Clean Power by the Hour

Assessing the Costs and Emissions Impacts of Hourly Carbon-Free Energy Procurement Strategies

Report / July 2021

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Mark Dyson, Sakhi Shah, and Chaz Teplin, *Clean Power by the Hour: Assessing the Costs and Emissions Impacts of Hourly Carbon-Free Energy Procurement Strategies,* RMI, 2021, **http://www.rmi.org/insight/clean-power-by-the-hour.**

Acknowledgments

The authors thank the following individuals for offering their insights and perspectives on this work. Inclusion on this list does not necessarily indicate endorsement of the report's findings.

Christen Blum, Primergy Solar
MaryAnne Brelinsky, EDF Energy
Jason Burwen, Energy Storage Alliance
Lynda Clemmons, NRG
Alla Jezmir, Earthrise Energy
Shayle Kann, Energy Impact Partners
Conor Kelly, Microsoft
Lorenzo Kristov
Tim Latimer, Fervo Energy
John Lemmon, Microsoft
Brian Marrs, Microsoft
Gavin McCormick, WattTime
Vanessa Miler, Microsoft
Greg Miller, UC Davis
Brent Morgan, Microsoft
Danita Park, NRG
Bojana Popovic, EDF Energy
Mark Porter, REBA
John Powers, Schneider Electric
Henry Richardson, WattTime
Ben Serrurier, RMI
Devon Swezey, Google
Maud Texier, Google
Carla Tully, Earthrise Energy
Shannon Wojcik, Microsoft

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About RMI

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Table of Contents

Executive Summary

Corporate procurement has played an important and growing role in decarbonizing global power systems, accounting for 10% of total renewable energy procurement globally in 2019.[1] Corporate buyers have long prioritized procurement of renewable energy to match their facilities' loads on an annual basis, but the urgency for climate action is motivating leading firms to consider more advanced procurement strategies that can accelerate progress toward a carbon-free electricity grid. In particular, leading buyers are increasingly focusing on hourly procurement strategies for carbon-free electricity (CFE), which explicitly recognize the time-dependent economic and emissions impacts of procured resources.

One emerging hourly procurement strategy is hourly load matching, also often referred to as "24x7 matching," where a buyer attempts to procure sufficient carbon-free energy to match a given facility's load in every hour. Because wind and solar, the lowest-cost carbon-free generators, are weather-driven and variable, achieving full grid decarbonization requires other resources to meet load during periods when renewable output is low. Hourly load-matching strategies therefore prioritize carbon-free technologies in addition to wind and solar and can potentially help create a market signal for these technologies.

In this study, we use a relatively simple model to assess the costs, near-term emissions impacts, and long-term emissions and renewables integration implications of hourly load-matching strategies in seven US and European electricity markets. Our analysis has three primary findings:

1. **As the level of hourly matching is increased, costs for hourly load matching rise in three distinct stages, well above costs for meeting annual procurement targets.** Costs to match 30%–80% (depending on the market) of hourly demand with wind and solar energy are relatively stable but increase significantly at higher levels of hourly load matching due to the need to use storage.

2. **Near-term emissions reductions from hourly load matching depend on the regional grid mix and how storage resources are operated.** Emissions reductions are greatest when buyers procure wind and solar in the most carbon-intensive grids and operate storage assets in response to system-level, not facility-level, price and emissions signals.

3. **Hourly procurement strategies can create demand for emerging technologies needed to fully decarbonize the grid.** Buyers targeting higher levels (e.g., >85%) of hourly matching will face high costs in most markets if they rely only on only wind, solar, and lithium-ion batteries, as modeled in this study. By setting 100% hourly matching targets, buyers create a demand signal for emerging technologies that can also meet valuable system-wide needs in decarbonized grids.

Overall, we find that hourly load-matching strategies can help lay the groundwork for a decarbonized grid in the long term but should be carefully tailored to region-specific grid dynamics to also maximize emissions reductions in the near term. Based on our analytical findings and interviews with a diverse set of industry stakeholders and other experts, we make several recommendations for buyers, policymakers, and other industry participants to maximize the impact of this emerging procurement model:

- **Match hourly procurement strategies to grid dynamics.** The electricity grid is a shared system, and corporate procurements cause ripple effects that affect more than just their own load and supply. Therefore, buyers should account for regional grid dynamics in designing procurement strategies to maximize both near- and long-term emissions savings. In particular, the current fossil intensity of the regional grid, including on an hourly basis, should inform procurement because it strongly influences the near- and long-term emissions impact of procured CFE resources. Furthermore, energy storage should be charged and discharged based on signals of system-level dynamics, including system-wide energy price and marginal emissions factors, instead of used solely to support hourly load matching by balancing facility-level loads with procured CFE.

- **Expand wholesale market access to scale the benefits of hourly procurement strategies.** Wholesale electricity markets provide the most natural venue for matching carbon-free generation with hourly demand because they can transparently reveal electricity prices, generation mix, and system-wide emissions. Further, if wholesale market designs are reformed to integrate least-cost procurement of CFE and storage resources with reliability planning, corporate buyers could join a broader movement toward market-based efforts to drive toward 100% hourly CFE at the grid level.

- **Balance hourly procurement goals against the science-based imperative to reduce emissions as fast as possible in the near term.** To avoid the worst impacts of climate change, the world must reduce emissions ~50% by 2030,[2] and offsetting fossil fuel used to generate electricity is one of the best near-term opportunities to do so. Achieving climate stability will require terawatt-scale CFE deployment over the next decade in the United States and other global markets.[3] Corporate procurement as it commonly exists today (i.e., to meet annual targets) can continue to play a major role in enabling that investment for the foreseeable future. Buyers who have not yet offset 100% of their annual electricity use with procured CFE can feel confident that doing so based on annual targets in regions with low renewable energy adoption will continue to create material climate benefits. This can be done even as buyers who have already met that goal continue to push the envelope of sophistication and pave the way toward a 100% CFE grid.

Science-based targets for climate change mitigation call for both maximizing near-term emissions reductions, in order to limit the cumulative carbon emissions that drive temperature rise, and reaching net-zero emissions by mid-century or sooner to avoid further warming. Carefully designed hourly procurement strategies can best support both outcomes if they take into account current grid dynamics and emissions reduction opportunities, as well as create incentives for the technology needed to fully decarbonize the grid.

The potential for coordinated action by buyers, developers, brokers, utilities, and policymakers around CFE procurement strategies that reflect hourly grid needs presents a rare opportunity to materially speed progress toward grid decarbonization. Alignment and standardization around procurement strategies that support both near- and long-term emissions reductions goals can accelerate progress toward a clean grid that delivers CFE cost-effectively to all customers, not just those who take the first steps.

Introduction: The Evolution of Corporate Renewable Energy Procurement

Over the past decade, corporate buyers have taken a leadership role in advancing decarbonization of global power markets, most notably through direct procurement of renewable energy. In 2019, corporate renewable procurement accounted for 10% of the total market for renewables globally and for 24% of the renewables market in the United States.[4] Over 260 companies have committed to procuring renewable energy equivalent to 100% of their load,[5] with many having already reached this milestone.

As the scale of corporate commitment has grown, so have a set of associated challenges. Siting of projects in the best resource regions has concentrated production of renewable energy in space and time, leading to lower realized prices and financial losses for corporate buyers under common virtual power purchase agreement (PPA) constructs. Mismatch of buyers' load and renewable production exacerbates this issue, in which buyers can be exposed to high costs for purchased power that are poorly offset by the relatively lower revenues from procured renewables projects.[6]

In spite of these challenges, renewable procurement generally remains financially viable, and supports the economy-wide decarbonization required to avoid the worst impacts of climate change. In the United States, for example, terawatt-scale wind and solar deployment over the next decade can pave the way for economy-wide net-zero emissions by 2050,[7] while lowering total 2030 electricity system costs compared with 2020 levels.[8] Corporations can support this future with continued procurement of wind and solar in every region of the country.

However, there is an increasing recognition in the industry that standard wind and solar PPAs offer only a partial solution to complete grid decarbonization. Most corporate targets are set based on procuring renewables equivalent to 100% of annual load. Annual targets do not guarantee that buyers' hourly load is entirely offset by renewables, due to mismatch between load and procured supply. For example, Google has published estimates that only 61% of its data centers' hourly loads are met by carbon-free energy,[9] even as it has met its 100% annual target. For the grid as a whole to decarbonize, hourly electricity demand must be met by carbon-free supply, meaning that annual procurement goals are not, by themselves, sufficient to solve the full scope of the challenge.

To mitigate both the financial and scalability challenges associated with annual procurement, some buyers are considering procurement that more accurately accounts for the balance of hourly demand and generation. In this study, we examine the costs and immediate emissions implications of matching procured CFE with buyers' loads on an hourly basis.

The Opportunity for Hourly Carbon-Free Electricity Procurement

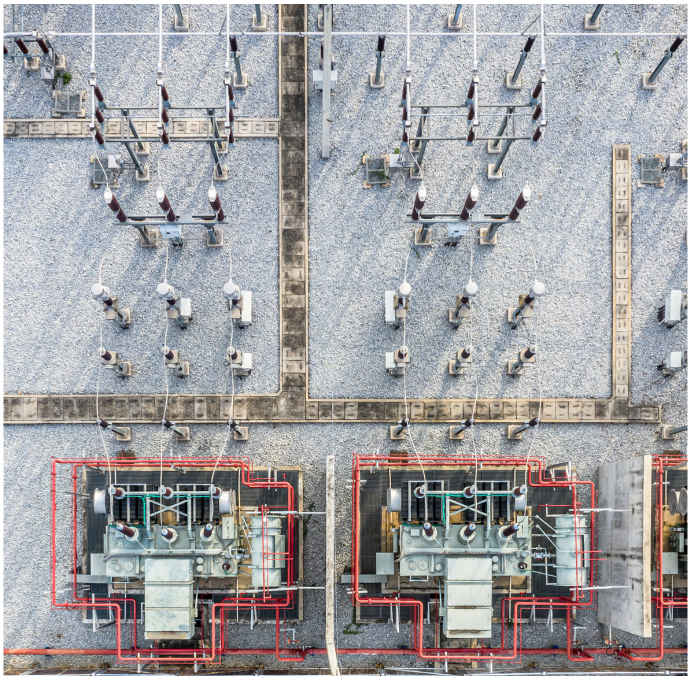
Hourly carbon-free electricity (CFE) procurement strategies, including hourly load matching–also known as "24x7 matching"—are gaining interest among buyers for their potential to better match consumption patterns and potentially lay the groundwork for system-wide decarbonization. Firms including Microsoft (with partners ENGIE and Vattenfall[10]) and Google have piloted or committed to hourly load-matching strategies for their facilities.[11] And within the broader industry (e.g., the Renewable Energy Buyers Alliance and suppliers including AES[12]), interest in hourly matching is growing.

Hourly load matching and other hourly CFE procurement strategies have the potential to address several of the challenges associated with traditional renewable PPAs:

- **Mitigate shape risk:** Optimizing the timing of procured energy as it relates to both system prices and hourly facility load in a given region can provide a hedge against volatile wholesale market prices and existing PPA positions. It can also stabilize buyers' net electricity costs better than a standard PPA.

- **Incentivize new technologies:** Hourly procurement strategies explicitly recognize the declining incremental value of wind and solar as their market share grows, and open the door for emerging technologies that, while perhaps more costly, can complement variable renewables in meeting hourly grid needs.

- **Demonstrate models for carbon-free grid balancing:** Hourly procurement strategies can illustrate technology combinations and balancing strategies that, at scale, could contribute to balancing a fully decarbonized grid.



While these advantages are compelling, several questions remain about the viability and impact of hourly CFE procurement strategies, and specifically the strategy of hourly load matching with carbon-free energy. This study evaluates a set of these questions, below, to inform recommendations for buyers and other industry stakeholders to maximize the benefits of this opportunity.

- **Costs:** how much do hourly load-matching strategies cost in different regional electricity markets, at different target levels of matching?

- **Emissions impact:** how do such strategies affect short-run emissions in different markets?

- **Emerging technology:** what technologies might hourly load matching incentivize that can enable deeper decarbonization of regional electricity grids?

Summary of Approach

To investigate the costs and emissions impact of hourly matching, we created a model that incrementally builds a least-cost portfolio to match a target fraction of a facility's hourly load with newly-built CFE resources, with a sensitivity examining the impacts of including existing CFE resources in the portfolio. We summarize the model's assumptions and approach in Exhibit 1.

To complement our analysis, we also interviewed over a dozen industry participants and other experts regarding the outlook for hourly procurement strategies; anonymized insights from these discussions are included as callout boxes in this report.

Exhibit 1 **Summary of analytical approach**

Topic	Approach
Study geographies	We used geographically specific data from seven regional electricity markets in North America and Europe: PJM (Northeastern United States), CAISO (California), SPP (Midwest United States), Duke Energy (Southeast United States), IESO (Ontario, Canada), PSE (Poland), and TenneT (Netherlands).
Facility loads	We evaluated hourly load-matching strategies for two facility types: • **Data centers:** We approximated a data center's demand profile as a flat 1 megawatt load. • **Office buildings:** We used EnergyPlus software to simulate hourly loads using ASHRAE 90.1-2019 appropriate for the geographic climate
Technologies assessed	To best represent decisions relevant to buyers in the near-term, we primarily assessed the role of currently commercial and widely available technologies in meeting hourly energy procurement goals. We used data from the National Renewable Energy Laboratory's Annual Technology Baseline (ATB) with the following parameters:[13] • **Solar PV:** ATB 2020 capital expenditure (CAPEX) and operating expenditure (OPEX) data for utility-scale solar, 2022 moderate case, single-axis tracking • **Onshore wind:** ATB 2020 CAPEX and OPEX for land-based wind, speed class 4, 2022 moderate case • **Lithium-ion batteries:** ATB 2020 US dollar per kilowatt and dollar per kilowatt-hour CAPEX for storage, 2022 low case, with a 2.5% OPEX multiplier We calculate levelized costs of energy using the cost inputs noted above and region-specific capacity factors (see below), and do not attempt to represent typical PPA pricing for each region. In Finding 3 below and the *Implications and Recommendations* section, we discuss the role of other technologies not directly modeled here, including "firm" resources, in meeting hourly load.
Renewable profiles	We created hourly wind and solar profiles using data from the renewables.ninja website corresponding to a characteristic regional wind or solar plant.
Existing grid mix	Our core analysis simulates procurement strategies that use only new-build CFE resources to match buyers' hourly loads and does not directly model the contribution of existing CFE resources within regional grids in matching hourly load. In a sensitivity analysis discussed below in Finding 1, we also assess and characterize the impact of including existing CFE (including nuclear and hydro as well as existing wind and solar) in the matching strategy.
Carbon emissions impact	We used WattTime's 2019 hourly marginal emissions estimates for the seven global markets to estimate the short-term emissions impacts.[14]

Cost impact of excess generation compared with facility load	We assume that wind and solar generation procured above a buyer's hourly load is either used to charge a battery, or if there is not sufficient battery storage capacity available, sold back to the grid. For energy sold back to the grid, we reduce the portfolio cost by an assumed value of $15 per megawatt-hour (MWh) to reflect an estimate of the economic value of available renewable energy resources reducing the operating costs of fossil or other dispatchable generators.
Emissions impact of excess generation compared with facility load	We assume that both matched facility load and excess generation reduce emissions as the marginal system emissions rate (i.e., the available wind or solar energy is not curtailed). This assumption is valid for most electricity markets where the renewables share is small (i.e., most global electricity markets), and we recognize that more detailed modeling is needed to validate this assumption over the long run in renewables-rich regions (e.g., CAISO, parts of SPP). In these regions both emissions and economic benefits of additional renewable energy resources may plateau absent additional load growth from electrification and/or new transmission capacity.
Hourly procurement metric	For a given market and facility type, we assess the ability of various portfolios of renewables and storage to meet the facility's hourly load, and report the following metric: % hourly load match = (MWh of hourly facility load matched/facility annual energy demand)
Battery dispatch	We assume that buyers dispatch batteries to optimize hourly matching, and only charge the batteries when there is excess wind or solar generation: • The battery is charged up to its peak power and energy rating using any excess wind or solar generation beyond that needed to meet facility demand. • In any hour where procured wind and solar fail to meet facility load, the battery discharges to the maximum extent possible until facility load is met or the battery reaches its power rating or runs out of charge. We assume a 90% battery round-trip charge-discharge efficiency. We do not model any co-optimization of the battery dispatch against system-level emissions or cost signals. This is a simplified version of battery dispatch and we recognize that more advanced dispatch procedures that optimize against system-level signals will provide more emissions savings and economic benefits.
Optimization methodology	We use an iterative approach to build matching portfolios: 1. Using the battery dispatch model above, calculate the hours matched when we add a small increment (i.e., 10% of facility load) of wind, solar, battery power, or battery energy to the existing portfolio. 2. Calculate the added cost per additional matched MWh for the four possible portfolio additions. 3. Select the resource with the lowest added cost per additional matched MWh and add this to the portfolio. For the first increment of battery storage, both energy and power are added. 4. Repeat until % matching reaches ~90%, at which point hourly matching with wind, solar, and storage alone becomes impractically costly (e.g., double or more the costs of procuring renewable energy alone).
Output metrics	We calculate the following metrics for matching in each market and facility type, at each level of hourly matching: • **Portfolio composition:** the mix of wind, solar, and storage selected. • **Costs:** we calculate both average (i.e., the total costs to meet a given level of hourly procurement divided by the facility load served by procured resources, in $/MWh) and marginal (i.e., the incremental cost to serve an additional MWh of hourly facility load with new resource procurement). • **Carbon savings:** we report the tons of CO_2 emissions reduced at each level of hourly load matching based on WattTime data, as noted above.

Analytical Findings

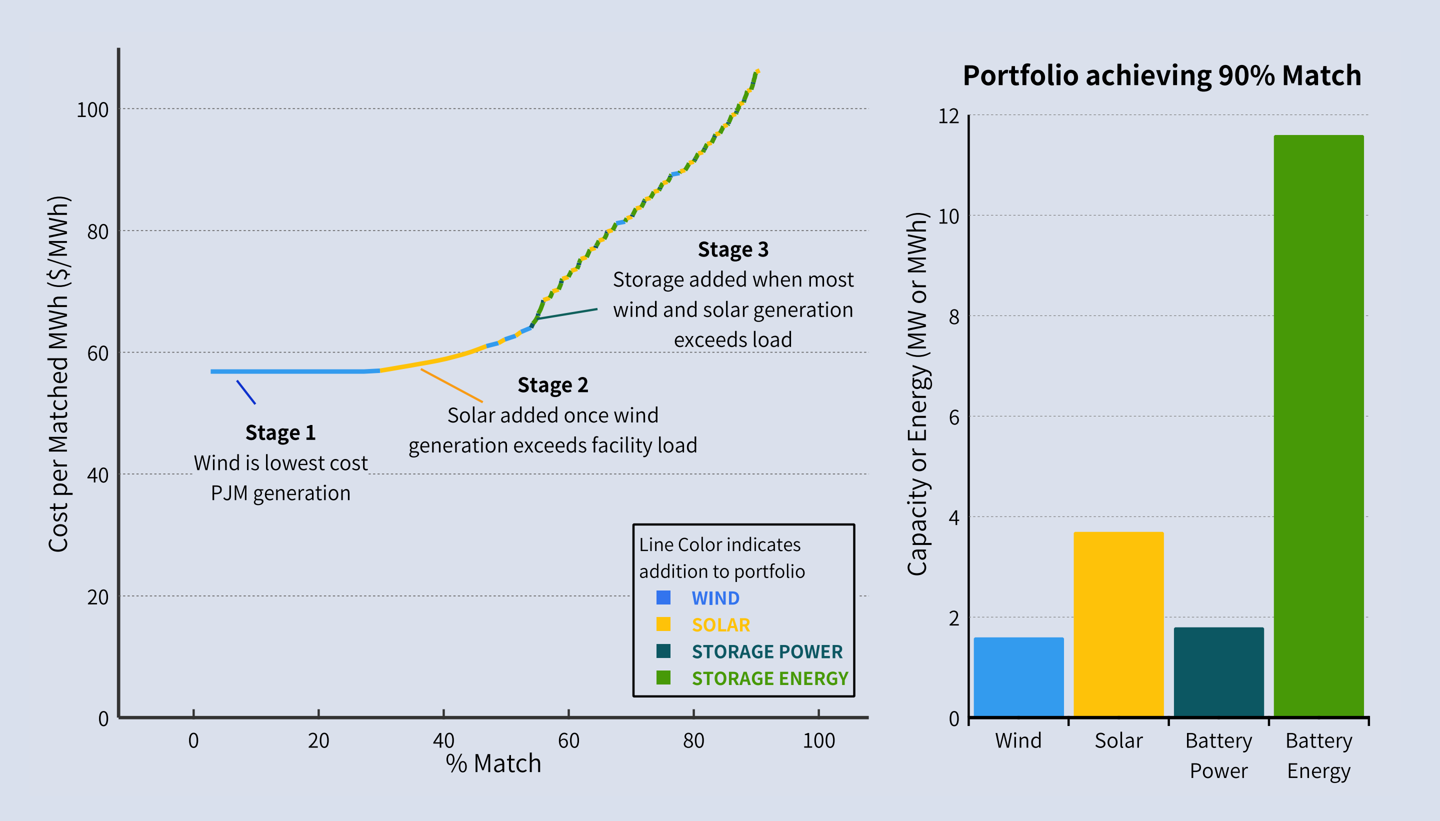
The analysis reveals three key findings, explored in detail below.

Finding 1: As the level of hourly matching increases, costs for hourly load matching rise in three distinct stages, well above costs for meeting annual procurement targets.

We find that matching costs increase in three distinct "stages," depending on the mix of local resources and facility loads in each geography. We highlight these stages in Exhibit 2, which shows the net cost per matched MWh versus the percent match for a data center in PJM.[i]

- **Stage 1: Facility load exceeds procured renewables in all hours.** Below 30% hourly matching level in this PJM example, wind is the lowest-cost option to increase the level of hourly load matching, and all generation contributes to meeting the flat data center load. Costs during this stage do not exceed the cost of "traditional" procurement of renewable energy via PPA.

Exhibit 2 Hourly load matching costs for a data center in PJM



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[i] While this analysis highlights the stages of cost escalation to match buyers' load with procured CFE, we also note that the costs to match load using a traditional, fossil fuel-based power system also rise in a similar manner. In any power system, investment is required in resources (e.g., "peaking" power plants) that run infrequently to meet rare peak load events, leading to increasing levelized costs as the share of hourly matching increases.

- **Stage 2: Procured renewable generation exceeds facility loads in some hours.** Stage 2 begins when generation begins to exceed facility load during peak wind hours. We assume this "excess" generation is sold back to the grid, but at a lower price than the levelized PPA costs, and so costs per MWh of load served begin to increase. In this PJM example, solar begins to play a role in Stage 2, even though it has a higher cost than wind, because solar complements wind's production and contributes more cost-effectively to meeting hourly facility load.

- **Stage 3: Storage used to balance renewables.** Beyond ~55% hourly load matching in this PJM example, most incremental wind and solar procurement occurs during hours when facility load is already met by the existing wind and solar in the portfolio, and the least-cost technology to increase hourly matching is storage. Storage can charge from "excess" wind and solar generation that would otherwise be sold to the market, and discharge to meet facility load during periods when it is neither windy nor sunny. Additional renewables and storage can be added together to meet load during remaining gaps, but marginal costs for increasing the hourly matching level rise significantly.

This analysis is focused on the direct resource costs associated with hourly matching strategies, not necessarily any associated economic benefits associated with the outcomes of these strategies. For example, load shaping and/or hedging benefits associated with procured CFE that is well-correlated to load can reduce buyers' energy price risk, and co-optimization of storage against system-level pricing signals can provide additional revenue for buyers. This analysis also excludes less immediately available options (e.g., renewable energy delivered via new transmission lines, emerging "firm" technologies that can provide power on demand) that could lower costs over the longer term. Additional analysis would be required to fully explore the net, long-term economic impacts, for buyers and at the system level, of the strategies simulated here.

In Exhibit 3, we show the portfolio costs for all seven study regions. Stage 1 costs are generally lower in regions with excellent wind resources, especially Ontario, Poland, SPP, and the Netherlands, where it is generally possible to achieve high match levels (further to the right in Exhibit 3) cost-effectively before needing to add storage. This is the case for both data center and office building load profiles, as Exhibit 4 shows the similarities of portfolios required for these different demand shapes. We note that some of these regions, particularly SPP, already have significant wind capacity in high-quality resource areas, and further installations may be limited by transmission that our model does not account for.

Depending on siting of resources deployed to meet hourly procurement targets, there may be an increase in deliverability of clean energy across the grid, or an increase in congestion. Integration of siting decisions for procured resources with system-level dynamics can avoid reliability and economic efficiency issues.

As shown in Exhibit 4, costs rise in similar ways for both offices and data centers. Because office loads are relatively higher during daytime hours, solar can cost-effectively increase hourly load matching levels even in regions like SPP, where wind is a lower-cost resource.

To explore the impact of using metrics that account for the existing share of CFE within a regional grid,[15] we also ran a sensitivity case where we included existing CFE in the portfolio optimization method.[ii] Exhibit 5 shows how costs to meet given matching levels fall compared to a metric that does not account for existing CFE, while procurement outcomes remain largely unchanged.

[ii] Our methodology in the sensitivity case is different from the methodology published by Google (*24/7 Carbon-Free Energy: Methodologies and Metrics*, February 2021). Our methodology considers grid CFE at a different stage of the optimization than that published by Google, and as a simplification only considers potential procurement of wind, solar, and batteries, versus a broader set of CFE resources. As such, our results are not directly comparable.

Exhibit 3 **Cost and portfolio comparison for data centers in seven different geographies**

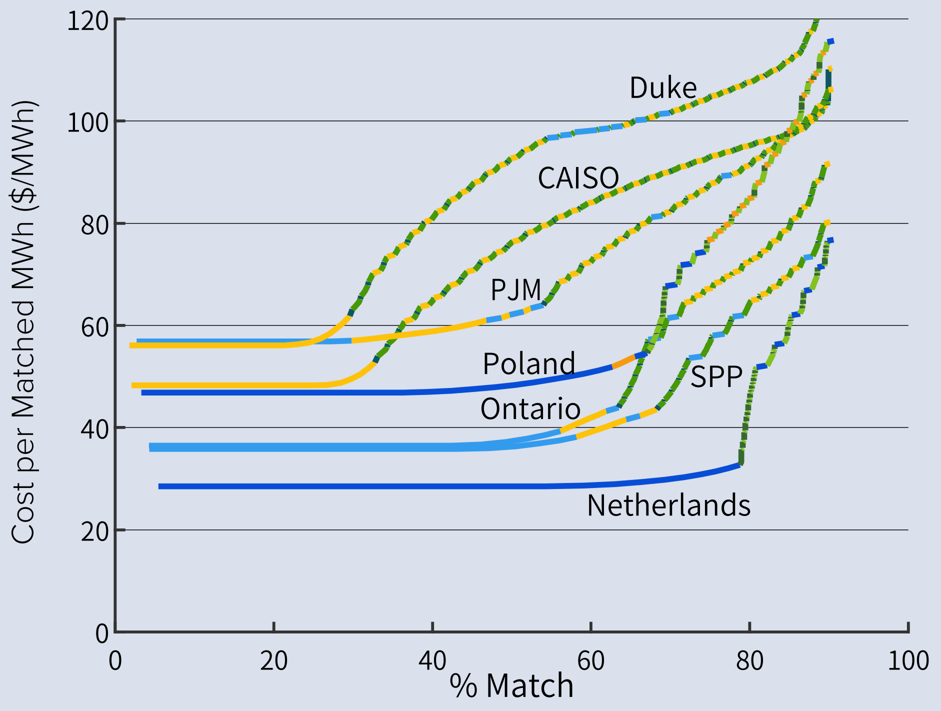
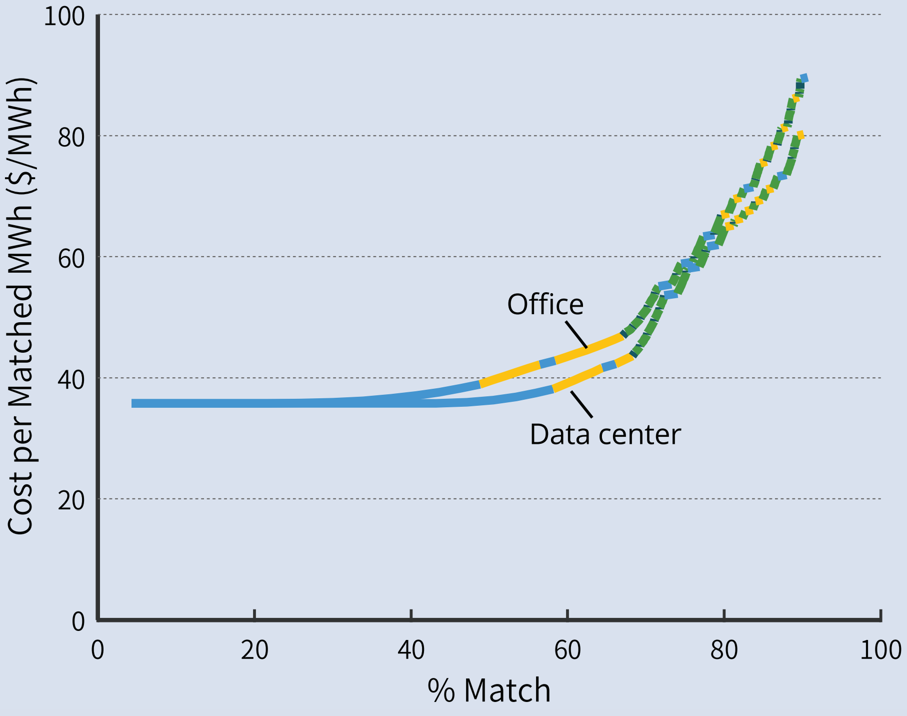


Exhibit 4 **Matching costs for typical office and data center profiles in SPP**



The impact of accounting for existing carbon-free energy resources

Our core analysis defines the level of hourly load matching based on the match between buyer-procured CFE resources and a buyer's facility load, and does not include the contribution of existing grid CFE resources. This modeling choice is distinct from some proposed hourly load matching methodologies that explicitly account for existing CFE in calculating the level of load matching. For example, in a grid where carbon-free resources like nuclear, hydro, geothermal, wind, and solar make up on average 30% of total generation in each hour, using a metric that accounted for existing CFE would result in a data center in that region having an approximately 30% match level without procuring any additional resources.

To illustrate the implications of the modeling choice made in this study to exclude existing CFE on the grid, we replicated our study's methodology for a data center in SPP but applied a different matching metric that accounted for the contributions of existing CFE.[iii] We used 2019 data on hourly grid CFE production in SPP to assess how a buyer might seek to procure resources beyond existing CFE to reach higher hourly matching levels. Exhibit 5 shows a comparison between procurement costs associated with reaching given levels of hourly matching where the metric excludes grid CFE (top line), and where the portfolio is selected to reflect the contributions of existing nuclear, hydro, wind, and solar in the metric (bottom line).

The SPP example in Exhibit 5 illustrates the differences and similarities in outcomes between the two metrics. SPP has a relatively high level of existing wind generation (~27%) as well as nuclear and hydro (~6% each). Therefore, a buyer with a flat load profile in SPP applying a matching metric that includes existing CFE would start at a ~41% match level without any additional procurement. From there, buyers seeking to procure additional CFE toward a higher level of hourly load matching would proceed in much the same fashion as a buyer only counting procured CFE:

- Procuring wind: a buyer prioritizing hourly load matching who accounts for grid CFE will procure less wind in SPP than a buyer who does not account for grid CFE, as the existing SPP grid mix is already wind-rich.

- Procuring solar: a buyer accounting for grid CFE in their hourly matching metric will prioritize solar investment starting at a ~75% match level, versus a ~58% match level, because SPP's existing CFE includes nuclear and hydro and thus already provides a more balanced hourly CFE portfolio than a wind-only strategy.

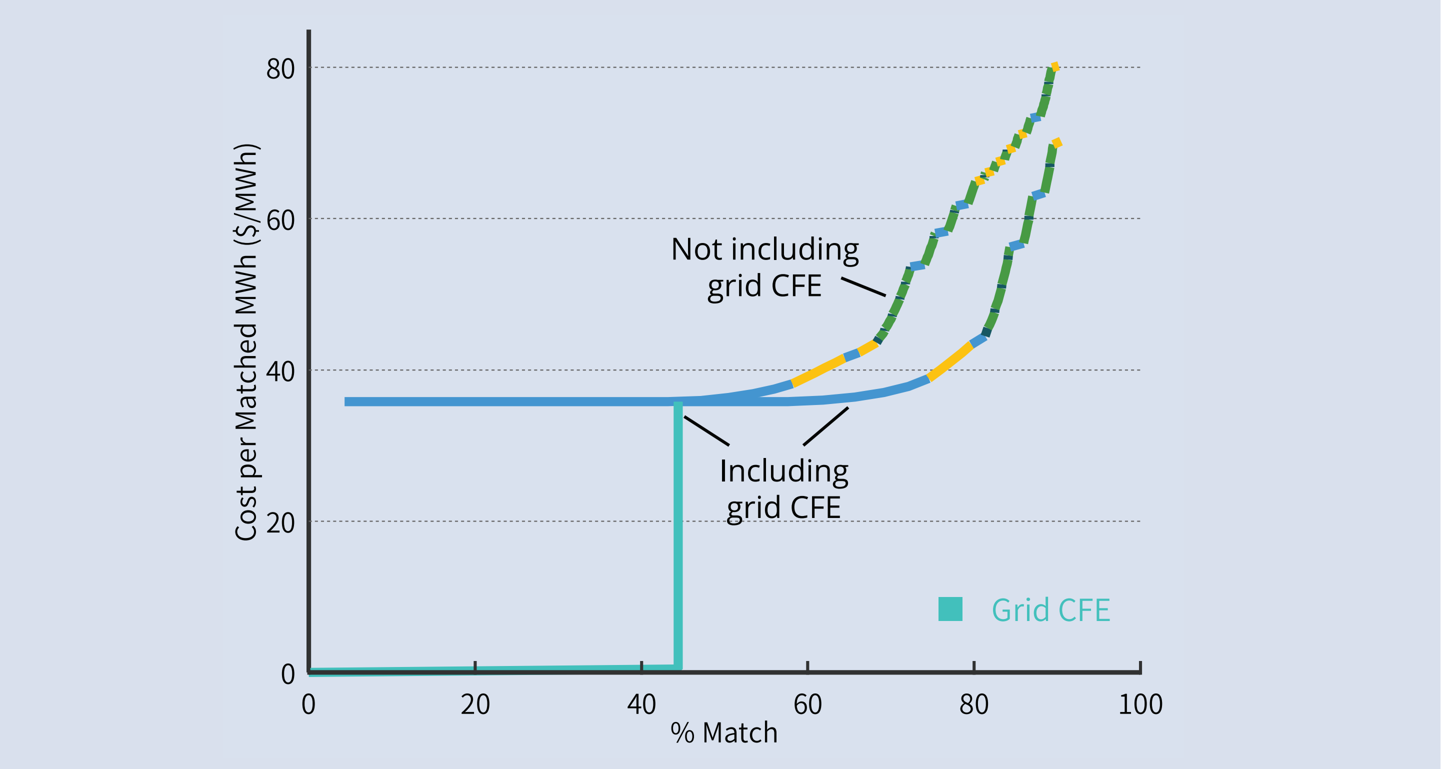
- Procuring storage: a buyer accounting for grid CFE in their procurement strategy will procure battery storage above an ~81% match level, rather than a ~67% match level, due to the more steady output of existing grid CFE and less need to balance wind and solar alone with storage.

In general, including existing CFE in an hourly match metric lowers the cost of achieving a given match level and slightly alters the resources procured to meet a given match level, but does not significantly change the cost structure of achieving higher levels of hourly matching. Thus, the findings presented in this study about the relative costs and procurement order of resources used to meet increasing hourly matching targets are likely robust to the methodology choice of whether to account for existing CFE or not in the definition of matching levels.

This study's modeling choice around inclusion of grid CFE in procurement metrics is not meant to be a recommendation for a specific approach in defining such a metric; rather, the model presented here shows indicative buyer cost outcomes that are consistent with a wide variety of metrics for hourly load matching. As we discuss in the *Implications and Recommendations* section, including grid CFE in an hourly procurement strategy can potentially address some of the cost challenges noted in Finding 1 and emissions impacts noted in Finding 2, and align hourly procurement better with system-level economic and emissions outcomes.

[iii] The metric used here is not directly comparable to that published by Google; see footnote on page 13.

Exhibit 5 **Impact of including existing grid CFE in matching metric for a data center in SPP**

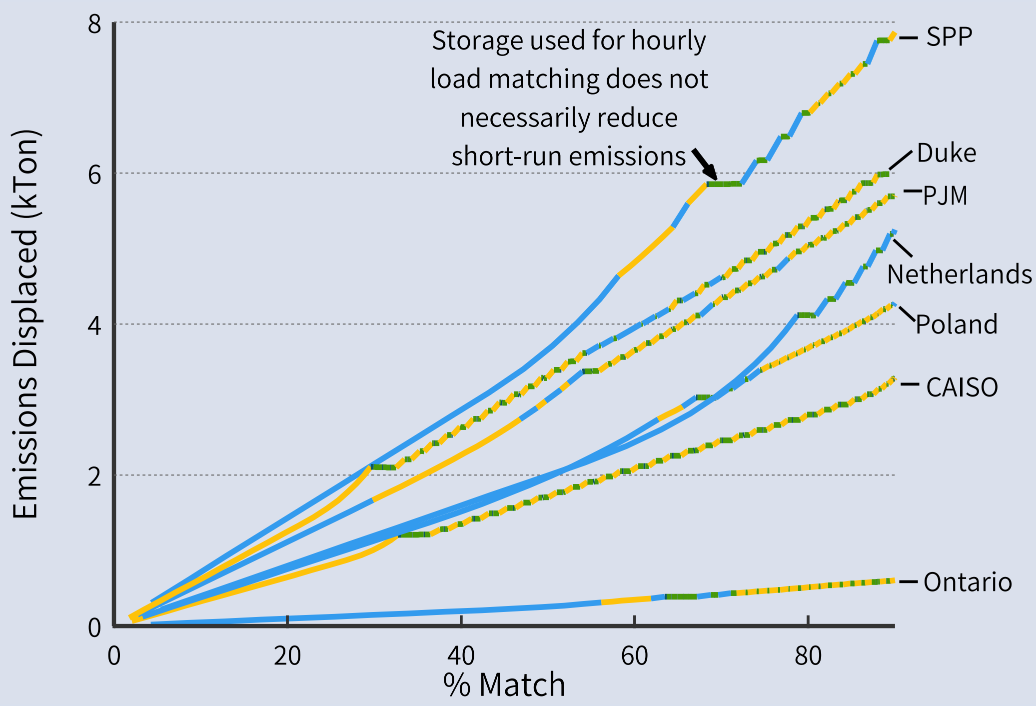


Finding 2: Near-term emissions reductions from hourly load matching depend on the regional grid mix and how storage resources are operated.

In the vast majority of regional power grids where fossil fuels dominate electricity production, any new renewable energy project reduces system-level emissions by displacing fossil generation with renewable generation. Exhibit 6 shows the annual emissions reductions of hourly matching portfolios in the seven modeled regions. We represent the ability for procured wind and solar energy to reduce emissions at the region's marginal emissions rate, regardless of whether the renewable generation contributes to facility load matching or is sold back into the grid and thus offsets fossil generation that would otherwise be used to meet system load.

Thus, as the hourly load matching strategies shown in Exhibit 6 lead to wind or solar procurement in each region above a given buyer's demand, system-level emissions savings increase faster than the level of hourly match achieved. As storage is added to the portfolio in each region to increase the hourly matching share, short-run emissions savings plateau (explained below). This finding results from our approach to modeling storage as being primarily used to increase the level of hourly load matching; below, we discuss options to more-effectively operate storage in response to system-level pricing and carbon signals and maximize its emissions benefits.

Exhibit 6 **Emissions reductions in the modeled regions**



Avoided emissions calculations can be used to prioritize investment both within and across regions to maximize near-term emissions savings. For example, for a buyer operating in multiple regions, avoided emissions estimates can be used to identify which location to invest in first, and prioritize the staging of technology investments in each region to maximize emissions reductions.

Regional differences

The difference in displaced emissions among regions shown in Exhibit 6 can be mostly attributed to the significant differences in the emissions intensity of the marginal resource (i.e., the generator with the most-expensive short-run operating costs) within each market. In the vast majority of global electricity systems, fossil fuel power plants, usually coal- or gas-fired, are “on the margin” and their output is lowered when new renewable generation is added to the system.[iv] Often, when new renewable generation displaces coal (e.g., in SPP, Duke, PJM) the emissions impact is very large. When local grid emissions are already relatively low, the emissions impact is lower (e.g., in Ontario).

The role of energy storage

In Stage 3 of hourly load matching, where energy storage is used to match facility loads with carbon-free energy in hours where renewables are not available, the emissions benefits of using storage for hourly procurement depend on the generation profile of the broader grid and the details of implementation.

[iv] Even in very low-carbon grids (e.g., Ontario as modeled in this study), where hydro, nuclear, wind, and solar plants together can at times cover ~100% of hourly load, other fuel-based resources in the same interconnection are needed at other times of the year to meet load when carbon-free resources are not available. Thus, any increase in wind or solar capacity will generally avoid use of hydroelectric energy in the short term (e.g., over the course of hours), but in the case of hydro systems with significant water storage capacity, that water can be saved behind the dam and avoid use of fossil generation in the medium- to long-term (e.g. days to months). As a result, even in hydro-heavy grids, gas and coal can still be considered “marginal” resources in the medium-term, with emissions that can be offset by additional renewable energy projects.

In general, in grids where fossil fuel is generally on the margin (i.e., nearly all regional grids today), operating storage solely to meet hourly load-matching targets at the facility level does not by itself reduce emissions, and may even increase system-level emissions. This is because fossil plants are on the margin at the system level during both charging and discharging, and batteries' ~10% round-trip efficiency losses and misalignment between facility load and grid needs tend to negate any savings from switching between types of marginal fossil fuel generation.

In Exhibit 6, most regions show a flat emissions impact when storage is first added (as an example, the arrow in Exhibit 6 indicates this flattening in the SPP curve). However, further load matching continues to reduce emissions because battery storage is combined with generation (usually solar) that does displace the marginal (fossil) resource.

While our findings show that storage operated to match procured CFE against a facility's load will not generally reduce emissions in the near term, there remains an important role for storage to play in both buyers' procurement strategies and in longer-term system-level decarbonization:

- **If optimized to maximize system value, batteries can be cost-effective today, reducing the need for new fossil generators and allowing existing fossil generators to retire or run less often.** In many markets, batteries comprise a significant and growing fraction of interconnection queues,[16] demonstrating the business case for both corporates and others to utilize battery storage as a complement to a broader market strategy. Further, new renewable energy projects are increasingly integrating battery storage in "hybrid" power plants, which can directly support the business case for renewables, reduce curtailment, and lead to near-term emissions reductions. The diversity and scale of new storage projects reflects the range of value streams available (e.g., capacity, resilience, ancillary services, energy price arbitrage, transmission cost reduction). However, in order to maximize emissions savings and accelerate the broader grid's decarbonization, storage projects need to be optimized for system-level economic value and emissions savings, not solely to match facility loads.

- **Future cleaner grids can leverage storage to balance renewable generation.** As the grid decarbonizes, numerous studies have illustrated that batteries can play a major role in balancing variable renewable output at the system level.[17] Thus, in addition to providing immediate benefits as noted above, procuring storage in the near term can jumpstart the storage market and demonstrate its viability for system balancing.

To illustrate how storage can directly reduce emissions as the grid decarbonizes, we calculated the emissions impact in PJM in a hypothetical future where marginal system emissions are zero in hours where wind and solar generation are plentiful (and likely curtailed)—but significant otherwise.[v] As shown in Exhibit 7, storage can continue to reduce emissions in this "Stage 3" system. In the upper curve (today's PJM, with a battery project optimized solely to increase hourly matching levels), the "stair-step" emissions curve represents the dynamic of each solar addition directly reducing emissions while battery additions do not. In contrast, we see a smooth emissions reduction in the lower curve (representing a future cleaner PJM with significant curtailment) because the storage, generally charged using otherwise-curtailed renewable energy, tends to shift renewable production from low marginal emission periods to high ones.

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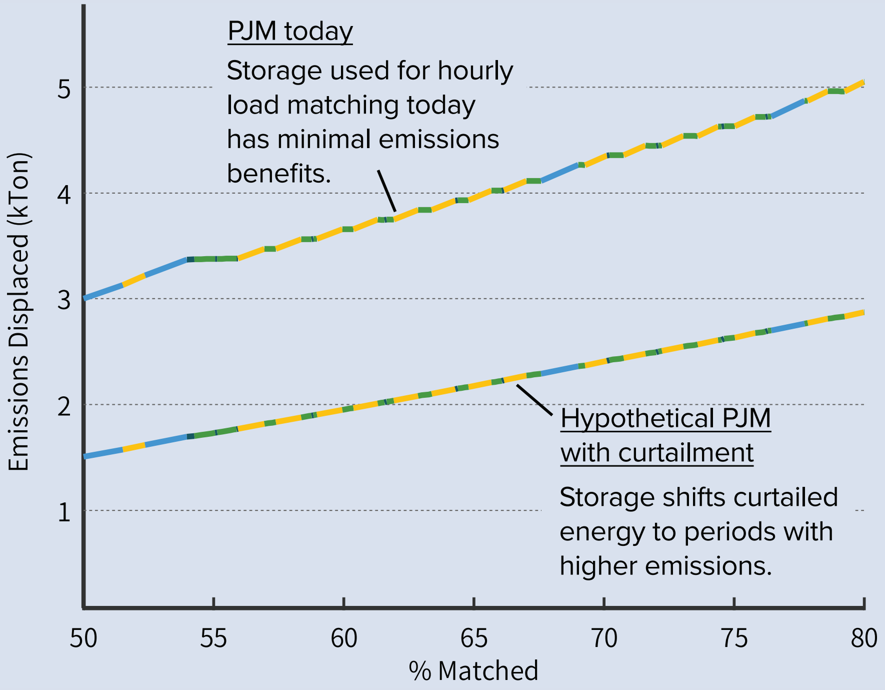
[v] To simulate this future system, we set the marginal emissions value to zero in hours when the sum of regional solar and wind capacity factor in the current system was greater than 0.8, and set to 0.5 tCO_2/MWh (consistent with combined-cycle gas turbine emissions intensity) for the remaining hours. This is consistent with a future cleaner grid that is mostly powered by renewables in hours when they have high capacity factors. However, in low renewable capacity factor hours, gas will be used to provide balancing energy.

Exhibit 7 **Emissions reductions in today's PJM and in a hypothetical, decarbonized PJM system**



Note: Top line represents a battery dispatched solely for hourly load matching. Co-optimization of battery dispatch with system needs can increase near-term emissions benefits.

Storage resources, even in high-emissions grids like PJM today, can also have significant long-term emissions benefits if they are well-integrated into and/or responsive to system-wide economic and market signals. For example, batteries play a critical role in portfolios of clean energy resources that together can avoid construction of new gas plants and accelerate retirement of costly, high-emitting coal plants.[18] Buyers' procured storage resources, properly optimized within the regional power system context, can unlock these market shifts and thus accelerate system-level decarbonization.

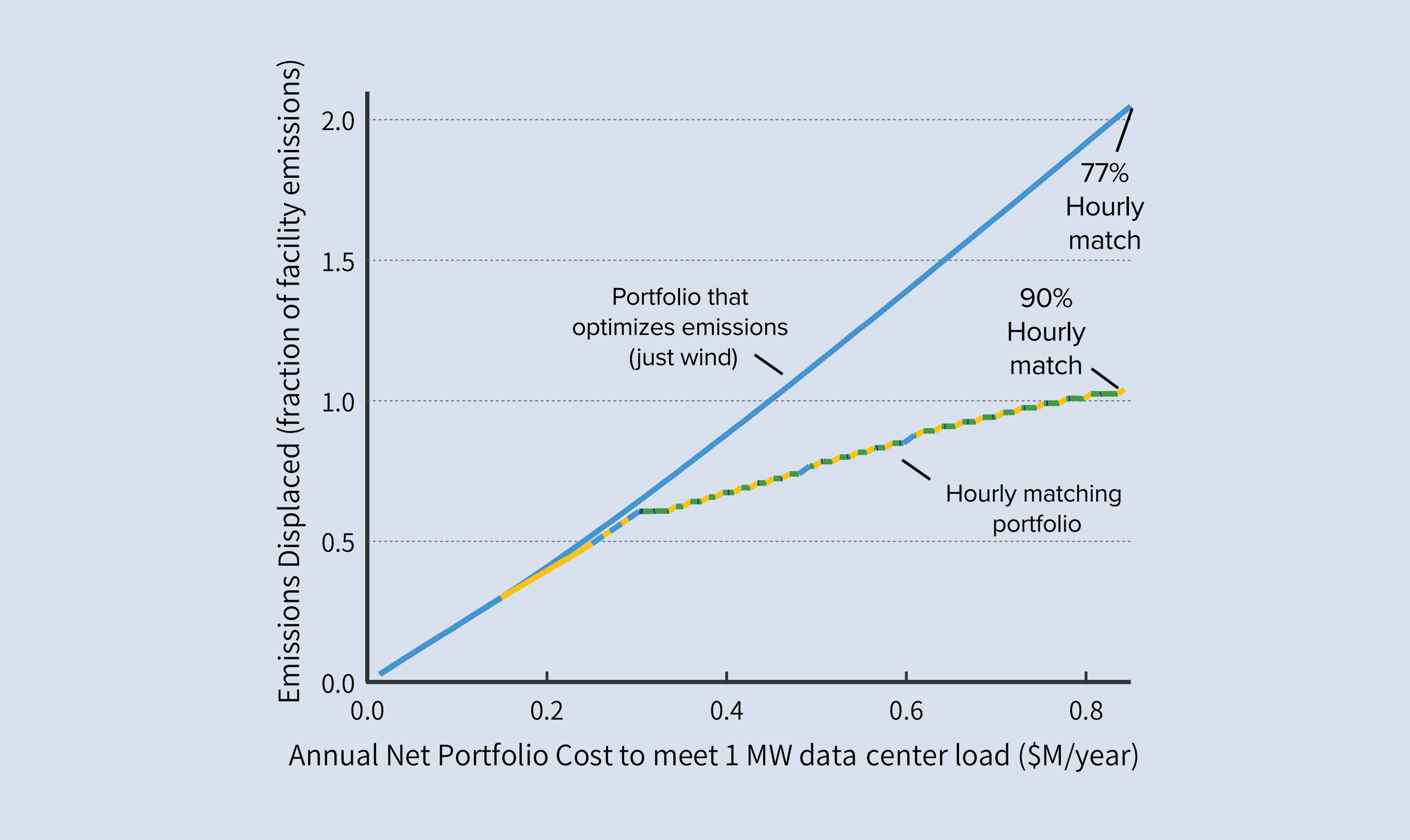
> There is a perceived risk that a move toward hourly procurement strategies would portray current renewable procurement as inadequate, which may discourage corporate involvement in renewable procurement altogether. Transparency of the impacts of different renewable targets is important to ensuring companies and the public are able to understand different options.

Least-cost strategies to maximize near-term emissions reductions

Most regional power grids around the world are dominated by fossil fuel generation. This results in near-term emissions savings enabled by hourly load-matching strategies generally costing much more than equivalent emissions savings from procurement strategies that target the same amount of CFE procurement at an annual level. Exhibit 8 shows the near-term emissions savings as a function of total procurement costs for a portfolio optimized to match the hourly load of a data center in PJM (bottom line), versus the savings from a wind-only portfolio that maximizes near-term emissions savings (top line). In this example, a combination of wind, solar, and storage resources that match 90% of a data center's hourly load offset just over 100% of its emissions, while a wind-only portfolio of equivalent cost doubles the near-term emissions savings.

This analysis omits any explicit modeling of long-run emissions savings or economic aspects associated with a buyer procuring renewable energy alone versus a portfolio that includes storage.[vi] But given the insignificant fraction of wind or solar in PJM currently (i.e., less than 5%[19]), it is unlikely that procurement of additional wind and solar by buyers will lead to market saturation and declining emissions benefits in the near future.

Exhibit 8 **Emissions savings and costs of hourly load matching versus renewables-only procurement**



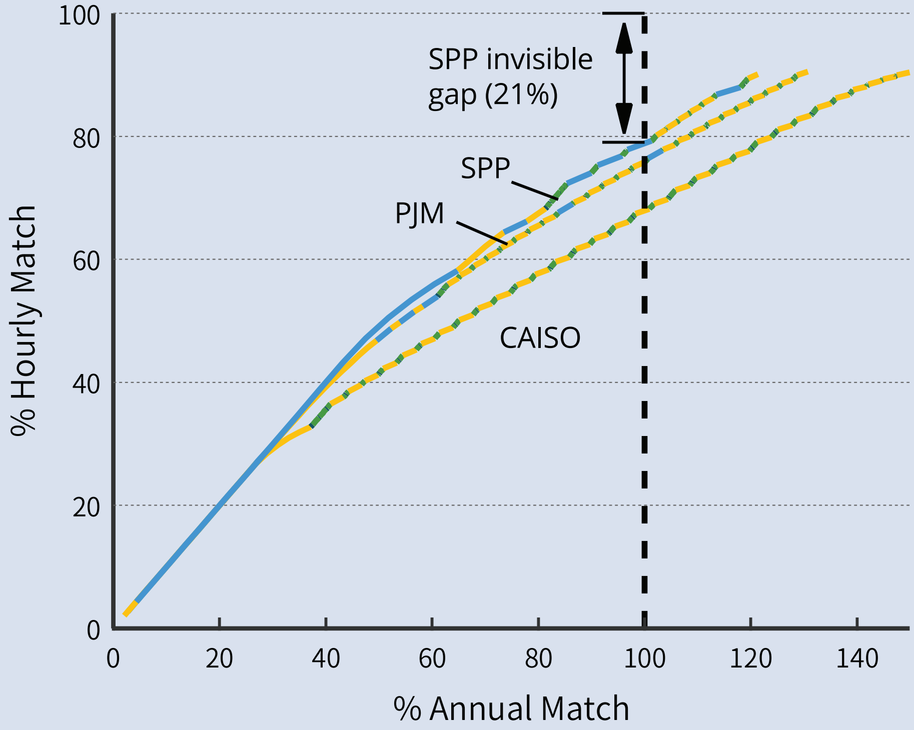
[vi] Exhibit 8 is not meant to represent an assessment of any specific, announced transaction in PJM or elsewhere. In particular, our analysis methodology, as outlined in Exhibit 1, is limited to assessing the role of wind, solar, and storage in meeting hourly procurement goals, and omits modeling the contributions of hydro and other CFE resources that buyers are prioritizing in PJM and other regions.

Finding 3: Hourly procurement strategies can create demand for emerging technologies needed to fully decarbonize the grid.

As discussed above and depicted in Exhibit 9 for three US regions, procuring energy to offset 100% of annual load with carbon-free energy results in only ~65%–80% of hourly load being matched by procured resources.[vii] An "invisible gap" remains for buyers that both reinforces reliance on fossil generation and limits the hedge value of the supply portfolio. A region with a larger "invisible gap" means that the renewables procured in the region do not match load as well as in other regions, because of differences in hourly patterns of resource availability.

Buyers seeking to close this gap between procured resources and facility load will face increasing costs. While readily available wind and solar technologies can meet up to 30%–60% (depending on the market) of hourly facility loads at stable costs, the costs increase rapidly in Stage 2 and 3 of procurement. We highlight the cost increases in Exhibit 10, which shows the marginal cost for each additional increment of matching a data center's load in PJM.[viii]

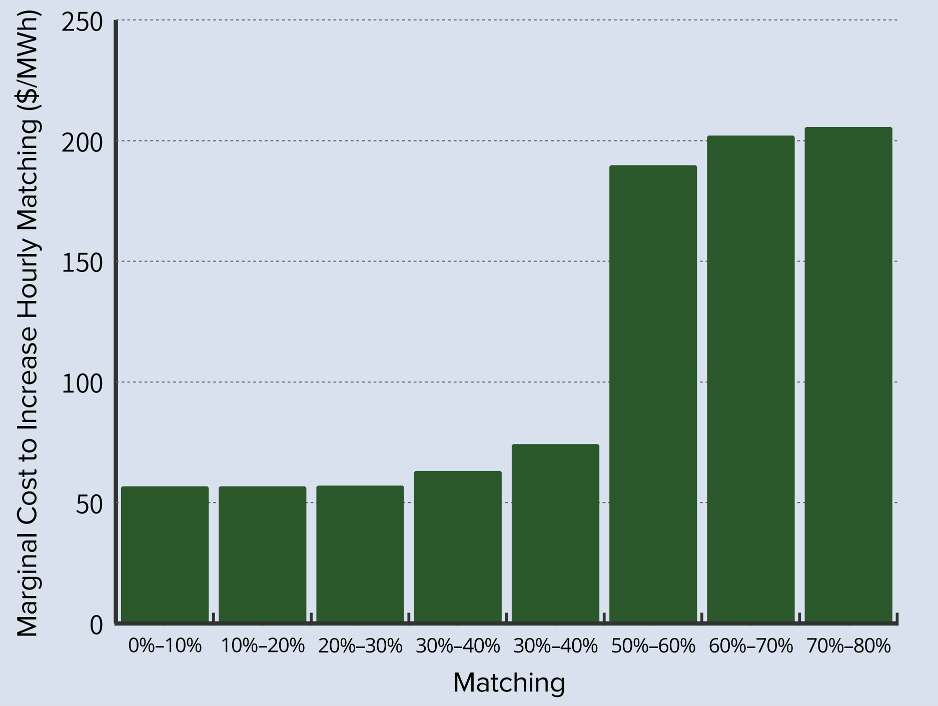
Exhibit 9 **"Invisible gap" between hourly and annual carbon-free energy procurement**



[vii] Assuming a buyer also procures storage using the optimization approach in this study; procuring only renewables would result in lower hourly load matching levels at 100% annual offset levels.

[viii] Exhibit 10 shows the average of marginal costs to increase hourly load matching at 10% intervals. The marginal cost for each potential addition of resources within those intervals varies, due to alternating solar and storage additions that are, together, least-cost to meet higher levels of matching. By showing average marginal costs, the figure better approximates the cost to add generation and storage together.

Exhibit 10 **Marginal costs to increase level of hourly load matching for data center in PJM**



Utilities may have a broader resource profile to offer hourly products to interested buyers than independent power producers. Green tariff programs are already available in regulated markets and some utilities are offering bespoke products. Retailers are in a unique position to innovate and are already offering evolved products, for example solar and wind blends to help with shape risk.

Exhibit 10 illustrates the cost impacts associated with adding and operating large batteries to achieve hourly load matching levels higher than 50% since their full capacity is used only a few times a year. At incremental costs of >$100/MWh for achieving these high levels of hourly load matching, there are a number of pre-commercial technologies that could play a valuable role in meeting hourly demand cost-effectively. There are several possible options:

- **Long-duration storage** with chemistries unique from Li-ion that decouple power output and energy storage. These can be designed to more cost-effectively bridge long periods of low wind and solar output.

- **Flexible, zero-carbon generation** that can meet peak demands and balance the variability of wind and solar with controllable generation. Candidate technologies include reservoir hydro and biomass and/or hydrogen burned in gas turbines; even with high marginal operating costs and/or limited energy availability, these resources can cost-effectively play a balancing role for low-marginal cost renewable generation.

- **High capacity-factor, zero-carbon generation** that can produce near-constant power appropriate for flat load profiles (e.g., data centers). For example, firms developing geothermal technologies and new gas generation technologies with carbon capture and storage are aiming to achieve prices between $50/MWh and $100/MWh, or potentially lower at scale. Run-of-river hydro is also a candidate for this application.

Energy technology start-ups that do not yet have economies of scale stand to benefit from corporate procurements to enable scaled deployment. Corporate procurement of these currently more-expensive technologies can spur cost reductions that benefit all customers as the grid decarbonizes.

Depending on the evolution of these and other technologies (including already commercialized technologies such as demand flexibility that can shift buyers' loads in response to grid emissions and prices[20]), they may either complement or offset wind and solar in least-cost strategies for hourly procurement and meeting broader grid needs. By setting hourly procurement targets and timelines, buyers can send a demand signal for developers of such technologies to deliver market-appropriate projects, and best meet the needs of buyers and the grid as a whole in different regional markets.

Implications and Recommendations

Overall, our analysis and interviews with industry participants and other experts support the broad finding that well-executed hourly procurement strategies can both reduce near-term carbon emissions and lay the groundwork for a grid that can meet all customer demand with zero-carbon energy. Our findings and interviews inform a set of recommendations for buyers, policymakers, and other industry participants to maximize the impact of this emerging procurement model.

1. Match hourly procurement strategies to grid dynamics.

The electricity grid is a shared system, and corporate procurements cause ripple effects that affect more than just their own load and supply. Therefore, buyers should account for the regional grid dynamics to maximize near- and long-term emissions savings. Exhibit 11 summarizes the implications of hourly load matching in regions with different stages of decarbonization.

> "Value stacking" of the grid benefits of storage can help justify investment and provide a business case for storage resources that can also support hourly procurement strategies. Relevant value streams include transmission or distribution upgrade avoidance, demand charge reduction, arbitrage, ancillary services, generation capacity, and reduced curtailment.

Overall, our findings suggest that buyers can cost-effectively maximize the emissions benefits of procurement in fossil fuel-dominated, low-CFE grids by prioritizing renewables in the near term. Buyers should also consider adding storage to their portfolios where a regional grid has a high and/or increasing level of CFE or where storage can provide other near-term economic values (e.g., capacity, ancillary services). They should additionally consider storage where it can contribute to a portfolio of clean energy resources that together can directly

Exhibit 11 **Summary of procurement implications for buyers in regions at different stages of grid decarbonization**

	Grid characterization		
	Phase 1: Fossil-dominated	**Phase 2: Some renewable curtailment**	**Phase 3: High renewables, significant curtailment**
Examples	PJM today	Parts of SPP today	CAISO in 5+ years
Buyers' wind or solar projects...	Always offset fossil generation and reduce CO_2 emissions	Are sometimes curtailed	Provide limited emissions reductions by themselves
Buyers' storage resources...	Can reduce emissions if optimized for system needs, but tend to increase emissions if used solely to shape facility load to match procured renewables.	Can reduce renewable curtailment, reduce emissions, and add grid value (e.g., capacity) that accelerates decarbonization.	Provide significant system-level value and emissions reductions if optimized for system needs.

lead to coal retirement or avoid new fossil generator construction. Buyers should consider the following elements in setting and executing against hourly procurement targets in different regional grids:

- **Granular data:** Hourly grid data, facility load data, and analytics to assess the system context of hourly procurement strategies are increasingly sophisticated and widely available; buyers can use this information to prioritize strategies that maximize near- and long-term emissions benefits.
- **Fossil intensity:** Marginal generation in most power grids is currently dominated by coal and gas. Timing of when different fuels are on the margin, and anticipated changes over time, dictate how near-term procurement decisions will reduce total system emissions. Buyers should account for the relative fossil intensity across hours at a regional, system-wide level, so that CFE procurement can be targeted to hours where the grid overall is most polluting.
- **The impacts of storage:** Storage is starting to play a valuable role in decarbonizing grids, and buyers' storage procurement can accelerate this trend. To maximize climate benefits, storage should be dispatched based on system-level economic and emissions signals, not used to balance facility loads against procured CFE. Operating storage in response to system-level signals can both reduce emissions (since hourly emissions intensity and price will be increasingly correlated as the grid decarbonizes) and increase the system value for further wind and solar deployment.[21]

The lack of transparent data about the composition of grid power in a given hour is a barrier to achieving effective hourly procurement strategies. The timing of procured generation and the state of grid emissions need to be tracked and made transparent to buyers to allow accounting for hourly procurement and maximize its potential benefits.

2. Expand wholesale market access to scale the benefits of hourly procurement strategies.

Wholesale energy markets provide the most natural venue for matching carbon-free generation with grid needs. To scale the potential benefits of hourly procurement strategies, policymakers, regulators, buyers, and other stakeholders who can influence wholesale electricity market design should prioritize:

- **Reforming wholesale market design to directly incorporate clean energy goals:** The growth of renewable energy to date and its expected future growth, driven in part by corporate procurement and state policy targets, has led to a variety of issues with current electricity market design paradigms in the United States and globally.[22] To address these issues and enable markets to accommodate policy goals, market designers have proposed reforms that would explicitly integrate policy- or buyer-driven clean energy goals with reliability planning mechanisms (e.g., capacity markets).

  For example, PJM and ISO-NE are considering a "Integrated Clean Capacity Market" concept introduced by the Brattle Group that simultaneously cost-optimizes clean energy and capacity procurement. In this or similar market designs, corporations could efficiently add their clean energy buying power to those of states and utilities. As clean energy purchases grew, these reformed markets could efficiently incent storage and the "clean firm" generation needed for 100% hourly CFE at the system level.

- **Expanding buyers' access to wholesale electricity markets:** Hourly load matching performed by a corporate "out of market" risks creating unpredictable impacts on the grid, because system-level grid needs are different than those of individual facilities. Providing buyers direct access to resources through reformed organized markets can enable hourly procurement strategies to integrate with system-level price signals and emissions savings opportunities, while maximizing both economic benefit and grid decarbonization.

3. Balance hourly procurement goals against the science-based imperative to reduce emissions as fast as possible in the near term.

To avoid the worst impacts of climate change, the world must reduce emissions ~50% by 2030,[23] and offsetting fossil fuel used to generate electricity is one of the best near-term opportunities to do so. Achieving climate stability will require terawatt-scale CFE deployment over the next decade in the United States and other global markets.[24]

Corporate procurement as it commonly exists today (i.e., against annual targets) can continue to play a major role supporting CFE deployment. Buyers who have not yet offset 100% of their annual electricity use with procured CFE can feel confident that doing so based on annual targets in regions with low renewable energy adoption will continue to create material climate benefits, even as buyers who have already met that goal continue to push the envelope of sophistication and pave the way toward a 100% CFE grid. These leading buyers can play an important role in laying the groundwork for a decarbonized grid by:

- **Incentivizing new technology development:** Setting targets and timelines for hourly procurement strategies can send a signal to developers of pre-commercial technologies that can provide valuable services as regional grids decarbonize. Hourly procurement strategies can provide a structure within which to assess the value of and incentivize these technologies.

- **Defining standards for emerging procurement models:** There remain important design questions regarding how to define, execute, and assess hourly procurement strategies to both maximize their near-term emissions benefits and accelerate full, system-wide decarbonization (e.g., treatment of existing carbon-free energy within regional grids; average versus marginal emissions estimates and accounting). Leading buyers can test and refine accounting, contracting, and validation approaches that pave the way for other buyers to follow, enabling deeper emissions savings for more customers.

It has taken a long time for corporate buyers to shift from unbundled renewable energy credits to renewable projects with additionality; changing procurement norms will take time. Larger companies can demonstrate demand and help create platforms for hourly procurement that enable both near-term emissions reductions and pave the way for broader grid decarbonization. This can enable more companies to participate without creating deal structures and program details from scratch.

Even as corporate buyers recognize and celebrate their successes over the past decade in driving grid decarbonization, the challenges of the next decade loom large. Leading corporations increasingly recognize science-based targets that call for both maximizing near-term emissions reductions, in order to limit the cumulative carbon emissions that drive climate change, and reaching net-zero emissions by mid-century to avoid further warming.

To meet these goals, buyers and the electricity industry at large need to accelerate the pace of carbon-free energy deployment, while grappling with the challenges of balancing generation against load in the renewables-dominated grids that such deployment will create. Alignment and standardization around procurement strategies that support both of these goals can enable a future grid that delivers carbon-free energy cost-effectively to all customers, not just those who take the first steps.

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