) to collect and report hourly locational marginal greenhouse gas emission rates.[2] PJM and ISONE have begun reporting marginal emission rates, and others may follow.

[1] "Carbon displacement" and "avoided emissions" are used interchangeably in this paper – both refer to the counterfactual carbon emissions that are not emitted due to incremental clean energy generation on the power grid, calculated using marginal emission rates.

[2] Infrastructure Investment and Jobs Act, Pub. L. No. 117–58, § 40418 (2021). https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

For individual customers, LMERs can be used to translate into a single carbon footprint electric consumption and generation that occurs at different locations and times. We used LMERs to calculate, for each customer and strategy, *net carbon footprint* (total of load emissions and avoided emissions) and *CO_2 abatement cost* (dollars spent per metric ton of CO_2 displaced).

Customers' costs for procuring clean energy were calculated using PPA index prices, or using LCOE values where PPA index prices were not available. The value of energy sold from the projects was determined using locational marginal prices (LMPs) in ISO/RTO regions and using avoided cost/feed-in tariff rates[3] in regulated utility regions. Hourly LMERs and LMPs were sourced from TCR's long-term market forecast for the year 2025. All costs were annualized to that year.

For the *annual* energy-matching strategies and the carbon matching strategy, the customer procured the least-cost clean energy to meet the strategy goal. For *hourly* energy matching, customer actions were modeled using a least-cost linear optimization formula to determine clean energy procurement, battery procurement, and battery operation. We acknowledge that there are other factors involved in corporate decision-making on procurement of clean energy, for example, local employment or community investment. Because those choices are situation-specific, we did not attempt to quantify them in this analysis.

Key Findings

Carbon matching is the **most effective strategy** in terms of both strategy cost and carbon abatement potential.

Both in terms of total cost per MWh of load served (see Figure ES-1) and in terms of CO_2 abatement cost for all location and load-profile scenarios, carbon matching emerged as the most effective strategy. Because this strategy moves customers beyond megawatt-hour matching to focus on the quantified emissions impact of their electricity consumption and generation, it allows customers to:

- **Consistently achieve carbon neutrality.** In our analysis, we found that carbon matching was the only annual matching strategy to consistently achieve carbon neutrality, regardless of customer load profile and location.
- **Target investment in areas and projects that maximize carbon displacement for each dollar investment.** Translating MWh of energy to carbon emissions means customers no longer must consider balancing authority boundaries. All customers, regardless of their load location, can procure projects with the highest carbon displacement potential. In the analysis depicted by Figure ES-1, the project with the highest carbon displacement potential is a utility PV project in southern SPP — an area with high-quality solar resources and considerable coal generation, which results in high LMERs. This project was selected by all customers pursuing the carbon matching strategy.

[3] Although merchant project can sell to market price in some parts of the country (*e.g.,* WECC), this study uses avoided cost and feed-in-tariff as proxy for value of energy because avoided cost and feed-in-tariff are guaranteed for qualifying facilities. More discussion in methodology section.

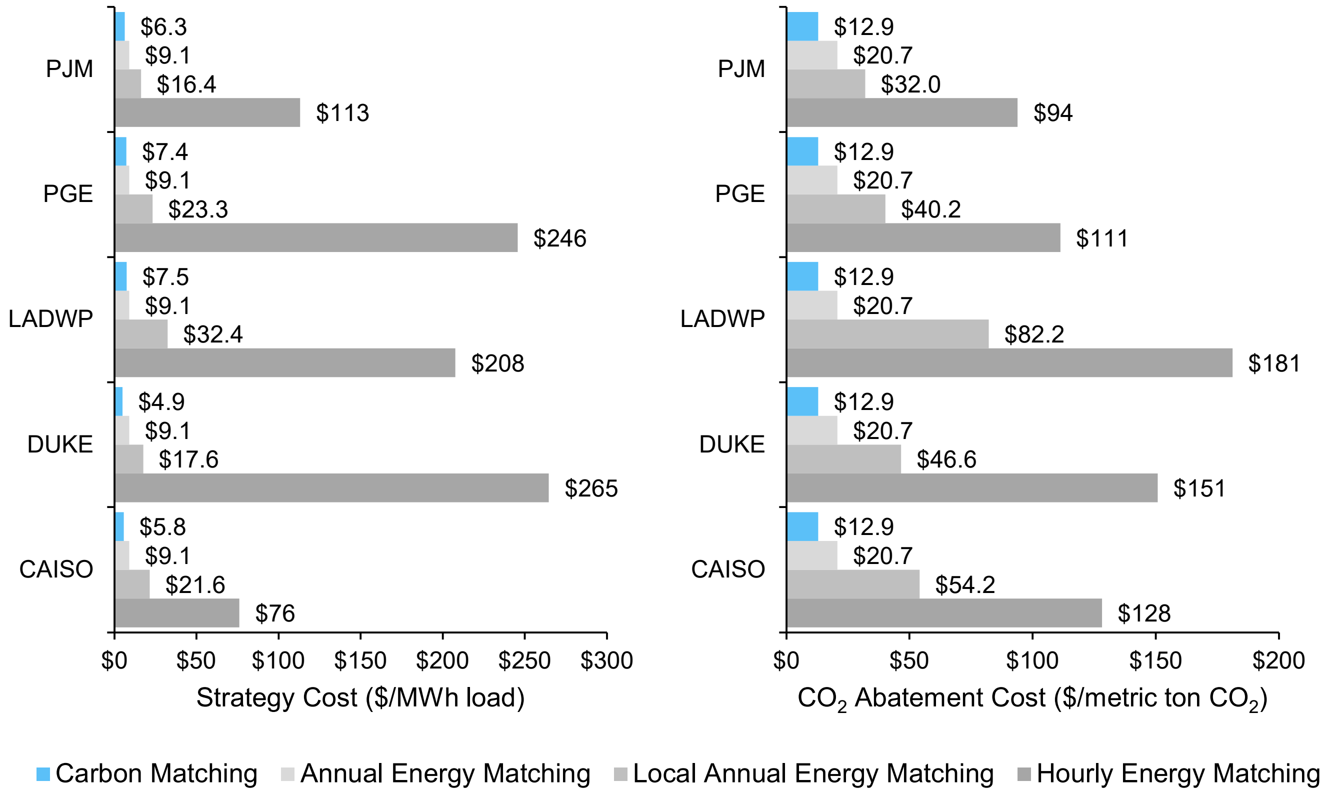

Figure ES-1: Strategy cost per MWh of customer load, for each strategy in each balancing authority. Results are shown for the customer with a commercial load profile. For hourly energy matching the target CFE score is 100%.

Energy matching does not guarantee carbon neutrality.

Because energy matching strategies focus on units of energy rather than units of carbon emissions, they do not guarantee achievement of carbon neutrality. In our analysis across all five balancing authorities, neither annual energy matching nor local annual energy matching achieved annual carbon neutrality.

The hourly energy matching strategy fails to achieve carbon neutrality on an hourly basis, despite local hourly matching of energy. It only achieves annual carbon neutrality — at a high cost — by significantly over-procuring energy (>200% of load).

The annual energy matching strategy only achieved carbon neutrality for customers in two of the five balancing authorities studied: CAISO and DUKE. This reflects the lower carbon intensity of the grid at those load locations. CAISO and DUKE have relatively higher generation from zero-emission energy sources, so emissions attributable to load in these two balancing authorities are lower than those in LADWP, PGE, and PJM.

Local annual energy matching requires customers to procure clean energy in the same balancing authority as their load. Advocates of this approach argue that the procured clean energy thus more closely "matches" load. But we found that while localizing procurement did increase cost, it did not consistently improve carbon displacement. Only two of the balancing authorities using local annual energy matching — PJM and PGE — achieved carbon neutrality.

Localized energy matching strategies **decrease** carbon displacement efficiency.

Both local annual energy matching and hourly energy matching aim to locate clean energy procurement within the same balancing authority as the customer's load location to better to "match" or "offset" load. We found that although localizing energy procurement increased customer costs, it did not guarantee a lower carbon footprint than non-localized annual energy matching. In many cases it actually raised the customer's net carbon footprint because it limited clean-energy procurement options.

The lowest-cost clean energy projects in our analysis were PV projects in ERCOT, while the most cost-effective projects for carbon abatement were PV projects in southern SPP. An annual energy matching and carbon matching strategy allows customers to procure energy from these projects regardless of load location.

However, customers choosing the local annual energy matching and the hourly energy matching strategy cannot access these most efficient projects unless their load is in ERCOT and SPP. For example, under the local energy matching strategy, a customer in CAISO can only procure energy from PV projects in CAISO — which cost significantly more than those in ERCOT, and are much less effective at displacing carbon than those in SPP.

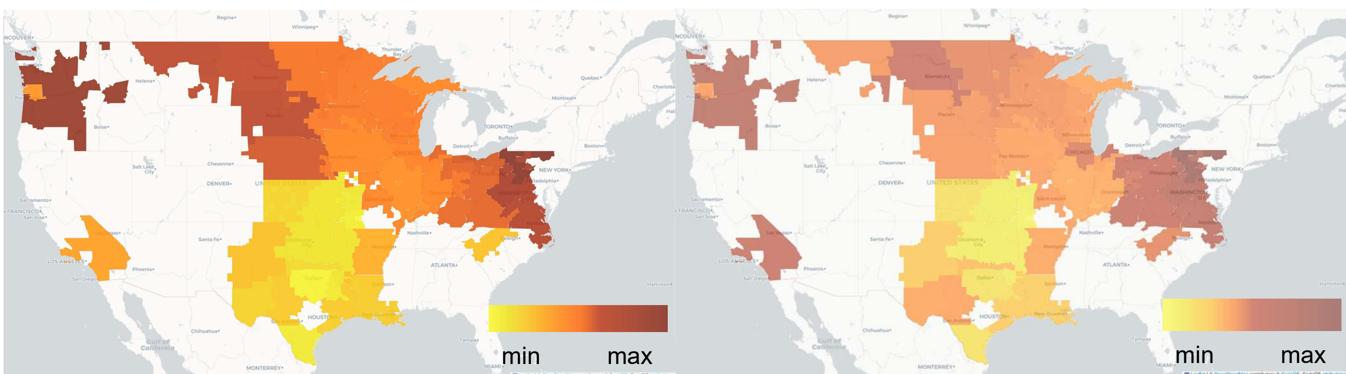

Figure ES-2: PV procurement cost in $/MWh load (left) and carbon abatement cost in $/metric ton CO_2 (right).

Hourly energy matching is the **least** efficient strategy at displacing carbon emissions.

The hourly energy matching strategy ensures that the customer's load is matched with clean energy on an hourly basis, within the same balancing authority. But to achieve this, the customer must procure significantly *more* clean energy than in any other strategy studied, and they must procure battery storage to maintain clean energy use during periods of low wind generation and solar generation. This pushes the cost an order of magnitude higher than the costs of the carbon matching and annual energy matching strategies.

Despite the additional clean energy procurement and hourly matching of load, hourly energy matching also carries the highest abatement cost of any strategy (Figure ES-3). In contrast, carbon matching and annual energy matching strategies allow customers to achieve higher emission reductions at a lower cost.

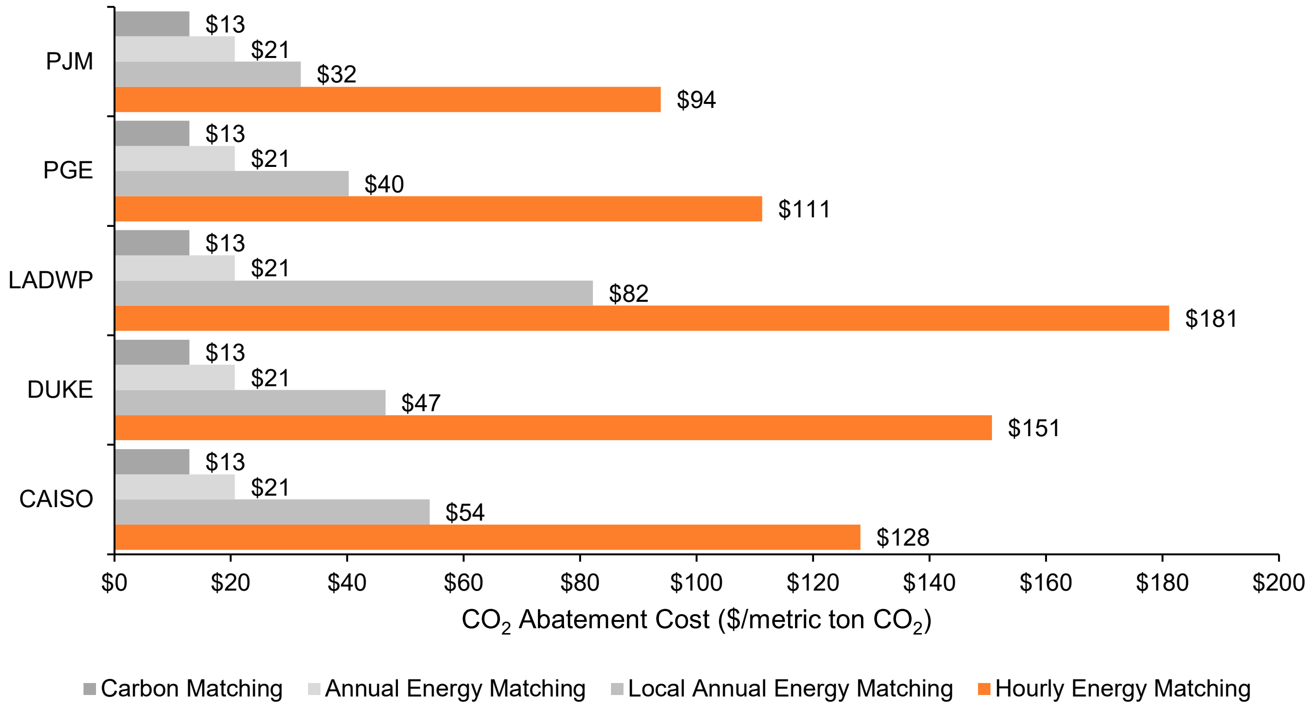

Figure ES-3: CO_2 emissions abatement cost ($ spent per metric ton of CO_2 displaced), for each strategy in each balancing authority. Results are shown for the customer with a commercial load profile. For hourly energy matching, the target CFE score is 100%.

Costs to implement the **hourly energy matching strategy** vary significantly, depending on customer load location and load profile.

Implementing hourly energy matching can cost as little as $68/MWh of load in CAISO, due to access to firm zero-emission geothermal energy — or as much as $289/MWh in DUKE. This wide gap in strategy costs may limit adoption, especially for customers with load spread across multiple Bas and customers who have load in Bas with limited clean energy resources.

In contrast, annual energy matching and carbon matching have a consistent cost. All such customers in this analysis had the same annual energy matching cost, and their carbon cost only varied slightly, based on the emission rates in the balancing authority where their load was located.

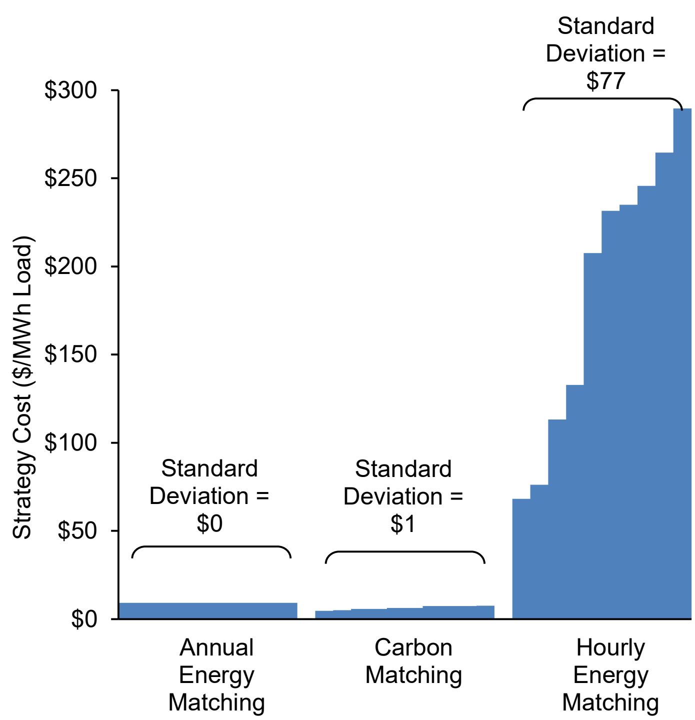

Figure ES-4: Strategy cost by strategy, load BA, and load shape. Hourly energy matching strategy shown with 100% CFE score.

Pursuing **localized energy matching strategies** may not be practical and can **deter participation.**

The cost metrics alone fail to capture other potential hurdles for localized energy matching (*i.e.,* procuring energy in the balancing authority where the load is located). Within some balancing authorities, especially smaller metropolitan ones like LADWP and PGE, clean energy projects may not be readily available for procurement.

For our analysis, we allowed LADWP and PGE customers to procure energy from nearby regions with a firm transmission contract. But transmission contracts add cost, and this distorts the concept of energy matching within a single balancing authority. Technology options may be restricted by other factors. For example, in DUKE there are legal, geographic, and regulatory obstacles that effectively rule out consideration of onshore wind projects.

With hourly energy matching, a small geographic region and restricted technology choices limit diversity in renewable energy generation profiles. Such customers are forced to procure additional battery storage as backup power for periods of low renewable generation. Finally, building a project in a regulated utility territory may demand lengthy, costly negotiations — a steep barrier for customers without the necessary time or resources.

While larger corporations may be able to leverage those circumstances as an opportunity to increase market access, such challenges can discourage participation by the wider corporate world.

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I Background

Electricity is vital to modern life, but almost everywhere the production of electricity creates carbon emissions that contribute to climate change. Private corporations and governmental entities have sought to tackle this problem by committing to carbon neutrality or by pledging to match all their electricity consumption with renewable electricity generation. For example, RE100 is a coalition of companies with a combined electricity demand of more than 450 TWh/year that have each pledged to match 100% of their electricity demand with renewable generation annually within each country in which they operate.[4]

Some have gone further, pledging to match 100% of their electricity demand with renewable generation at all times. This approach, pioneered by Google in 2020[5] as 24/7 carbon-free energy, attempts to imitate and accelerate full-grid decarbonization by accounting for the fact that solar and wind energy are not available in all hours, meaning that other carbon-free energy sources or electricity storage will be required. Since this announcement, other entities have also announced 24/7 commitments, including Peninsula Clean Energy (a community choice aggregator in California) and the cities of Los Angeles and Des Moines.

Other organizations have taken a different approach. Rather than focusing on matching electricity consumption, their focus has been on quantifying and accounting for the carbon emissions caused by electricity consumption and displaced by additional renewable electricity generation. The Emissions First partnership, launched in December 2022 by a group of corporations including Meta and Amazon, advocates for this approach.[6]

Some previous analyses have been done to evaluate the impact and cost of clean energy procurement strategies. The ZERO lab at Princeton University released an analysis of the cost and system-level impacts of 10% of commercial and industrial load choosing to reach the 24/7 carbon-free energy goal.[7] In addition, Peninsula Clean Energy developed an optimization model to determine the cost and best path to reach 24/7 carbon-free energy for their specific load and location and published a white paper detailing the results.[8] These studies found that although hourly energy matching comes with significant cost premiums and excess generation, the strategy is feasible with current technology in the markets studied (PJM and CAISO).

4 RE100 Climate Group, "RE100 TECHNICAL CRITERIA."

5 Google, "Moving toward 24x7 Carbon-Free Energy at Google Data Centers: Progress and Insights."

6 Emissions First, "Principles"

7 Xu et al., "System-Level Impacts of 24/7 Carbon-Free Electricity Procurement."

8 Pepper, "Our Path to 24/7 Renewable Energy By 2025."

For the emissions-focused approach, a 2021 paper published in the *Electricity Journal* by the authors compared the cost and carbon footprint of annual energy matching, 24/7 hourly energy matching, and carbon matching strategies in PJM, MISO, CAISO, and NYISO, using forecasted marginal emission rates[9]. A 2022 white paper co-authored by the Brattle Group and Resurety compared an on-site 24/7 energy matching approach against an annual energy matching and carbon matching approach in ERCOT, using marginal emission rates to calculate carbon footprint.[10] These papers found that the emission-focused approach is the most efficient at displacing carbon emissions.

The objective of this paper is to provide a comprehensive, comparative study covering a variety of factors impacting the cost and implementation of corporate clean energy procurement strategies.

These existing studies on clean energy procurement strategies are limited in scope. Some focus solely on a single strategy (Princeton, Peninsula), some are limited to a single market (Resurety), and some only studied deregulated markets (*Electricity Journal*). The objective of this paper is to provide a comprehensive, comparative study covering a variety of factors impacting the cost and implementation of corporate clean energy procurement strategies:

- *Location*: we analyzed strategy implementation for customers in five different U.S. balancing authorities, ranging from PJM, the largest RTO in the U.S., to metropolitan balancing authorities in Los Angeles and Portland, Oregon.
- *Regulatory structure*: we considered both ISO/RTO regions with wholesale power markets and vertically integrated utility territories with regulated avoided cost rates or tariffs.
- *Load profile*: this paper analyzed commercial (retail/shopping) building load as well as flat (data center or industrial) load.
- *Forecast scenarios*: we considered a range of future market scenarios under different gas price forecasts, providing a range of potential costs for strategy implementation.

This paper builds on previous analyses by comparing the cost and carbon footprint of four clean energy procurement strategies, using an optimization model to determine least-cost procurement and battery operation. 2025 hourly power prices and locational marginal emission rates (LMERs) from TCR's proprietary long-term market forecast were used, and the results were calculated for multiple future natural gas price scenarios.

In addition, we present the methodology for computing carbon footprint and carbon displacement using LMER and demonstrate that they provide an internally consistent way to assign responsibility for carbon emissions and displacement when applied across all loads and generators.

This paper is focused on comparing the cost efficiency of emissions reductions via different procurement approaches. There are other factors influencing clean energy procurement decisions. For example, some buyers may choose to

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[9] He et al., "Using Marginal Emission Rates to Optimize Investment in Carbon Dioxide Displacement Technologies."

[10] Oates and Spees, "White Paper."

procure projects in the same grid as their operations due to projects' benefit to local community and energy prices. These are important factors to consider when making procurement decisions and they are not quantified in this analysis. The goal of this analysis is to determine how to maximize emission reductions per dollar of capital allocation, and thereby accelerate system-level grid decarbonization.

II Introduction

This study evaluated four clean energy procurement strategies:

1. **Annual energy matching** (industry standard): annual energy matching is the current industry standard strategy for Scope 2[11] CO_2 emissions reduction. Using this strategy, a customer procures clean energy assets such that the annual generation from these assets matches the customer's annual electricity consumption. This strategy does not restrict clean energy procurement location within the bounds of this study (U.S. power markets). For example, a customer could offset their load in New York with energy generated by a wind farm in Texas. Because this analysis is confined to the U.S., this strategy matches the commitment of the RE100 initiative (which treats the U.S. and Canada as a single "market").
2. **Local annual energy matching**: local annual energy matching is a location-constrained version of annual energy matching. Power grid emission rates vary by location, so emission rates might be higher at the load location than the generation location. To address this concern, using this strategy the customer locates clean energy assets in the same power system balancing authority as their load. Like annual energy matching, this strategy matches annual electricity load with annual clean energy output.
3. **Hourly ('24x7') energy matching**: the hourly energy matching strategy is bound by both locational and temporal constraints. To achieve hourly energy matching, the customer must match their electricity consumption with clean energy on an hourly basis in the same balancing authority. This is the commitment made by Google and others. Under this strategy, a customer must procure clean energy assets in the same balancing authority as their load. In addition, the customer can procure battery storage to shift clean energy between hours.
4. **Carbon matching**: carbon matching is an alternative approach to Scope 2 CO_2 emissions reduction. Rather than attempting to match energy in terms of megawatt-hours (MWh), this strategy addresses carbon emissions directly. Using this strategy, CO_2 emissions are accounted for directly using the hourly locational marginal emissions rate at the customer's load and clean energy generation locations. A customer would procure clean energy assets such that the generation from these assets displaces a quantity of carbon emissions equal to or greater than the emissions generated by the customer's electricity consumption.

[11] According to the EPA, Scope 2 emissions are "indirect GHG emissions associated with the purchase of electricity, steam, heat, or cooling."

Important to note is that for the annual energy matching strategies (annual energy matching and local annual energy matching), the customer load profile is inconsequential – the only metric that matters is total annual load. For the hourly energy matching strategy, the load profile is relevant because the customer must match their load with clean energy generation every hour. For the carbon matching strategy, the load profile is relevant because LMER varies temporally, so load in one hour may have a different carbon footprint than load in another hour.

Each of these strategies are evaluated on three metrics:

- **Strategy cost** ($/MWh) measures the estimated cost to procure clean energy to achieve each strategy. For projects in deregulated ISO/RTOs, the clean energy procurement cost is the difference between the power purchase agreement (PPA) contract price and hourly locational marginal price (LMP). For projects located in vertically integrated utility territories without wholesale markets, the clean energy procurement cost is the project's levelized cost of energy minus the revenue generated by the project through avoided cost or feed-in tariff rates. For hourly energy matching, cost also includes battery storage procurement cost and battery operation cost/revenue.
- **Net carbon footprint** (metric tons CO_2) measures the difference between carbon emissions attributable to electricity consumption ("load emissions") and carbon displaced by clean energy generation from incremental investment ("avoided emissions").[12] For hourly energy matching, net carbon footprint also includes the carbon emissions and displacement associated with battery operation. In this paper, "carbon neutrality" is defined as when a customer has a net carbon footprint of zero or less. Note that this figure only considers emissions from electricity consumption and avoided emissions from investment in clean energy generation. It does not include emissions or offsets from any other source.
- **Carbon abatement cost** ($/metric tons CO_2) measures the amount of investment required for each unit of carbon displaced by each strategy. A lower value indicates the strategy or asset is more efficient at displacing carbon. This metric does not consider the total carbon footprint of the customer, only the effectiveness of customer action.

[12] "Carbon displacement" and "avoided emissions" are used interchangeably in this paper – both refer to the counterfactual carbon emissions that are not emitted due to incremental clean energy generation on the power grid, calculated using marginal emission rates.

II.1 Measuring Carbon Footprint

Operation of the power grid is a highly complex process that requires balancing supply and demand in real-time at the lowest cost to consumers. In an interconnected power system, an incremental injection (generation) or withdrawal (load) of electricity at a given location within the system (node) will result in a system-wide change in the mix of generating resources (economic dispatch) and with it, a change in carbon emissions. As is the case with the LMP, this carbon emission impact is dependent on the **time** and **location** of the injection or withdrawal.

- **Time.** The carbon emissions impact of electricity consumption/generation is directly related to time of operation. Net demand (load minus renewable generation) changes constantly, requiring system operators to dispatch different generators and types of generators to meet load. These dispatchable generators are typically carbon-emitting, and their emission rates vary based on fuel type and efficiency. For example, in CAISO, incremental load during midday is often met with PV generation, while incremental load in the evening is often met with gas-fired combustion turbine generation, as the system ramps up high-emitting peaker units to replace declining solar generation. This means that the carbon impact of 1 MWh of energy consumption in CAISO is significantly lower at midday compared to evening.
- **Location**. Among power grids, differences in generation mix causes differences in system-wide carbon emissions. Within a single grid, transmission constraints and losses cause marginal emission rates in one area to be higher than another. In New York, for example, transmission constraints often prevent New York City from accessing renewable energy generation from sources located upstate. These constraints force the grid to dispatch high-emitting generators located in the city to meet marginal load, making marginal energy much more carbon intensive in the city than upstate.

Locational marginal emission rate (LMER) is a physically and mathematically accurate, reliable, and transparent way to quantify carbon emissions at any specific grid location and point in time.

II.1.1 Locational Marginal Emission Rate (LMER)

Locational marginal emission rate (LMER) is a physically and mathematically accurate, reliable, and transparent way to quantify carbon emissions at any specific grid location and point in time. LMER measures the change in systemwide emissions in response to a marginal increase or decrease in demand at a given location, as shown in the equation below[13]. LMER is expressed in units of CO_2 per unit of electrical energy. Looking node by node, if 1 MWh of increased demand results in systemwide emissions rising by 400 kilograms, then the LMER at the node is 400 kilograms/MWh.

[13] Ruiz and Rudkevich, "Analysis of Marginal Carbon Intensities in Constrained Power Networks.", and Rudkevich and Ruiz, "Locational Carbon Footprint of the Power Industry."

$$MER_{node\ A} = \frac{\Delta Systemwide\ Carbon\ Emissions}{\Delta Demand_{node\ A}}$$

Mathematically, LMER is calculated using a similar methodology to the marginal prices used for economic dispatch of power systems worldwide. Like the locational marginal prices (LMPs) used in U.S. power markets, LMER is a function of time and location.

Since Fall of 2021, PJM has published real-time LMER data for each substation and aggregate node. These data provide a real-world example of the locational and temporal nature of LMER.

Figure below shows PJM real-time system-wide generation mix and emission rates for August 14th, 2022. The stacked area represents system generation fuel mix, the solid lines show the LMER at high voltage substations in different parts of PJM, and the black dashed line shows the estimated average emission rate of the system. System load has a typical summer profile, lowest in the early morning, and peaking in the late afternoon and early evening. To meet this load, the system dispatches a fleet of natural gas combined cycle (NGCC), coal, and gas-fired peaking units based on their cost and operating parameters. As load starts to increase around 7am, the system ramps up thermal generation and increases coal and gas output gradually until load reaches its peak at 5pm. As night approaches, load starts to decline. The system reduces coal and gas dispatch in response.

LMERs closely follow the change in thermal dispatch. High natural gas prices in 2022 made natural gas the predominate marginal fuel in PJM. On this particular day, LMER is often about 0.45 metric ton CO_2/MWh (a typical NGCC emission rate), indicating that NGCC was the main marginal energy source. During morning and afternoon ramp periods, quickly changing load and renewable energy output (decreasing wind in the morning and PV at night) requires the system to redispatch thermal generation, causing coal to replace NGCC in some areas. This caused LMERs to quickly increase above 1 metric ton CO_2/MWh and diverge significantly due to transmission constraints. LMER also diverged in the early afternoon when high demand and transmission constraints required some areas to dispatch additional coal and fuel oil generation to meet load.

By contrast, average emission rate (AER), calculated based on fuel mix, does not offer the same level of temporal and locational granularity. AER remained relatively flat on this day, offering little signal to differentiate hours of high and low grid carbon intensity.

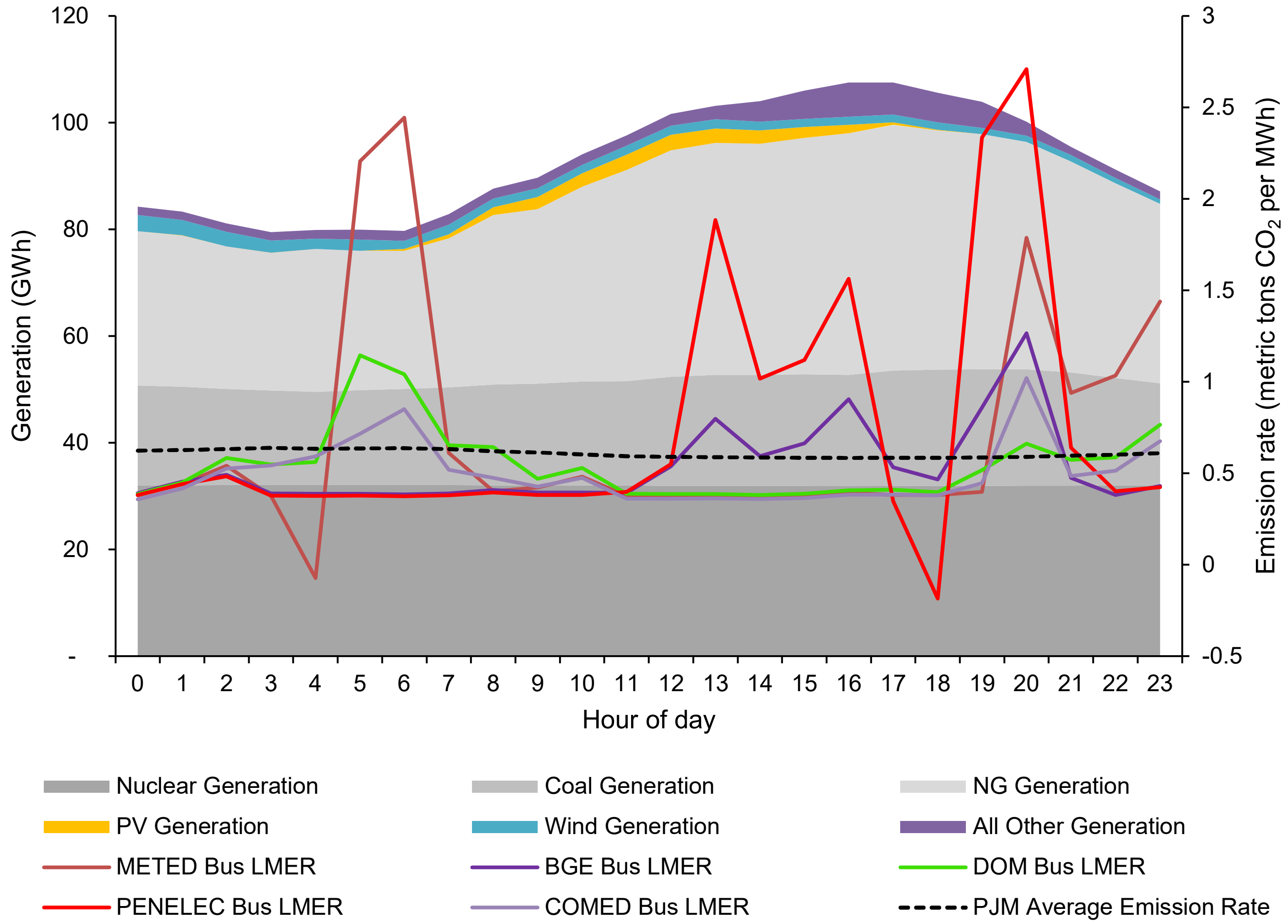

Figure 1: PJM systemwide emission rates and fuel mix for a 24-hour period

Figure 2 shows a 5-minute snapshot of PJM published zonal LMER for an afternoon interval in August 2022. In this hour, transmission constraints caused a clear separation in LMER across the system. The system saw LMER ranging from 0.4 metric ton-CO_2/MWh to 0.7 metric ton-CO_2/MWh, a difference of more than 50%. Because average emission rate does not take transmission into account, it is typically calculated on a balancing authority level. Average emission rate cannot offer this level of spatial granularity, which is critical to siting assets to minimize carbon footprint.

Comparing Figure 1 and Figure 2 demonstrates the additional information gained from the locational measurement of LMER as opposed to average emission rates.

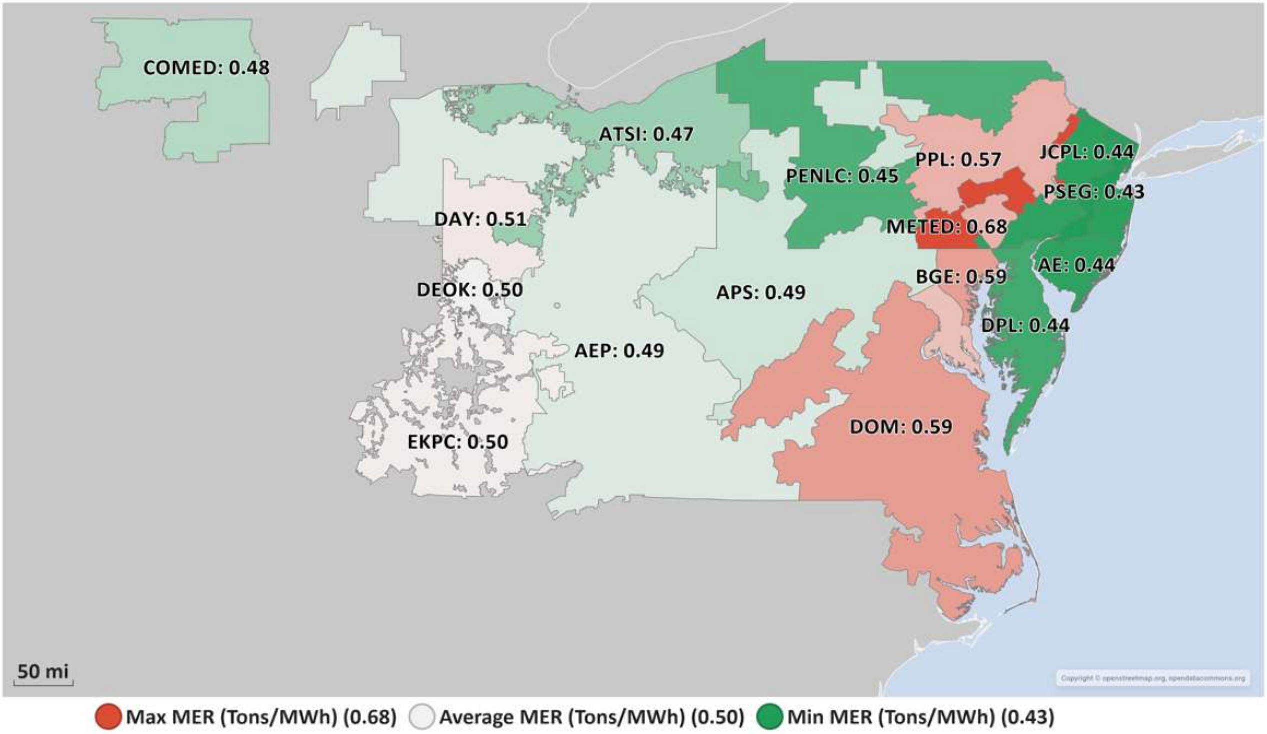

Figure 2: PJM zonal marginal CO_2 emission rate for a single 5-minute interval

II.1.2 Carbon footprint accounting

LMER can be used to attribute CO_2 emissions and displacement to individual generation assets and loads on the power grid at any point in time and location. When applied to all assets in the system, the emissions attributed to each generation asset, transmission line[14], and load equal the total physical system carbon emissions.

LMER can be used to attribute CO_2 emissions and displacement to individual generation assets and loads on the power grid at any point in time and location.

The carbon footprint of electricity consumption at a specific location (e.g., node or area) at a particular time is calculated as quantity of electricity consumed multiplied by the LMER at that location:

$$Carbon\ Footprint_{consumption} = MER_{Location} * Consumption_{location}$$

The carbon footprint of generation at a specific node at a particular time is calculated as the amount of generation multiplied by the difference between the generator's emission rate and the LMER at that location:

$$\begin{aligned} Carbon\ Footprint_{Generation} \\ &= (Physical\ Emission\ Rate\ of\ Generator - MER_{Gen.\ Node}) \\ &* Generation_{location} \end{aligned}$$

[14] Attribution of emissions to transmission lines occurs due to transmission congestion. See Rudkevich and Ruiz (2012) for further discussion of that effect.

For renewable resources, the generator emission rate is 0, so the equation cancan be simplified to:

$$Carbon\ Footprint_{Generation} = -\ MER_{Gen.Node} *\ Generation_{location}$$

Table 1 illustrates carbon emission accounting for a simple balanced system using both direct physical accounting and the marginal carbon emission rate footprint method. Column A shows the load and generation level of assets in the network. Column B lists the physical emission rate of each generating asset. Column C shows the total physical emissions, the product of generation level and physical emission rate. Column D shows the LMER at each asset and load location. In this simple example, the system is assumed to have no transmission constraints. Therefore, all assets in the network observe the physical emission rate of the marginal generator, the gas turbine (GT), as their LMER. Column E shows the carbon footprint of each asset, calculated based on the LMER and equations listed above.

Table 1: Sample carbon accounting using LMER for a simple, unconstrained network.

			Physical Emission		**Marginal Carbon Footprint**	
Type	**Asset**	**Generation (MW)**	**Physical Emission Rate (kg/MWh)**	**Physical Emissions (kg)**	**Locational Marginal Emission Rate (kg/MWh)**	**Carbon Footprint (kg)**
		[a]	[b]	[c] = [a]x[b]	[d]	[e]=[a]x([b]-[d])
Generator	Wind	500	0	0	600	-300,000
Generator	Coal	2,000	1,000	2,000,000	600	800,000
Generator	NGCC	1,000	400	400,000	600	-200,000
Generator	GT	300	600	180,000	600	0
Sub-total Generation		*3,800*		*2,580,000*		*300,000*
Load	Customer 1	-800	0	0	600	480,000
Load	Customer 2	-2,000	0	0	600	1,200,000
Load	Customer 3	-1,000	0	0	600	600,000
Sub-total Load		*-3,800*		*0*		*2,280,000*
System Grand Total		**0**		**2,580,000**		**2,580,000**

As shown in Table 1, when LMER is applied to each asset in the system, the sum of each asset's carbon footprint equals the total physical emissions of all generating assets in the system.

On an asset level, using an LMER-based carbon footprint allows an asset's impact on system-wide carbon emissions to be calculated at any specific time and location. It provides a way for a generation or storage asset to claim the carbon benefit it provides to the system. Using the same calculation, it also attributes the carbon impact of consuming electricity to load assets as a function of their location and time of consumption.

Because the LMER accounting methodology consistently assigns system emissions to both load and generation, the net carbon footprint of any collection of load and generation assets can be easily calculated by summing the individual assets' carbon footprints. In the example above, if Customer 1 procures 50% of wind capacity in the above example, then its net carbon footprint would simply be 330,000 kg-CO_2.

The LMER-based accounting methodology assigns system emissions to energy consumers and producers reflecting their net contributions to system emissions. Consumers are attributed emissions they cause at the time of consumption at their respective locations on the electrical grid. Producers are attributed emissions they physically inject into the atmosphere net of emissions they prevent from being injected by marginal generators.

With LMER-based accounting, the efficacy of renewable energy as an emissions-abating technology is proportional to renewable energy produced and to marginal emission displaced by that production. Renewable energy displacing coal generation would be valued higher as a carbon abating technology than renewable energy displacing natural gas-based generation. When and where renewable energy resources compete with each other, no carbon is displaced and under the LMER methodology, and such renewable energy has zero carbon abating value.

Consumers can rely on lower LMER values in selecting, to the extent feasible, the location and timing of their electricity consumption, and can enter into PPAs with renewable energy producers at high LMER locations.

By contrast, the allocation of carbon emissions using average emission rates provides neither temporal nor spatial signals and results in inefficient investments in renewable energy and in carbon abatement policies.

III Methodology and Input Data

The four clean energy procurement strategies were evaluated for customers with commercial retail load and customers with flat load in five different balancing authorities: CAISO, DUKE, LADWP, PGE, and PJM[15]. PJM and CAISO are large electric system operators with multiple member utilities, tens of millions of customers, a large geographical spread, and which operate wholesale energy markets. DUKE, LADWP, and PGE are smaller regions served by vertically integrated electric utilities (VIEU) that do not operate organized wholesale markets. The commercial load profile for each balancing authority was sourced from NREL's End-Use Load Profiles for the U.S. Building Stock database[16]. For the flat load profile, the customer load was the same in every hour.

Each customer could procure clean energy from up to six regions – five RTO/ISOs with active virtual power purchase agreement (PPA) markets (CAISO, ERCOT, MISO, PJM, and SPP), as well as the balancing authority in which the customer was located, which could be an ISO/RTO region (PJM and CAISO) or a vertically-integrated utility region (DUKE, LADWP, PGE), where clean energy was available for procurement through long-term avoided cost contracts offered to qualifying facilities. This analysis assumes that the customer sells clean energy generated into the market or to the utility but keeps any clean energy attributes (such as RECs). Therefore, net procurement costs were based on the difference between the PPA or avoided cost contract price and the market value of energy.

- For ISO/RTO regions, the contract price was based on the LevelTen Energy's 2022Q3 PPA Index Price[17], and the value of energy was based on the 2025 zonal hourly locational marginal prices (LMPs) from TCR's proprietary long-term forecast of U.S. nodal power prices.
- For VIEU regions and for geothermal in CAISO, the contract price was the 'high' LCOE estimate from Lazard Levelized Cost of Energy (LCOE) Analysis v15.0[18], adjusted using EIA EMM for regional multipliers and for inflation[19]. In these regions, utility avoided cost or feed-in tariff rates were used for the value of energy. These rates were used instead of bilateral contracts tied to market prices because these rates are guaranteed to certain qualifying facilities, while bilateral contracts have no liquid market and may or may not be available for a specific time period and region.

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15 CAISO – California Independent System Operator; DUKE – Duke Energy Carolinas; LADWP – Los Angeles Department of Water and Power; PGE – Portland General Electric; PJM – PJM Interconnection

16 NREL, "End-Use Load Profiles for the U.S. Building Stock."

17 LevelTen Energy, "LevelTen's Q3 2022 PPA Price Index Reports."

18 Lazard, "Lazard's Levelized Cost of Energy Analysis — Version 15.0."

19 EIA, "Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2022."

Utility-scale solar and wind energy were available for procurement in each balancing authority except DUKE, where only utility-scale solar was available. Due to geographic limitations, wind and solar procurement in LADWP and wind procurement in PGE were only available through wheeling from CAISO (for LADWP) and Bonneville Power Administration (for PGE). This was accompanied by a firm transmission contract, which raised procurement costs. In CAISO, geothermal energy was also available for procurement. In DUKE and LADWP, rooftop solar PV was also made available for procurement due to the existence of specific avoided cost rates or tariffs for rooftop solar. However, due to its higher cost, it was not selected for procurement by any customer. For the hourly energy matching strategy, battery storage was also available for procurement in the same balancing authority as the customer's load.

Each strategy was implemented in the following way:

- Annual energy matching: the 2025 annualized cost per unit of generation is calculated for each available solar, wind, and geothermal generator in all balancing authorities, and the customer procures the generator with the lowest procurement cost at a capacity that ensures that the total generation from the generator over the year is equal to the total customer load.
- Local annual energy matching: same as annual energy matching, but the customer must choose the least-cost resource within their own balancing authority.
- Carbon matching: the 2025 annualized cost per unit of displaced CO_2 was calculated using LMERs for each available solar, wind, and geothermal generator in all balancing authorities. Also, the carbon footprint of the customer's load was calculated based on the load magnitude and profile, using LMERs. The customer procured the generator with the lowest cost per unit of CO_2 displaced across all balancing authorities, at a capacity that ensured that the total carbon displacement from the procured energy generation matched the carbon footprint from the customer's annual consumption.
- Hourly (24/7) energy matching: a linear optimization problem [20] was formulated and solved to determine the least-cost mix of resources to meet the hourly energy matching criteria. Details are available in the appendix.

[20] The optimization problem was formulated in python (using pyomo) and solved with Gurobi.

IV Results

For all four strategies, the customer selects the least-cost project(s) subject to strategy limits and constraints. For the energy matching strategies, the customer selects the project(s) with the lowest cost per MWh of generation.

Figure 3 and Figure 4 below show the net procurement cost of solar and wind projects calculated based on the methodology described above. Procurement costs are only shown in areas with available projects. The results show that the overall least-cost projects are PV in ERCOT and southern SPP. The least cost wind projects are in northern SPP and southwestern SPP.

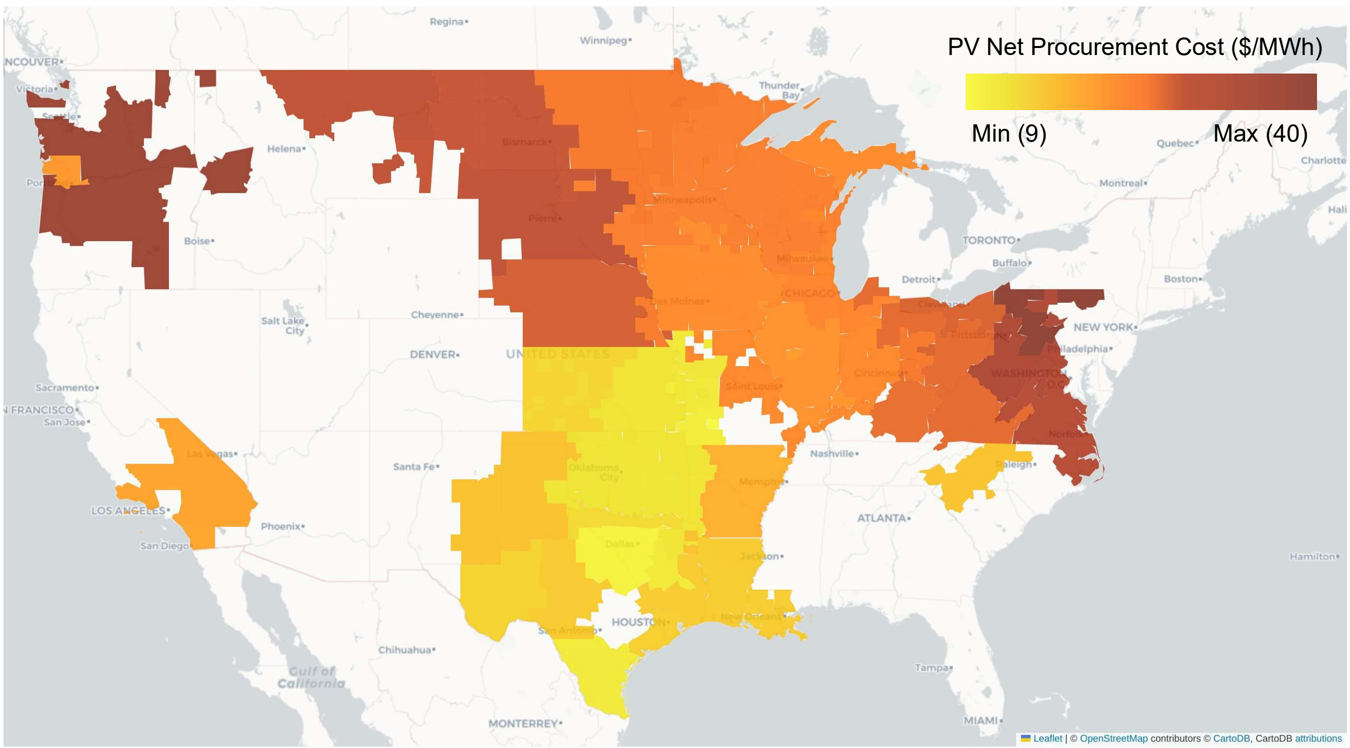

Figure 3: Net procurement cost for PV projects

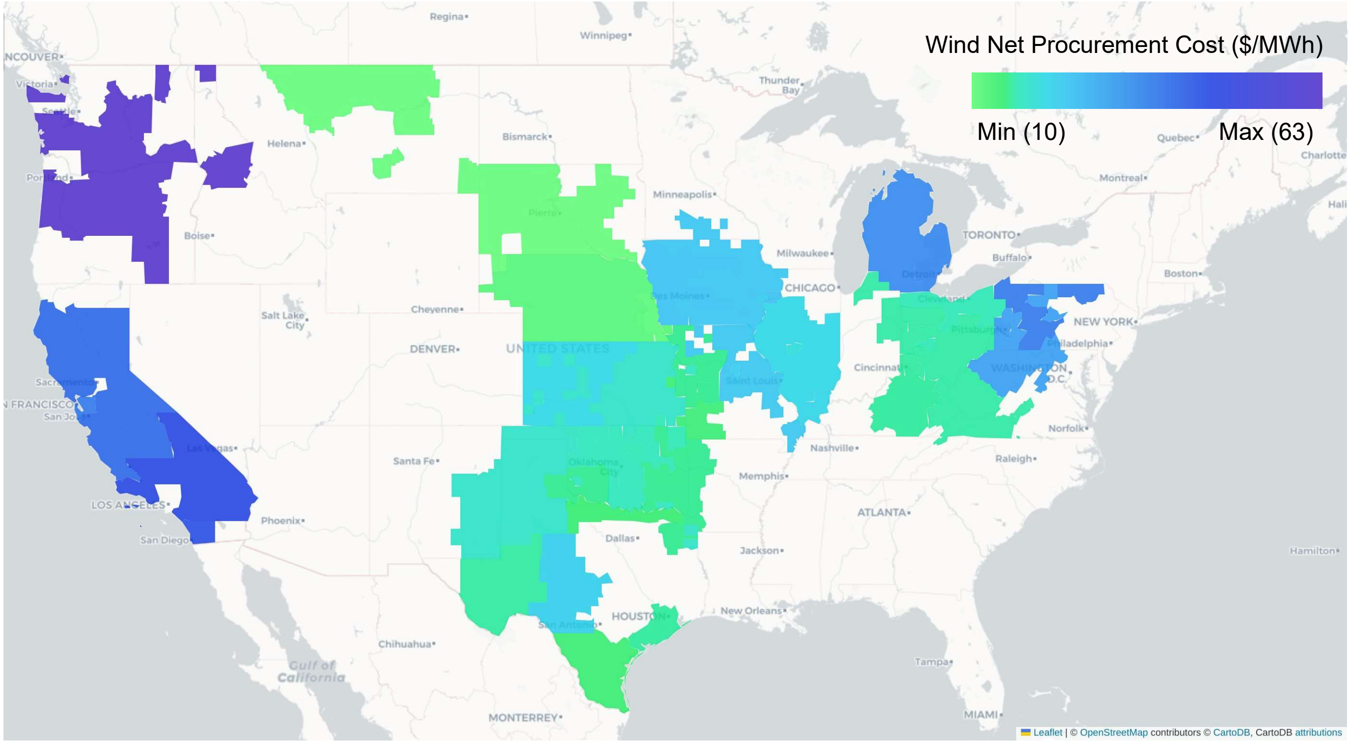

Figure 4: Net procurement cost for wind projects

The carbon matching strategy optimizes for projects with the least lowest carbon abatement cost.

Customers pursuing the carbon matching strategy select the project with the lowest carbon abatement cost. Figure 5 and Figure 6 below show carbon abatement cost for available clean energy procurement. Carbon abatement cost ($/metric ton of CO_2 displaced) measures a project's effectiveness at displacing carbon. A low carbon displacement cost means the project can displace more carbon emissions per dollar spent. In this analysis, the most preferable project in terms of carbon abatement cost is PV in southeastern SPP.

Although SPP PV projects have similar procurement cost to those in ERCOT, PV projects can displace more carbon emissions in SPP because SPP on average has higher LMERs due to more marginal coal generation.

It is also worth noting that while PV projects in western ERCOT and southwestern SPP have low procurement costs, they are generally less preferable to customers because transmission constraints often island clean energy in that region, lowering LMPs and LMERs, which reduces revenue and carbon displacement.

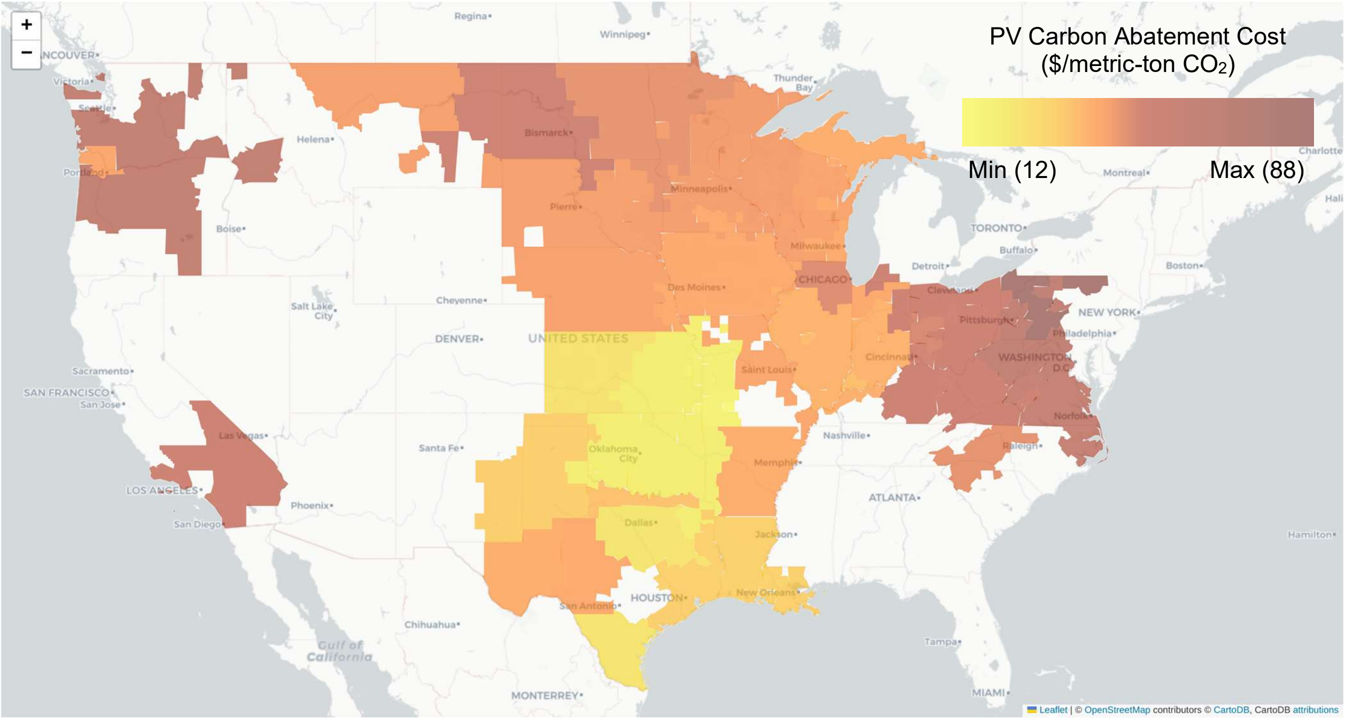

Figure 5: Carbon abatement cost for PV projects

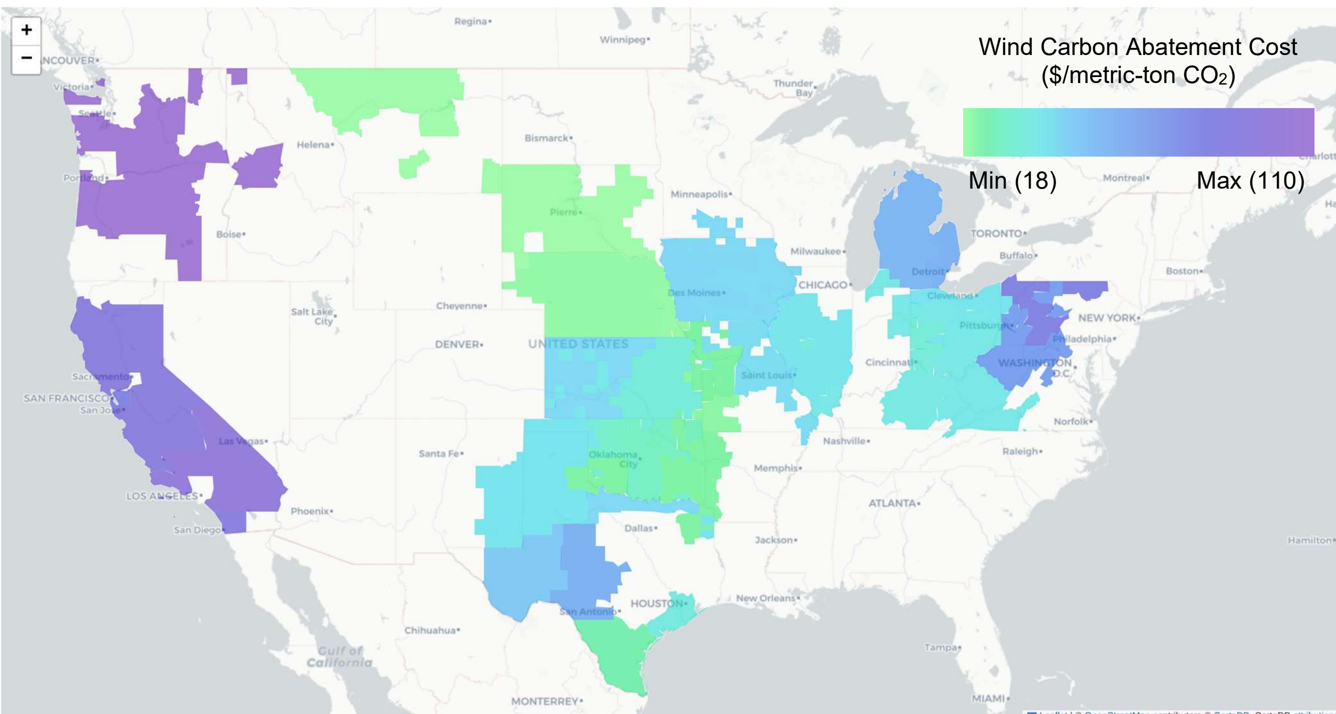

Figure 6: Carbon abatement cost for wind projects

IV.1 Strategy Cost Results

Figure 7 compares the strategy cost per MWh of load of the four procurement strategies for a customer with the commercial load profile. Figure 8 compares the strategy cost for the carbon matching and hourly energy matching strategies between a customer with the commercial load profile and a customer with the flat load profile.[21]

IV.1.1 Commercial Load Profile Results

For the annual energy matching strategy, customers in all balancing authorities can procure the least-cost renewable energy available, which in this case is utility-scale PV in ERCOT at a (net) procurement cost of $9.9/MWh.

The cost of the local annual energy matching strategy ranges from $16/MWh in PJM to $32/MWh in LADWP. The cost of this strategy is driven by the procurement cost within each balancing authority, which is subject to local constraints. For example, wind energy is only available for procurement in PGE through wheeling, so in PGE utility-scale PV is used for energy matching despite a poor climate for solar energy. In LADWP, utility-scale PV must be wheeled from southern CAISO as part of a high-cost firm transmission contract, since neither utility-scale wind nor PV are available for procurement within the balancing authority area. In PJM and CAISO, wind and solar are available across a broad region with different PPA price points and settlement hubs, resulting in lower costs. However, the requirement of procurement within the same balancing authority excludes the lowest-cost renewable generation, which is mostly located in ERCOT and SPP.

[21] The strategy cost of the annual energy matching strategies does not change based on load shape, because those strategies only consider total load throughout the year.

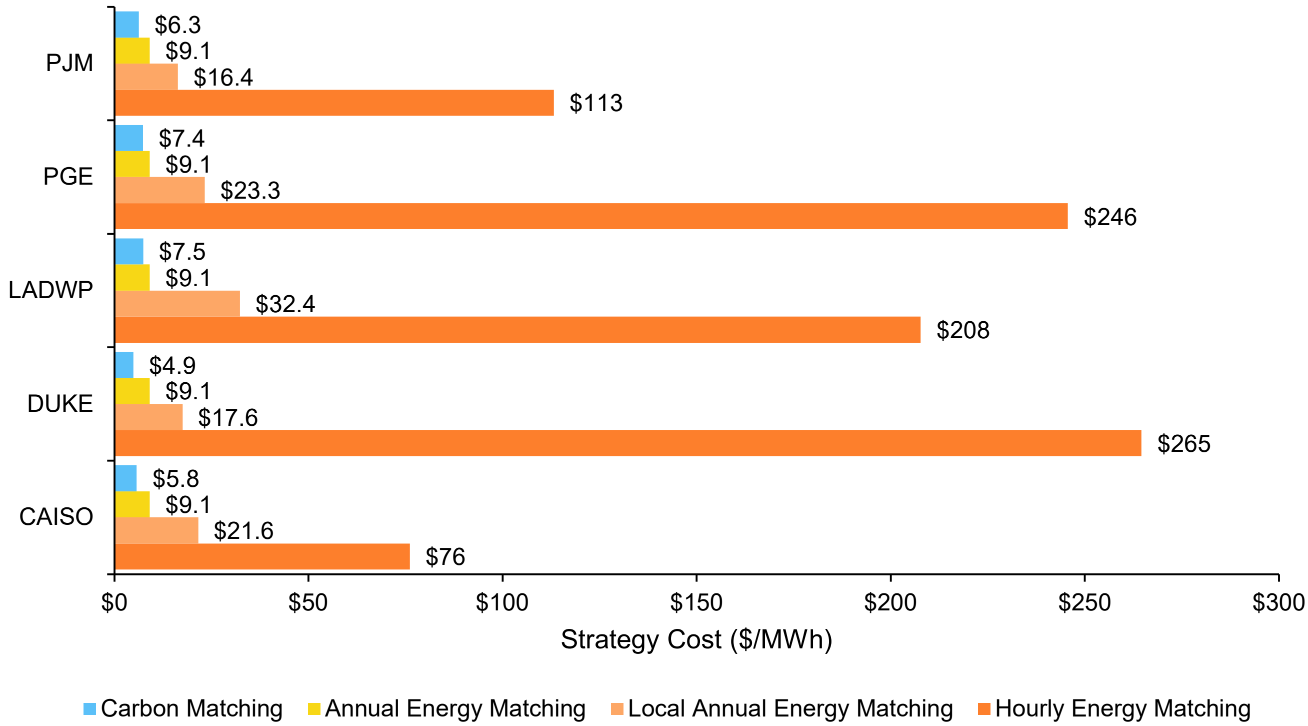

Figure 7: Comparison of cost per MWh of customer load by strategy and customer balancing authority for customers with commercial load. For hourly energy matching, the target CFE score is 100%

The cost of the hourly energy matching strategy greatly exceeds the cost of all the annual matching strategies.

The cost of the carbon matching procurement strategy ranges from $4.9/MWh in DUKE to $7.5/MWh in LADWP. For this strategy, the procured generation does not need to be located in the same balancing authority as the load, so customers in all 5 balancing authorities can procure energy from the generator with the highest carbon displacement relative to procurement cost (this happens to be a utility PV plant in southeast SPP). Thus, the cost differences are driven only by load magnitude (which varies for commercial load) and load carbon footprint, determined by the LMERs in each balancing authority. Relative to the other balancing authorities, DUKE has a combination of low load and relatively low LMERs, resulting in the smallest carbon footprint to displace, and the lowest cost at $4.9/MWh. On the other hand, LADWP has high load due to summer cooling needs, and relatively high LMERs, especially at times of high load, resulting in a higher carbon footprint and the highest cost at $7.5/MWh.

The cost of the hourly energy matching strategy greatly exceeds the cost of all the annual matching strategies. As shown in the discussion section, this cost reflects much higher procurement (MWh) of renewable energy, as well as the procurement and operating costs of battery storage to balance energy across hours. hourly energy matching also exhibits the most variation in cost between the ISO/RTO balancing authorities and the VIEU balancing authorities – all VIEU regions have costs over $200/MWh due to higher battery storage requirements and restricted clean energy procurement, while CAISO and PJM have costs of $76/MWh and $113/MWh, respectively.

IV.1.2 Flat Load Profile Results

The procurement strategies were also analyzed for customers with a flat load profile, meant to represent data center or industrial load. The strategy and abatement costs of the annual energy matching strategies are independent of load profile because they only count the total amount of energy consumed over a year. The strategy and abatement costs of the hourly energy matching strategy, however, depends significantly on load profile because load must be balanced by renewable generation in every hour, and because the carbon footprint of the customer's load is calculated using LMERs that vary on an hourly basis.

Figure 8 compares the difference in strategy cost per MWh of the hourly energy matching and carbon matching strategies for a customer with a commercial load and a customer with a data center (flat) load. There are some differences – in DUKE, for example, hourly energy matching cost has much higher strategy cost for a customer with a data center load profile than one with a commercial load profile. This is because only solar PV can be procured in the DUKE balancing authority, and the generation profile for PV lines up well with the commercial load profile because electric demand in DUKE is in large part driven by air conditioning demand, which peaks in the afternoon when temperatures are highest and solar PV is generating. A flat load profile means less demand during the afternoon and evening and more at night, so extra battery storage is required to shift solar generation from day to night.

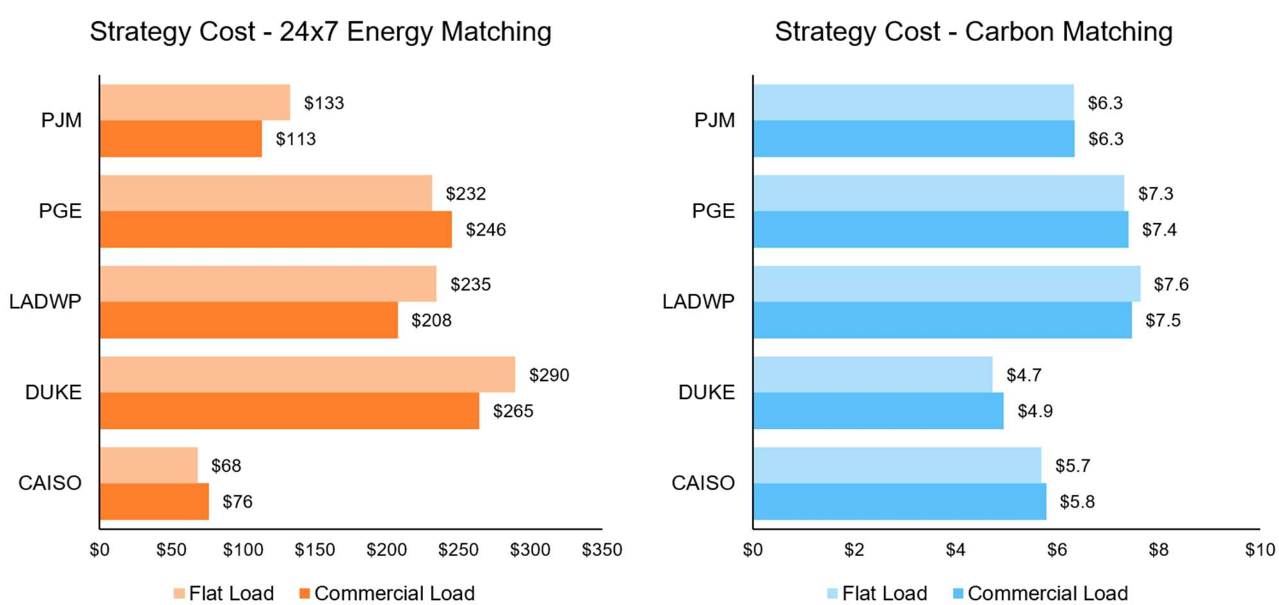

Figure 8: Cost comparison for the hourly energy matching and carbon matching strategies for customers with commercial load and flat load in each balancing authority

Overall, though there are differences, changing the load profile does not alter the key conclusions. Under both load profiles, hourly energy matching has a much higher strategy cost than the annual matching strategies and requires procurement of clean energy far in excess of the total load being matched. With either load profile, carbon matching is the least-cost strategy and incentivizes targeted investment in the most effective projects for carbon displacement.

Carbon matching is the least-cost strategy for both flat and commercial load profiles

One advantage of carbon matching and hourly energy matching compared to the annual and local energy matching strategies is that they incentivize intentional changes to the customer load profile. Hourly energy matching incentivizes shifting the load profile to hours of higher renewable generation, while carbon matching incentivizes shifting the load profile to hours of lower LMERs. With an annual energy matching strategy, only total load matters, so customers are not incentivized to shift load in ways that could lower their carbon footprint.

IV.2 Net Carbon Footprint Results

Because the overarching goal of corporate clean energy procurement is to reduce carbon emissions, it is also critical to examine the actual carbon emissions reduction achieved through each strategy in addition to strategy cost. We define three key parameters: "carbon displacement" or "avoided emissions", which is the total amount of CO_2 displaced by procured clean energy (a negative value), "load emissions", which is the sum of emissions attributable to customer load, and "carbon footprint", the sum of load emissions and avoided emissions.

Figure 9 and Figure 10 show the percentage of load emissions displaced by each strategy in each balancing authority for customers with commercial load and flat load, respectively. The carbon matching strategy (blue bar) ensures that the carbon emissions attributable to the customer's load are equally displaced by the procured clean energy, resulting in 100% displacement and carbon neutrality. Bars shorter than the red bar (lower than 100%) for each balancing authority represent a positive carbon footprint, meaning the strategy failed to displace all of load emissions, and bars longer than the red bar represent a negative carbon footprint.

The energy matching strategies do not guarantee carbon neutrality

The annual energy matching strategies do not guarantee carbon neutrality. The results show that for both annual energy matching strategies, avoided emissions are sometimes less than load emissions and sometimes more, depending on the balancing authority. For hourly energy matching, the carbon footprint is negative in all balancing authorities because the total renewable generation procured greatly exceeds total load.

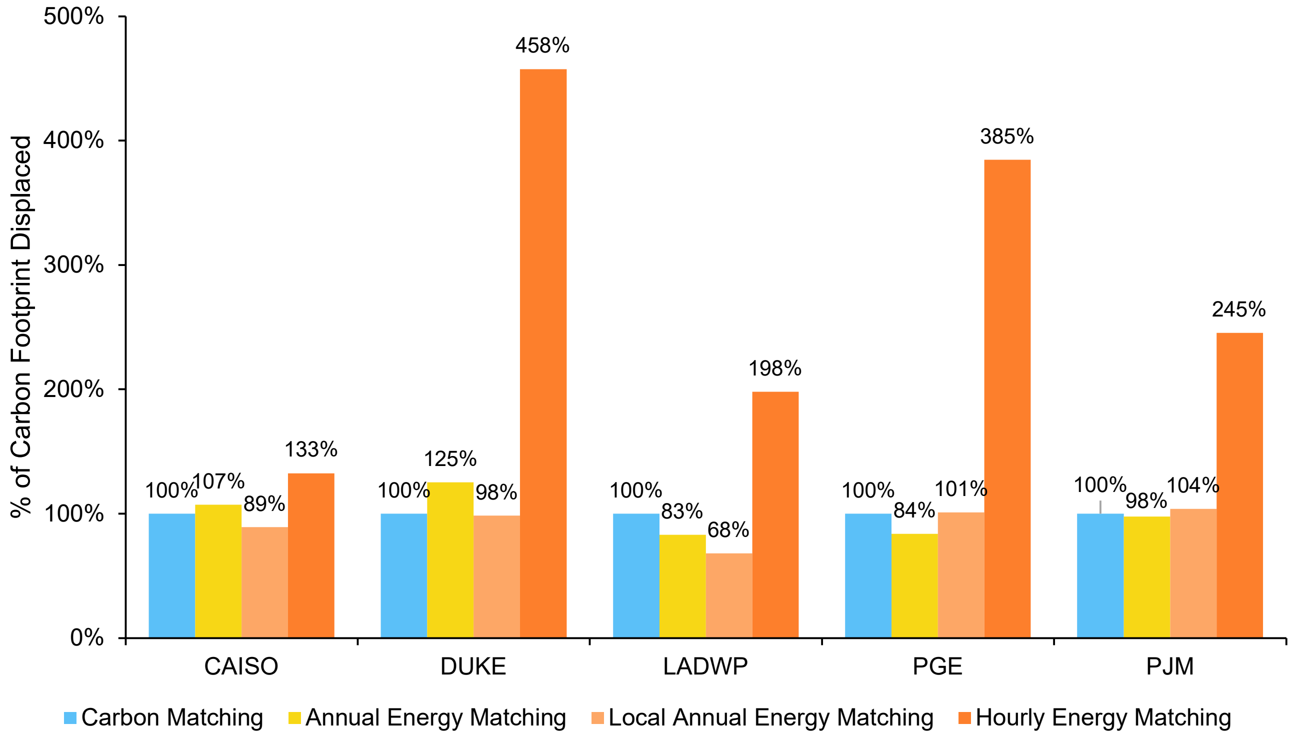

Figure 9: Carbon displacement by strategy and balancing authority, commercial load. For hourly energy matching, the target CFE score is 100%.

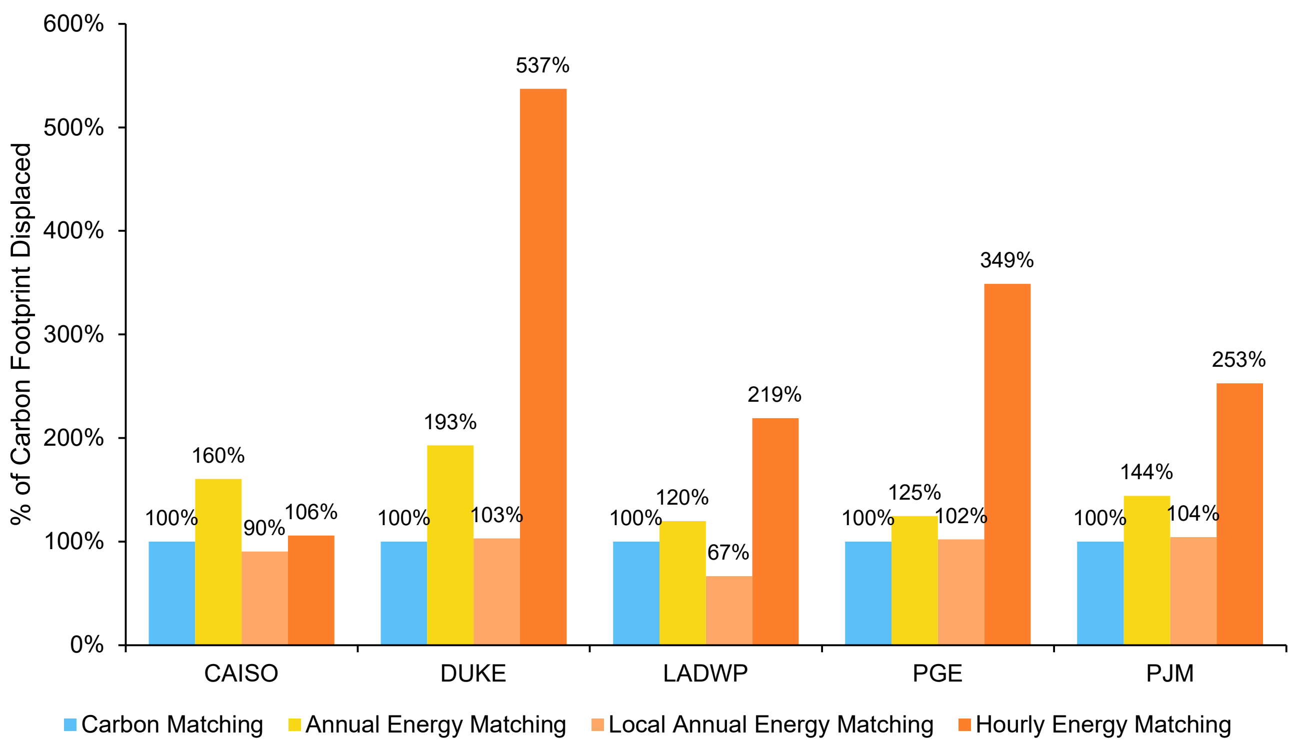

Figure 10: Carbon displacement by strategy and balancing authority, flat load. For hourly energy matching, the target CFE score is 100%.

IV.3 Carbon Abatement Cost Results

Figure 11 shows the abatement cost (cost per unit of CO_2 displaced) for each strategy and balancing authority, in \$/metric ton CO_2, for customers with commercial load.

The carbon matching strategy ensures that the carbon emissions attributable to the customer's load are equally displaced by avoided emissions from the procured clean energy.

The carbon matching strategy (red bar) ensures that the carbon emissions attributable to the customer's load are equally displaced by avoided emissions from the procured clean energy. Since this strategy allows U.S.-wide procurement, the abatement cost is \$12.9/metric ton for all balancing authorities. The annual energy matching strategy has a higher abatement cost, since the generator selected for that strategy is in ERCOT, while the generator selected for carbon matching is in SPP. SPP has relatively higher LMERs than ERCOT, meaning that, in general, more carbon will be displaced by clean energy generated in SPP.

In the previous section, we saw that local annual energy matching does not guarantee carbon neutrality. This is despite a much higher abatement cost than carbon matching and annual energy matching – between \$32/ton in PJM and \$82/ton in LADWP. These higher abatement costs are driven by much higher procurement costs in the balancing authorities with customer load, especially the VIEU balancing authorities.

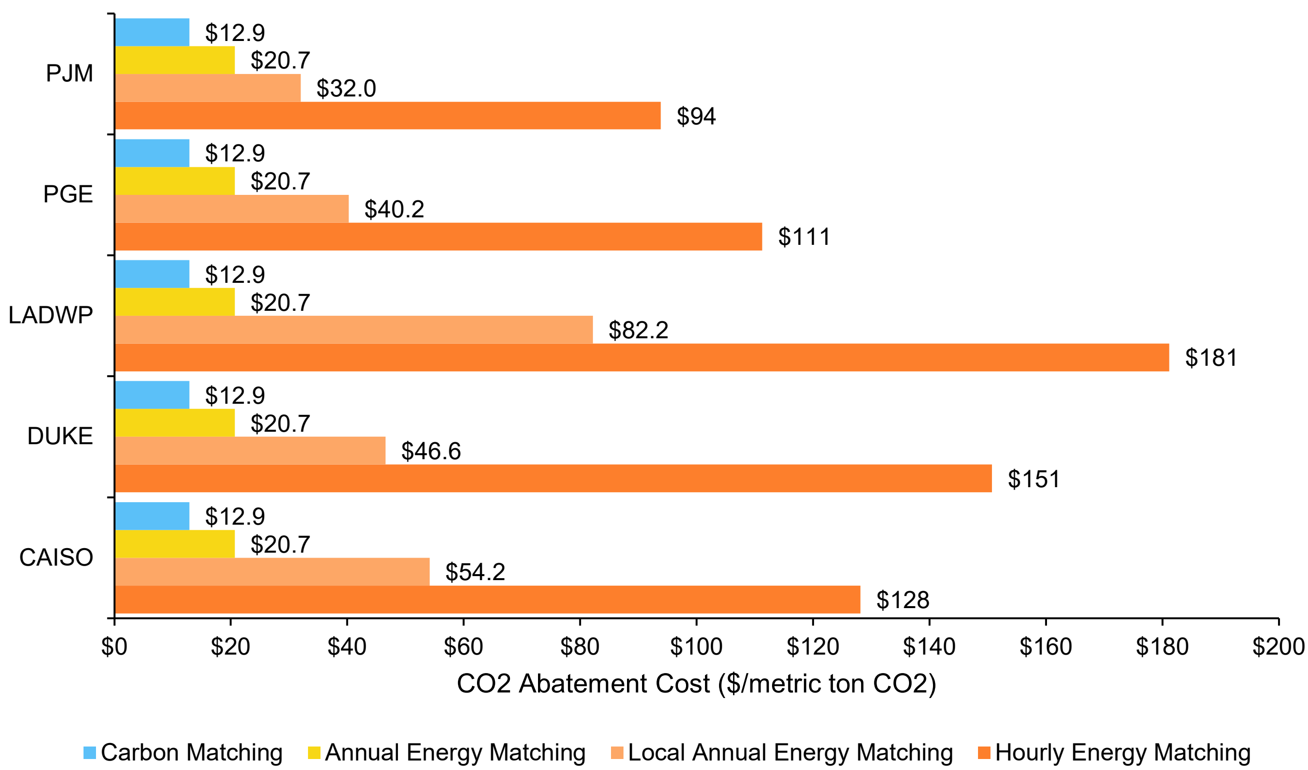

Figure 11: CO_2 abatement cost by strategy for customers with commercial load in each balancing authority. For hourly energy matching the target CFE score is 100%.

IV.3.1 Flat Load Profile Results

In terms of carbon abatement cost, the customer load profile is only relevant to the hourly energy matching strategy. Both the strategy and abatement costs of the annual energy matching strategies are independent of load profile because they only count the total amount of energy consumed over a year. The abatement cost of the carbon matching strategy is independent of load profile because the best option for the customer is to procure the clean energy with the lowest abatement cost, regardless of the customer's load profile. The customer's load profile determines their carbon footprint and therefore how much carbon they must displace through clean energy procurement, but not the abatement cost.

The abatement cost of the hourly energy matching strategy, however, depends significantly on load profile because load must be balanced by renewable generation in every hour, and because the carbon footprint of the customer's load is calculated using LMERs that vary on an hourly basis.

Figure 12 compares the difference in carbon abatement cost of the hourly energy matching strategy for a customer with a commercial load and a customer with a data center (flat) load profile. As seen above in the strategy cost results, there are some differences that vary by balancing authority. However, different customer load profiles do not alter the conclusion that hourly energy matching is the least effective strategy in terms of carbon emissions displaced per dollar spent.

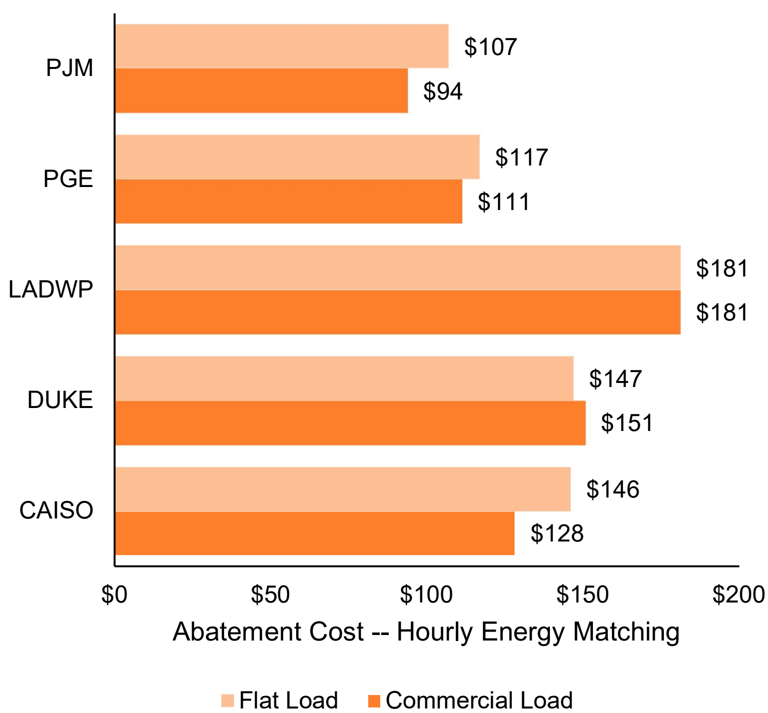

Figure 12: Cost comparison for the hourly energy matching strategy for customers with commercial load and flat load in each balancing authority

V Discussion

V.1 Annual Energy Matching

The results show that annual energy matching has a relatively low strategy cost, at only $9/MWh; however, it does not guarantee carbon neutrality. This is because LMERs may vary significantly between the customer's load location and the location where the clean energy is procured, and between the hours when energy is consumed and produced.

The annual matching strategy optimizes for least cost, and does not limit procurement geography, so in this analysis all customers chose the same least-cost PPA contract: a PV project in ERCOT[22]. This means all customers displace the same amount of carbon through PPA procurement, and their net carbon footprint difference is a result of the emissions of their load emission. The results show a negative carbon footprint for customers in CAISO and DUKE, where LMERs are relatively low due to high zero emission generation, and a positive carbon footprint for customers in LADWP, PGE, and PJM, where LMERs are somewhat higher (see Figure 13). For customers with the commercial retail load profile, load emissions are also impacted by load profile, which are different based on location.

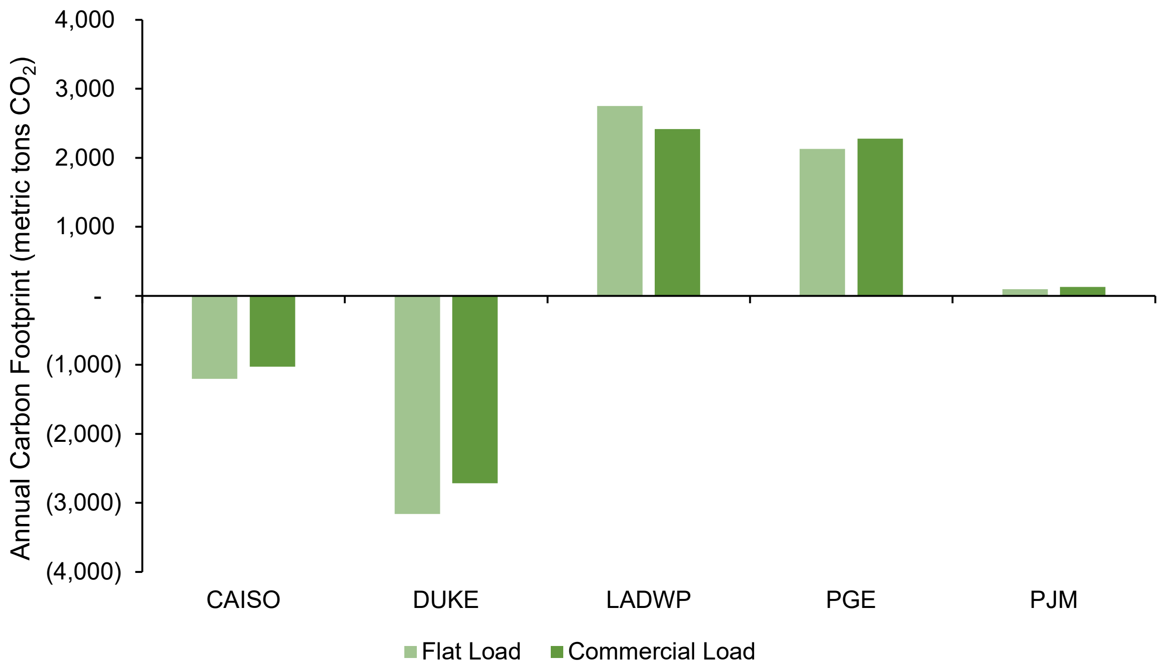

Figure 13: Comparison of carbon footprint for the annual energy matching strategy between the commercial load customer and the flat load customer. The commercial load footprint has been scaled up so that each customer uses the same amount of energy per year.

[22] Based on the analysis of procurement costs, the least cost PPA projects are a ERCOT PV and a SPP PV project. Both share similar net cost. We had the customers choose the ERCOT generator, since ERCOT is the most active PV PPA market.

V.2 Local Annual Energy Matching

Local energy matching also can't guarantee carbon neutrality due to differences in LMER between hours of energy consumption and generation, and LMER differences within the same BA.

As shown above, the annual energy matching strategy does not guarantee carbon neutrality, because of differences in LMERs between the load location and the procurement location. Because of this, some customers choose the local annual energy matching strategy because it means that procured clean energy is generated in the balancing authority in which their load is located.

However, we find in this analysis that for the commercial load customer, local annual energy matching achieves a negative carbon footprint in PGE and PJM, but not in CAISO, DUKE, or LADWP (see Figure 14). For flat load, DUKE achieves a negative carbon footprint as well as PGE and PJM. This variation is due to differences in hourly generation profiles, load profile, and LMER across balancing authorities.

Local annual energy matching also has a much higher strategy cost than traditional annual energy matching because the strategy restricts procurement to balancing authorities where customers have load. This prevents customers from accessing low-cost projects in ERCOT and SPP.

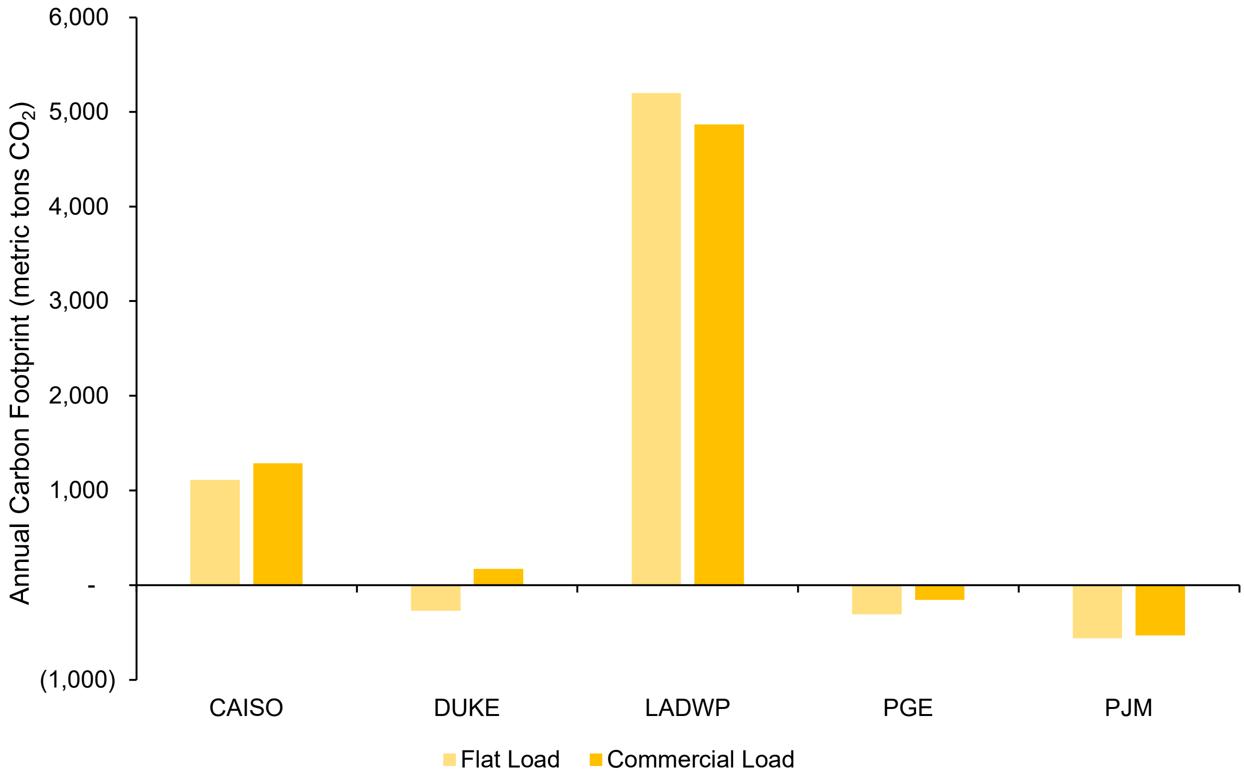

Figure 14: Comparison of carbon footprint for local annual energy matching strategy between the commercial load customer and the flat load customer. The commercial load footprint has been scaled up so that each customer uses the same amount of energy per year.

V.3 Hourly Energy Matching

The hourly energy matching procurement strategy requires matching load with clean energy generation in the same balancing authority in every hour, even in hours when renewable generation from solar and wind is not available.

To achieve high CFE scores at the lowest cost, it is necessary to procure renewable energy in excess of total load. This is especially true in small balancing authorities which lack climatic diversity or where wind generation is unavailable for procurement.

V.3.1 CFE Score and Excess Energy Procurement

The degree to which hourly energy matching has been achieved can be quantified using the carbon-free energy (CFE) score, the percent of total load that has been matched with clean energy on an hourly basis[23]. Figure 15 shows the strategy cost of the hourly energy matching strategy at different target CFE scores (orange bars) of 95%, 98%, 99%, 99.5%, and 100%. It also shows the strategy cost and CFE score of the local annual matching strategy (green bar), which can be seen as a starting point for customers moving towards hourly energy matching. Results for customers with flat load are shown.

These results show that most of the cost of the hourly energy matching procurement strategy is incurred in matching the last 5% of load. Stated differently, improving from a CFE score of 95% to 100% more than doubles the cost of this strategy in all balancing authorities.

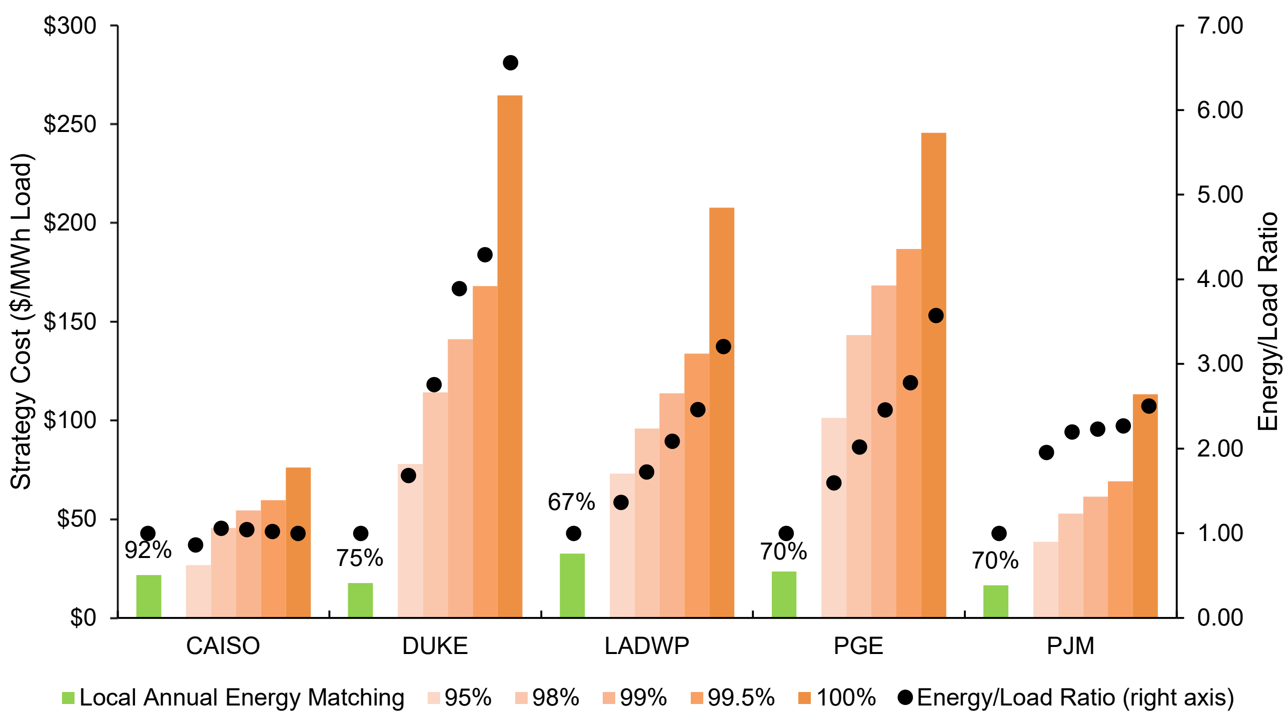

Figure 15: Customer cost ($/MWh) to achieve hourly energy matching at different target CFE scores (95%, 98%, 99%, 99.5%, and 100%, shown in orange bars). Strategy cost and CFE score of local annual energy matching is shown with the green bar and label, respectively. Black dots indicate energy/load ratio, equal to total procured energy divided by total load. This is for a customer with flat load and no limit on energy procurement.

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[23] See Google, "24/7 Carbon-Free Energy: Methodologies and Metrics.",." and Xu et al., "System-Level Impacts of 24/7 Carbon-Free Electricity Procurement."

Improving from a CFE score of 95% to 100% more than doubles the cost of the hourly energy matching strategy in all balancing authorities.

Why does the last 5% of hourly energy matching cost so much to achieve? One reason is the necessity to procure increasing amounts of renewable generation far in excess of total customer load. Because of the intermittent nature of renewable generation, to ensure the generation matches load on an hourly basis customers have only a handful of options:

1. To procure so much renewable generation so that even on low output hours (for example, when wind capacity factor is less than 5%) the customer still has sufficient generation to cover load. This naturally leads to excess generation during normal and high output hours.
2. To use battery storage to store clean energy generation when output is high and release them when output is low. This requires less energy procurement but increases costs due to battery storage procurement.

Our analysis optimizes for least total cost by balancing these two options. The black dots in Figure 15 show "energy/load ratio", which is the total amount of annual renewable energy procured divided by the customer's total annual load. For the annual energy matching strategy, the energy/load ratio is 1, because annual renewable generation is matched exactly to annual load. To achieve high CFE scores at the lowest cost, it is necessary to procure renewable energy in excess of total load, shown by energy/load ratios greater than 1. This is especially true in small balancing authorities which lack climatic diversity or where wind generation is unavailable for procurement, such as DUKE, where the energy/load ratio for a 100% CFE score reaches 6.6. This excess energy is captured by battery storage and released later when renewable generation is low.

We assume in our analysis that customers have perfect foresight of hourly solar and wind generation profiles, as well as hourly LMPs. This allows them to procure only the exact amount of clean energy that they need and operate battery storage with maximum efficiency. These assumptions will not hold in practice, and in this regard our results understate the costs of guaranteeing a certain CFE score and overstate potential revenue from battery operation.

V.3.2 Energy Balancing with Hourly Energy Matching

Figure 16, Figure 17, and Figure 18 below illustrate the dynamics of hourly energy matching, and show why achieving it is much more challenging in a smaller balancing authority where clean energy procurement is limited. Figure 16 shows a ten-day period in LADWP, with a flat 1 MW load and 100% CFE score. In this scenario, the customer procured 12 MW of utility-scale PV, 1.5 MW of utility-scale wind, and 7 MW of 4-hour battery storage for a total cost of $235/MWh to match a 1 MW flat load. The total clean energy procured was 3.2 times greater than the total customer load.

The wind and solar profiles somewhat complement each other, with wind often generating in the middle of the night, or during the day on days when solar generation is low. When wind generation is low at night or for a multi-day period, battery storage (charging from solar) is used to match load. Because the customer is targeting a 100% CFE score, battery storage must be sized for the longest stretch of low renewable generation throughout the year. At other times, the whole battery capacity is not needed, and the battery is used to generate revenue through price arbitrage – this can be seen in Figure 16, as battery discharge spikes each evening well above the customer load. Total net revenue from battery arbitrage decreases the cost of the strategy by 9% in this specific scenario.

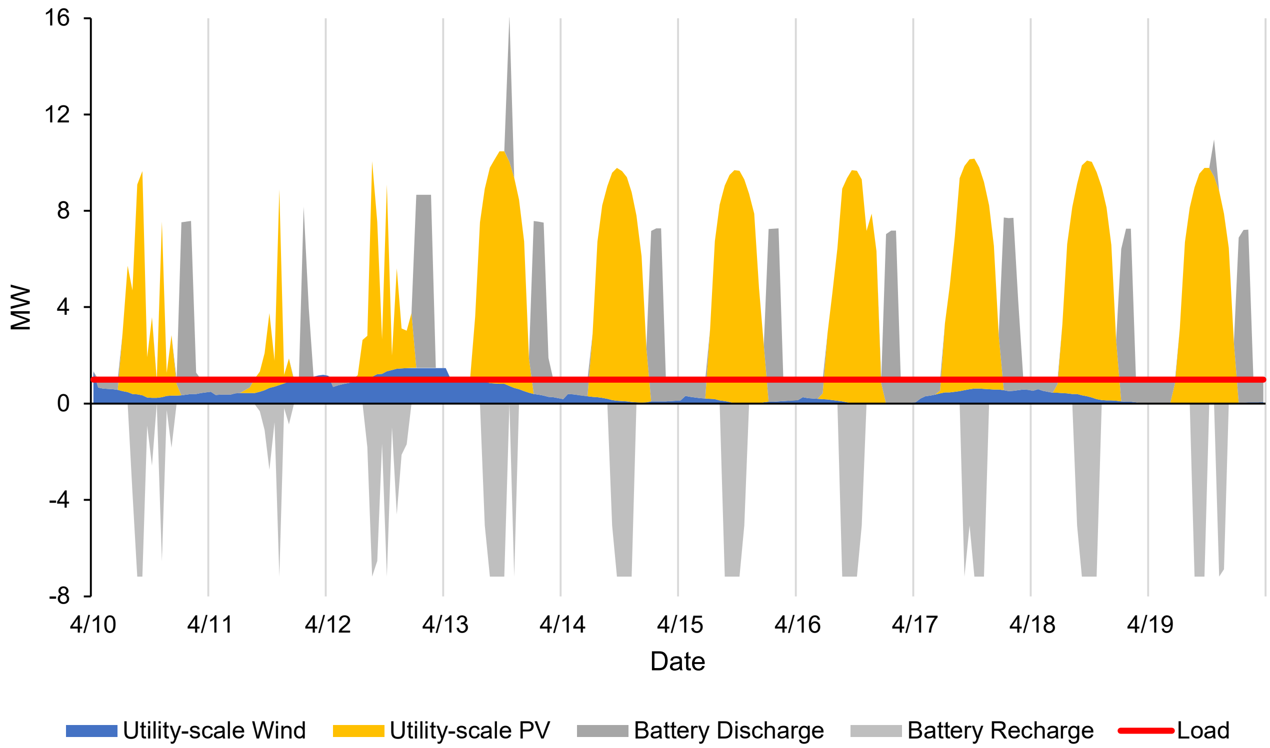

Figure 16: 10-day period in 2025 for customer in LADWP balancing authority, 100% CFE score, flat load

Figure 17 shows a 10-day period in DUKE, with a flat 1 MW load and a 100% CFE score. In this scenario, the customer procured 36 MW of utility-scale PV and 7 MW of 4-hour battery storage for a total cost of $257/MWh to match a 1 MW flat load. The total clean energy procured was 6.6 times greater than the total customer load.

With only solar and battery storage available, the DUKE customer must procure much more clean energy than the LADWP customer, resulting in the highest customer costs out of all the balancing authorities studied. This excess procurement is necessary to cover stretches of a day or days with minimal solar generation, as shown on January 18th-21st.

The amount of energy procured leaves the DUKE customer most exposed to changes in energy market prices. Also, the lack of any generation outside of daytime hours also reduces the customer's ability to use the battery for price arbitrage, with net battery revenue reducing cost by only 1%.

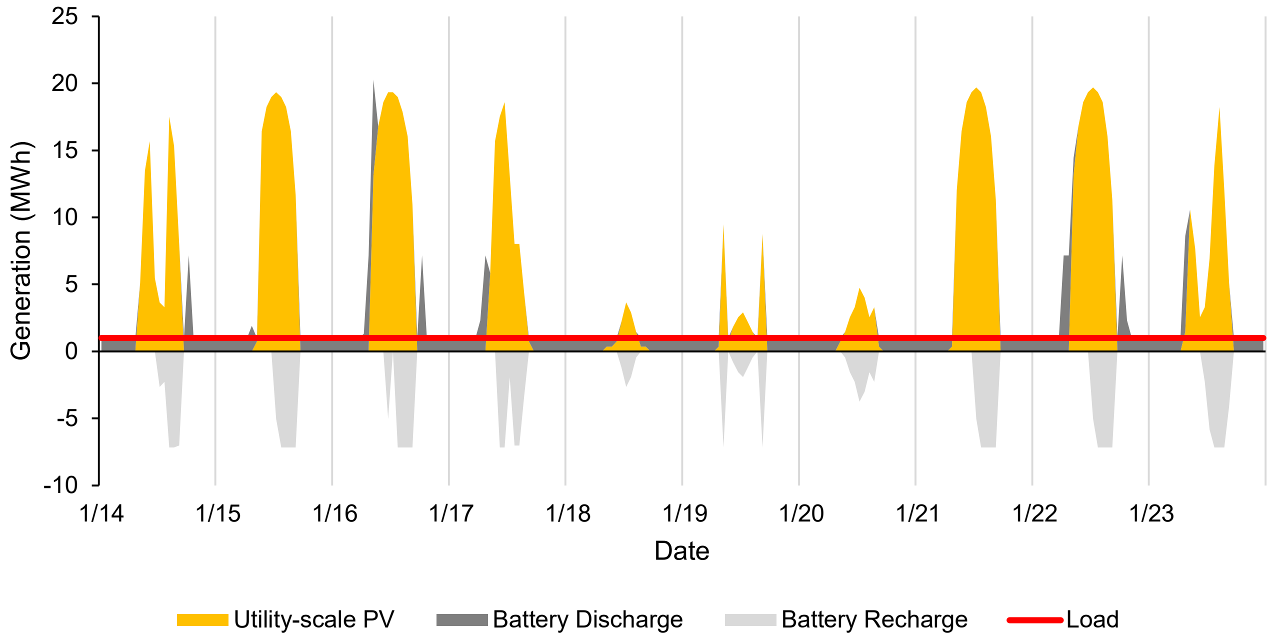

Figure 17: 10-day period in 2025 for customer in DUKE balancing authority, 100% CFE, flat load

The example above contrasting the experience of the LADWP and DUKE customers shows the importance of procuring both solar and wind generation for hourly energy matching. But both LADWP and DUKE are relatively small balancing authorities with limited diversity among their wind and solar generation profiles. PJM provides a different example. Figure 18 shows a ten-day period in PJM, for a customer with a flat 1 MW load and 100% CFE score. In this scenario, the customer procured 10 MW of utility-scale PV, 2.6 MW of utility-scale wind, and 3.6 MW of 4-hour battery storage for a total cost of $132/MWh to match a 1 MW flat load. The total clean energy procured was 2.5 times greater than the total customer load.

Note how clean energy procured across PJM provides a diversified portfolio of generation, not just between the solar and wind technology types but also among the solar and wind generation profiles. Different wind generators provide clean energy at somewhat different times due to the movement of weather systems across the balancing authority footprint as well as local conditions. The procurement of solar from multiple locations with different longitudes widens the daily solar generation curve and hedges against cloudy days.

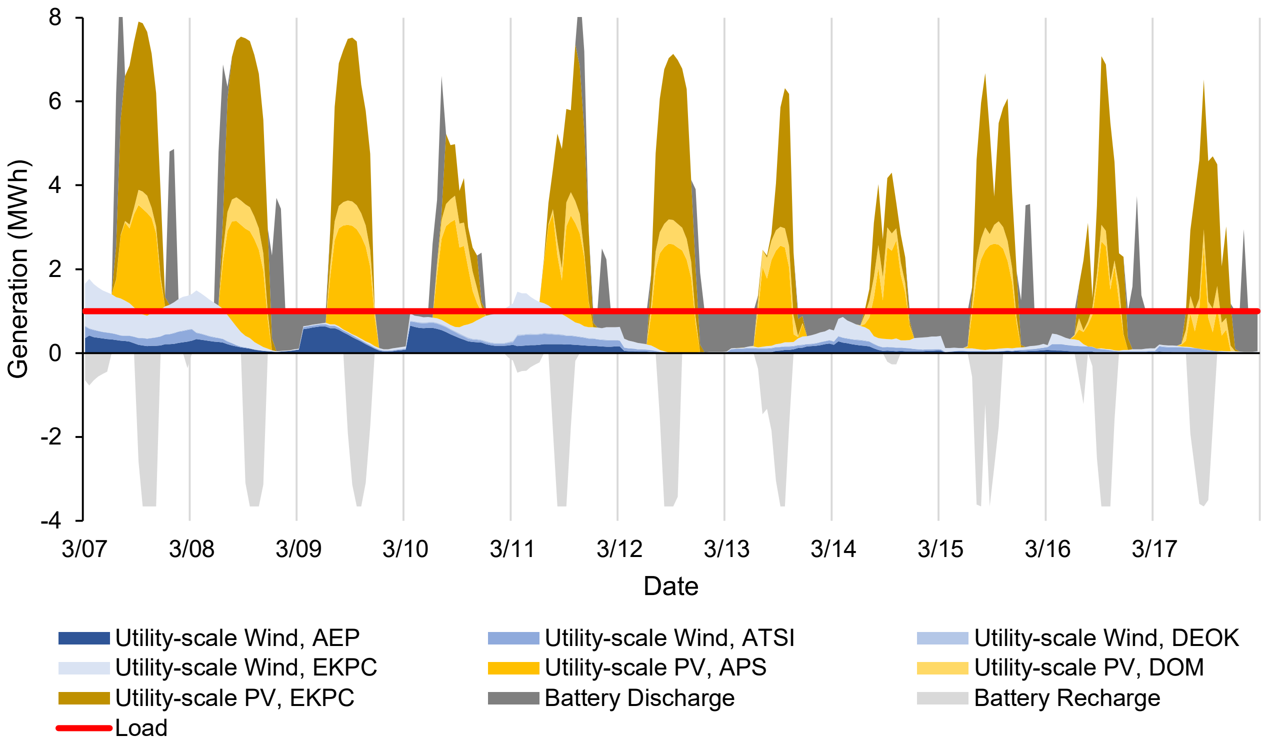

Figure 18: 10-day period in 2025 for customer in PJM balancing authority, 100% CFE, flat load

CAISO was the only region in which customers were allowed to procure geothermal energy, though it has far higher procurement cost than solar PV and wind on a capacity basis due to its high LCOE. As a result, it was only procured by customers pursuing the hourly energy matching strategy, and only when targeting a CFE score of 98% or higher. Despite the high cost of procurement, the availability of geothermal energy meant that the hourly energy matching strategy had the lowest strategy cost for customers in CAISO and required the least total procured energy of all five balancing authorities, as shown in Figure 15.[24]

Figure 19 shows the capacity procured to achieve hourly energy matching in CAISO for both the commercial load and flat load customer at different CFE scores. We see that geothermal procurement rises with higher CFE scores for both load profiles, but geothermal is more helpful for the flat load customer since geothermal provides a steady output that matches well with flat load. For the commercial load customer, geothermal helps prevent excess additional solar and wind capacity, but a diverse mix of resources is still necessary for achieving hourly energy matching at least cost.

[24] Although it is worth noting that local annual energy matching alone in CAISO achieved a CFE score of 92%, much higher than any other balancing authority.

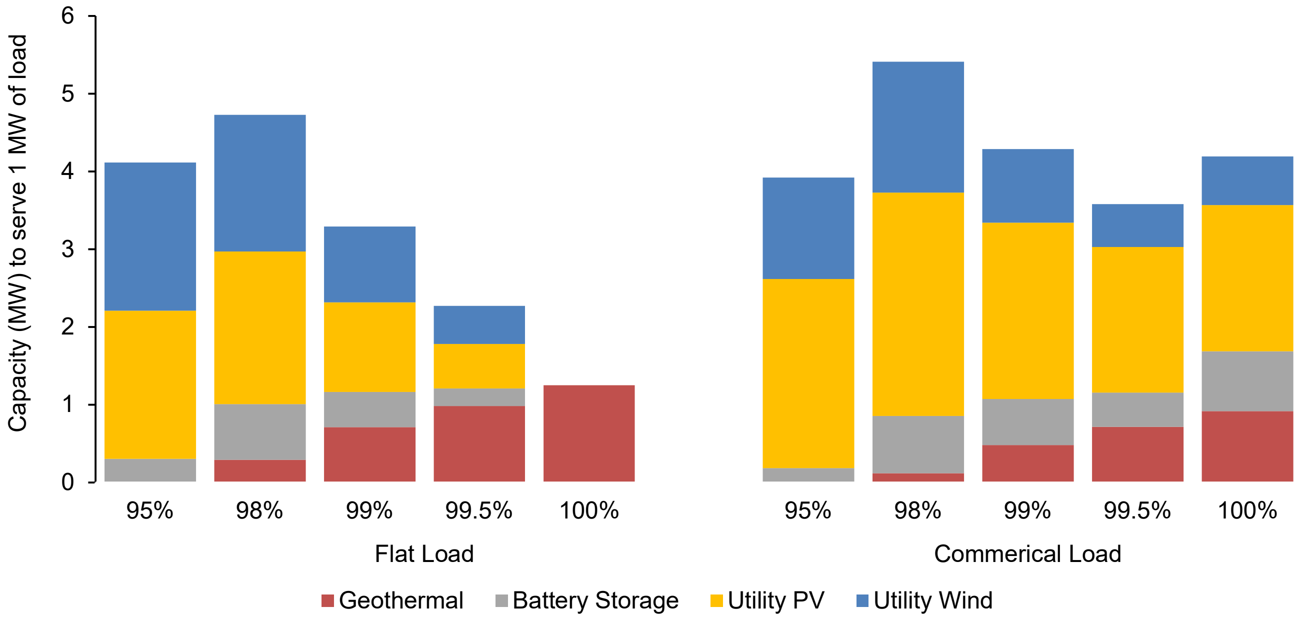

Figure 19: Capacity mix procured by customers with commercial load and flat load in CAISO, by CFE score. The commercial load customer's capacity mix has been normalized to the same total load (8760 MWh / year) as the flat load customer.

V.4 Carbon Matching

Carbon matching achieves carbon neutrality by definition and is the least-cost strategy.

The carbon matching strategy requires procuring energy that displaces enough carbon such that avoided emissions are greater than load emissions, rather than procuring clean energy to match load. In this analysis, customers pursuing the carbon matching strategy procure PV in SPP, where PPA prices are low and LMERs are relatively high[25]. Carbon matching is the least-cost strategy, in part because the available clean energy procurement that is most effective per dollar at displacing carbon (PV in SPP) also has relatively low procurement cost. Carbon matching also has lower cost than other strategies because the amount of energy that needs to be procured is less than the total customer load, unlike the three energy matching strategies. This is because the procurement location has higher LMERs than the customer load location, such that one MWh of procured clean energy displaces more CO_2 than one MWh of load is responsible for.

Differences in the abatement cost of procured clean energy between balancing authorities are significant and span an order of magnitude. Table 2 shows the PV and wind generators with the lowest abatement cost in each balancing authority. SPP, with both high LMERs and low PPA prices, has several locations where both wind and PV procurement can displace carbon emissions at less than $20/metric ton. Prices in other ISO/RTOs range from the $20s in ERCOT up to $83 metric ton for wind in CAISO. For vertically integrated balancing authorities, prices rise even higher due to the necessity of wheeling contracts to satisfy the "local" generation requirement.

Table 2: Lowest CO_2 abatement cost ($/metric ton CO_2) for PV and wind in each balancing authority

Balancing Authority	PV	Wind
CAISO	$54.1	$83.1
DUKE	$46.6	--
ERCOT	$20.7	$28.1
LADWP[26]	$82.2	$123.4
MISO	$29.0	$31.7
PGE[27]	$40.2	$112.9
PJM	$48.3	$31.0
SPP	$12.9	$17.9

[25] For the annual energy matching strategy, we had the customers select an ERCOT PV PPA rather than an SPP PV PPA, because they were very close in price, and ERCOT has a much more active PPA market than SPP. For carbon matching, customers chose generators based on the cost per CO_2 displaced, and gap between SPP PV and ERCOT PV is much larger on this metric ($12.9/metric ton CO_2 for SPP PV, $20.72/metric ton CO_2 for ERCOT PV). The SPP Wind PPA market is much more active than the SPP PV market, but the best SPP wind generator costs $17.9/metric ton CO_2. Thus, for this strategy we had the customers select the SPP PV PPA, reasoning that these large price differences were enough to overcome the obstacles in obtaining a PPA in SPP vs. ERCOT.

[26] For LADWP, the utility-scale PV and wind generators in this table are located in CAISO under a wheeling contract.

[27] For PGE, the utility-scale wind generator in this table is located in Bonneville Power Authority under a wheeling contract.

V.5 Gas Price Sensitivity Analysis

In this analysis, locational marginal prices (LMPs) and locational marginal emission rates (LMERs) are based on TCR's proprietary, long-term nodal forecast for 2025. The long-term forecast includes scenario cases, and we also analyzed each strategy under a low gas price scenario and a high gas price scenario case. The gas price scenarios assume an average annual Henry Hub price, accounting for monthly variation and basis spread to other hubs. In the low gas price scenario, the 2025 average annual Henry Hub price is $2/MMBTU, and high gas price scenario, it is $6/MMBTU.

Our conclusions do not change in high and low natural gas price market scenarios.

The gas price scenario results support the overall conclusions drawn from the base case scenario results. Figure 20 shows the cost results by strategy for the low gas price scenario, and Figure 21 shows the cost results by strategy for the high gas price scenario. In ISO/RTO regions, the low gas price increases customer cost, and the high gas price decreases customer cost. This is because natural gas prices drive changes in LMP, while PPA prices remained constant across scenarios. With low gas prices, LMPs are lower, and because customers are paying the difference between PPA price and LMP, they pay more.

In VIEU regions, gas price does not have much impact on customer cost. This is because our analysis assumed projects in regulated utility territories opt for avoided cost or feed-in tariff rates. Therefore, both procurement cost (based on LCOE) and the value of energy (based on long-term avoided cost rates or feed-in tariffs) are fixed and independent of market volatility. The only impact is on wheeled energy from Bonneville Power Authority (for PGE) and from southern California (for LADWP), where the value of energy is indexed to local pricing hubs. Additionally, battery cost and revenue are slightly impacted, since batteries charge and discharge based on modeled LMP in all regions.

Note that in the high gas price scenario, the annual energy matching and carbon matching strategies have negative costs. This is because the value of the energy based on LMP exceeds the PPA contract price on average for the least-cost units in SPP and ERCOT. The energy matching strategies that require local procurement still have positive costs.

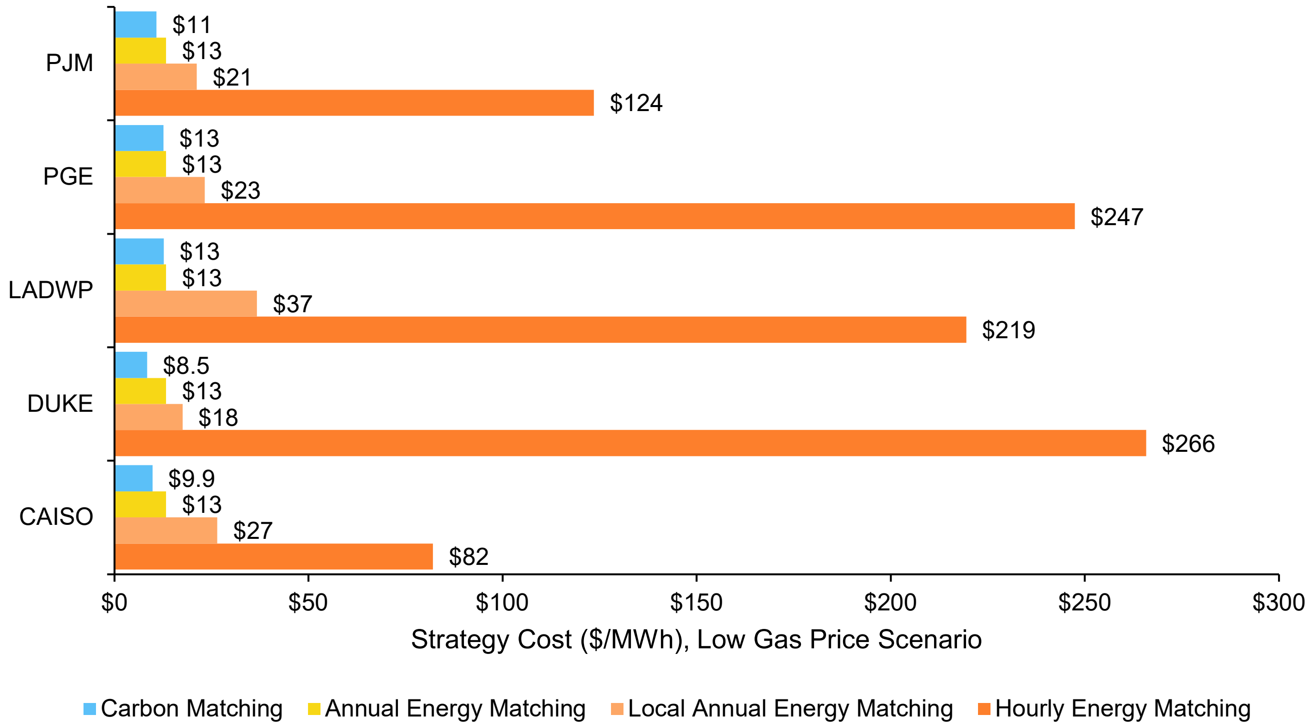

Figure 20: Comparison of cost per MWh of customer load by strategy and customer balancing authority, low gas price scenario. For hourly energy matching the target CFE score is 100%

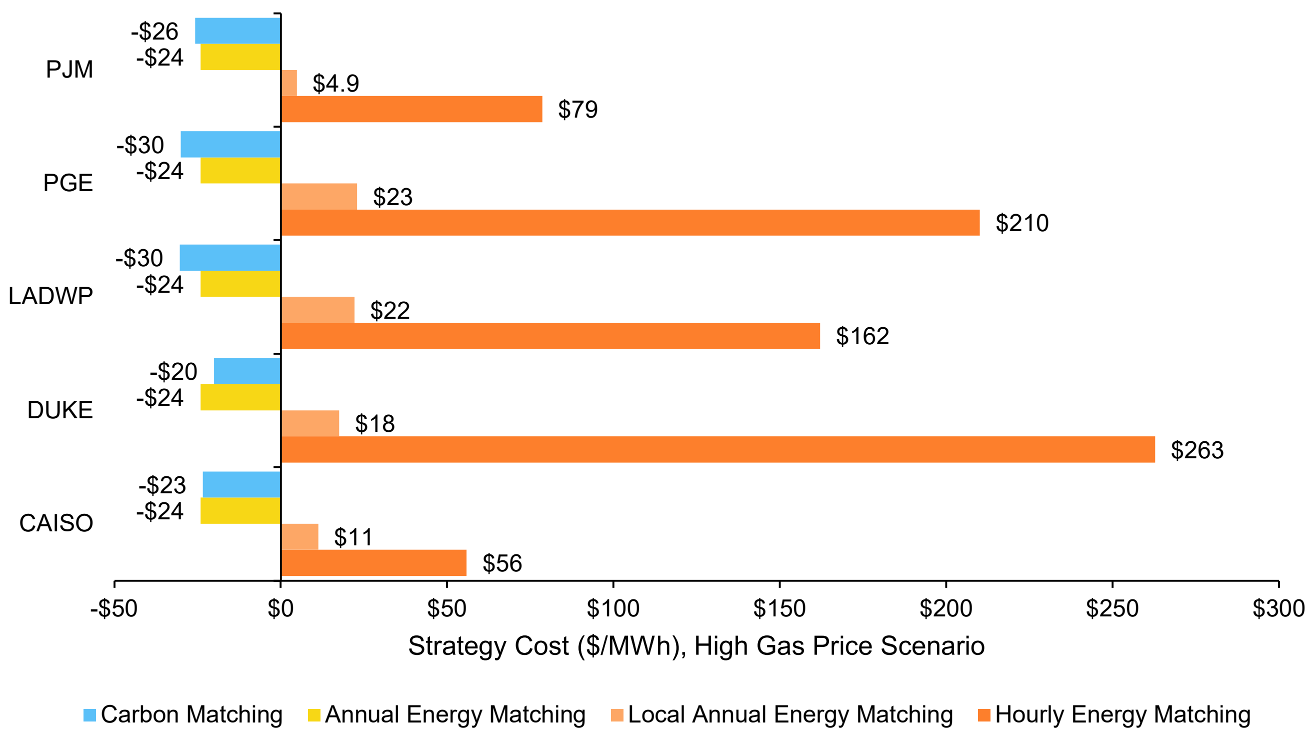

Figure 21: Comparison of cost per MWh of customer load by strategy and customer balancing authority, high gas price scenario. For hourly energy matching the target CFE score is 100%

VI Conclusion

VI.1 Carbon matching is the most effective strategy in terms of energy procurement and carbon abatement costs.

The results show that carbon matching is the most effective strategy in terms of total strategy cost and carbon abatement cost. It consistently achieves carbon neutrality at lowest cost regardless of load location and profile. This is not surprising, because the carbon matching strategy allows the customer to directly address carbon by investing in projects with the highest carbon impact.

The carbon matching strategy consistently achieves carbon neutrality at the lowest cost regardless of load location and load shape.

Annual energy matching strategy was the only option available to customers when corporate clean energy procurement began more than a decade ago. It was the most feasible solution in the market and relatively effective at reducing carbon due to low renewable penetration on the grid. However, with increasing renewable penetration, annual energy matching is not as effective, and availability of accurate, granular emissions data means it is no longer the only option. Our analysis found it to be a relatively effective strategy, but it costs more than the carbon matching strategy and is less effective at displacing carbon emissions. Customers may choose local annual energy matching to more directly 'offset' their consumption because they feel that there is no proper way to directly account for the carbon impact of their renewable procurement. However, the results show that this raises costs significantly while decreasing carbon displacement. This is because the most cost-effective procurement locations (ERCOT in terms of procurement cost and SPP in terms of carbon abatement cost) have relatively higher LMERs than the local balancing authorities in which the customers were located for this analysis.

Hourly energy matching has by far the highest energy procurement cost and carbon abatement cost, even when targeting a CFE score of less than 100%. Though all customers reached a negative carbon footprint using hourly energy matching, they were forced to over-procure renewable energy relative to their load even when using battery storage to time-shift excess renewable energy. Abatement costs for the hourly energy matching strategy were an order of magnitude higher than those for the carbon matching strategy because local renewable procurements are less effective at displacing carbon, and because customers had to procure battery storage for energy shifting, which had a mostly negligible impact on overall carbon footprint.

VI.2 Energy matching does not guarantee carbon neutrality. Companies seeking carbon neutrality should account for carbon emissions directly.

Energy matching matches MWh, not tons of carbon dioxide.

Companies wanting to offset their Scope 2 carbon footprint may seek to achieve an energy matching goal, whether it is a traditional one (such as annual energy matching) or new, more difficult one (such as hourly energy matching). However, carbon footprints are measured in terms of CO_2 emissions, not MWh of energy. As discussed in Section II.1 , marginal carbon emission rates in an interconnected system depend on location and time. Despite constraints and conditions, energy matching without emissions analysis cannot guarantee carbon neutrality unless the load and renewable generation are co-located and fully matched temporally. Though hourly energy matching achieves a negative carbon footprint for every customer in this analysis, this is due to excess procurement of renewable energy, and the high abatement cost makes it a very inefficient way to displace carbon emissions. This is why the recently announced Emissions First Partnership aims to prioritize emission impact of procurement over MWh and incentivize innovation in emissions data ecosystems.

Locational marginal emission rates provide a consistent and accurate way to account for the carbon displacement and footprint associated with renewable energy generation and electricity consumption. LMERs can be used for individual customer carbon accounting and can also equitably attribute total system carbon emissions to individual generators and customers. Using LMER, customers can choose to match carbon directly rather than matching energy, and the results of this analysis show that carbon matching is the most effective strategy in terms of both total strategy cost and CO_2 abatement cost.

VI.3 Localizing energy procurement increases strategy cost and carbon abatement cost.

Local energy matching strategies prevent customers from procuring the most cost-effective and carbon-impactful clean energy projects.

The localized energy matching strategies (local annual energy matching and hourly energy matching) require procurement of clean energy in the same balancing authority where the customer has load, in an effort to minimize the difference between the emission rates of load and clean energy generation. Our analysis shows that local energy matching increases strategy cost significantly but does not consistently improve net carbon footprint. In some instances, local annual energy matching even decreased carbon displacement compared to annual energy matching. This is because forcing clean energy projects to be procured in the same balancing authority as load prevents buyers from accessing the most economic and carbon-impactful projects.

As shown in Figure 3 through Figure 6 in the result section, the lowest cost projects are PV projects in ERCOT and SPP. However, local energy matching strategies prevent customers from procuring energy from these projects unless their load is in ERCOT or SPP. These customers are required to procure projects locally, which can cost significantly more to procure and sometimes are also less effective at displacing carbon. For example, PV projects in CAISO have higher procurement cost and higher carbon abatement cost than PV in ERCOT, meaning they are more costly but less effective at displacing carbon.

Technology availability is also a concern. Small balancing authorities, such as LADWP and PGE, have very limited space for wind and solar project development. Although wheeling from neighboring regions was allowed in this analysis, it came at a significant cost increase. For hourly energy matching, a small geographic region also means a lack of weather pattern diversity, limiting the customer's ability to hedge against periods of low renewable generation by procuring a diverse portfolio of projects. Therefore, customers in small BAs needed to procure more battery storage as backup power for these periods, significantly increasing costs.

Some BAs may also have restricted technology choices. For example, in North Carolina, a 1983 ordinance prohibits construction of any tall structure on protected mountain ridges, making it nearly impossible for economically viable wind projects to gain approval[28]. Because of this, the DUKE customer in our analysis was limited to procuring PV and battery storage only.

VI.4 The cost to implement hourly energy matching differs significantly based on customer location and load profile.

The cost of implementing hourly energy matching depends heavily on the customer's load profile and the resource mix of the customer's load BA. Implementing hourly energy matching can cost as low as $68/MWh of load for a customer in CAISO because of the availability of geothermal to provide firm clean energy, and as high as $289/MWh for a customer in DUKE due to lack of wind energy for procurement.

Hourly energy matching cost 400% more in DUKE than CAISO, where geothermal is available to provide firm clean power.

Compared to hourly energy matching, annual energy matching and carbon matching have more consistent costs across customer locations. Because annual matching does not constrain procurement location, all customers can access the same least-cost project and can therefore expect the same cost no matter where their load is located. The cost of the carbon matching strategy can change slightly based on the customer's load emission, but all cusomters can still procure the project with the lowest abatement cost.

This wide variation in costs for hourly energy matching means this strategy could cost much more for some customers than others. This could be challenging for customers who have load spread across multiple BAs and customers who have load in BAs with a lack of clean energy available for procurement.

[28] See the Mountain Ridge Protection Act of 1983 and N.C. Gen. Stat. § 143 Article 21C for restrictive legislation.

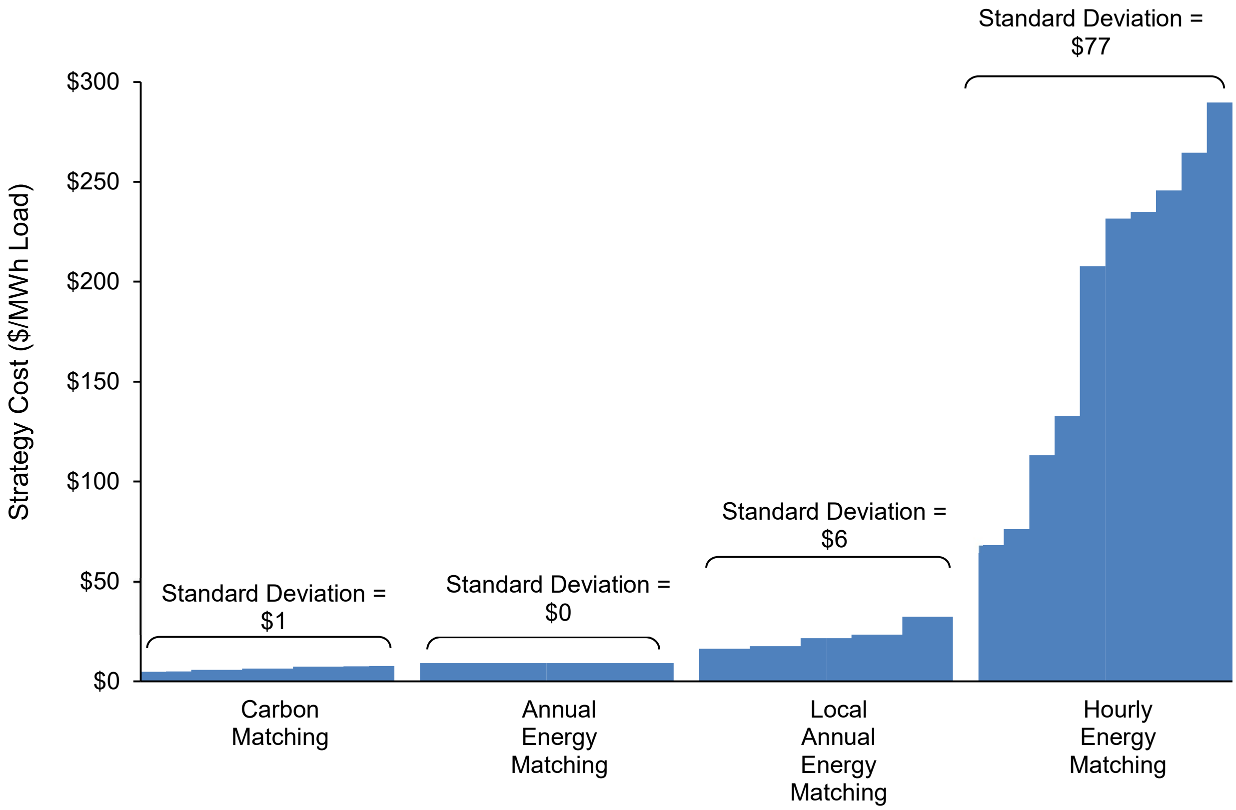

Figure 22: Strategy Cost by strategy, balancing authority, and load profile. Ranked from lowest to highest.

VI.5 Localized energy matching strategies may not be practical for all customers.

Local energy matching faces many challenges not captured by quantitative cost metrics. If a company has load in balancing authorities that are regulated utility territories, the localized energy matching strategies require clean energy procurement in the same territory. However, clean energy projects are not always available in non-ISO/RTO regions. Building a project in a regulated utility often requires lengthy and costly negotiation and regulatory approval, and sometimes requires amending existing legislation[29]. While large energy buyers with concentrated load in a selected number of balancing authorities may be able to navigate the negotiation process, implementing a localized energy matching strategy can be a significant challenge for companies with small loads scattered across multiple balancing authorities.

[29] Google, "Let the Sunshine In."

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GLOSSARY

Term	Definition
AEO	EIA Annual Energy Outlook
AER	Average Emission Rate
Annual Energy Matching	The customer procures clean energy assets such that the annual generation from these assets matches the customer's annual electricity consumption.
ATB	NREL Annual Technology Baseline
Avoided Emissions	See 'carbon displacement'
BA	Balancing authority
CAISO	California Independent System Operator
Carbon Abatement Cost	The cost to displace one unit of CO_2 ($/metric tons CO2).
Carbon Displacement	The total amount of CO_2 displaced by procured clean energy (a negative value).
Carbon Matching	A customer must procure clean energy assets such that the generation from these assets displaces a quantity of carbon emissions equal to or greater than the emissions generated by the customer's electricity consumption.
Carbon Neutrality	Achieving a net carbon footprint of less than zero. See 'Net Carbon Footprint'
CFE	Carbon-Free Energy
DUKE	Duke Energy Carolinas
EAC	Equivalent Annual Cost
EIA	US Energy Information Administration
EPC	Engineering Procurement and Construction
ERCOT	Electric Reliability Council of Texas
ES	Energy Storage
FiT	Feed-in Tariff
GT	Gas Turbine
Hourly ('24/7') Energy Matching	The customer must match their electricity consumption with clean energy on an hourly basis in the same balancing authority.
IIC	Initial Installed Cost
IIJA	Infrastructure Invest and Jobs Act, part of the Inflation Reduction Act (2022)
ISO/RTO	Independent System Operator/Regional Transmission Organization
kW	Kilowatt
kWh	Kilowatt-hour
LADWP	Los Angeles Department of Water and Power
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
LMER	Locational Marginal Emission Rate
LMP	Locational Marginal Price
Load Emissions	The sum of emissions attributable to customer load.
Local Annual Energy Matching	A location-constrained version of annual energy matching, where energy must be procured in the same balancing authority as the customer's load.
MER	Marginal Emission Rate
MISO	Midcontinent System Operator

Term	Definition
MW	Megawatt
MWh	Megawatt-hour
Net Carbon Footprint	The difference between carbon attributed to electricity consumption and carbon displaced by clean energy generation (metric tons CO2) . Measured as the sum of load footprint and carbon displacement.
NGCC	Natural Gas Combined Cycle
NREL	National Renewable Energy Laboratory
PGE	Portland General Electric
PJM	PJM Interconnection
PPA	Power Purchase Agreement
PV	Photovoltaic
RE100	A coalition of companies that have each pledged to match 100% of their electricity demand with renewable generation annually within each country in which they operate.
REC	Renewable Energy Certificate/Credit
SPP	Southwest Power Pool
Strategy Cost	The estimated cost to procure clean energy to achieve each strategy ($/MWh).
VIEU	Vertically Integrated Electric Utility
WIND	NREL Wind Integration National Dataset