Highlights

System-level Impacts of Voluntary Carbon-free Electricity Procurement Strategies

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- Analysis of the system-level, consequential impacts of voluntary carbon-free electricity procurements.
- In the current U.S. policy environment, matching a consumer's demand on an annual basis with new, locally-generated carbon-free electricity has zero or nearly zero long-run impact on system-level carbon emissions.
- Strategies that aim to eliminate a consumer's emissions impact based on short-run marginal emissions accounting are similarly ineffective.
- Matching a consumer's demand hour-by-hour with new, locally-generated carbon free electricity significantly reduces system-level carbon emissions, but does so at a cost premium.
- Hourly temporal matching increases early uptake of advanced clean energy technologies.

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Abstract

This study enhances a capacity expansion planning model to study the system-level impacts of carbon-free electricity procurement by voluntary actors in the western United States, accounting for changes in both system operations and installed capacity. We assess multiple proposed strategies for voluntary procurement of new, locally generated carbon-free electricity, including those that match a participating consumer's demand with carbon-free generation on an annual basis ("volumetric matching"), on an hourly basis ("temporal matching"), or aim to eliminate a consumer's emissions impact as measured via short-run marginal emissions accounting ("emissions matching"). We find that in the current U.S. policy environment, voluntary carbon-free electricity procurements made under volumetric or emissions matching strategies have zero or near-zero long-run impact on system-level CO_2 emissions. Carbon-free electricity procurements made under these strategies reduce deployment of similar carbon-free resources by independent developers, but have little impact on fossil-fired generation. By contrast, temporal matching drives significant reductions in system-level CO_2 emissions by requiring generation of carbon-free electricity even in hours when fossil-based resources would normally be preferred. Temporal matching also incentivizes procurement of advanced clean firm generation and long-duration storage technologies that would not otherwise see market uptake. Electricity cost premiums for voluntary participants are near-zero under volumetric and emissions matching strategies and can exceed $20/MWh under temporal matching, but are reduced when a larger portfolio of advanced technologies is available for procurement. These outcomes are sensitive to changes in policy: while volumetric matching has near-zero impact under current federal and state policies, it is the most cost-effective means of incremental CO_2 mitigation in a scenario with a binding system-wide clean electricity standard, although total emissions reductions remain modest.

Keywords: Macro-energy systems, electricity, climate mitigation, voluntary clean energy procurement, carbon-free electricity, renewable energy

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1. Introduction

While declining technology costs and increasingly ambitious government policies are major ongoing drivers of carbon-free electricity growth and electricity system decarbonization (Millstein et al., 2021; Steinberg et al., 2023), individual electricity consumers may wish to accelerate the decarbonization of their own electricity supply beyond the pace that would be achieved by markets or government policies alone. Voluntary procurements of carbon-free electricity, either through dedicated markets or via direct contracts with generators, are the primary means by which corporations, universities, municipalities, and individuals have historically sought to accomplish this goal. Such procurements can not only allow the consumer to claim a lower carbon footprint themselves, but could also help to accelerate the decarbonization of the broader electricity sector by driving clean energy technologies down "experience curves"(U.S. Energy Information Administration, 2020a) that reduce their future costs and encourage adoption by other consumers. The aggregate demand for carbon-free electricity from voluntary actors has been historically significant: in 2021, large energy buyers in the U.S. procured 11 gigawatts of new renewable energy, representing about one third of all renewable energy capacity additions in the United States (Clean Energy Buyers Association, 2022; U.S. Energy Information Administration, 2021c).

Current international standards for emissions accounting enable corporations and institutions to claim complete decarbonization of their own electricity supply if they voluntarily procure enough carbon-free electricity to match their total annual electricity consumption on a volumetric basis, either via direct power purchase agreements (PPAs) or through purchases of "unbundled" energy attribute certificates (EACs) that track environmental attributes separately from delivered energy (Mary Sotos, 2015). While this annually-matched volumetric procurement approach has underpinned the vast majority of voluntary clean electricity purchases to date, it has also been criticized in the academic literature and by some clean electricity buyers as inadequately accounting for the true carbon impacts of an actor's electricity consumption and procurement. Although an actor may claim to run on 100% renewable electricity using a volumetric matching strategy, the variable wind and solar generation that it purchases is unlikely to align with the timing of its electricity consumption. During times when the wind is not strong or the sun does not shine, voluntary buyers are still physically reliant on carbon-emitting power plants such as coal or gas-fired generators (de Chalendar and Benson, 2019). The ability of a company or institution's volumetric clean electricity purchases to displace an equivalent amount of carbon emissions from fossil plants is thus critical to the credibility of its carbon-free electricity use claims, and yet such displacements are not validated in any way under current accounting standards. Compounding this issue, past studies of voluntary carbon-free electricity attribute markets have concluded that volumetric purchases of unbundled EACs not tied to long-term electricity purchases drive little if any additional clean electricity generation beyond what would have otherwise occurred (Bjørn et al., 2021; Gillenwater et al., 2014; Brander et al., 2018; Mulder and Zomer, 2016).

Perceived flaws in volumetric matching standards have led some clean energy buyers to pursue alternative procurement strategies. One approach that has gained recent popularity is to match a buyer's electricity demand, hour-by-hour, with corresponding clean electricity generation from within the same electricity grid region as the buyer's operations. This is sometimes called "24/7 carbon-free electricity" procurement (Google, 2022) and is referred to in this paper as "temporal matching." Supporters of temporal matching argue that it eliminates the impact uncertainties of volumetric matching by ensuring that a buyer can claim use of carbon-free electricity only when the generation and consumption of that electricity are physically and temporally linked. Additionally, because it approximately replicates the end state of a fully decarbonized electricity system on a smaller scale, proponents argue that this procurement strategy could act as an important early demand pull for the nascent long-duration storage and clean firm power technologies that are seen as critical for cost-effective complete decarbonization of power systems (Sepulveda et al., 2018, 2021; California Energy Commission, 2021).

A growing number of organizations, from individual load-serving entities to large corporate buyers like Google and Microsoft to the U.S. Federal Government, have announced plans to procure carbon-free electricity matched as closely as possible in time with their electricity consumption (Pepper et al., 2023; Google, 2022; Microsoft, 2020; U.S. General Services Administration, 2022). In September 2021, the 24/7 Carbon-free Energy Compact was launched by Sustainable Energy for All and UN-Energy to help others to achieve this goal. It has now been signed by over 60 companies, governments, and organizations (United Nations, 2021). U.S. President Joseph R. Biden also issued an executive order on December 8, 2021 requiring federal agencies to procure 100% carbon free electricity by 2030, with half of this procurement matched hourly with consumption (U.S. Federal Government, 2021).

A second proposed alternative to volumetric procurement eschews energy-based matching entirely and instead focuses on using marginal emissions rates with high temporal and spatial granularity to directly measure the emissions impacts of both an actor's electricity consumption and a portfolio of contracted generators (Oates, 2022; WattTime, 2022). This strategy is referred to in this paper as "emissions matching." Proposals for emissions matching systems generally measure the impacts of a participant's consumption and procurement via *short-run* marginal emissions rates (SRMERs), which are designed to estimate the instantaneous impact of a change in electricity demand in a given time and place on system-level CO_2 emissions, as certain marginal generators in the system ramp their power output up or down in response to these changes in demand. This SRMER metric implicitly assumes fixed generation and storage capacity and thus ignores the emissions impact associated with generation capacity deployment or retirement decisions that might result from changes in demand (sometimes referred to as 'long-run' marginal emissions impacts). Under an emissions matching framework, consumption of electricity is penalized based on the SRMER in the time and place in which it occurs, and procured carbon-free electricity is assumed to offset emissions based on the SRMER in the time and place in which it is generated. A company could therefore claim net-zero emissions under an emissions matching framework by procuring smaller amounts of carbon-free electricity generated in times or places with high SRMERs, or by procuring larger amounts generated in times or places with low SRMERs. Proponents argue that the flexibility offered by this framework can enable credible emissions offsets at minimal cost. A number of large corporate clean energy buyers, including Amazon, Meta, Salesforce, and General Motors, have announced aims to pursue an emissions matching procurement strategy (Emissions First Partnership, 2023).

Figure 1 illustrates the different accounting approaches that would be used under volumetric, temporal, and emissions matching voluntary procurement frameworks to assess identical stylized electricity consumption and procurement profiles over a four-hour period. Under volumetric accounting, consumption of electricity in excess of procured carbon-free generation in some hours may be counterbalanced by excess procurement of carbon-free generation in other hours, allowing the participant to claim 100% carbon-free electricity use over this particular four-hour period. Under temporal accounting, the excess generation in some hours is *not* allowed to offset shortfalls in others, and so the participant can only claim 75% carbon-free electricity use over this same period. Finally, an emissions matching strategy separately measures the emissions incurred and offset by the participant's electricity consumption and procurement by multiplying the amount of electricity consumed/procured with the local SRMER (we assume here for simplicity that supply and demand are exposed to the same SRMER, although this need not be the case). Because the SRMER is lower during hours of excess clean generation and higher during hours of shortfall, the participant is not considered to have fully offset its emissions impact in this four-hour period under this emissions matching framework.

Despite the large and increasing volume of voluntary carbon-free electricity purchases and the emergence of multiple competing procurement strategies, there is to the best of our knowledge no study in the literature demonstrating the system-level impacts of any of the three strategies discussed above, accounting for changes in both system operations and installed capacity. While a recent analysis by He et al. (2021) did evaluate and compare all three strategies, finding that emissions matching was the most cost effective in terms of CO_2 abatement, that study's methodology calculated emissions outcomes based on fixed SRMER time-series and did not capture the interactions between voluntary carbon-free electricity procurement and the operational and investment decisions made by other electricity market participants. In the present study, we use a system-level modeling approach that does capture these interactions to address key open questions, including:

- What are the cost-optimal technology portfolios for voluntary buyers pursuing volumetric, temporal, or emissions matching strategies, and how do voluntary carbon-free electricity procurements made under each strategy change the overall generation mix in the electricity system?

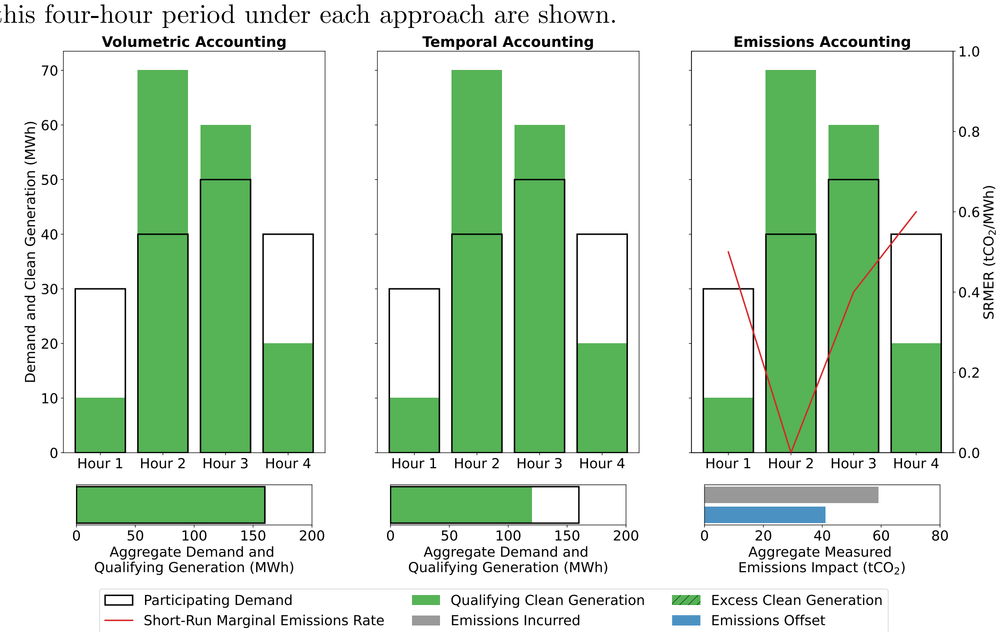
- What are the system-level emissions impacts of carbon-free electricity procurements made under each of the three matching strategies, and how credible are the emissions mitigation claims made under their respective accounting frameworks?

- How do different voluntary procurement strategies compare in terms of overall cost for the buyer and cost per ton of CO_2 abated at the system level?

- How do the impacts of voluntary procurements change as the number of participating customers increases?

- What is the impact of government policy on the efficacy of voluntary carbon-free electricity procurements?

Figure 1: Stylized illustration of accounting approaches used under volumetric (left), temporal (center), and emissions (right) matching strategies for voluntary carbon-free electricity procurement. Details for four representative hours and aggregate accounting over this four-hour period under each approach are shown.



Herein we use macro-scale energy systems modeling to provide novel answers to these key questions. Specifically, we enhance an existing electricity system capacity expansion planning model to study system-level impacts of a share of commercial and industrial (C&I) electricity consumers participating in voluntary carbon-free electricity procurement using volumetric, temporal, or emissions matching strategies. We assess outcomes under each respective strategy for C&I consumers located in California and the U.S. Mountain West, and our method can be easily generalized to analyse the system-level impacts of these three procurement strategies in other contexts. This paper updates a prior public facing technical report (Xu et al., 2021) focused on volumetric and temporal matching with the latest data and updated modeling features and extends the work to assess emissions matching strategies.

In the following sections, we begin by describing the analytical approach used to model the three voluntary procurement strategies. We then present the simulated numerical results, e.g. system-level impacts on technology deployments and emissions, and cost to the participants. These results provide quantitative answers to the key questions posed above. Finally, a discussion section concludes this study, highlighting key insights and policy implications.

1.1. Approach

In this section, we briefly describe the analytical approach and experimental design of this paper. The mathematical formulation and a detailed discussion of data assumptions and sources are available in the supplementary information (SI). The open-source model code and all underlying data are available in the associated repository.

1.1.1. Modeling Voluntary Carbon-Free Electricity Procurement in a Capacity Expansion Planning Model

In this study, we enhanced GenX (MIT Energy Initiative and Princeton University ZERO lab, 2022), an open-source, highly-configurable electricity system planning model with detailed operational constraints, by introducing several new sets of constraints to model voluntary carbon-free electricity procurement under volumetric, temporal, or emissions matching strategies. Like other optimization-based electricity system capacity expansion models, e.g., (Brown et al., 2018; Johnston et al., 2019; Electric Power Research Institute, 2021; National Renewable Energy Laboratory, 2022), GenX's objective is to minimize the system-wide cost of meeting electricity demand in a future planning year subject to a variety of engineering, economics, and policy-related constraints. The model thereby simulates outcomes that would be observed under a well-functioning competitive electricity market or in an optimal centrally-planned system subject to the same constraints. Decisions optimized by GenX include siting, capacity sizing, and retirement of generation, storage, and inter-regional transmission lines, as well as hourly commitment, dispatch and power flow decisions within the planning year. The default constraints considered in GenX include hourly operating limits, unit commitment for thermal units, siting constraints, state policies such as renewable portfolio standards, clean energy standards and technology-specific mandates, inter-regional transmission power flow limits, and resource adequacy requirements (e.g., a capacity reserve margin). As a capacity planning model, GenX is well suited to assessing the system-level impacts of electricity system interventions such as voluntary procurements over long timescales, including impacts on resource deployment and retirement decisions that would be ignored by models focusing only on optimal dispatch in electricity systems with fixed capacities (Foley et al., 2010; Ringkjøb et al., 2018).

For all three voluntary carbon-free electricity procurement strategies, GenX optimizes investments in portfolios of carbon-free generation and storage capacity by participating C&I consumers in order to meet the requirements of the chosen strategy in the model's planning year. We model participating consumers as procuring capacity from these resources and subsequently optimizing their operation to meet goals under the relevant procurement strategy. For all three strategies, we place certain common constraints on the carbon-free resources that may qualify for procurement, namely that they are located in the same model zone as the participating C&I load that they are procured to serve, and that they had not already been built at the beginning of the model planning period. The 'local procurement' requirement, while not explicitly called for under some of the three procurement strategies (emissions matching proposals notably highlight the benefits of procuring clean electricity in high-emissions markets far from the point of demand (He et al., 2021)), helps to simplify the experimental setup while maintaining conditions that are readily comparable across all three strategies. The 'new resources' requirement prevents voluntary market participants from procuring clean power that is by definition non-additional, i.e. power that would have been generated regardless, and whose procurement therefore has no impact on system-level emissions. It should be noted that power from an existing carbon-free resource could technically meet the definition of additionality if that resource had been saved from retirement by revenue from voluntary procurement, though we ignore this case here for simplicity. The following paragraphs discuss how each of the three voluntary matching constraints is implemented in the present study.

To model a **volumetric matching** strategy, we add constraints using GenX's existing energy share requirement policy module which ensure that the total annual generation from qualifying carbon-free resources procured by participating C&I customers is no less than the total annual electricity consumption by those customers. Where there are other policy-based energy share requirements in place, e.g. a state renewable portfolio standard (RPS), we allow a percentage of the carbon-free generation used by the C&I consumer to meet their voluntary matching commitment to also count towards their legal requirement. This means that for a C&I consumer pursuing 100% volumetric matching in California, which has a 60% RPS, the customer may count 60% of their procured renewable electricity toward the state requirement but must retire the credits for the remaining 40% themselves. This ensures that when higher levels of voluntary participation are combined with more ambitious clean energy policies, overall carbon-free electricity procurement requirements do not add up to more than 100% of total electricity demand.

Modeling a **temporal matching** strategy requires the addition of novel constraints to GenX. The first of these is an hourly matching constraint, which measures the carbon-free electricity consumption by participating C&I customers in each hour:

demand of the participants (as modified by storage and demand flexibility) = *generation* from procured carbon-free resources − *excess* carbon-free electricity + *grid supply*.

Excess will occur if the generation from the procured carbon-free resources exceeds the demand of the participants in a given hour. On the other hand, grid supplied electricity will fill the gap if the procured carbon-free electricity is less than the demand.[1] Participants can procure and operate storage

[1]These two situations will not happen together in the model. That is, under mild conditions, if the model is solved to optimal with a basic solution, excess and grid supply will not simultaneously be non-zero. The proof is trivial by contradiction. If a basic optimum includes an hour with both excess and grid supply being non-zero, the same

capacities or delay/advance available flexible demand to reshape the electricity demand profile closer to the procured carbon-free electricity profiles (i.e., modify the left-hand side of the hourly matching constraint).

The second temporal matching constraint is the excess limit constraint. Suppose the participants have an excess limit of X, expressed as a percentage of the annual demand of participating customers. The excess limit constraint states:

$$\text{Annual sum of hourly } \textit{excess} \leq X\% \text{ of annual } \textit{demand} \text{ of participants (including storage losses).}$$

Procuring carbon-free electricity in excess of participating customers' hourly demand creates spillover effects, because procured carbon-free electricity meets the demand of non-participants during these periods. These can have ambiguous consequences on long-run capacity additions/retirements, and may dilute the impact of temporally-matched procurement on the deployment of clean firm resources. Reliance on large-volume sales of excess clean electricity on markets may also introduce additional basis risk for participants, increasing realized costs (Pepper et al., 2023). Participating customers will likely therefore wish to limit excess hourly carbon-free electricity, and this constraint captures such a limit on the annual sum of excess hourly carbon-free electricity supply. Since storage can be used to modify participants' electricity demand profile, the storage losses need to be accounted for in the annual total demand.

Overall, we define *consumed carbon-free electricity* at each hour as:

$$\textit{consumed carbon-free electricity} = \textit{generation} \text{ from procured carbon-free resources} - \textit{excess}.$$

By definition, the excess is the clean generation from procured capacity that cannot be consumed by participants, and thus is not counted as consumed carbon-free electricity. This definition of consumed carbon-free electricity is incorporated into a final constraint representing the temporal matching target, which requires that the total annual consumed carbon-free electricity be no less than a certain percentage of the total annual participating C&I demand:

objective can be achieved by decreasing one variable to zero, and decrease the other one with the same amount. The size of non-zero variable set is reduced by one via this action, implying the original solution is not basic, forming a contradiction.

$Y\%$ of Annual *demand* of participants (including storage losses) $\leq$ annual sum of hourly *consumed carbon-free electricity.*

Finally, we model an **emissions matching** strategy using a novel set of short-run marginal emissions accounting constraints. We define the *marginal emissions impact* of a participant's consumption and carbon-free electricity procurements at each hour as:

marginal emissions impact = [*demand* of the participants (as modified by storage and demand flexibility) - *generation* from procured carbon-free resources] $\times$ *SRMER.*

In this case, the marginal emissions impact in a given hour can be positive or negative depending on the balance of demand and procured carbon-free supply in that hour, and its magnitude will depend on the SRMER for the local grid zone in that hour. A 100% emissions matching constraint requires that the sum of hourly marginal emissions impacts over the course of a year be less than or equal to zero, i.e. that the consumer has a net-zero emissions impact under the SRMER accounting framework.

In implementing these constraints, we note that the SRMER cannot be calculated and endogenously optimized against in a linear capacity expansion model, as this would introduce nonconvexity. For this reason we adopt an iterative process to calculate hourly SRMERs, optimize the operations and investments of participating C&I consumers based on these, and then re-calculate SRMERs until the overall emissions impact of the intervention converges (see the SI for a detailed procedure description). While there are many potential methodologies that can be used to estimate SRMERs based on real-world data or model outputs, including regression approaches or those that seek to identify specific marginal generators (Ryan et al., 2016), we adopt a method here that directly measures the change in hourly system-level emissions resulting from the addition of a small amount of electricity demand in the relevant model zone. Because SRMERs do not take into account capacity expansion or retirement, we exogenously fix all capacities in the model before adding this marginal demand. The subsequent optimization of voluntary procurements against this calculated SRMER implicitly assumes that the C&I consumer has perfect foresight into hourly SRMERs in the model's planning year.

1.1.2. Impact Measurement

Real-world corporate emissions accounting practices rely on measurable metrics like average or short-run marginal grid emissions rates to estimate the emissions impacts of electricity consumption and carbon-free electricity procurement by individual consumers (Mary Sotos, 2015). While such systems allow corporate participants to *claim* certain emissions impacts based on the best available information, they do not necessarily reflect how these participants' actions actually change emissions outcomes, i.e. their procurement strategy's true effectiveness as a carbon mitigation tool. This true "consequential" impact on emissions, as well as similar impacts on electricity system technology mixes and costs, cannot be measured in the real world because doing so would require observation of counterfactual realities in which the buyer did not procure carbon-free electricity (Ekvall, 2019).

In this paper, we take advantage of our system-level modeling framework to calculate and report such metrics for the first time. Rather than assigning responsibility for emissions to particular market participants, we report only the consequential impacts of voluntary buyers' carbon-free electricity procurement, accounting for system-wide changes in both operations and capacity. These are measured by comparing system-level outcomes in modeled counterfactual scenarios where this procurement does or does not take place. For example, we calculate the *consequential emissions impact* of a given procurement strategy as:

consequential emissions impact = (*total system-level emissions without voluntary procurement - total system-level emissions with voluntary procurement*) ÷ *total participating demand.*

While such consequential outcomes are only observable in a controlled model setting where all variables except the voluntary buyer's actions can be held fixed, they can offer important insight into the expected effectiveness of voluntary carbon-free electricity procurement strategies as real-world carbon mitigation tools.

1.1.3. Data Assumptions

In this study, we investigate the system-level impact of voluntary carbon-free electricity procurement within a six-zone model of the U.S. portion of the Western Electricity Coordinating Council grid (WECC, Supplementary Figure 1). Model zones represent single regions or aggregations of regions from the EPA's Integrated Planning Model (IPM; U.S. Environmental Protection Agency (2021)) and are assumed to be internally well-connected, with inter-zonal transmission constraints and expansion costs represented explicitly within the model. We focus in this study on participating C&I load located in California (the *CA_N* and *CA_S* model zones combined), and alternatively in Wyoming & Colorado (the *WECC_WYCO* model zone). The planning framework is a single period optimization reflecting expansion from 2022-2030 and optimized to meet projected demand in the year 2030. Hourly demand and generation profiles are based on the 2012 weather year. All data are compiled using power system data compiler PowerGenome (Schivley et al., 2022). To reduce computation time while maintaining accuracy in investment decisions, we optimize over a reduced time series of 18 representative weeks at hourly resolution derived from the full year data via PowerGenome's internal time domain reduction functionality.

On the supply side, existing generation data is aggregated from EIA 860m (December 2021 edition; U.S. Energy Information Administration (2021c)). The capital cost of new generation is obtained from NREL's *Annual Technology Baseline 2021* (Vimmerstedt et al., 2021), with regional multipliers from EIA's *Annual Energy Outlook 2020* (U.S. Energy Information Administration, 2020b). Each region can expand natural gas combined cycle gas turbines (CCGTs) and combustion turbines (CTs) without limit. Wind and solar candidate project areas at 4 km $\times$ 4 km resolution from the Princeton REPEAT Project (Leslie et al., 2021) are grouped into 135 resource clusters across the whole WECC to create a supply curve for wind and solar capacity additions in GenX. Additionally, 2.7 GW of geothermal hydro-flash potential is assumed to be available in WECC, of which 1.7 GW is available to California, based on the DOE's *GeoVision* Study (U.S. Department of Energy, 2019). The capital cost and operation & maintenance cost of long-duration storage (i.e., metal-air storage and hydrogen storage) are obtained from Baik et al. (2021) and Mongird et al. (2020), respectively. Natural gas CCGTs with carbon capture and sequestration (CCS) are also assumed to be responsible for the CO_2 pipeline construction cost derived from Larson et al. (2021) and the basin specific injection costs derived from Morgan and Grant (2017). The average fuel cost is taken from from EIA *Annual Energy Outlook 2021* Reference Case fuel projections for 2030 (U.S. Energy Information Administration, 2021a) with monthly prices based on historical monthly natural gas price variations from the mean annual price in 2019 (U.S. Energy Information Administration, 2021b).

On the demand side, the subsector demand profiles are calculated with the load time-series in NREL's *Electrification Futures Study* (Mai et al., 2018) with stock values for electric vehicles, heat pumps, etc. from Princeton's *Net-Zero America* study (Larson et al., 2021). We then allocated the state-level data to each IPM zone based on population-weighting. Based on this approach, we project that C&I demand would account for 69% of the 2030 annual California electricity demand (278.4 TWh), and 67% of the 2030 annual Wyoming and Colorado demand (83.8 TWh) in this case study. Supplementary Figure 2 presents a visualization of the sectoral demand time series in California. We refer readers to the SI for flexible demand (time-shiftable demand) and curtailable demand assumptions.

For state-level policies, we modeled policies as codified in 2021 (Barbose, 2021). We modeled the California Cap-and-Trade via a $20/metric ton carbon tax applied to California generation.[2,3] For federal-level policies, we modeled a 30% investment tax credit (ITC) or alternative $26/MWh production tax credit (PTC) for carbon-free electricity (determining exogenously which resources are likely to choose the ITC or the PTC), a 30% energy storage ITC, a $3/kg clean hydrogen PTC, and an $85/ton 45Q carbon sequestration credit codified in the *Inflation Reduction Act of 2022* (H.R.5376, 2022), alongside certain applicable bonus credits. Further details on the implementation of these tax credits are provided in the SI.

1.1.4. Modeled Scenarios

We evaluate the system-level impact of voluntary carbon-free electricity procurement in the two target regions in the year 2030 subject to existing

[2]We chose a carbon tax approach because California's carbon pricing system is multi-sector and this study focuses on the power sector. The $20/ton carbon price in 2030 is obtained with a linear regression model with California's historical auctioned carbon price (California Air Resources Board, 2022). The resulted regression model is auction price (in nominal $) = $10.562/ton + $0.203/ton-auction * (index of auction), with a R-square = 83%. If the auction continues to the year 2030, the four auctions in the year 2030 will be 70th to 73rd, and the projected price will be $24.8/ton-$25.4/ton in nominal $. Assuming a 2.5%/year inflation rate, the average carbon price will be 2020$19.6/ton.

[3]Note that California has a carbon border adjustment mechanism which requires electricity importer to surrender allowance per contract, with emissions measured at the seller's emission rate. However, we dropped the carbon border adjustment as literature shows that this mechanism can be highly ineffective due to contract shuffling (Chen et al., 2011; Bushnell et al., 2014; Xu and Hobbs, 2021).

federal and state policies. We model a central set of scenarios where 10% or 25% of C&I consumers in either California or Wyoming & Colorado participate in voluntary carbon-free electricity procurement, as well as sensitivity cases exploring outcomes with 50% or 100% C&I participation in California. For each region and each participation rate, we model separate scenarios where all participants pursue 100% volumetric matching, 100% emissions matching, or temporal matching with targets ranging from 84% to 100%. For temporal matching cases, the excess limit is set as the matching target less 80 percentage points. We also include sensitivity cases where the excess limit is alternately removed or set to zero. Finally, for all central cases (i.e. all voluntary procurement strategies with 10% or 25% C&I participation in each of the two target regions), we model additional sensitivity cases where a system-level 80% clean electricity standard (CES) requirement is put in place. All cases assume that all participating consumers follow the same voluntary procurement strategy, and thus we do not explore the impacts of multiple strategies being pursued simultaneously.

We pair each case with the three scenarios for available technologies that can be deployed to meet grid electricity demand or voluntary procurement requirements:

- **Established Technologies:** onshore & offshore wind, utility-scale solar PV, lithium-ion battery storage, and conventional geothermal.
- **Advanced Technologies, No Combustion:** Established Technologies plus long-duration metal-air storage, long-duration hydrogen storage, and near-field enhanced geothermal.
- **Advanced Technologies, Full Portfolio:** Above plus natural gas CCGT with CCS (100% post-combustion CO_2 capture rate) and CCGT with zero-carbon fuel (ZCF, e.g., imported hydrogen, synthetic methane, biomethane, ammonia).[4]

The first scenario reflects only commercially mature technologies available at scale today, while the latter two "Advanced Technology" scenarios illustrate

[4]While we assume cost and performance metrics for a post-combustion CCS with near-100% capture, this role could also be filled by less mature CCS technologies like the oxy-combustion Allam-Fetvedt Cycle. Likewise, the source of the zero-carbon fuel is left intentionally ambiguous. In reality, both resources may have associated lifecycle emissions that should be included in an emissions accounting scheme.

the potential impact of voluntary carbon-free electricity procurement on the introduction of more nascent low-carbon energy technologies. One class of technologies that is not included is negative emissions technologies (i.e. direct air capture or bioenergy with CCS), which could theoretically allow for continued use of fossil resources under some accounting schemes. The potential role of such technologies in meeting voluntary emissions targets should be explored in future work. Note that a set of carbon-free electricity resources is available in the model for voluntary participants to procure, distinct from general resources available to meet other users' grid needs. These candidate resources share the maximum development potential with resources that are available for general grid needs (e.g., only so much wind, solar or geothermal capacity can be built in total).[5]

Finally, for every modeled voluntary procurement case, we also include a corresponding reference case where no voluntary procurement takes place, but which is otherwise identical. This reference case is used as the point of comparison for system-level consequential outcomes. We also include variations of these reference cases where participating C&I demand is simply removed from the system rather than matched with procured carbon-free electricity. These cases are used as benchmarks for the system-level impacts of voluntary procurement, with the reasoning that this procurement should aim to replicate or exceed the emissions benefits of simply eliminating the buyer's electricity consumption or supplying it entirely with behind-the-meter carbon-free generation. In total, this study includes more than 600 individual modeled cases.

2. Results

In this section, we first illustrate the carbon-free resource capacity and energy procured by participants in the voluntary market under volumetric, temporal, and emissions matching strategies (Subsection 2.1). Then in Subsection 2.2, we show how these translate to system-level emissions outcomes in each of the modeled scenarios. Subsection 2.3 presents the overall cost of each procurement strategy for voluntary market participants, as well as the cost-effectiveness in terms of \$/ton of system-level CO_2 abatement. Finally,

[5]From the modeling perspective, we doubled the clean energy candidates, and designated half of them as the candidate pool for voluntary procurement. Then we constructed a common expansion upper bound for each pair of replicated resources.

Subsection 2.4 shows how the above results change under a system-wide 80% CES policy.

2.1. Optimal Carbon-Free Electricity Procurement Strategies

Figure 2 and Supplementary Figure 3 show system-level changes in annual generation and installed capacity by technology compared to the reference case for volumetric matching, emissions matching, and selected temporal matching central scenarios[6]. Supplementary Figures 4 and 5 show results for the full range of temporal matching scenarios. These figures show both the direct procurements made by participating C&I consumers *and* the changes in capacity and generation from other sources in response to these procurements. Supplementary Figures 6 and 7 show baseline capacity and energy mixes by model region from the reference case. Observing optimized portfolios under each matching strategy (see Supplementary Tables 7-10 for numerical capacity procurement results by technology and case), it is immediately clear that volumetric matching leads primarily to procurement of a single renewable resource type, either solar in the case of California or wind in the case of Wyoming & Colorado, alongside marginal amounts of other carbon-free resources. This outcome is intuitive, as the most economical choice for voluntary volumetric carbon-free electricity procurement is naturally to start from the cheapest available clean resource – i.e., the resource with the smallest revenue requirement after subtracting the energy, capacity and other possible market revenues and policy incentives from the resource's levelized cost of energy. Unfortunately, these bulk procurements of the cheapest available renewable resources are not without their externalities. As shown in Figure 2, any increases in carbon-free generation from these procurements are offset mostly or entirely by reductions in generation from third-party installations of the same resource type. Because renewable generation is self-correlated, the addition of large amounts of it depresses electricity prices during hours of peak production and thereby discourages development of similar projects. That is to say: renewable generators procured to meet voluntary volumetric matching requirements directly compete with and displace similar market-driven projects from independent developers. The displacement of fossil generation, on the other hand, is zero or near-zero in all volumetric matching cases.

[6]Because no advanced technologies were deployed by the model in any of the reference cases, all of the cases shown in these figures effectively share the same reference case

This displacement of competing renewables by voluntary volumetric procurements is a product of market dynamics, and different outcomes can be expected if other factors like government clean energy mandates play a role in determining final carbon-free electricity penetration. An example of this can be found in the 25% C&I participation California case, where the combination of greater voluntary EAC demand and a 45% in-state RPS requirement forces more in-state renewable generation (totaling to around 55% of annual aggregate demand) than can be economically exported to displace similar resources in other markets, driving minor net gains in clean energy and displacement of fossil generation. We explore the interactions between government mandates and voluntary clean energy procurements in greater detail in Section 2.4.

A 100% emissions matching strategy leads to procurement outcomes that are qualitatively similar to those observed under a 100% volumetric matching strategy. While the total quantity of procured energy varies somewhat due to the lack of a hard volumetric procurement target, there is a similar reliance on the cheapest local form of renewable energy and a near-complete displacement of competing clean resources of the same type. Figure 3, which shows energy procurement outcomes by annual-average hour of the day for the 10% C&I participation, advanced technologies case in California, illustrates why this occurs. While there is high penetration of variable renewables in the reference system (see Supplementary Figure 7), the short-run marginal generators are still often fossil-fired, resulting in only limited variation in the local SRMER across an average day. While the annual-average hourly SRMER is lower in California during midday when solar generation is at its maximum and curtailment occasionally occurs, it is not so low as to prevent procurement of primarily solar power from being the least-cost strategy for voluntary buyers. So while fossil generators are on the short-run margin (not accounting for changes in generating capacity), the consequential impact of this procurement is actually to displace other potential solar capacity additions, rather than fossil generation.

In contrast to volumetric and emissions matching strategies, we find that a temporal matching strategy encourages procurement of a more diverse portfolio of clean resources. Combinations of solar and battery energy storage, with small amounts of wind and geothermal, are most affordable at lower matching targets in California, while combinations of wind and solar are chosen in Wyoming & Colorado. As the temporal matching target approaches 100%, advanced technologies like metal-air and hydrogen LDES, gas plants with

Figure 2: System-level changes in generation as a result of voluntary carbon-free electricity procurements, for 10% and 25% C&I participation rates in the California and Wyoming & Colorado target regions.

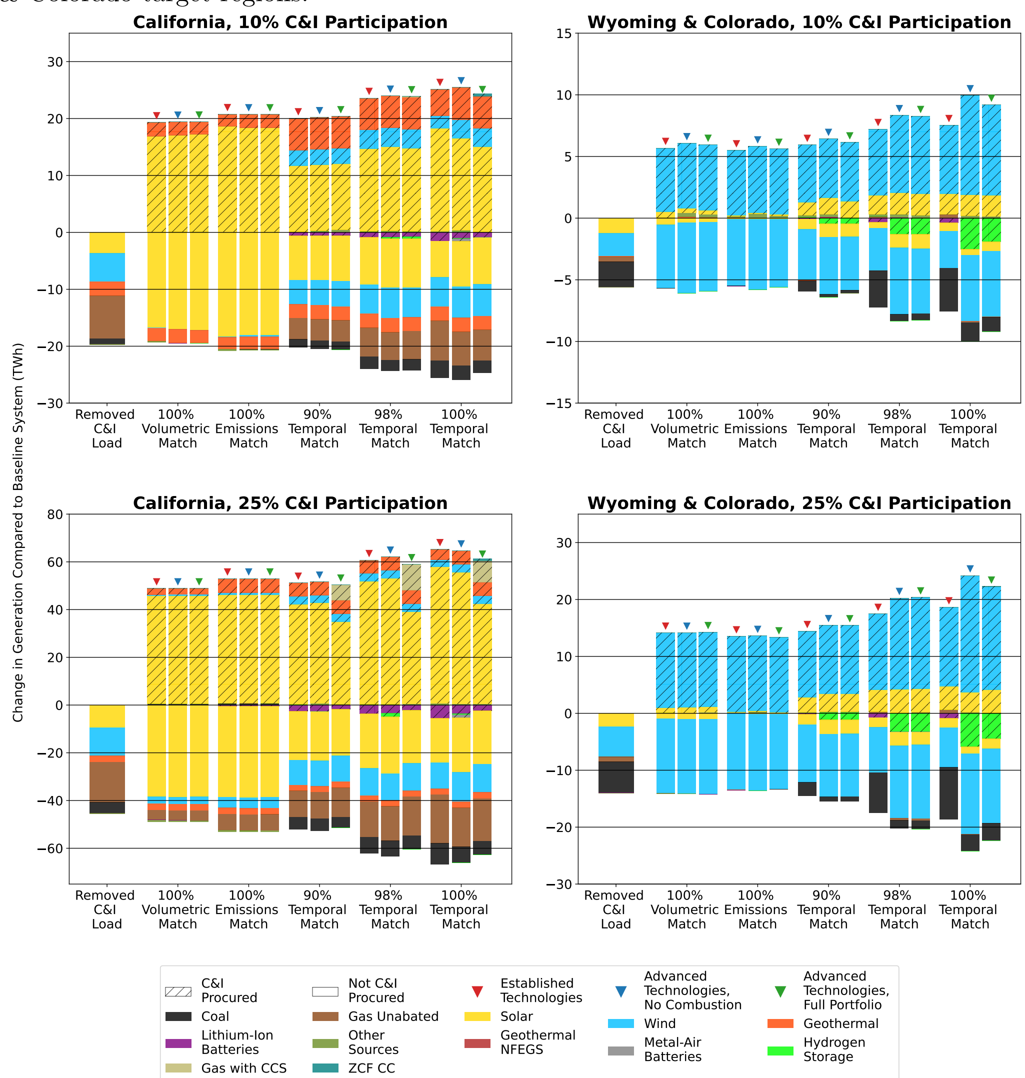
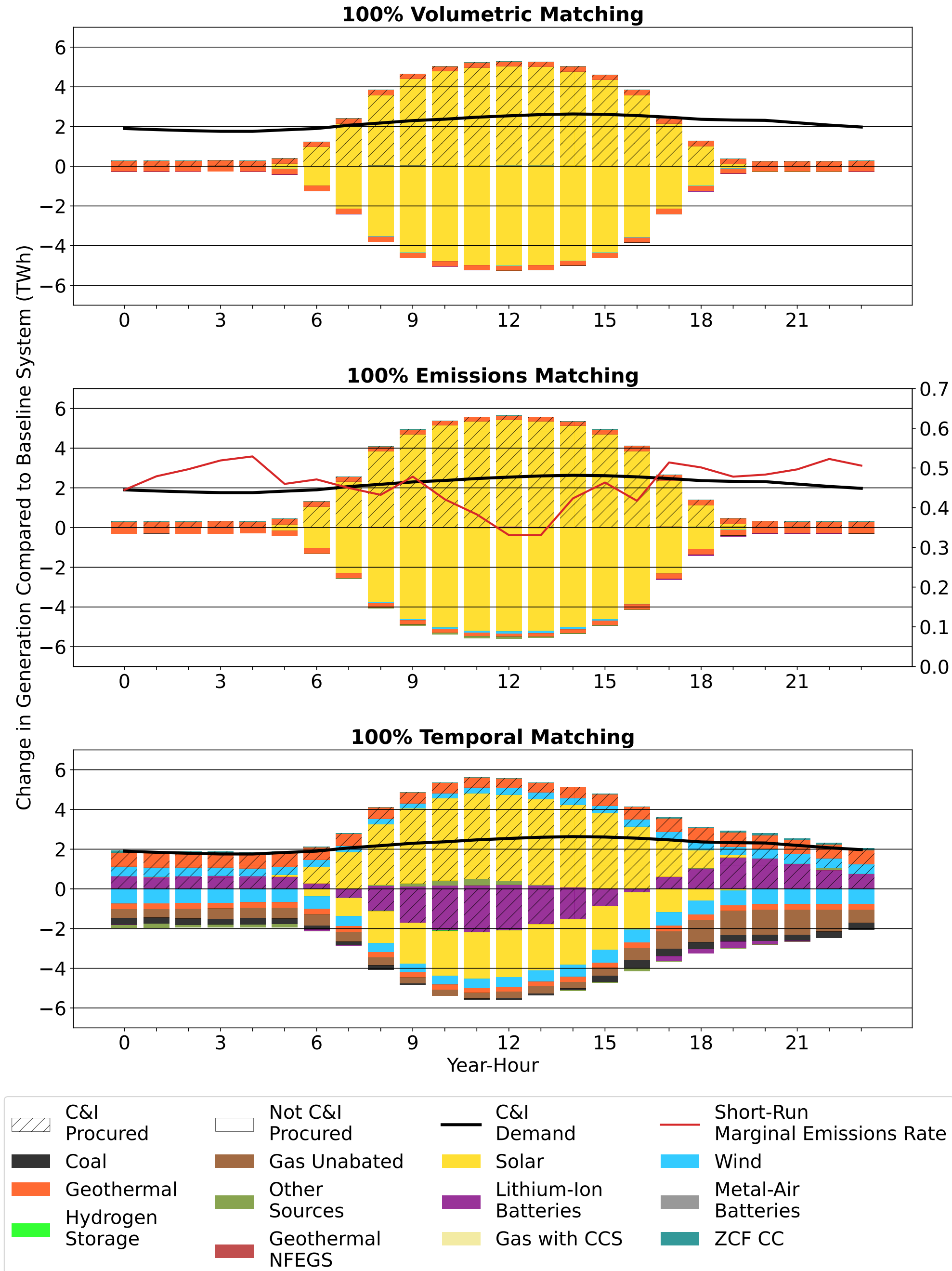


Figure 3: Change in hourly generation by source over an average day as a result of voluntary carbon-free electricity procurement, for the case with 10% C&I participation in California and the full portfolio of advanced technologies available for procurement.



CCS, and ZCF combined cycle plants are deployed as part of the lowest-cost portfolio when available (see Supplementary Figure 3 and Supplementary Tables 7-10). These generally account for a fairly small portion of total procured capacity and energy, as is to be expected of clean firm and LDES resources in a fully decarbonized electricity system (Sepulveda et al., 2018, 2021), but play an important role in meeting demand during periods when wind and solar generation is at a minimum (see Figure 3, bottom). Overall, a 100% temporal matching requirement leads to greater total energy procurement than occurs under volumetric or emissions matching strategies, as some level of wind and solar overbuilding is typically optimal. Displacement of competing clean energy also occurs to a much lesser degree than under volumetric or emissions matching strategies, and reductions in generation from unabated gas and coal are fairly significant in all cases.

As shown in Supplementary Figures 8-11, the lowest-cost procurement portfolio under a temporal matching strategy exhibits some sensitivity to the level of excess sales permitted. With no excess sales allowed, the buyer must effectively replicate the end state of a fully-decarbonized electricity system, either storing excess renewable power or curtailing it and relying on clean firm resources to fill gaps in output. On the other hand, when unlimited excess sales are permitted, the buyer may significantly oversize renewable procurements relative to their own demand in order to maximize availability of qualifying power, while financing this oversizing by selling the excess generation into the electricity market. We observe an extreme case of this in the Wyoming & Colorado zone, where total procured generation is more than five times the demand of the participating consumers for a 10% C&I participation rate. In this case, the procured portfolio is nearly entirely wind power, as is the generation that it displaces in the broader electricity system. At a higher 25% C&I participation rate, the local electricity market in Wyoming & Colorado can absorb proportionally less excess sales and the ratio of excess to consumed carbon-free electricity is significantly reduced. Still, it should be noted that only 100% temporal matching sees any displacement of fossil generation in either Wyoming & Colorado case if unlimited excess sales are permitted.

Aside from the specific case of unlimited excess sales noted above, we do not generally observe large changes in least-cost portfolios with increasing C&I participation rate. Higher participation rates of 50% and 100% do force somewhat greater displacement of fossil capacity and generation in California under volumetric and emissions matching strategies (Supplementary Figures

12 and 13), though as noted above this is primarily a result of the combination of voluntary demand with an in-state RPS requirement forcing more in-state carbon-free generation than can be economically exported. At very high participation rates, all strategies begin to displace some amount of *existing* clean capacity from the system due to the requirement for new power procurement. This suggests a need to find a place for existing resources that would otherwise be forced to retire in voluntary procurement schemes.

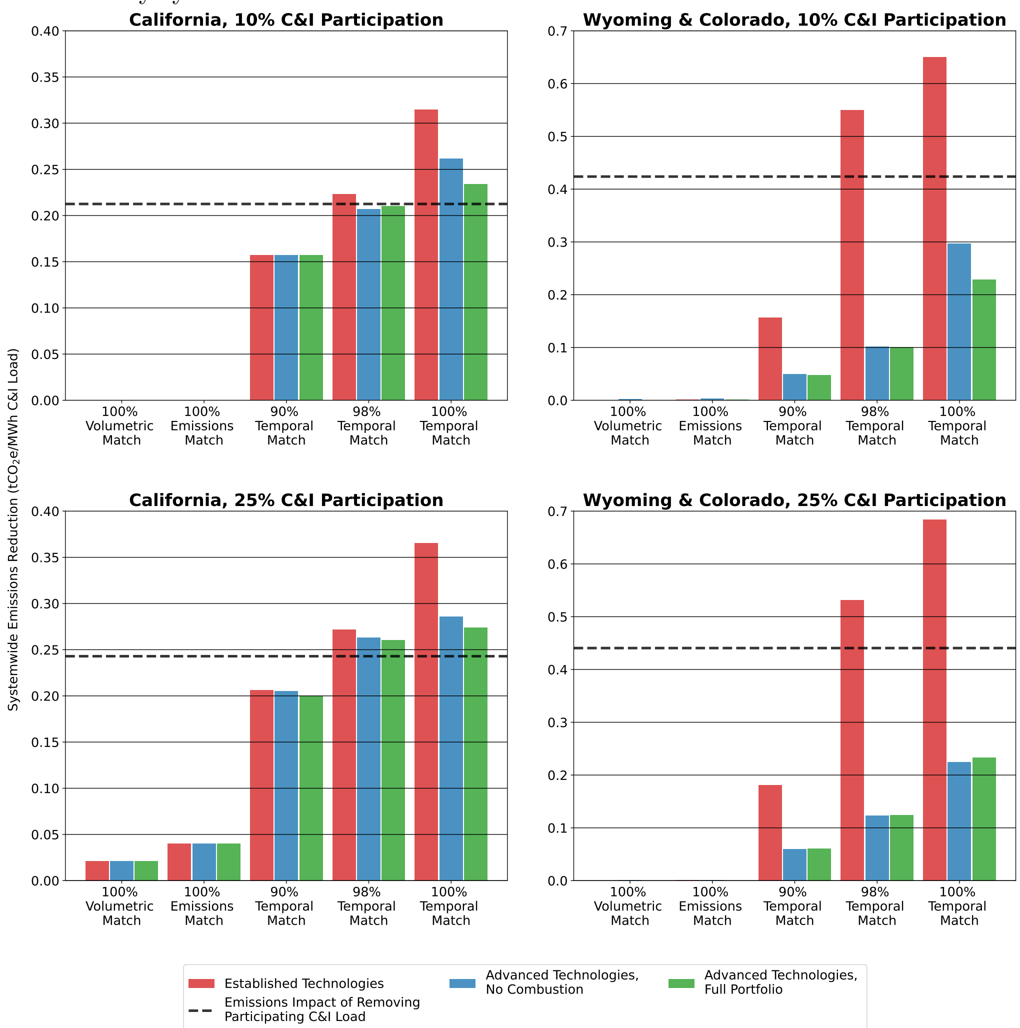
2.2. Emissions Impacts

Figure 4 shows observed emissions reductions per MWh of participating C&I load for volumetric matching, emissions matching, and a selected set of temporal matching central cases, alongside benchmarks showing the emissions reduction rate if that same load were to be removed from the electricity system entirely. (Supplementary Figure 14 shows results for the full set of central cases.) Notably, we find that for 10% and 25% C&I participation rates, 100% volumetric and emissions matching voluntary procurement strategies have zero or negligible impact on system-level emissions outcomes. This finding aligns with the system-level energy mix results discussed in the previous subsection, which showed that voluntary carbon-free energy procurement under these strategies almost exclusively displaces other carbon-free energy rather than fossil fuels. At 50% and 100% participation rates in California these strategies do drive more substantial emissions reductions, though still at less than half the benchmark reduction rate (Supplementary Figure 15).

By contrast, we find that a temporal matching approach does drive real system-level emissions reductions in all cases, with the reduction rate increasing in step with the matching target. In California, a 100% temporal matching target leads to system-level emissions reductions greater than those of the benchmark ($\sim$0.25 tCO_2/MWh). In general, emissions reductions exceeding the benchmark rate can be attributed to the consumer's procured clean portfolio generating excess power beyond their consumption in certain periods. We find that the emissions reduction rate is greatest for scenarios with a more limited technology portfolio, where overbuilding of wind and solar is more heavily relied on to meet round-the-clock reliability needs. In Wyoming & Colorado the benchmark emissions reduction rate is significantly higher ($>$0.4 tCO_2/MWh) due to the region's heavy reliance on coal power, and 100% temporal matching manages to meet this benchmark only when the pool of available technologies is limited to wind, solar, and batteries.

As in California, introduction of advanced technologies lowers the effective emissions reduction, though in this case the difference is much larger. The failure to meet the benchmark reduction rate in these cases can be attributed in large part to participating customers procuring power from high-quality, capacity-limited clean resources that then become unavailable for procurement by other consumers, causing them to rely on fossil electricity instead (Ricks et al. (2023) discuss this phenomenon in the context of clean hydrogen production). Still, even the minimum system-level emissions reduction of 0.2 tCO_2/MWh in the 100% hourly matched advanced technologies cases is not insubstantial. We observe little variation in system-level emissions impacts with increasing C&I participation in either region. However, as noted above, these results are also sensitive to the level of excess sales permitted. While emissions outcomes are fairly consistent in California regardless of the excess sales limit, system-level emissions reductions become less variable between cases for a 10% participation rate in Wyoming & Colorado if no excess sales are allowed, and disappear almost entirely if unlimited excess sales are allowed (Supplementary Figures 16 and 17). The importance of this observation will be discussed further in Section 3.

Figure 4: System-level reductions in CO_2 emissions per MWh of C&I load participating in voluntary carbon-free electricity procurement, for 10% and 25% C&I participation rates in the California and Wyoming & Colorado target regions. Dotted lines indicate the benchmark reduction rate associated with complete removal of the participating load from the electricity system.



2.3. Cost Premium for Voluntary Carbon-Free Electricity Procurement

Results presented in the previous sections showed that voluntary carbon-free electricity procurement under volumetric or emissions matching strategies had little if any consequential impact on system-level generation mixes or emissions outcomes. It follows logically that the additional cost of these strategies for participating C&I consumers should be low or zero. Figure 5 and Supplementary Figures 18 and 19 illustrate precisely this outcome, showing zero cost premium for these strategies compared to standard purchase of grid electricity in all cases except those with higher C&I participation in California, where some CO_2 reductions were observed. In other words, in these cases, the resources procured by voluntary buyers are already economic and require no additional revenue from voluntary buyers. In the 25% participation California cases the cost premium is \$4/MWh for volumetric matching and \$6/MWh for emissions matching. Although this absolute cost is fairly low, the emissions reductions driven by these approaches are also minimal. As a result, we find that the effective cost of CO_2 abatement in these cases, measured by comparing the participant's cost premium with the observed system-level reduction in CO_2 emissions and shown in Figure 6, is high at \$180/ton for volumetric matching and \$140/ton for emissions matching.

Temporal matching incurs a greater cost premium, as this strategy requires generation of carbon-free electricity even in hours when output from cheap wind and solar is lowest. They also require operation of procured generation and storage capacity in a manner that is not necessarily aligned with price incentives from the broader electricity market (see Supplementary Figure 20). For C&I load in California, the cost premium for 84% temporal matching is \$8/MWh (Supplementary Figure 18). This increases to as much as \$27/MWh for 100% temporal matching in the 25% participation case when only established technologies are available. At higher participation rates the cost of 100% temporal matching increases further, peaking at nearly \$40/MWh for the case with 50% participation and declining slightly at 100% participation (Supplementary Figure 19). Absent a full portfolio of clean firm resources, the cost of 100% temporal matching can be significantly greater than 98% temporal matching. When advanced clean firm and LDES technologies are utilized, the cost premium for 100% temporal matching falls by roughly 20%. This reduction in cost is consistent with past findings regarding the value of LDES and clean firm technologies in fully-decarbonized electricity systems (Sepulveda et al., 2018, 2021; California Energy Commission, 2021)[7]. Because effective emissions reductions increase with the temporal matching target, the overall CO_2 abatement cost in these California cases is fairly consistent as a function of the temporal matching target, rising from \$60/ton for an 84% matching target to \$70-80/ton for a 100% matching target (Supplementary Figure 21).

In Wyoming & Colorado, where high-quality wind resources are available, the cost premium for temporal matching is much lower than in California. It starts at around \$1/MWh for 84% temporal matching and rises to \$6-15/MWh for 100% temporal matching depending on the technologies available (Supplementary Figure 21). As in the California cases, the availability of advanced technologies lowers the cost premium of meeting a 100% temporal matching target in Wyoming & Colorado. Although we observed in Section 2.2 that overall CO_2 abatement, by comparison to the benchmark of removing the participating C&I load, was less robust under temporal matching in Wyoming & Colorado than in California, the observed CO_2 abatement *cost* in this region is actually significantly lower than in California at \$20-40/ton. This is due both to the relatively low cost premium for procuring temporally-matched power in wind-rich regions, and to the fact that the displaced fossil resources in Wyoming & Colorado are almost entirely coal (Figure 2). As with energy and emissions outcomes, we observe only minor changes in cost premiums as a function of the C&I participation rate in these cases.

We also observe that the actions of voluntary participants have a small impact on local electricity prices (shown in yellow in Figure 5). In California, temporally-matched voluntary procurement at higher participation rates can reduce local wholesale electricity prices by up to \$2/MWh, providing small external benefits to other customers. Because volumetric and emissions matching strategies do not change overall energy mixes, they have little to no impact on wholesale prices. In Wyoming & Colorado, we observe no substantial local price impacts from any matching strategy.

[7]While conventional geothermal is a clean firm resource and part of the established technologies pool, its natural capacity limitations prevent it from being a major contributor to portfolios and cost reductions.

Figure 5: The incremental cost of voluntary carbon-free electricity procurement for C&I participants, broken down by category. California participants' wholesale electricity cost in the reference case is \$33.9/MWh, including a \$33.4/MWh energy payment, \$2.4/MWh capacity payment, -\$1.6/MWh congestion revenue (as negative cost), -\$0.7/MWh carbon dividend (as negative cost, assuming cap-and-trade revenue is reimbursed to consumers), \$0/MWh RPS/CES payment (Simulated EAC price is zero in 2030), $<$ \$0.1/MWh incremental transmission cost (excluding existing transmission cost as of 2021), and \$0.4/MWh transmission loss cost. Wyoming & Colorado participants' wholesale electricity cost in the reference case is \$22.9/MWh, including a \$22.9/MWh energy payment, \$1.60/MWh capacity payment, -\$1.7/MWh congestion revenue, \$0/MWh RPS/CES payment, \$0/MWh incremental transmission cost, and \$0.2/MWh transmission loss cost. Reference costs do not include costs associated with distribution or existing transmission. The clean electricity premium (zero for the Reference) reflects the additional payments made to procured generation via hourly or annual EAC purchases.

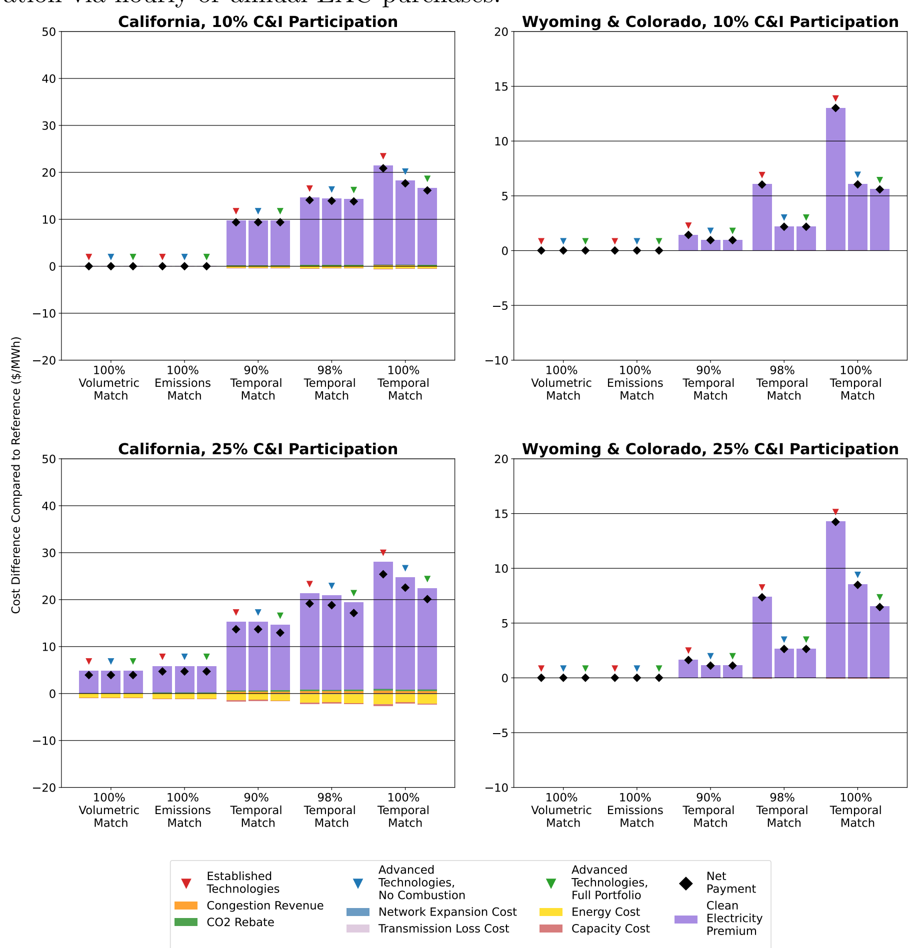
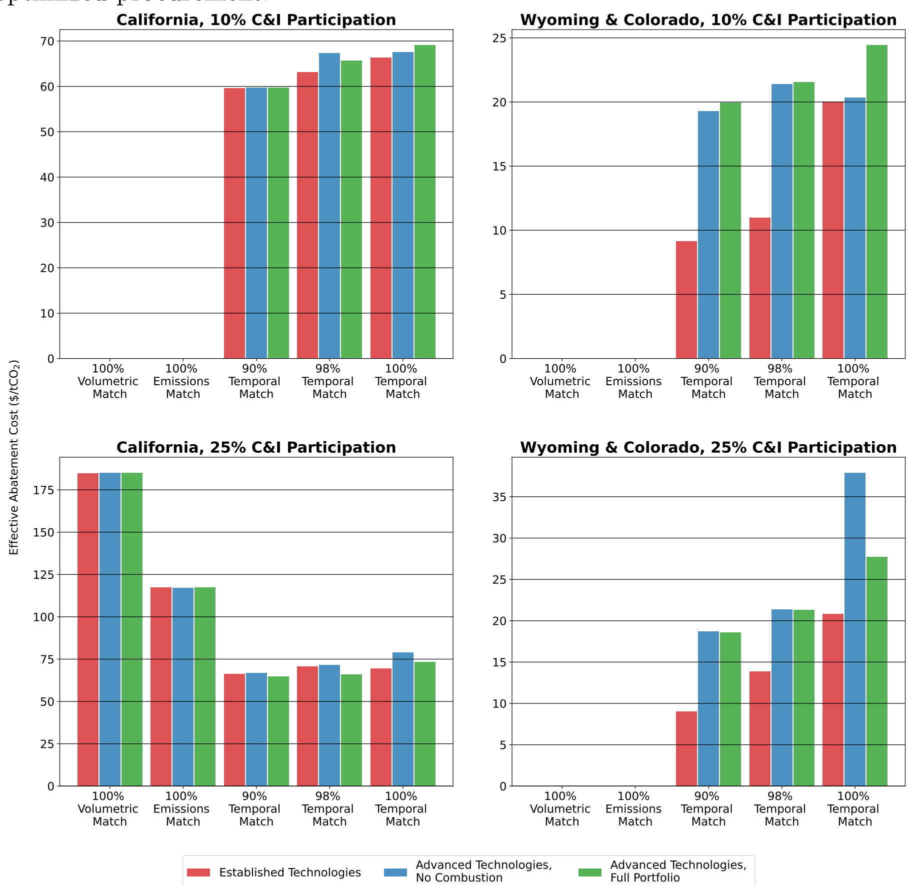


Figure 6: Effective CO_2 abatement cost of voluntary carbon-free electricity procurement, for 10% and 25% C&I participation rates in the California and Wyoming & Colorado target regions. Scenarios without data do not have zero abatement cost, but instead represent strategies driving no effective CO_2 abatement and incurring no cost premium over purely cost-optimized procurement.



2.4. Impacts of Voluntary Action under a Binding Clean Electricity Standard

The results presented in the previous subsections regarding the minimal system-level emissions impact of voluntary carbon-free electricity procurement under volumetric or emissions matching strategies, and the apparently muted impact of temporal matching in some cases, center on a revealed lack of "additionality." That is to say: while corporate buyers might claim to add generation from specific carbon-free resources to the electricity system, the *total* carbon-free generation does not increase as a result of their actions because the resources they procure would have been built by others anyway, and effectively force other similar projects out of the electricity market. This can occur because basic project economics, rather than demand for clean power attributes, is the primary determinant of final clean electricity penetration in our central cases. Supported by generous federal subsidies established under the Inflation Reduction Act (H.R.5376, 2022), carbon-free electricity generation in our 2030 WECC base case significantly outpaces the levels required under the combined RPS policies currently enacted by western states. This leads to an oversupply in carbon-free EACs, conditions under which additional EAC demand from voluntary procurement does not require additional clean generation. The market-based displacement effects discussed in Section 2.1 are thus free to occur without any backstops to guarantee true additionality for voluntary procurement.

However, some level of additionality presumably *would* be guaranteed if demand for clean attributes were already the binding determinant of the system's overall carbon-free energy share. This could occur in the case of an ambitious system-wide CES (or a combination of multiple local CES policies) that sets a requirement for carbon-free generation beyond what would be achieved otherwise. To observe outcomes in such a hypothetical policy environment, we model an alternative set of cases where a binding system-level CES of 80% is put in place, exceeding the 74% carbon-free electricity generation observed in our original reference case. Capacity, energy, emissions, and cost outcomes for these CES scenarios are shown in Supplementary Figures 22-26. We find that while all three strategies procure similar least-cost portfolios to those observed in Section 2.1, this procurement now drives additional carbon-free generation and real reductions in fossil generation at the system level in all cases. For volumetric and emissions matching strategies, these reductions in fossil generation lead to emissions reductions that surpass the benchmark reduction rate in California, but fail to meet it in Wyoming & Colorado. Temporal matching surpasses the benchmark rate in both cases for targets above 94%.

Although temporal matching still provides greater emissions reductions than volumetric or emissions matching in cases with a binding CES, it does so at a significantly greater cost premium. While added costs for 100% volumetric or emissions matching are roughly \$1-3/MWh, they can still be greater than \$20/MWh in California and up to \$15/MWh in Wyoming & Colorado for 100% temporal matching cases (Supplementary Figure 25). The low costs for volumetric and emissions matching can be traced to the fact that these strategies allow for procurement of only the cheapest carbon-free resources and, assuming well-functioning market signals, enable the system to efficiently add new carbon-free generation to maintain overall CES compliance wherever this is most cost-effective. By contrast, a temporal matching strategy requires that the procurer incur the full cost of meeting demand in a particular location with carbon-free generation at every hour of the year, a task which is not substantially less difficult than it was in cases without a binding CES. These discrepancies are reflected in the effective CO_2 abatement costs, which are \$10-40/ton for 100% volumetric matching, \$10-60/ton for 100% emissions matching, and \$20-100/ton for 100% temporal matching (Supplementary Figure 26). When rated purely on effective CO_2 abatement cost, volumetric matching is the most efficient voluntary carbon-free electricity procurement strategy when a binding CES is present. However, as discussed in the previous subsections, the effectiveness of both volumetric and emissions matching evaporates entirely in the absence of strong government mandates for clean electricity deployment, while the emissions benefits of temporal matching are for the most part preserved.

3. Conclusions and Outlook

In this study we have enhanced a capacity expansion planning tool to assess for the first time the system-level impacts of different voluntary carbon-free electricity procurement strategies. Our modeling approach allows us to causally link the actions of electricity consumers pursuing volumetric, temporal, or emissions matching procurement strategies with changes in system-level emissions and technology mixes, a relationship which is unobservable in the real world. While each of these three matching strategies provides an accounting framework under which voluntary buyers of carbon-free electricity can claim reductions in emissions, our results illustrate the extent to which these claims correlate with actual changes in system-wide CO_2 emissions.

We find that in the current U.S. policy environment, both volumetric and emissions matching procurement strategies drive little to no change in system-level CO_2 emissions compared to counterfactual scenarios where no voluntary procurement occurs. In both cases, participating consumers meet matching requirements most cost-effectively by procuring the cheapest available renewable energy resources. While both matching strategies implicitly assume that this procurement offsets CO_2-emitting fossil fired generation, we find that it instead almost exclusively displaces capacity additions and generation from other renewable resources. In other words, all or nearly all of the carbon-free energy procured by voluntary market participants pursuing volumetric or emissions matching strategies would have been generated anyways. We also find that 100% volumetric and emissions matching targets can typically be met at zero additional cost to the consumer, implying that an accounting system based on either strategy would allow voluntary participants to very easily claim zero emissions without making any real contributions to electricity decarbonization overall.

By contrast, our results indicate that temporal matching *does* consistently drive reductions in system-level CO_2 emissions. This occurs because meeting a high temporal matching target requires procurement of carbon-free generation even in hours when it would otherwise be more cost-effective to meet electricity demand with fossil-based generation than with new clean power. As an added co-benefit, cost-optimal portfolios used to meet 100% temporal matching targets typically include advanced clean firm and/or LDES technologies that would not otherwise be deployed in the near-term. Voluntary 100% temporal matching commitments could thus provide early markets for the nascent technologies that will likely be critical components of fully-decarbonized electricity systems in the long run (Sepulveda et al., 2018, 2021), allowing for earlier scale-up and cost reductions via learning curve effects. These benefits come at a cost, however, and we find that C&I consumers pursuing 100% temporal matching in 2030 can expect to pay premiums that in some cases exceed \$20/MWh, though the added cost is sensitive to the quality and availability of carbon-free resources in the consumer's local grid region.

While temporal matching does consistently reduce system-level emissions, the precise level of consequential impact cannot be accurately predicted based on real-world observable metrics. We find that for C&I consumers in California, the consequential reduction in system-level emissions from 100% temporal matching is greater than the reduction that would occur if the same C&I

consumers instead stopped consuming electricity entirely. The opposite is true, however, for C&I consumers in Wyoming & Colorado, as both procurement of capacity-limited clean resources and sales of excess clean electricity from a procured portfolio can drive different system-level impacts from simply curtailing demand. We find that the level of emissions reduction under temporal matching can be sensitive to the amount of excess sales permitted, with significantly lower emissions benefits being observed in Wyoming & Colorado if unlimited excess sales are allowed. In these scenarios, extreme oversizing of procured wind resources relative to participating demand can allow participants to 'skim the bottom' of the wind production profile to meet their temporal matching requirements, while not deploying significantly more wind power overall in the region than would otherwise be economically optimal. This result suggests that in order to maximize emissions benefits of temporal matching, voluntary participants should ideally contract with resources that sell electricity primarily to them rather than to other consumers. This is likely to occur naturally to some degree when carbon-free energy procurement occurs through direct PPAs, as the purchaser will seek to limit the exposure to volatility in merchant electricity markets that would result from reliance on significant sales of excess generation (Pepper et al., 2023). If "unbundled" EACs are instead purchased on an open market separately from energy, it could be easier for independent generators to sell the large majority of their electricity to other buyers while maintaining enough residual EAC supply to meet a small amount of demand from temporal matching consumers in all or most hours of the year. However, because consumers relying entirely on the availability of qualifying EACs in open markets will face some risk of insufficient supply in key hours, PPA-based strategies that lock in EAC access may be preferred by those with high temporal matching targets. In either case, we find that the feasibility of 'skimming the bottom' and selling large amounts of excess clean power to more easily meet a temporal matching goal declines as the voluntary participation rate increases, meaning that greater overall participation can increase the emissions abatement effectiveness of every participants' carbon-free energy procurement.

Although all voluntary procurement strategies face some level of challenge driving real emissions reductions in the current U.S. policy environment - very acutely in the case of volumetric and emissions matching and situationally in the case of temporal matching - our results indicate that supportive government policies creating binding demand for EACs can drive substantially different outcomes. In markets where aggressive CES policies exist and where external trading (and therefore carbon leakage) is minimal, demand for EACs can be the driving factor behind carbon-free electricity procurement. In this policy context, adding voluntary demand for EACs via any of the three matching strategies will necessarily increase the total carbon-free generation in the system. In such a scenario, the current practice of volumetric matching is actually the most cost-effective strategy per ton of CO_2 reductions in the electricity sector, indicating that while this strategy is likely to have been effective historically in states with binding RPS policies, it will soon be decidedly ineffective going forward given that incentives established by the Inflation Reduction Act are likely to lead to oversupply of state compliance markets. Temporal matching is significantly more costly, though it is still the only modeled strategy that results in procurement of nascent clean firm and long-duration storage technologies and that reliably reduces system-level emissions. It should also be noted that the status of a CES policy as binding is not definitively observable in the real world, though it may be inferred through elevated EAC prices, and cannot be predicted with high confidence over the full lifetime of a clean energy investment. Temporal matching is therefore the only one of the three modeled voluntary procurement strategies that delivers fairly consistent carbon mitigation impacts regardless of the current status and future evolution of the local policy environment. In any case, the observed positive impact of government mandates for clean electricity procurement on the efficacy of all voluntary procurement strategies may provide further motivation for more ambitious CES policies at the regional and national levels.

In presenting these results, we also note several limitations of the current study which may motivate future investigation. First, in order to simplify the comparison of the three matching strategies, we have omitted the potential impact of transmission constraints by limiting procurement of carbon-free electricity to resources located within the same "copperplate" (i.e. internally well-connected) model zone as the participating C&I customers. Such zones can be defined only loosely in real electricity grids based on the location of major transmission bottlenecks, and transmission constraints of varying severity do in fact exist across all spatial scales. Past work studying temporal matching of carbon-free electricity procurement with electrolytic hydrogen production found that the presence of such transmission constraints between the points of generation and consumption could reduce the emissions benefits of matching (Ricks et al., 2023), although it should be noted that the hydrogen case in question involved co-optimization of new load and new supply, whereas the voluntary procurement cases investigated in the present work typically involve very little modification of load and may thus be less sensitive to congestion. It is plausible, however, that procurement of carbon-free electricity over very large areas could dilute the impact of a temporal matching strategy by enabling participants to procure power from disparate renewable resources exposed to different weather patterns, instead of the diverse technology portfolio needed to achieve full temporal matching in any single region. Future work should therefore investigate the sensitivity of the outcomes reported here to greater spatial scope and/or granularity.

We also note that while voluntary carbon-free electricity procurement following volumetric, temporal, or emissions matching strategies might be relatively straightforward to model, the complexity of some strategies may make them more difficult to implement in the real-world. For example, in analyzing temporal and emissions-based procurement, our model has perfect foresight in projecting hourly participating electricity demand, wind and solar variability, and local SRMERs hour by hour. In reality, meeting any granular matching goals will face both long-term uncertainty at procurement or contracting stage and short-term operational uncertainties and price volatility. Participating consumers and clean power suppliers working under temporal or emissions matching regimes need to estimate the demand and generation profiles *ex ante*, at a higher resolution than the annual capacity factors required for annual volumetric matching. This can involve higher estimation error and performance risk. Future work therefore should explore the impact of uncertainty on more temporally-granular contracting and operations, which may increase the challenge as compared to modeling in this study.

In addition, this study implicitly assumed that all C&I customers participating in a given form of carbon-free electricity procurement pool together purchases and manage portfolios in aggregate. This allows for individual variations in customer demand profiles to be aggregated and partially smoothed out and for multiple resources to be aggregated to supply this combined demand profile. Consequently, this assumption likely leads to an underestimate of the costs of temporally-granular carbon-free electricity procurement by individual actors. Future work should evaluate the possible efficiency benefits and system-level emissions outcomes of multi-lateral versus bi-lateral procurement, and if the cost-savings are significant, explore potential structures for multi-lateral procurement markets, retail aggregation, and/or secondary markets for time-based energy attribute credits or carbon-free electricity attributes.

Finally, we recognize that none of the matching strategies investigated in this paper may represent the theoretically optimal means of reducing grid CO_2 emissions via voluntary carbon-free electricity procurement. Although temporal matching is the most consistently effective of the three modeled strategies, its focus on aligning procurement with the participant's demand profile does not necessarily target times when the consequential carbon impact of bringing online new clean generation is greatest. As discussed in Gagnon and Cole (2022), aligning procurement of new carbon-free generation with the *long-run* marginal emissions rate (LRMER, distinguished from SRMER by its inclusion of the impacts of marginal demand on capacity deployments and retirements in the electricity system) may be a more efficient means of maximizing carbon impact. Unfortunately, LRMER is entirely unobservable in the real world and can only be calculated within the framework of an electricity system capacity expansion model like the one used in this study, making it challenging to implement a quantitative LRMER-based emissions accounting system. Temporal matching does technically meet the requirements of a LRMER-based emissions matching strategy in an observable manner, but only because it requires that consumption and procured generation cancel each other out in each hour. Further work should be dedicated to exploring the theoretical efficiency and real-world feasibility of carbon-free electricity procurement strategies that more directly incorporate LRMERs to estimate emissions impacts.

4. Acknowledgment

This work is funded by a grant from Google and by the Princeton Zero-carbon Technology Consortium, supported by unrestricted gifts from GE, Google, ClearPath, and Breakthrough Energy. The authors have retained full editorial independence, and are responsible for any errors or omissions. The simulations presented in this article were performed on computational resources managed and supported by Princeton Research Computing, a consortium of groups including the Princeton Institute for Computational Science and Engineering (PICSciE) and the Office of Information Technology's High Performance Computing Center and Visualization Laboratory at Princeton University.

5. Declaration of Interests

J.D.J. is part owner of DeSolve, LLC, which provides techno-economic analysis and decision support for clean energy technology ventures and investors. A list of clients can be found at https://www.linkedin.com/in/jessedjenkins. He serves on the advisory boards of Eavor Technologies Inc., a closed-loop geothermal technology company, and Rondo Energy, a provider of high-temperature thermal energy storage and industrial decarbonization solutions, and has an equity interest in both companies. He also provides policy advisory services to Clean Air Task Force, a non-profit environmental advocacy group, and serves as a technical advisor to MUUS Climate Partners and Energy Impact Partners, both investors in early-stage climate technology companies.

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