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The Influence of Demand-Side Data Granularity on the Efficacy of 24/7 Carbon-Free Electricity Procurement

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The content of this report, including any errors or omissions, are the responsibility of the authors alone.

Note: This study is published in the spirit of a working paper for public dissemination and has not been subject to peer review. Any final publications based on this report will be subject to further peer review and may be revised.

Introduction & Motivation

In January 2024, the Princeton ZERO lab published the first peer-reviewed system-level impact analysis of several popular corporate energy procurement strategies, including 24/7 Carbon-Free Electricity (CFE)—also known as hourly matching. The study concluded that voluntary procurement of 24/7 CFE incurs an increase in energy costs for participating customers but can achieve the following impacts:

- **Promotes Emission Reduction:** 24/7 CFE can fully eliminate a buyer's physical reliance on carbon-emitting electricity resources if the procured power is new and deliverable. 24/7 CFE procurement is also associated with robust system-level emissions reductions across a wide range of policy scenarios and market conditions, and reduces emissions far more consistently than traditional annual volumetric matching approaches to clean power procurement.

- **Accelerates Adoption of Advanced Technologies:** 24/7 CFE drives early deployment of advanced, "clean firm" generation and/or long-duration energy storage technologies, creating initial markets for deployment, innovation, and cost-reductions that make it easier for society at large to follow the path to 100% carbon-free electricity.

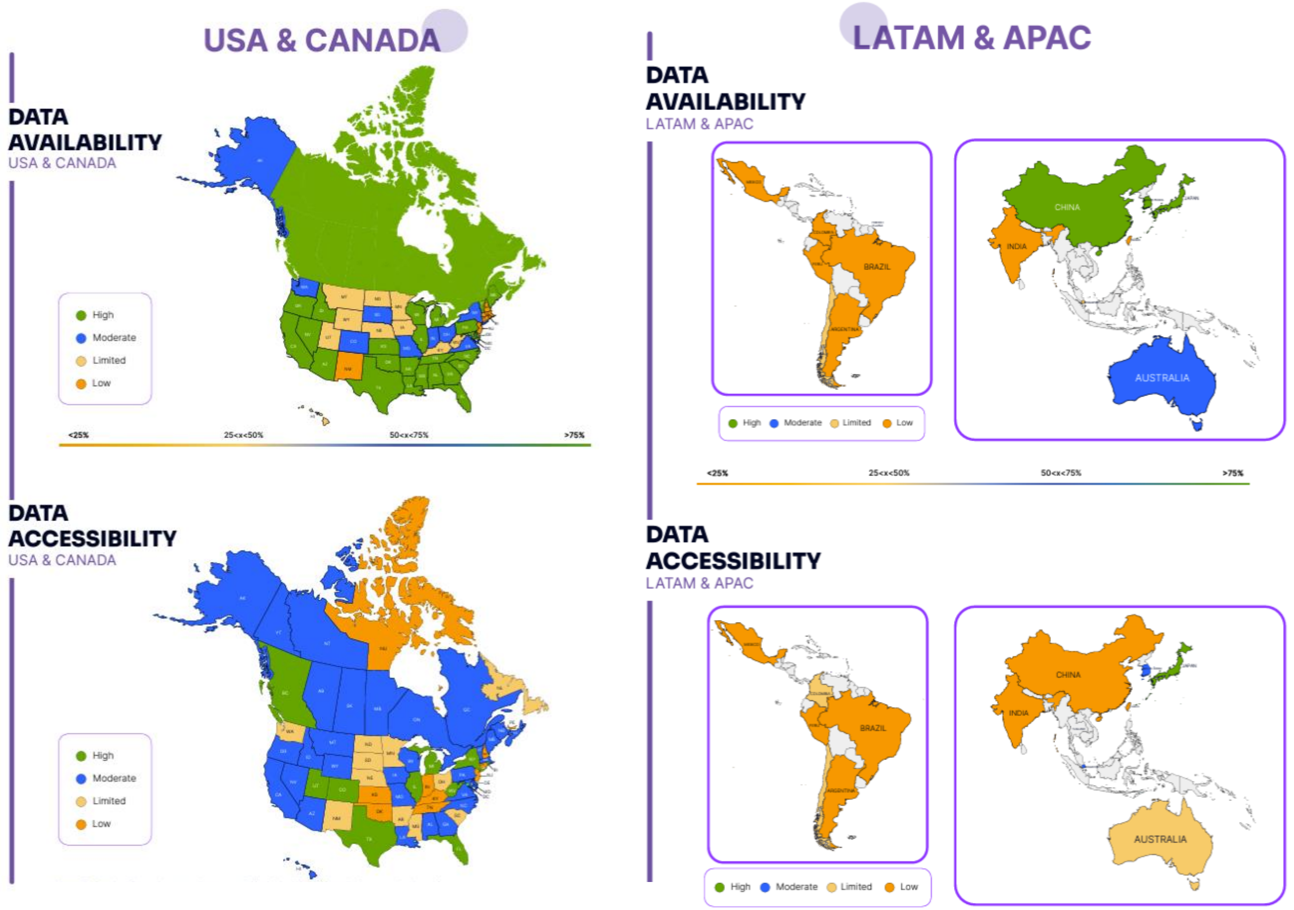
Introduction & Motivations, Cont'd

In prior work we assumed that all voluntary actors pursuing 24/7 CFE procurement had full access to their own hourly electricity consumption data via smart metering technology. However, despite the increasing penetration of smart meters in markets around the world, only a fraction of electricity consumers have demand-side data access at this level of granularity.

In many regions, electricity consumers may only have access to the annual or monthly bills they receive from their utilities. This billing data can be used to calculate a facility's volumetric electricity consumption over a period, but the facility would need to invest on its own in smart metering technology to access hourly consumption data.

While demand-side data access barriers may be costly to overcome, granular CFE *generation* data can likely be provided by energy attribute certificate (EAC) registries at fairly low incremental cost due to the widespread use of smart meters at utility-scale generation facilities.

Some consumers interested in 24/7 CFE may therefore find themselves able to procure clean generation on a granular basis but unable to match it to their precise hourly demand. Is 24/7 CFE still possible and impactful in this scenario?



Current accessibility of granular electricity consumption data in multiple geographic regions. Consumers in some electricity markets are able to easily access hourly-granularity consumption data via smart meters installed by their utilities. In other markets, hourly-granularity data is technically recorded via smart meters but can be difficult for end users to access. In still other markets, a lack of smart metering prevents recording of hourly-granularity consumption data without additional private investment.

Source: Flexidao – "Granular Electricity Meter Data Access: A Practical Guide for Corporate Clean Energy Buyers"

The Influence of Demand-Side Data Granularity

This study explores the system-level impacts of 24/7 CFE procurement in scenarios **where electricity buyers are able to access granular supply-side data**, i.e. hourly-granularity energy attribute certificates (EACs) produced by generators, **but are unable to access granular data describing their own electricity demand**. The study aims to answer the following questions:

- → To what extent are the benefits of 24/7 CFE procurement lost or preserved if participating consumers match temporally granular CFE supply to estimated representations of their own demand?
- → How do outcomes change across different possible demand profiles?
- → How does the use of non-granular load profiles affect the accuracy of attributional emissions accounting?
- → How consistent are findings across different electricity grids, technology portfolios, and matching targets?

Methods: In this study, we model procurement of 24/7 CFE by hypothetical commercial and industrial electricity consumers who can access their own consumption data at varying levels of granularity. We use a 24/7 CFE module implemented in the open-source GenX electricity system planning model to assess the impacts of this procurement on large-scale electricity sector outcomes, including total CO_2 emissions and energy technology deployments. We also compare the 'attributional' emissions that would be calculated and reported by electricity consumers under a granular inventory accounting approach using estimated load profiles to those that would be calculated if the true hourly profile were known and calculate any discrepancies.

Executive Summary

Key findings of this study include the following:

- The system-level impacts of 24/7 CFE procurement are relatively consistent even when using an approximation of a consumer's true demand profile.
- System-level emissions and generation impacts of 24/7 CFE procurement are very consistent across different possible demand-side representations and are much more sensitive to other factors including system conditions, matching targets, and technology availability.
- Costs for participating consumers exhibit minor variability across different demand-side representations, with no consistent direction.
- Participants' incentives to procure nascent CFE generation and storage technologies are not significantly affected by use of estimated load profiles.
- Use of load profiles with different levels of granularity has very little impact on the accuracy of granular attributional emissions accounting; technology portfolios procured to match approximate profiles are very similar to those used to match the true demand.
- All of the above findings are consistent whether consumers pursue 100% 24/7 CFE matching or a lower target matching percentage.

Summary of Methods

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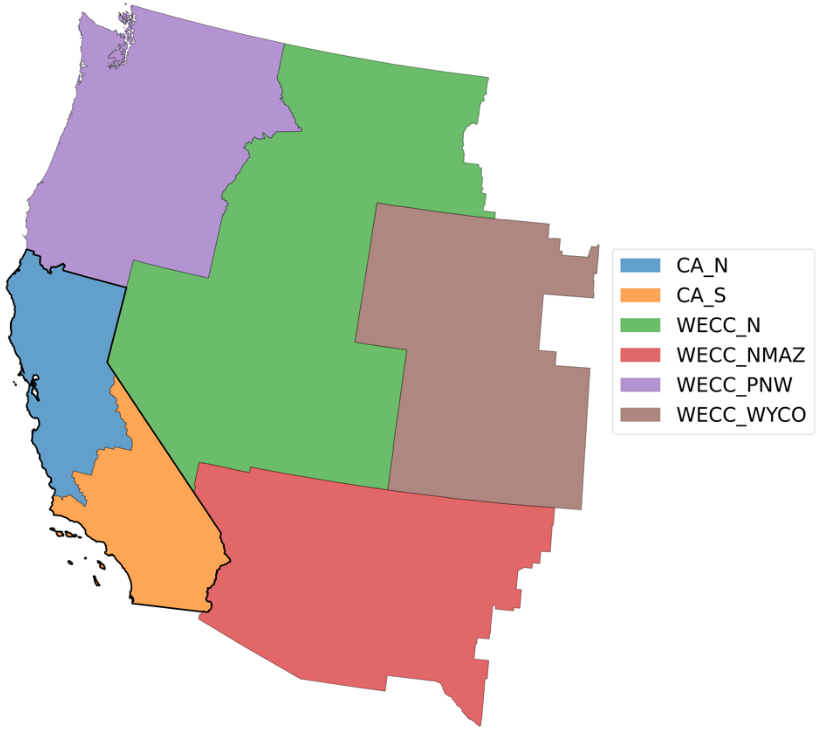
Experimental Design: Key Assumptions

- **2030 target year:** We use **GenX** to optimize the expansion of the US electricity system from the present day through **2030** subject to physical and policy constraints.
- **Multiple target regions:** We assess the impacts of voluntary 24/7 CFE procurement by corporate and industrial (C&I) electricity consumers in two target regions: the territories of the California Independent System Operator (**CAISO**) and the **PJM** Regional Transmission Operator.
- **Voluntary demand representation:** We assume that **15%** of commercial and industrial (C&I) electricity demand in each target region participates in 24/7 CFE procurement. We model sets of scenarios where granular CFE supply is matched to **different demand-side profiles** representing different levels of data availability and approximations of a user's true consumption profile.
- **Technology availability:** We model two technology availability scenarios: one where only established CFE technologies (solar, onshore and offshore wind, conventional geothermal, and lithium-ion batteries) are available for voluntary procurement, and one where more nascent technologies (near-field enhanced geothermal, nuclear small modular reactors, natural gas with carbon capture and sequestration, zero-carbon fuel combustion, and metal-air storage) are also available.
- **System-wide counterfactual analysis:** As in Xu et al. (2024), all impacts of 24/7 CFE procurement are calculated by **comparison to a counterfactual** modeled scenario in which voluntary CFE procurement does not take place. All differences in outcomes are therefore directly attributable to the voluntary action. We measure outcomes at the **system level** rather than just in the target region to capture the full scope of impacts.

Modeled Regions

We model the impacts of voluntary demand for 24/7 CFE in two US target regions: **CAISO** and **PJM**. We additionally model the entire US portion of the synchronous electric grid to which each target region is connected, thereby capturing the direct and indirect impacts of voluntary procurement on the deployment and operation of electricity resources both within and outside of the target region.

CAISO and the Western Interconnection



PJM and the Eastern Interconnection

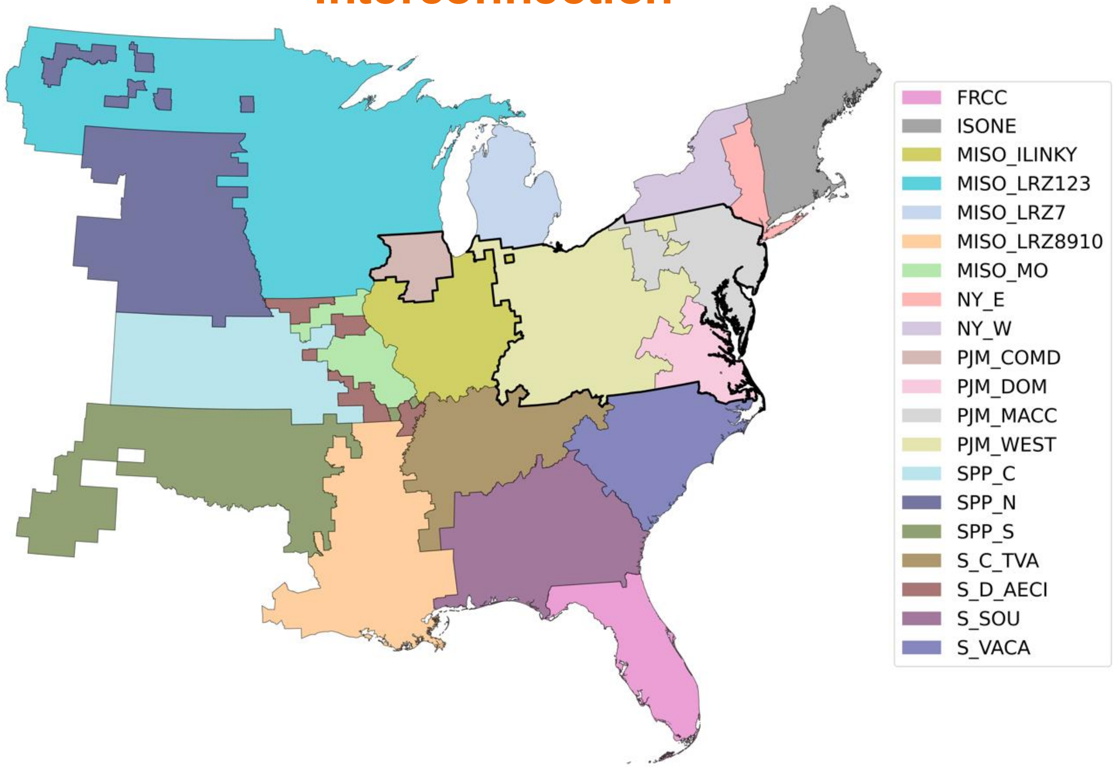


Figure 1: Regional topologies for models of the US Western (left) and Eastern (right) Interconnections used in this report. Target regions for 24/7 CFE procurement within each modeled synchronous grid are outlined in bold.

Demand Profiles

For both CAISO and PJM, we model the impact of 24/7 hourly matching against participating C&I load profiles with different levels of temporal granularity:

1. **True hourly demand** of the participants
2. **Monthly average on-peak and off-peak flat demand**, where on-peak hours are 4-9 pm local time, reflecting billing on a rate design similar to [PG&E's time-of-use plan]
3. **Monthly average flat demand**, reflecting monthly metering and/or billing
4. **Annual average flat demand**, reflecting annual metering and/or billing

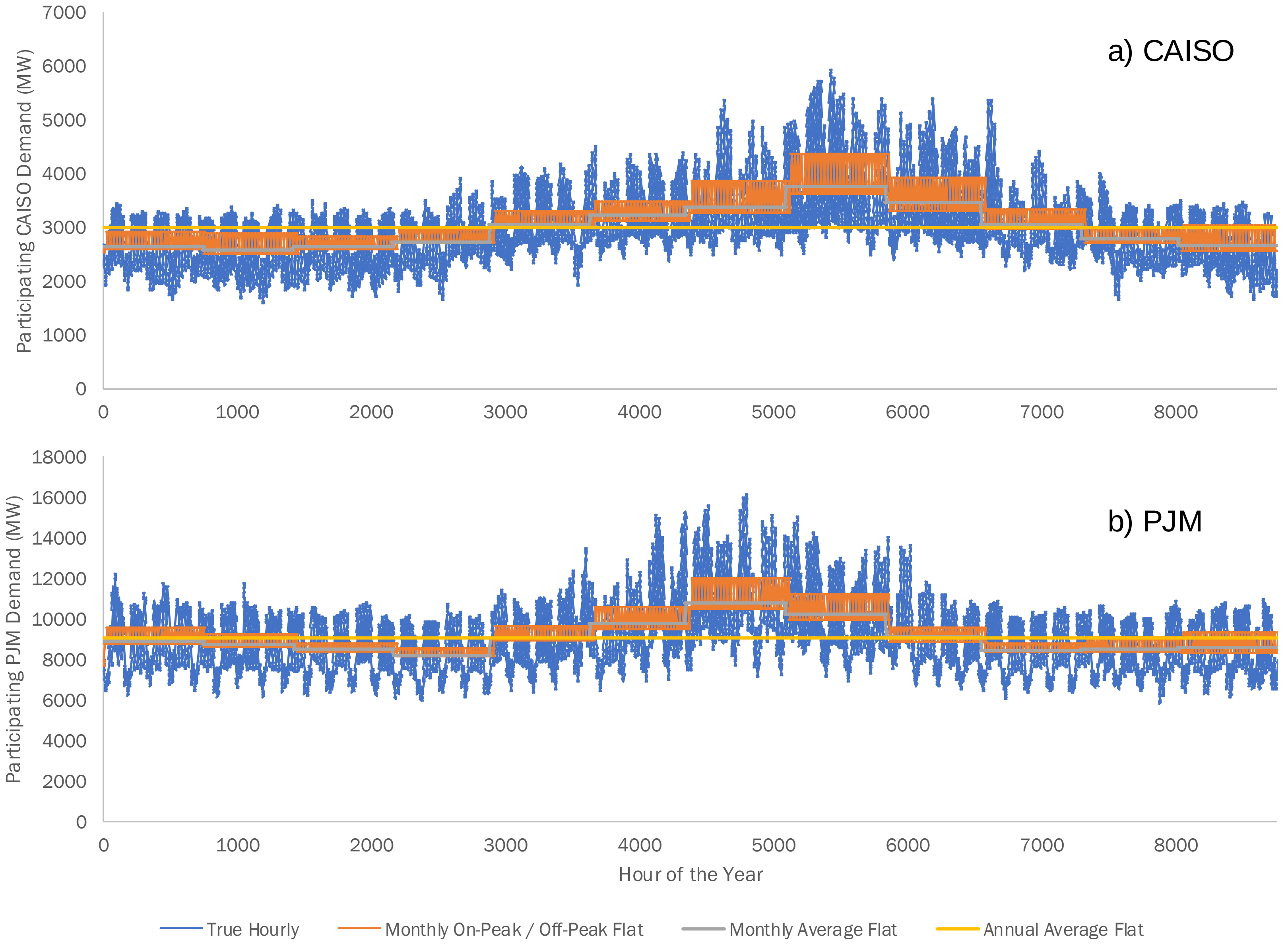


Figure 2: Hourly- and lower-granularity demand data representing 15% of C&I load in CAISO (top) and PJM (bottom) in the year 2030. Total participating demand is 26 TWh in CAISO and 79 TWh in PJM.

Measuring Impact

Consequential Impacts

- *How does use of estimated load profiles change the direct impacts of 24/7 CFE procurement on system-level outcomes?*
- The consequential impact of an action on metrics of interest (e.g. emissions) is measured by comparing system-level outcomes between two counterfactual scenarios where the action did and did not occur. Note that consequential emissions are not directly observable in reality, as they depend on a comparison to a counter-factual, but they can be estimated directly in this modeling framework.

Attributional Assessment

- *How does use of estimated load profiles change the calculated emissions attributed to a CFE buyer within a Scope 2 emissions inventory compared to a calculation based on the buyer's actual hourly profile?*
- Attributional emissions in each scenario are calculated by multiplying the shortfall in a buyer's CFE procurement with respect to its assumed demand by the local grid average emission rate (inclusive of imports) in each hour.

Results

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Key finding: System-level impacts of 24/7 CFE are relatively insensitive to demand-side granularity

System-level impacts of 24/7 CFE procurement on **net generation** from different clean and fossil-fired electricity resources are **relatively insensitive** to the precise demand-side profile being matched.

Small differences are sometimes noticeable, e.g. in the generation mixes for CAISO.

In line with prior work, changes in net generation by technology due to 24/7 CFE procurement do not precisely match changes observed when participating demand is removed.

Impacts on Net Generation

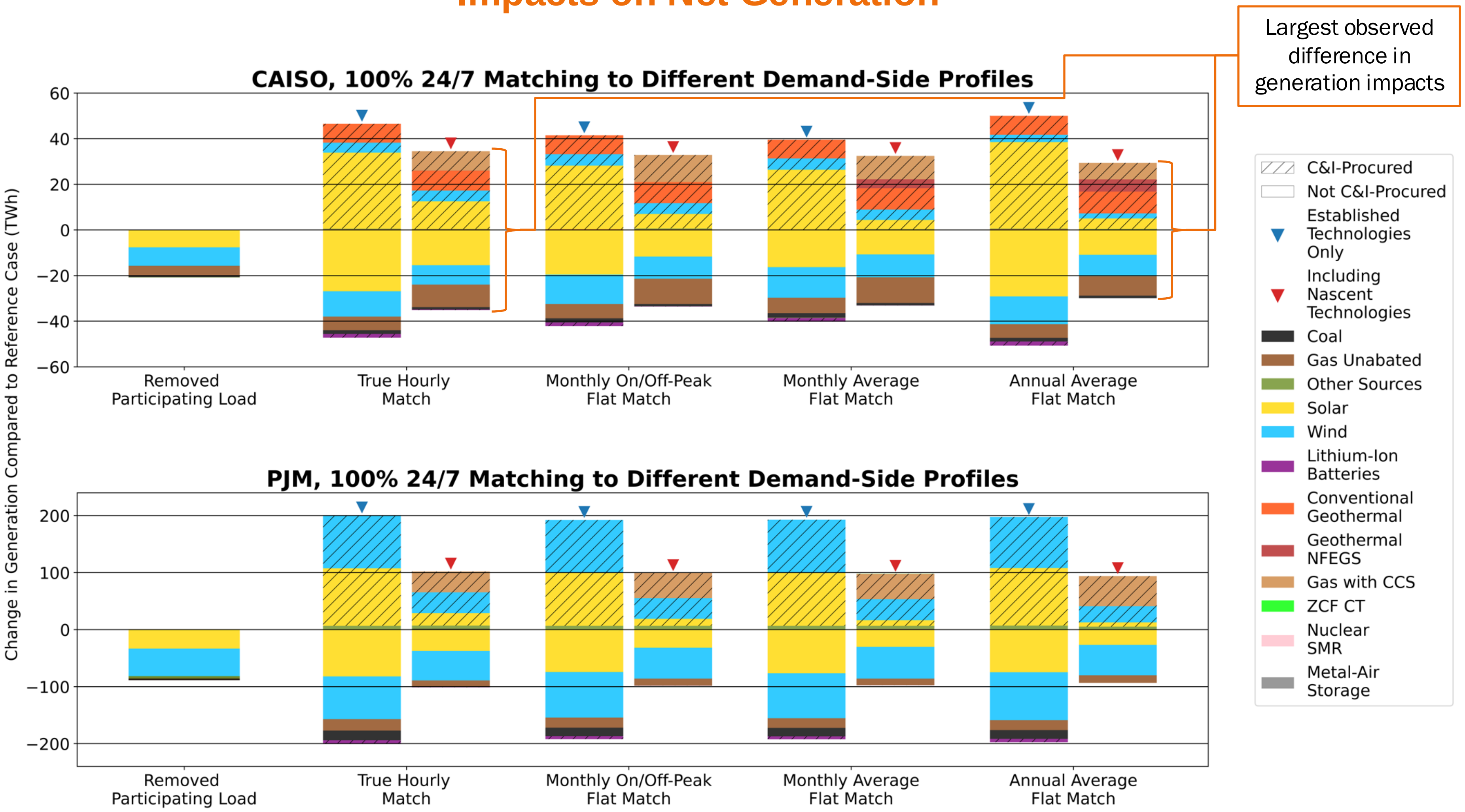

Figure 3: Observed changes in systemwide net generation by technology relative to a reference case where participating C&I demand does not procure any CFE, for cases with 100% 24/7 CFE matching targets in CAISO and PJM. The left column shows a scenario where instead of procuring CFE, the participating demand is removed from the system (simulating islanded self-supply). Other columns illustrate outcomes using different demand-side profiles under scenarios where only established technologies or both established and nascent technologies are available for procurement.

Key finding: System-level impacts of 24/7 CFE are relatively insensitive to demand-side granularity

System-level **emissions impacts** of 24/7 CFE procurement are **relatively insensitive** to the precise demand-side profile being matched.

There is **no demand-side profile** that consistently leads to the largest emission reduction, and total observed reductions **vary by no more than 25%.**

Note: we also ran cases where buyers pursued volumetric procurement and observed **no consequetnail impacts** on installed capacity, generation, or emissions in either PJM or CAISO.

Impacts on Emissions

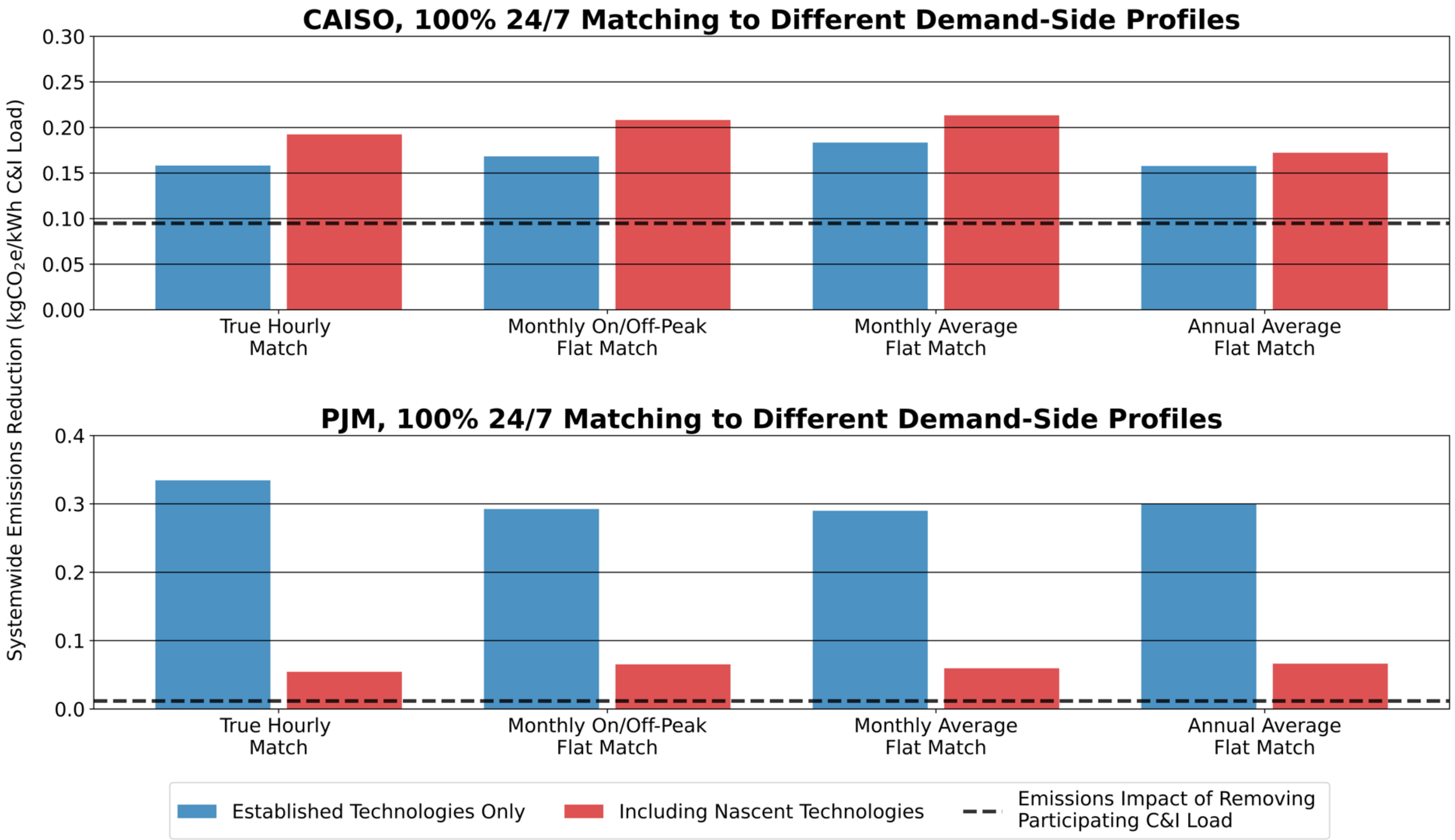

Figure 4: System-wide changes in greenhouse gas emissions for cases with 100% 24/7 CFE matching targets in CAISO and PJM. In this figure the dashed line indicates the emissions reduction observed when participating demand was removed from the system, and is presented as a benchmark for comparison. Impacts can exceed this benchmark due to over-procurement, different profile shapes for procured power and demand, and fundamental asymmetries between adding supply and subtracting demand (e.g. non-linear supply curves and/or physical resource limitations).

Key finding:
Cost premiums for 24/7 CFE participants are relatively insensitive to demand-side granularity

Electricity cost premiums paid by consumers procuring 24/7 CFE are also **relatively consistent** across cases with different demand shapes.

In CAISO cases, an annual average flat demand profile sees the greatest divergence from costs under true hourly profiles.

As with emissions, there is no consistent direction to the influence of the demand-side profile on participant costs across scenarios.

Impacts on Participant Costs

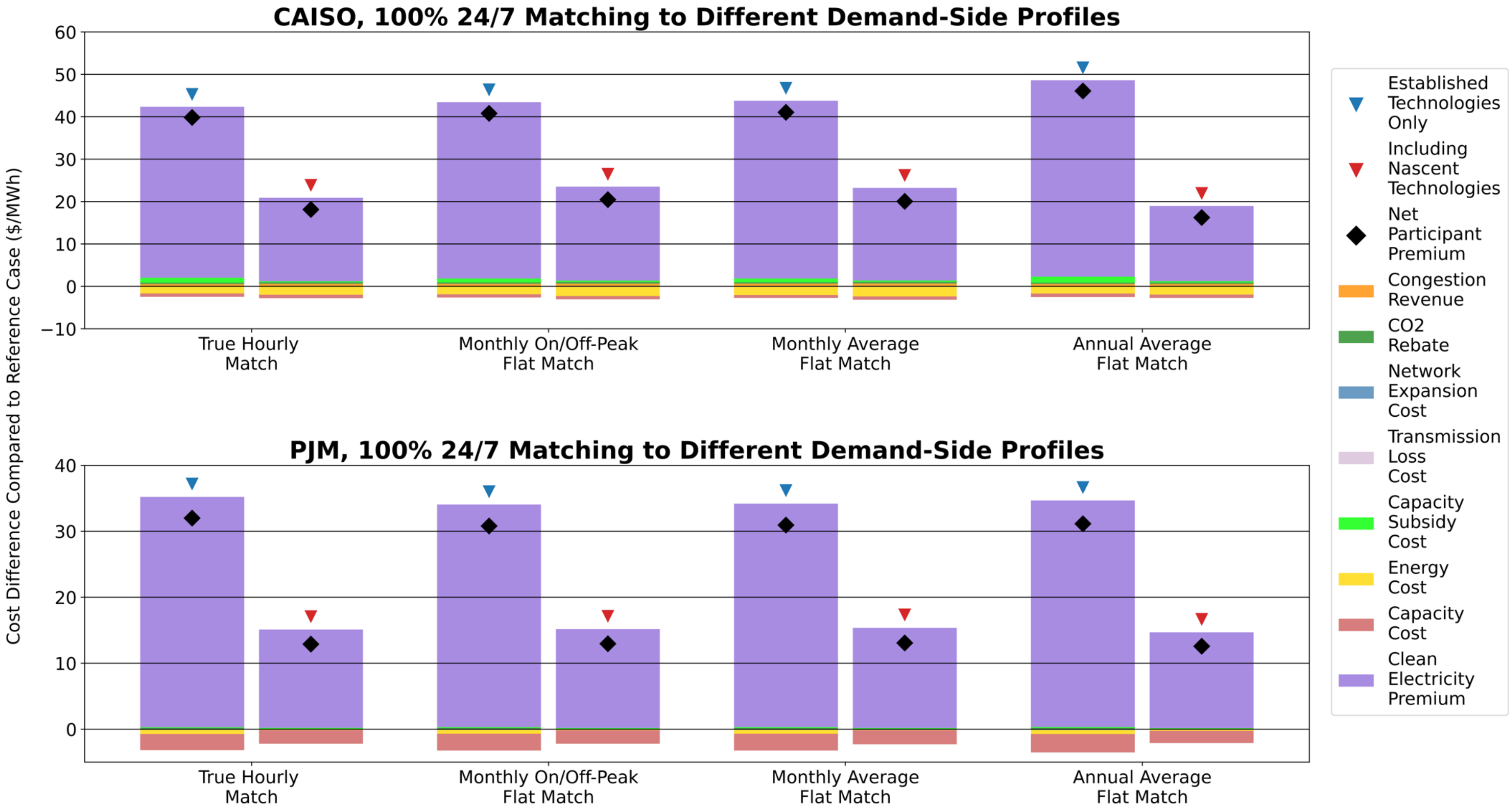

Figure 5: Change in total electricity costs for C&I consumers pursuing 24/7 CFE compared to a baseline where no CFE procurement takes place, for cases with 100% 24/7 CFE matching targets in CAISO and PJM. Costs are broken down by category and assume that all system costs are passed through to end users fully and efficiently based on their true hourly consumption. Baseline costs (without voluntary procurement) are $41.25/MWh for consumers in CAISO and $47.18 for consumers in PJM.

Key Finding: Optimal 24/7 CFE portfolios are moderately sensitive to demand-side granularity

As with generation impacts, capacity portfolios procured by 24/7 CFE participants are **qualitatively similar** under different demand-side matching targets, but can exhibit moderate variability.

Most differences arise from changes in wind, solar, and battery deployment (for example, changes in solar deployment between the 'True Hourly Match' and 'Annual Average Flat Match' cases with nascent technologies in CAISO). **Nascent technology deployment is similar across cases.**

Impacts on Capacity Deployment

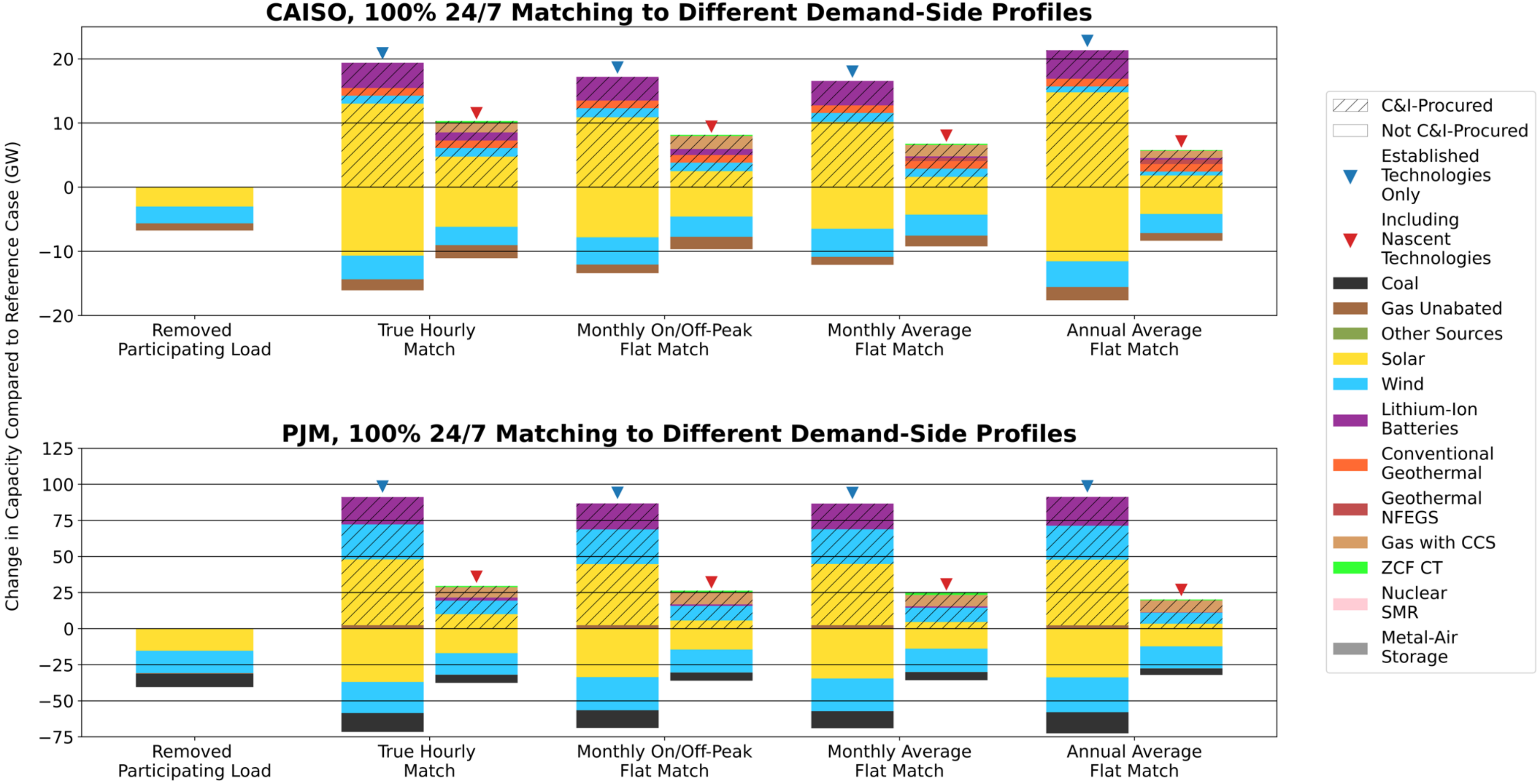

Figure 6: Observed changes in systemwide installed capacity relative to a reference case where participating C&I demand does not procure any CFE, for cases with 100% 24/7 CFE matching targets in CAISO and PJM.

Explaining the outcomes

Across all demand profiles, the **need for reliable clean capacity** (either delivered by clean firm resources or sufficient storage) is similar.

For example, nighttime capacity needs in CAISO (where wind resources are poor) are similar when matching to both hourly and annual average load profiles.

The resources that deliver this clean capacity are the same ones that **most consistently displace fossil resources** and account for the bulk of consequential emissions reductions.

Impacts on Net Generation over an Average Day

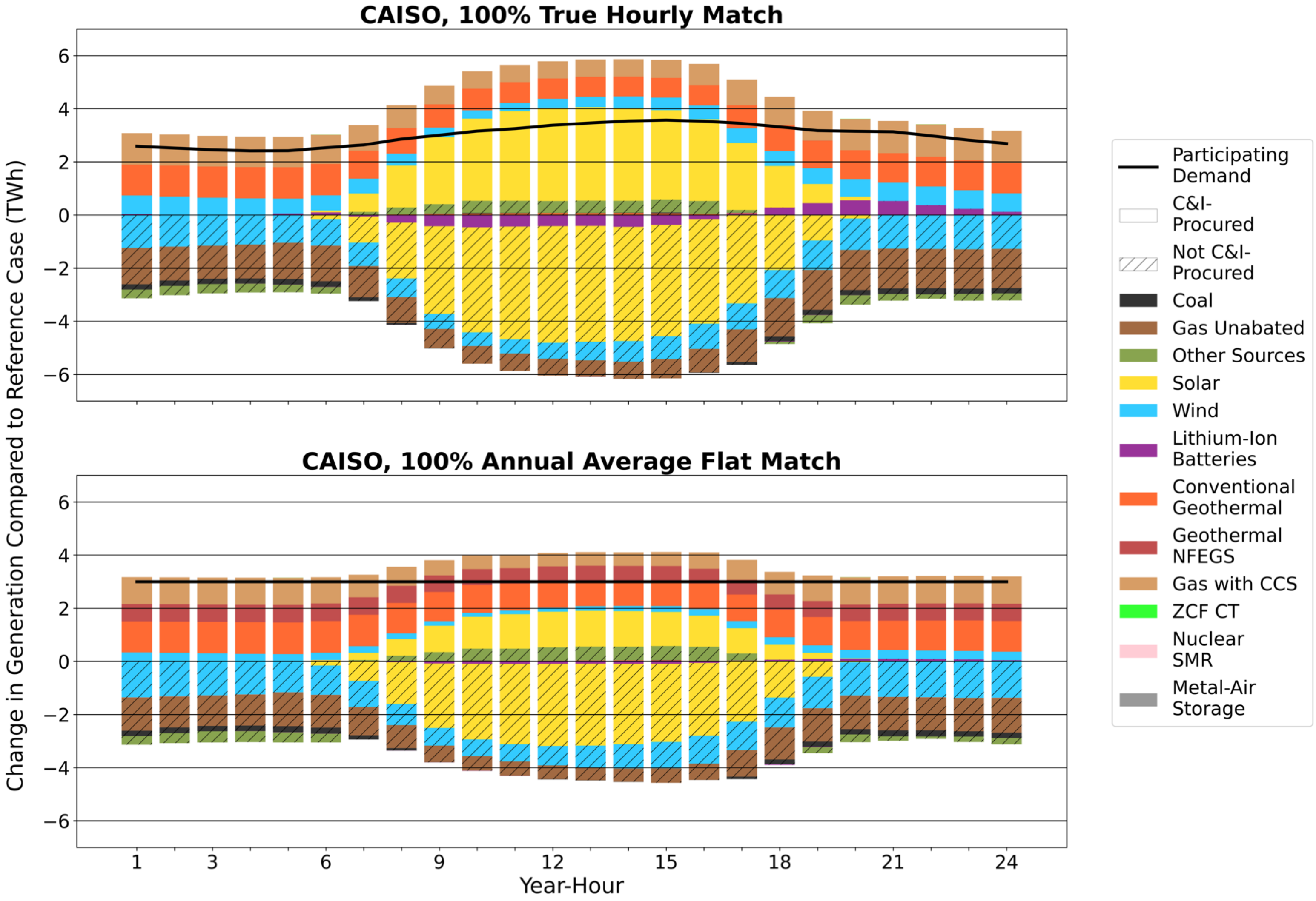

Figure 7: Change in hourly generation by resource over an average day in CAISO as a result of 24/7 CFE procurement against either a true hourly load profile (top) or an annual average flat load profile (bottom), for a scenario with nascent technologies available.

Key Finding: Outcomes are more consistent with lower matching targets

Technology procurement trends and emissions impacts are very consistent across demand shapes when the matching target is less than 100%.

Impacts on Net Generation

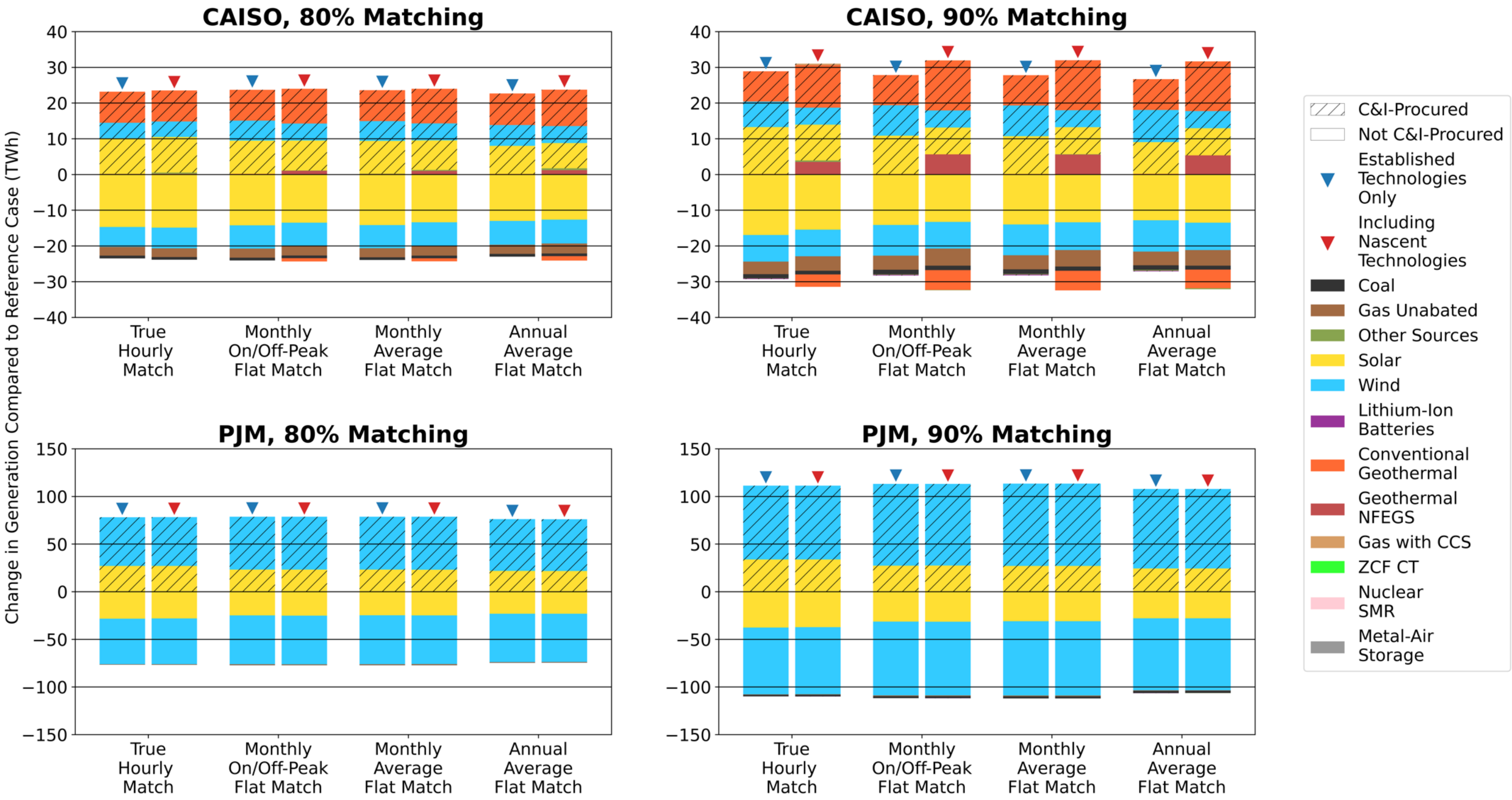

Figure 8: Changes in net generation by technology relative to a reference case case where participating C&I demand does not procure any CFE, for cases with 80% and 90% 24/7 CFE matching targets in CAISO and PJM.

Key Finding: Outcomes are more consistent with lower matching targets

Emissions impacts are similarly consistent with lower matching targets, and are notably lower than for cases with 100% matching.

This is because targets less than 100% CFE permit use of grid power during the most costly/challenging periods, which reduces the need for new clean capacity—and clean capacity is responsible for the bulk of consequential emissions impacts.

Impacts on Emissions

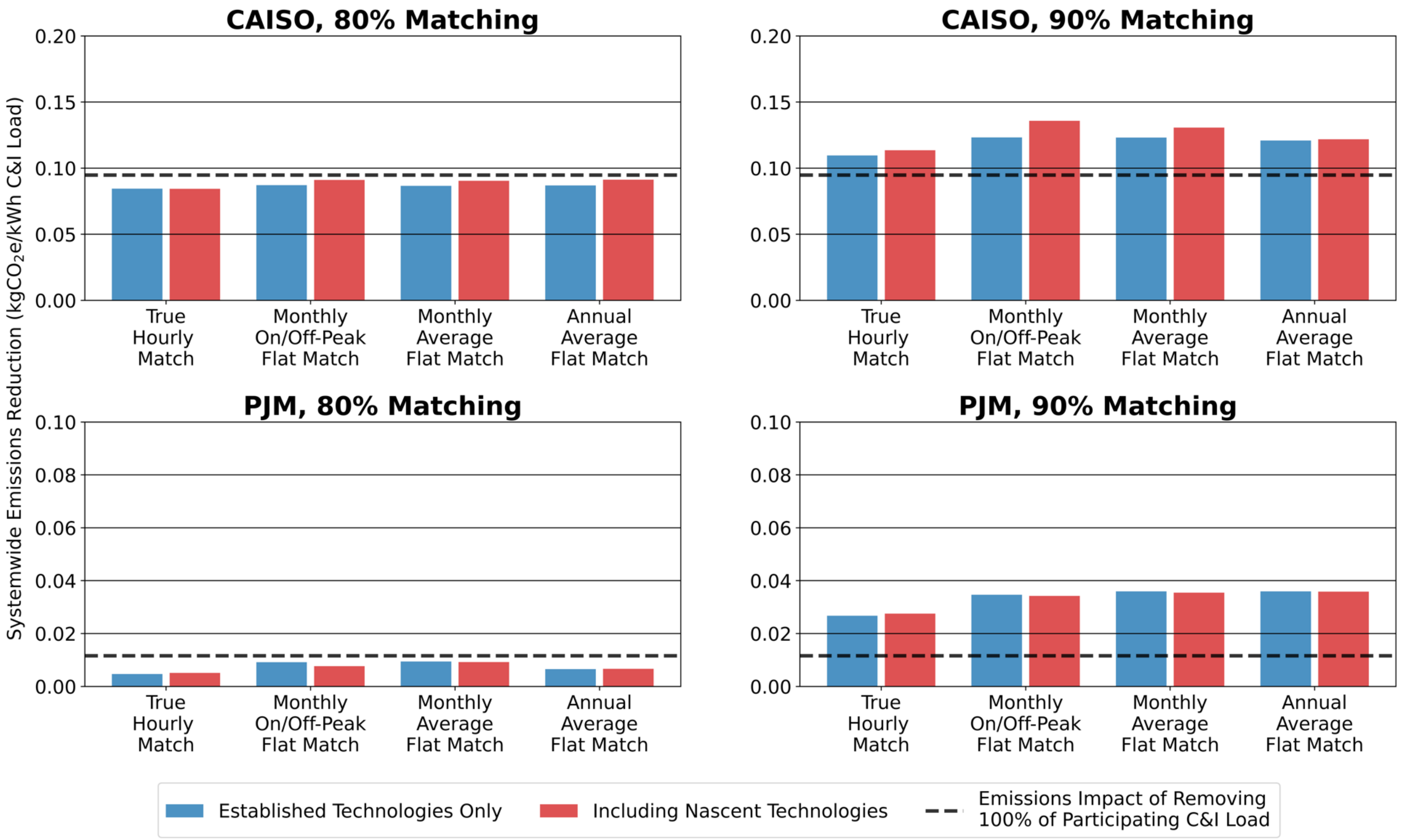

Figure 9: Changes in system-wide emissions relative to a reference case case where participating C&I demand does not procure any CFE, for cases with 80% and 90% 24/7 CFE matching targets in CAISO and PJM.

Key Finding: Outcomes are more consistent with lower matching targets

Costs are relatively consistent across cases with 80% and 90% matching targets, though the cost of 80% matching against a participant's true hourly load in CAISO is notably lower than the cost of matching against the approximate load profiles. This is because more of the participating demand's true hourly load is aligned with periods that can be met cost-effectively by solar power.

Impacts on Participant Costs

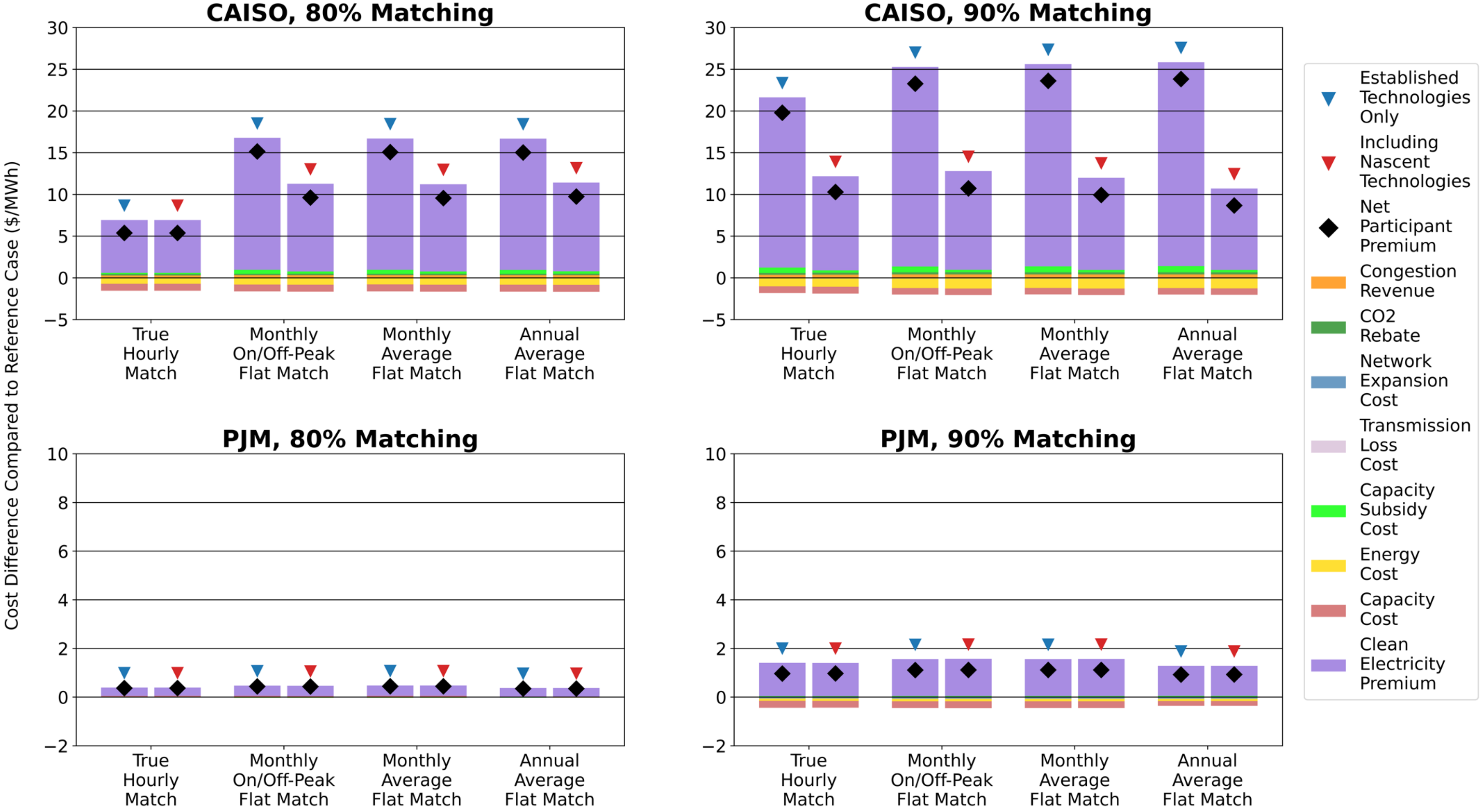

Figure 10: Change in total electricity costs for participating C&I consumers relative to a reference case case where participating C&I demand does not procure any CFE, for cases with 90% 24/7 CFE matching targets in CAISO and PJM.

Key Finding: Demand-side representations have little impact on the accuracy of attributional emissions accounting

The consequential outcomes reported above can only be observed by comparison of counterfactual scenarios, and thus cannot be incorporated into real-world emissions accounting. Instead, 'attributional' emissions accounting methodologies are typically used to assign grid emissions to consumers.

We find that under a granular attributional accounting system (see Slide 13), **the unavailability of hourly-granularity demand data for both matching and calculation has little impact on final reported values.** This is because the technology portfolios procured to match approximate demand profiles are very similar to those used to match the true demand.

Impacts on Reported Attributional Emissions

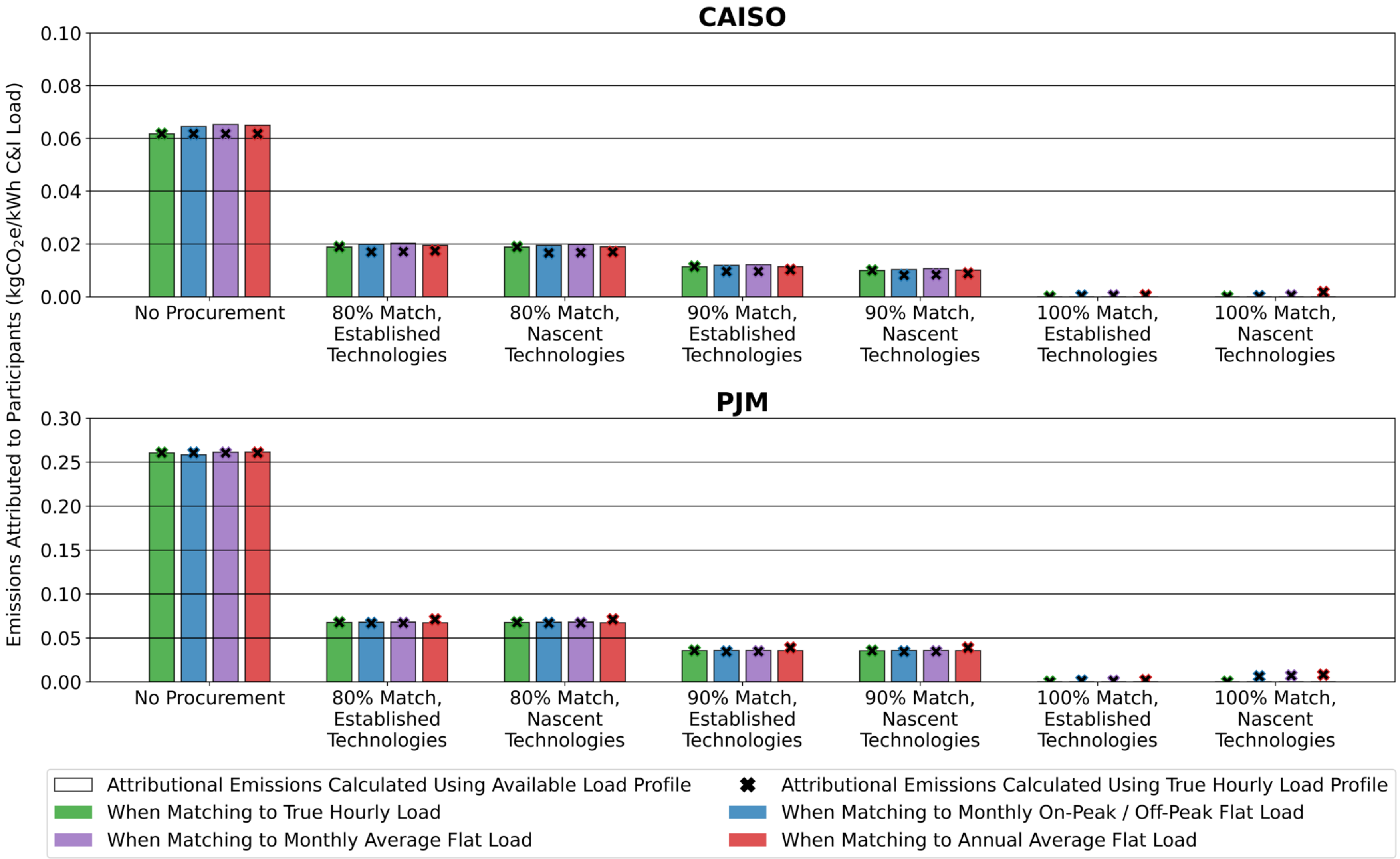

Figure 11: Reported attributional emissions for voluntary CFE buyers across scenarios with different matching targets, technology availability, and demand-side granularity. Bars show the hourly-average attributional emissions calculated and reported by participants based on the demand profiles they are able to access, and markers show the attributional emissions that would be reported in the same scenario if the buyer were able to use their true hourly load profile in the calculation.

Conclusions

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Results Summary

In summary, this study finds that:

- ➔ The system-level impacts of 24/7 CFE procurement are relatively consistent even when using an approximation of a consumer's true demand profile.
- ➔ System-level emissions and generation impacts of 24/7 CFE procurement are very consistent across different possible demand-side representations and are much more sensitive to other factors including system conditions, matching targets, and technology availability.
- ➔ Costs for participating consumers exhibit minor variability across different demand-side representations, with no consistent direction.
- ➔ Participants' incentives to procure nascent CFE generation and storage technologies are not significantly affected by use of estimated load profiles.
- ➔ Use of load profiles with different levels of granularity has very little impact on the accuracy of granular attributional emissions accounting; technology portfolios procured to match approximate profiles are very similar to those used to match the true demand.
- ➔ All of the above findings are consistent whether consumers pursue 100% 24/7 CFE matching or a lower target matching percentage.

Implications

Broader implications of our results include the following:

- ➔ Access to hourly-granularity demand data is not strictly necessary for electricity consumers to drive significant consequential emissions reductions and additional technology adoption through 24/7 carbon-free electricity procurement.
- ➔ Near-term efforts to match procured CFE with an approximation of a buyer's load profile are not incompatible with a long-run goal of matching with the buyer's true hourly load profile, as the technology portfolios needed to accomplish each goal are very similar.
- ➔ Costs for buyers are similar regardless of the precise load profile being matched, suggesting that there is not a financial incentive to use estimated profiles when accurate hourly data is available.
- ➔ However, access to hourly data will still be required for buyers to unlock the benefits of demand-side flexibility, which can significantly reduce[1] the cost of 24/7 CFE matching. Increasing data access should still be a priority.
- ➔ The accuracy of hourly-granularity Scope 2 emissions accounting is not significantly impacted when an estimated demand profile is used in attributional emissions calculation, suggesting that such an accounting system can retain its integrity if hourly-granularity demand data is not universally available to participants.

1. Riepin, I. and Brown, T., "The value of space-time load-shifting flexibility for 24/7 carbon-free electricity procurement." 2023. https://doi.org/10.5281/zenodo.8185849

Limitations and Opportunities

While the system modeling approach used in this report is the most robust available means of assessing the full impacts of electricity system interventions, it also involves various assumptions and abstractions that could limit the applicability of results to real systems. These include limited spatial granularity, assumptions of perfect foresight, and a lack of modeled market frictions. These limitations are discussed in greater detail in Xu et al. (2024). Here we note several additional limitations that are specifically relevant to the analysis conducted in this report and which could provide motivation for future work:

1. The hourly electric load profiles used in this report are representative of the entire aggregated C&I demand in each target region. In reality, individual consumers have more diverse load profiles for which outcomes may differ from those reported here (as an extreme example, imagine a consumer that only uses power during the day). While our results are therefore applicable to the average C&I consumer, future work should explore the range of possible C&I load profiles and the extent to which these results hold for various individual consumers.
2. To enable an apples-to-apples comparison of the impacts of 24/7 CFE procurement using load profiles of varying granularity, this work does not explicitly consider the role of demand-side flexibility (i.e. load-shifting) in meeting a 24/7 CFE target, as this is only relevant when matching to a consumer's true hourly load profile. The cost benefits of unlocking demand-side flexibility could be significant, as shown in existing literature, and may provide a strong incentive for participants to move toward use of more granular load profiles. Future work should assess the extent to which these benefits could incentivize adoption of granular metering by consumers in various industries.

Appendix: Experimental Methods

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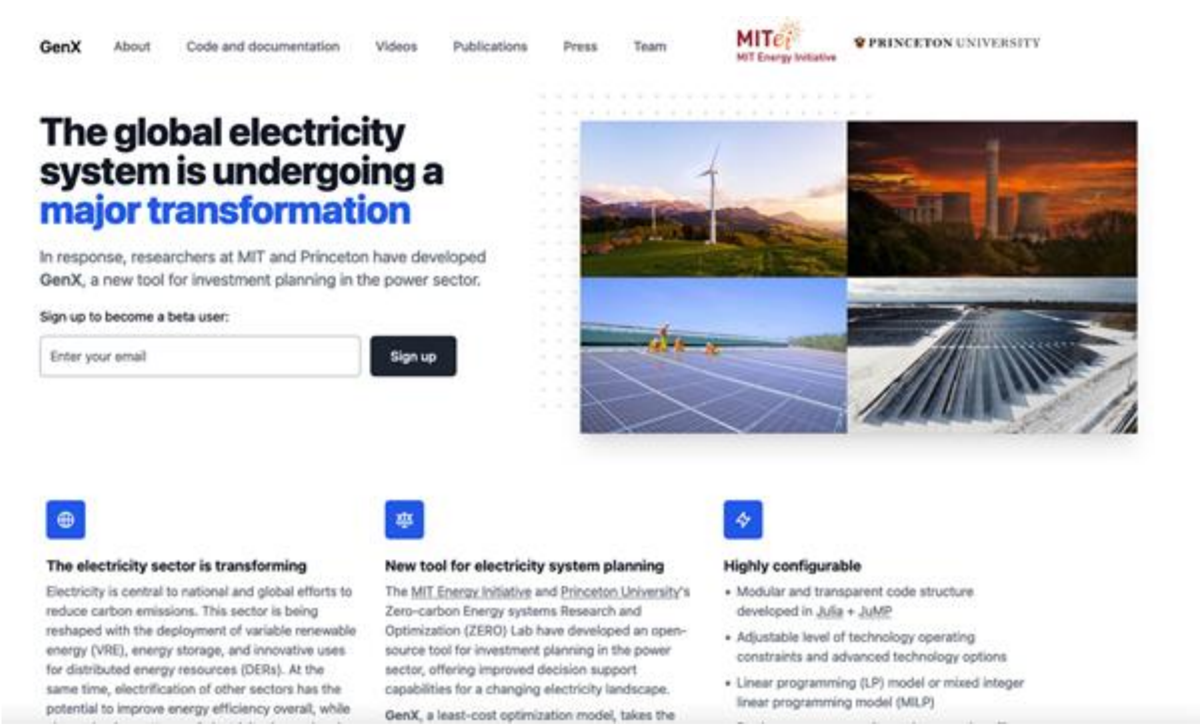
GenX: an Electricity System Planning Tool

- ➔ Open-sourced & highly configurable
- ➔ Optimization based (LP or MILP)
- ➔ Objective:
  - ◆ Minimize system cost (equivalent to maximizing welfare w/opportunity cost of price elastic demand curtailment)
- ➔ Decision variables:
  - ◆ Generation / storage / inter-regional transmission expansion, retirement, and operations
- ➔ Subject to
  - ◆ Operation limits and unit commitment
  - ◆ Hourly operations and renewable resources/demand variability
  - ◆ Siting constraints & renewable energy supply curves
  - ◆ Policies including carbon pricing/RPS/CES/ technology-specific mandates
  - ◆ Resource adequacy (capacity reserve margin/capacity market)
- ➔ Modular and transparent code structure developed in Julia + JuMP



https://energy.mit.edu/genx/
https://github.com/GenXProject/GenX

Experimental Design: 24/7 CFE Procurement

- We use the same modified version of GenX used in Xu et al. (2024) to model voluntary procurement of 24/7 CFE by participating C&I electricity consumers.
- Participants must procure enough qualifying CFE to meet a specified matching target (equal to a percentage of their total annual electricity consumption).
- Participants can only claim consumption of CFE that is: a) generated in the same hour for which it is claimed, b) generated in the same target region as the participating demand (i.e. CAISO or PJM), and c) generated by a newly-built resource.
- Charging by procured storage devices is added to participants' effective hourly electricity demand.
- Participants can claim consumption of CFE in a given hour in an amount less than or equal to their demand in the same hour (based on the load profile they are attempting to match, and inclusive of storage charging).
- Any net power procurement beyond what participants are able to consume in a given hour is counted as 'excess' and is assumed to be resold to the market. To reflect participants' aversion to unhedged merchant exposure, all excess power sales are assigned a $5/MWh risk premium in the model. This risk premium is not factored into the calculation of actual costs for participants.

New-Build Technology Assumptions

Technology	Technology Class	2030 Power CAPEX ($/kWac) / Energy CAPEX ($/kWh)	Annualized Power CAPEX + Interconnection Cost + FOM + Pipeline cost for CCS ($/MW-year)	Annualized Energy CAPEX + FOM ($/MWh-year)	VOM ($/MWh)	Heat Rate (MMBTU /MWh)	Capacity Factor	Round-Trip Efficiency / Duration Limit	Original Cost Assumption Reference (data processed by PowerGenome)
Solar†	Established	1,242	99k – 160k	-	-13.26 – -14.46	-	21-31%	-	NREL ATB 2024
Onshore Wind†	Established	1,306	126k – 440k	-	-13.96 – -15.22	-	12-52%	-	NREL ATB 2024
Battery*	Established	203 / 163	26k – 28k	21k – 22k	0.15	-	-	85% / 1 – 10 hours	NREL ATB 2024
Offshore Wind*	Established	2,929	336k – 28k	-	0	-	33-54%	-	NREL ATB 2024
Geothermal (Hydrothermal)*	Established	2,231 – 2,371	405k – 422k	-	0	-	92%	-	Ricks and Jenkins (2024)
Geothermal (Near-Field EGS)*	Nascent	4,950 – 10,577	482k – 1030k	-	0	-	92%	-	Ricks and Jenkins (2024)
Nuclear Small Modular Reactor*	Nascent	6,199	544k – 650k	-	3.52	10.45	-	-	Baik et al., 2024.
Metal-Air Long-duration Storage*	Nascent	882 / 9	98k – 106k	1k	0.15	-	-	42% / 100 – 150 hours	Baik et al., 2024.
ZCF or Natural Gas Combustion Turbine	Nascent	1,295	113k – 143k	-	7.24	9.72	-	-	NREL ATB 2024
Natural Gas Combined Cycle	Nascent	1,473	131k – 168k	-	2.08	6.13	-	-	NREL ATB 2024
Natural Gas Combined Cycle w/97% CCS	Nascent	2,672	240k – 273k	-	-7 – -11	7.04	-	-	NREL ATB 2024 + CO_2 sequestration costs from Larson et al. 2021

- All costs are given in post-subsidy 2023 USD.
- (*) indicates technologies that are assumed to receive the Inflation Reduction Act's technology-neutral investment tax credits, while (†) indicates technologies that receive the production tax credit. NGCC+CCS plants are assumed to receive the 45Q carbon sequestration credit. All non-investment tax credit values are adjusted to reflect their effective value over a 30-year plant financial lifetime based on technology-specific costs of capital.
- NREL (National Renewable Energy Laboratory). 2024. "2024 Annual Technology Baseline." Golden, CO: National Renewable Energy Laboratory. https://atb.nrel.gov/.
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Fuel and Carbon Price Assumptions

Fuels

Fuel	CO_2 Content (tCO_2/MMBTU)	Western Interconnection Price Range ($/MMBTU)	Eastern Interconnection Price Range ($/MMBTU)	Original Cost Assumption Reference (data processed by PowerGenome)
Coal	0.09552	1.87	1.83-2.62	EIA AEO 2022
Natural Gas	0.05306	4.72-4.89	3.50-4.60	EIA AEO 2022
Fuel Oil	0.07315	22.88-24.11	18.37-25.32	EIA AEO 2022
Uranium	0	0.82	0.82	EIA AEO 2022
Zero-Carbon Fuel (Biomethane)	0	40	40	EPA RIN Trades and Price Information

- All costs are given in 2023 USD.
- Conventional fuel costs sourced from EIA (Energy Information Administration) Annual Energy Outlook 2022. https://www.eia.gov/outlooks/archive/aeo22/
- Biomethane fuel cost based on latest data from EPA (Environmental Protection Agency) RIN Trades and Price Information page: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information

Carbon Prices

Policy	Assumed 2030 Price ($/$tCO_2$)	Affected Model Zones	Reference
California Cap-and-Trade	50	CA_N, CA_S	Extrapolation from current trends
Regional Greenhouse Gas Initiative	20	ISONE, NY_E, NY_W, PJM_MACC	Extrapolation from current trends

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