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Zero-carbon Energy Systems Research and Optimization Laboratory

System-level Impacts of 24/7 Carbon-free Electricity Procurement

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Note: This study is published in the spirit of a working paper for public dissemination prior to peer review. Final publications based on this report will be subject to further peer review and may be revised.

- Introduction and Motivation……5
- Key Findings……………………14
- Summary…………………………...19
- Summary of Methods…………….....20
- Experimental Design and Key Assumptions……………………….28
- California Results………………...38
- PJM Results……………………...54
- Sensitivity Analysis……………….68
  - C&I Participation Rates, California…68
  - C&I Participation Rates, PJM………73
  - Natural gas price……………………78
  - Technology support policies………...80
  - Higher clean energy standards……....82
- Limitations and Future Work……..84
- Conclusions and Implications……90

Introduction and Motivations

- Voluntary purchases of renewable energy by corporate, institutional, and government entities have historically procured a significant share of U.S. wind and solar resources.
- In 2020 alone, large energy buyers in the U.S. procured 10.6 gigawatts of new renewable energy (see figure on following slide), representing about 1/3rd of all renewable energy capacity additions in the United States that year.
- A growing number of companies, universities, municipalities, and individuals have opted to purchase enough renewable energy to match 100% of their annual consumption of electricity (100% annual matching). Many are members of RE100, an organization focused on this approach.
- In the best cases, this voluntary procurement drives additional and accelerated deployment of wind and solar capacity, above and beyond policy requirements.
- Accelerating deployment of clean energy reduces greenhouse gas emissions and helps drive the transformation of the electricity sector by driving wind and solar down "experience curves," which refers to the collection of mechanisms by which costs decline as cumulative capacity deployed increases: e.g. due to learning-by-doing, incremental innovation, process improvements, economies of scale, and financial innovation and experience.
- Many early actors in this space also helped pave the way for followers by establishing standard contracting and procurement methods and building investor confidence in financing wind and solar projects.

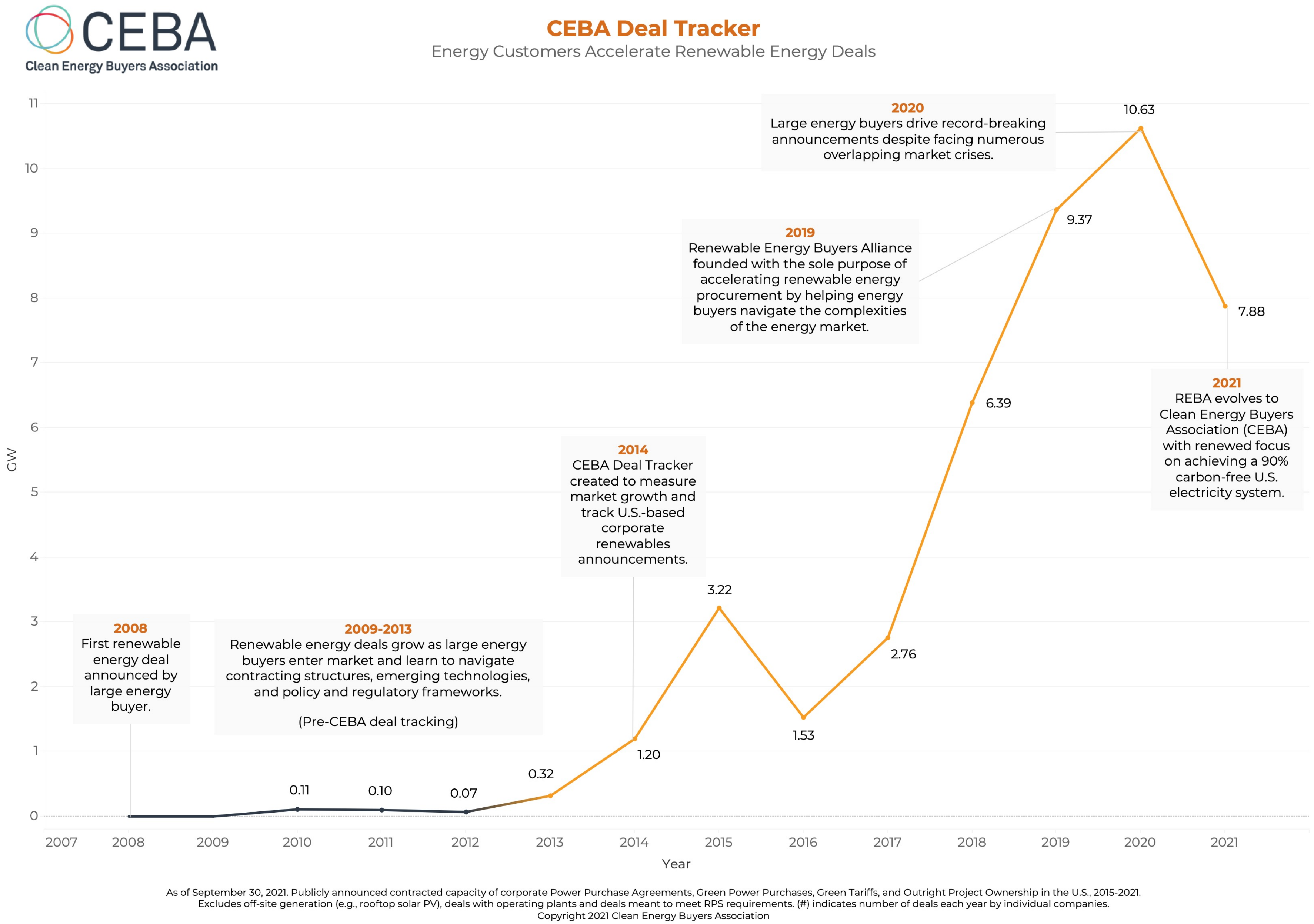
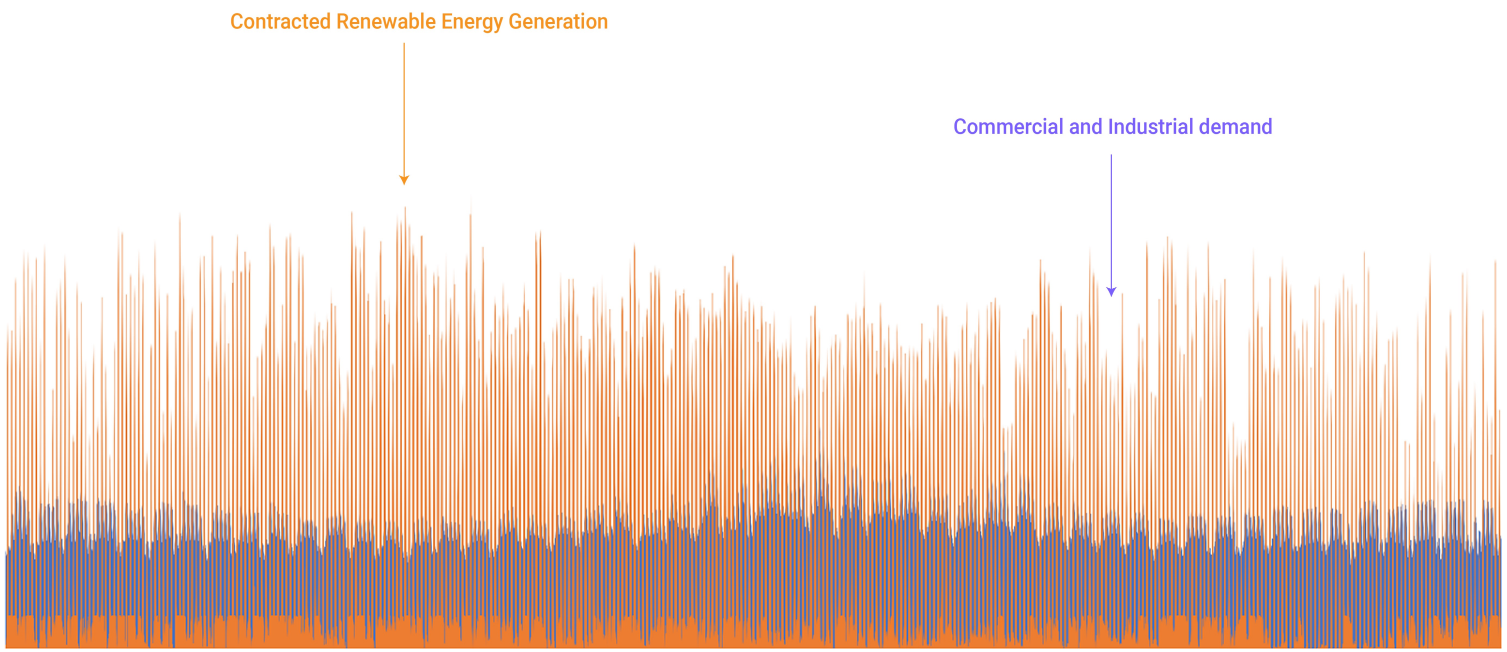


Image source: Clean Energy Buyers Alliance (CEBA), https://cebuyers.org/deal-tracker/

- While 100% annual matching reduces CO_2 emissions and helps drive clean energy growth, the variable generation of wind and solar power purchased by a voluntary buyer is unlikely to align with the timing of the buyer's electricity consumption (see figure below).
- During times when the wind isn't strong or the sun doesn't shine, voluntary buyers have to rely on carbon-emitting power plants such as coal or gas-fired generators.
- Additionally, some buyers procure 'renewable energy certificates' or RECs, from locations far away from their consumption and 'unbundled' from long-term electricity purchases. This practice de-links generation and consumption in both space and time, provides less revenue certainty for clean energy projects, and creates a more tenuous link between buyers and the clean energy they claim to consume.

Example annual time profile of hourly renewable energy generation contracted to match 100% of annual participating commercial and industrial demand in PJM.



The next frontier in clean energy procurement is to match a buyer's electricity demand, hour-by-hour, 24/7, with corresponding clean electricity generation from within the same electricity grid region as the buyer's operations.

This is 24/7 carbon-free electricity procurement.

- A growing number of leaders in voluntary clean energy procurement, from Google and Microsoft to the U.S. Federal Government are working to procure 24/7 carbon-free electricity (CFE) to match their hourly electricity use as closely as possible.
- 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 40 companies, governments, and organizations.

Google Pledges 24/7 Carbon-Free Energy by 2030

NEWS BRIEF

24/7 Carbon-Free Energy Is the New Net-Zero

Des Moines, Iowa, joins Google in aiming for 24/7 carbon-free electricity—a target that necessitates managing energy loads in buildings.

by Candace Pearson

Capitol Report

Biden pledges to buy 24/7 carbon-free electricity pushed by Clean Air Task Force, Google and others

Last Updated: March 31, 2021 at 8:03 p.m. ET
First Published: March 30, 2021 at 6:03 p.m. ET

By Rachel Koning Beals

Federal government, a huge purchaser of power, says it will promote demand-driven, regional green electricity use

AFP/GETTY IMAGES

Microsoft Announces New 100/100/0 Commitment By 2030

24/7 carbon-free electricity procurement has the potential to:

1. Enable much **deeper reductions in CO_2** emissions from electricity consumption than 100% annual matching;
2. Replicate the **transformative impact** voluntary procurement has had on wind and solar **for a set of advanced, "clean firm" power generation and long-duration energy storage technologies** that can make the broader transition to 100% carbon-free electricity more affordable and readily achievable; *and*
3. **Hedge price volatility and risk** for the electricity buyer by providing long-term fixed price contracts for electricity that match the time and location of electricity consumption.

Options for voluntary corporate and institutional leadership on clean energy and climate mitigation

	Carbon Offsets *Can enable carbon neutrality and maximize emissions reductions per dollar spent* achieved by purchasing carbon offsets that reduce or prevent global emissions	**100% Annual Matching (Unbundled RECs)** *Can indirecly reduce emissions and support renewable energy* achieved by purchasing renewable electricity attributes / credits (RECs) separately from electricity purchases	**100% Annual Matching (Electricity contracts)** *Can reduce emissions and directly support renewable energy* achieved by purchasing renewable electricity attributes / credits and electricity via long-term contracts	**24/7 Carbon-free Electricity** *Can eliminate emissions from electricity consumption and transform electricity grids* achieved by procuring electricity and associated attributes from a portfolio of resources to match a buyer's electricity demand, hour-by-hour, 24/7, with corresponding clean electricity generation within the same electricity grid region	OR	**Carbon-optimized Procurement** *Can maximize emissions reductions from an electricity portfolio* achieved by financially supporting and operating a portfolio of resources to maximize emissions reductions in some grid region
Helps combat climate change	✅	✅	✅	✅		✅
Accelerates full-scale transformation of electricity grids	❌	❌	❌	✅		❓
Eliminates all carbon-emissions associated with the buyer's electricity use	❌	❌	❌	✅		❌
Directly reduces carbon emissions associated with the buyer's electricity use	❌	❌	✅	✅		❌
Matches *annual* electricity consumption with clean energy	❌	✅	✅	✅		❌
Matches *hourly* electricity consumption with clean energy	❌	❌	❌	✅		❌
Supports investment in clean electricity	❌	❓	✅	✅		✅
Supports investment in clean electricity *in the electric grid region where your electricity is consumed*	❌	❌	✅	✅		❓
Hedges price volatility/risk for the electricity buyer	❌	❌	❓	✅		❌
Maximizes overall emissions reductions per $ spent	✅	❌	❌	❌		❓
Maximizes overall emissions reductions per megawatt-hour generated	❌	❌	❌	❌		✅

This study represents the first analysis of the electricity system-level impacts of 24/7 carbon-free energy procurement (24/7 CFE).

- We use a detailed open-source electricity system optimization model, GenX, which plans investment and operational decisions to meet projected future electricity demand while meeting all relevant engineering, reliability, and policy constraints at lowest cost.
- In this study, we implement a set of new constraints to model the impact of a share of corporate and industrial (C&I) electricity consumers participating in voluntary 24/7 CFE procurement, where a portfolio of carbon-free generation from within the same grid region is used to meet hourly electricity demand profiles of participating C&I consumers.
- We model impacts of 24/7 CFE procurement in two regional power systems: California and the PJM Interconnection. These two systems differ in patterns of electricity demand, weather, renewable resource quality, state policy, and existing generation capacity and help generalize the impacts of 24/7 CFE procurement.
- For comparison, we also model reference cases with no voluntary procurement and cases where the equivalent share of C&I consumers meet 100% of annual energy demand on a volumetric basis with renewable energy procurement (100% annual matching). This case assumes procured renewable energy is from within the same model region and is 100% additional to state RPS requirements.*

* These assumptions are more restrictive than the current market-based method for Scope 2 emissions accounting in the GHG Protocol, which has a larger market boundary (permitting procurement from anywhere in the U.S.) and does not distinguish between unbundled RECs and direct purchases of renewable electricity via long-term contract.

We focus this analysis on the impacts of 24/7 carbon-free electricity procurement on:

1. The greenhouse gas emissions rate associated with electricity used by participating corporate and industrial (C&I) electricity consumers;
2. Electricity generation and storage technologies deployed as part of the 24/7 CFE portfolio;
3. Electricity generation and storage technologies deployed at the regional grid level;
4. Electricity system-level greenhouse gas emissions (and emissions abatement);
5. Costs of emissions abatement; and
6. Costs of electricity for participating C&I electricity consumers.*

* Note that we find that increases in system-level costs resulting from 24/7 CFE procurement are fully internalized and paid for by participating C&I customers, so we do not separately present system-level cost impacts in this study.

24/7 carbon-free electricity (CFE) procurement…

1. **Can eliminate carbon dioxide emissions associated with a buyer's electricity consumption, going beyond the impact of procurement of renewable energy to meet 100% of annual volumetric demand.**
   - CO_2 emissions associated with electricity consumed by participating C&I customers are significantly lower than 100% annual matching (for all modeled CFE scores 80% or greater) due to better alignment between electricity consumption and generation, which reduces periods of reliance on emitting grid-supplied electricity.
   - At 100% CFE, 24/7 procurement can completely eliminate emissions associated with participating customer's electricity consumption.
   - 100% annual matching reaches a CFE of 75% in California and 62% in PJM.

24/7 carbon-free electricity (CFE) procurement…

2. Can drive greater system-level emissions reductions than 100% annual matching if the CFE target is high enough.

- System-wide emissions reductions are driven by two effects: (1) a timing effect, in which CFE supply is better matched to demand, generally increasing the displacement of natural gas-fired generation and associated emissions at times when wind and solar generation are low, and (2) a volume effect where a larger/smaller total quantity of CFE generated by the procured resources displaces more/less emitting generation, which can vary depending on the composition of the 24/7 portfolio and how much excess generation it produces.
- The timing effect becomes more important and the volume effect less important as the share of variable renewable energy in a regional grid increases, and vice versa (e.g. California vs PJM).
- For California (PJM) with 10% C&I participation rate, 24/7 procurement cuts emissions more deeply than 100% annual matching for CFE targets of 88% (92%) or greater.

24/7 carbon-free electricity (CFE) procurement…

3. **Drives early deployment of advanced, 'clean firm' generation and/or long-duration energy storage, creating initial markets for deployment, innovation, and cost-reductions that make it easier for societal at large to follow the path to 100% carbon-free electricity.**
   - Depending on cost assumptions, 24/7 portfolios include conventional and advanced geothermal, advanced nuclear, natural gas power plants w/CCS, gas plants using zero-carbon fuels and/or long duration energy storage (while 100% annual matching procures solar and wind only).
   - Higher CFE targets drive more advanced energy technology deployment.
   - If 10% of C&I customers participate and reach 100% CFE, 1.9-2.3 GW of clean firm generation and long-duration storage capacity is deployed in California and 5.9-7.1 GW in PJM by 2030.
   - The mix of resources is sensitive to relative costs, local resource availability (e.g. geothermal in California, nuclear in PJM), and policy support for different advanced energy technologies (e.g. the 45Q CCS tax credit).

24/7 carbon-free electricity (CFE) procurement…

4. **Better matches participating demand during periods of limited supply and thus drives significantly more retirement of natural gas generating capacity than 100% annual matching.**

- The wind and solar exclusively procured by 100% annual matching portfolios have relative low capacity substitution value, displacing only 12.5 MW per 100 MW of capacity deployed in California and 22 MW per 100 MW of capacity deployed in PJM (capacity substitution falls as system-wide renewable energy penetration increases).
- Clean firm generation in 24/7 portfolios (e.g. geothermal, nuclear, natural gas w/CCS, zero-carbon fuel plants) displaces natural gas generating capacity on a one-for-one basis.
- If 10% of C&I customers participate and reach 100% CFE, natural gas combined cycle capacity deployed on California by 2030 is reduced by 1.9-2.3 GW (vs only 400 MW for 100% annual matching) and 6.2-7.5 GW in PJM (vs 4 GW for 100% annual matching).

24/7 carbon-free electricity (CFE) procurement…

5. **Comes at a more significant cost premium relative to 100% annual matching; this premium is significantly reduced if a full portfolio of clean firm resources is available and procured and/or CFE targets below 100% are selected.**

   - At 10% C&I participation rate, reaching 100% CFE costs 39% (54%) more than business as usual electricity costs in California (PJM), when a full portfolio of clean firm resources is available spanning high fixed/low variable cost options like geothermal or nuclear to low fixed/high variable cost options like generators running on a zero-carbon fuel such as hydrogen.
   - With only currently mature technologies (wind, solar, batteries, demand flexibility and, in California only, conventional geothermal), reaching 100% CFE costs 64% (139%) more in California (PJM).
   - Targeting 98% CFE (or lower) can be significantly lower cost than 100% CFE, as filling the final gap between participating demand and carbon-free electricity supply can be costly.

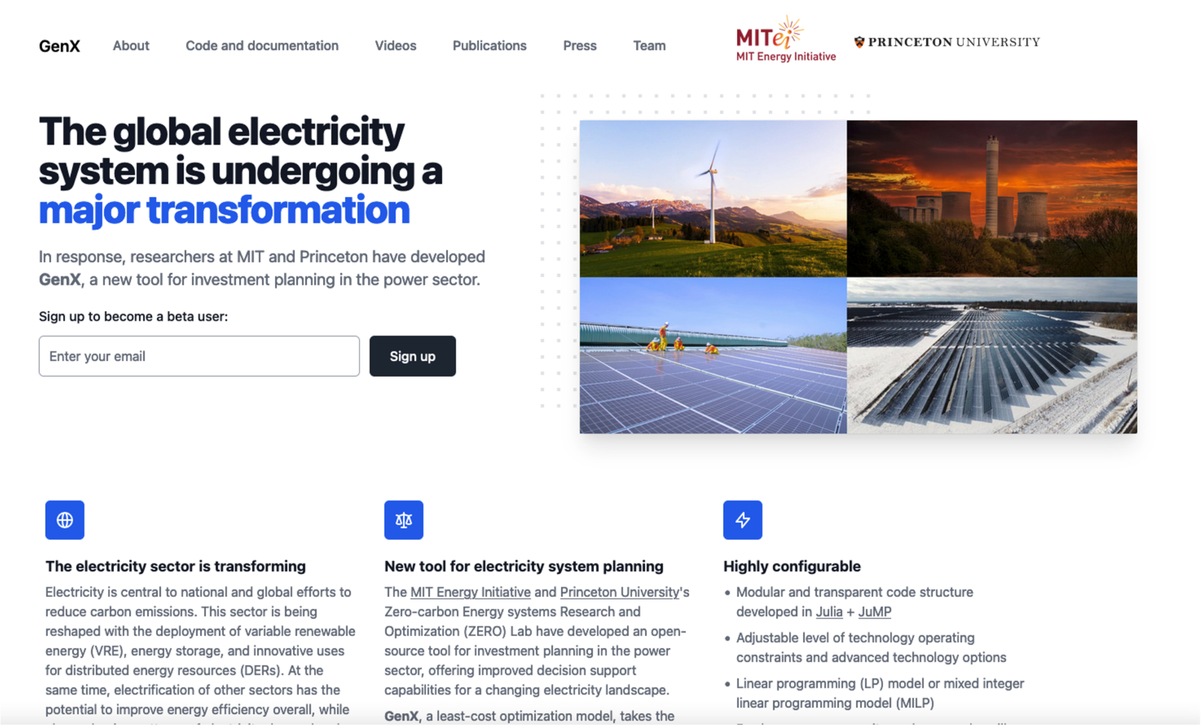
This study finds that 24/7 carbon-free electricity enables deeper emissions reductions and deeper transformation of the electricity sector than 100% annual matching by driving early deployment of advanced clean firm and long-duration energy storage technologies. But it does so at a potentially significant cost premium for early leaders, a premium paid to accelerate innovation, maturity, financeability, and widespread availability of clean firm resources that can make it much easier for broader society to follow on the path to a 100% carbon-free grid. Just as 100% annual matching helped transform wind and solar PV from expensive "alternative energy sources" to mainstream, affordable options for the world, 24/7 procurement is likely to have similar transformative impacts on clean firm resources.

Summary of Methods

GenX, Modeling 24/7 purchase and carbon-free electricity (CFE) score, Modeling grid-level carbon-free electricity (CFE) score, Evaluating emissions and costs

GenX: an electricity system planning tool

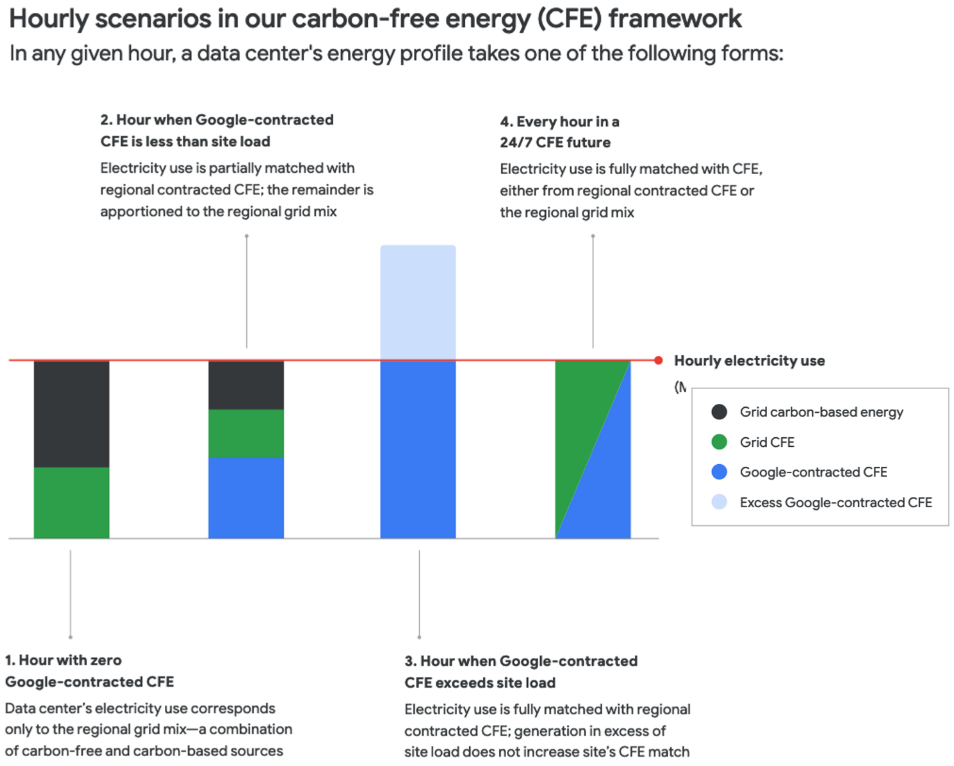
- Open-sourced & Highly configurable
- Optimization based (LP or MILP)
- Objective:
  - Minimize system cost (equivalent to maximizing welfare w/opportunity cost of price elastic demand curtailment)
- Decision variables:
  - Generation / storage / inter-regional transmission expansion, retirement, and operations
- Subject to
  - Operation limits and unit commitment
  - Hourly operations and renewable resources/demand variability (in this study: PJM 12x7 days; WECC: 18x7 days)
  - 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

Modeling 24/7 carbon-free electricity matching (additional constraints to GenX, based on Google's CFE framework)

Google's 24/7 CFE procurement framework



Google, "24/7 Carbon-Free Energy: Methodologies and Metrics," 2021, Available: https://www.gstatic.com/gumdrop/sustainability/24x7-carbon-free-energy-methodologies-metrics.pdf

GenX Constraints

Constraint 1: Hourly matching

$$Demand_t + DemandResponseUp_t - DemandResponseDown_t + ContractedStorageCharge_t - ContractedStorageDispatch_t = TotalContractedCFE_t - Excess_t + GridSupply_t$$

Grid supply occurs when hourly demand from participating consumers is > total contracted CFE generation in that hour (Columns 1 & 2 in the diagram at left). Excess occurs when hourly demand < total contracted clean generation (Column 3). Storage and demand flexibility can help to accommodate clean generation by shifting hourly net load.

Constraint 2: CFE Target

$$\frac{\sum_t (TotalContractedCFE_t - Excess_t + GridSupplyCFE_t * GridSupply_t)}{\sum_t (Demand_t + ContractedStorageCharge_t - ContractedStorageDispatch_t)} \geq CFETarget$$

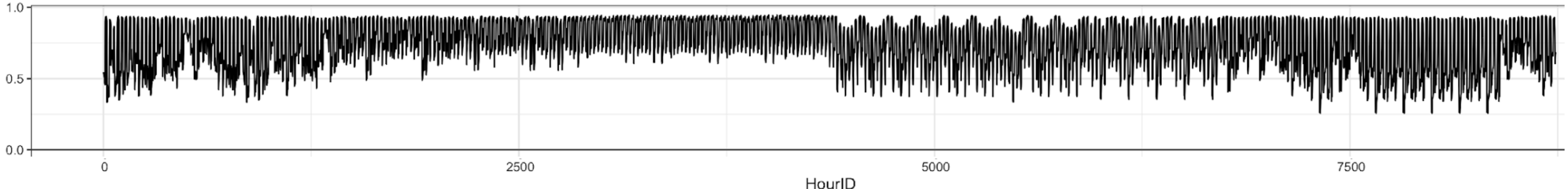
This constraint states that the ratio between the total consumed CFE and the total load + net storage loss must be higher than a certain target on an annual basis.

Constraint 3: Excess Limit

$$\frac{\sum_t (Excess_t)}{\sum_t (Demand_t + ContractedStorageCharge_t - ContractedStorageDispatch_t)} \leq ExcessLimit$$

The total amount of hourly excess generation cannot be higher than a certain level on an annual basis. In this study, this limit is set as the CFE target less 80 percentage points; e.g., if target is 100% CFE, 20% excess is allowed.

Example of $GridSupplyCFE_t$: how much the grid supply is clean energy; (California, year 2030, simulated by GenX).



Estimating carbon-free electricity in the grid supply

A key step in implementing this modeling framework is to calculate the share of carbon-free electricity (CFE) in grid supply used to meet deficits in hourly 24/7 procurement; that is, for each MWh of electricity withdrawal from the grid to supply participating 24/7 loads, what percentage of MWh are supplied by clean energy in a given hour. Because both our study regions (PJM and California) are embedded in larger interconnections (Eastern Interconnection, EI and Western Electricity Coordinating Council, WECC), it is also important to estimate what share of imports into the study region is produced by carbon-free and emitting sources.

Here are the steps of calculating the Grid Supply CFE.

Step 1: Calculate the net import into California / PJM from the rest of the region

$$Import_t = \max(0, TotalWithdraw_t - Injection_t)$$

Step 2: Calculate the average cleanness of the rest of the system and the imported clean power. Using the notation on the right, this is calculated as:

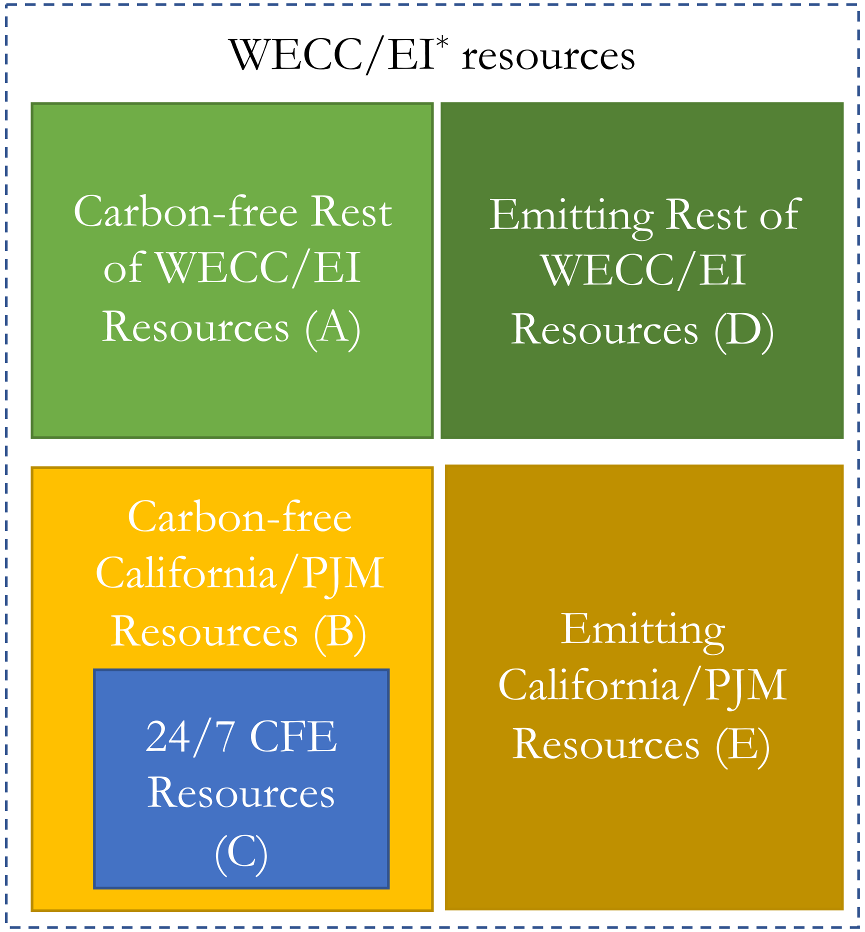
$$ImportedCFE_t = \frac{A_t}{A_t + D_t} * Import_t$$

Step 3: Calculate the average CFE share of the grid supply. Because 24/7 consumers contract specifically with 24/7 resources, these resources are not considered as part of the general grid supply.

$$GridSupplyCFE_t = \frac{B_t - C_t + ImportedCFE_t}{B_t - C_t + E_t + Import_t}$$

In hours when California/PJM is not importing, this formula reduces to:

$$GridSupplyCFE_t = \frac{B_t - C_t}{B_t - C_t + E_t}$$

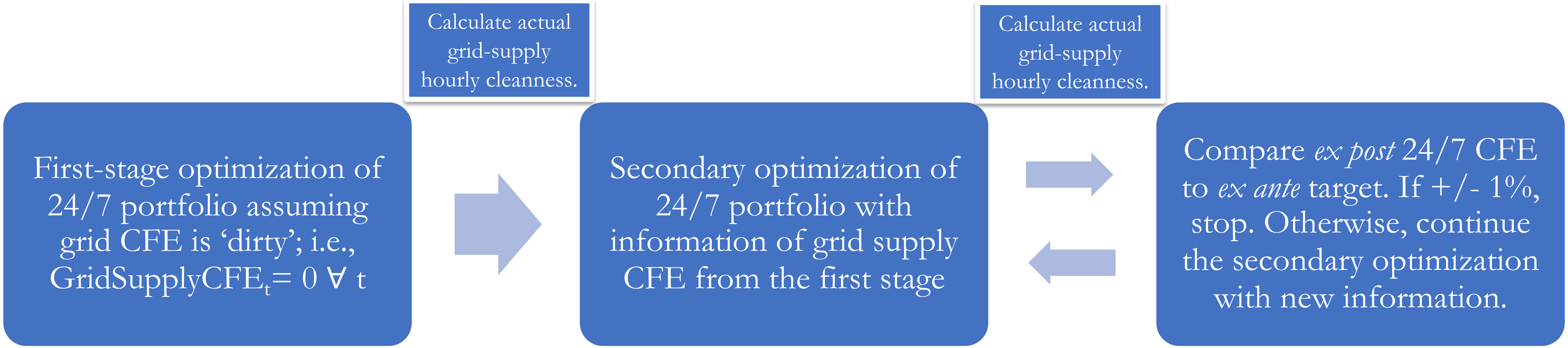


*In this study, we cover the neighboring regions of PJM in EI, namely NYISO, parts of MISO, and part of SERC, including TVA, NC and SC. See study region for more details.

Forcing the model to anticipate the hourly grid supply cleanness in the CFE Target constraint will introduce nonconvexity and cannot be solved using linear programming. That is, nonlinearity will arise if $GridSupplyCFE_t$ and $GridSupply_t$ are both variables in the CFE Target Constraint:

$$\frac{\sum_t (TotalContractedCFE_t - Excess_t + GridSupplyCFE_t * GridSupply_t)}{\sum_t (Demand_t + ContractedStorageCharge_t - ContractedStorageDispatch_t)} \geq CFETarget$$

Here, we use an iterative planning process to overcome this difficulty:*



*The planning process for the cases considered here converges (with less than 1% error in calculated CFE) with one forward pass, which we consider adequate for this study.

Calculating CO_2 emissions rate of generation that serves participating 24/7 demand

We calculate the long-run CO_2 emissions associated with electricity consumed by participating C&I customers using the process below.* Because both our study regions (PJM and California) are embedded in larger interconnections (EI and WECC), the calculation also considers emissions associated with imported emissions. The emissions avoided by 24/7 procurement is calculated as the difference in emissions associated with participating load with or without 24/7 procurement.

Here are the steps of calculating CO_2 emissions associated with electricity consumed by 24/7 participating demand and the California/PJM system.

Step 1: Calculate the net import into California / PJM from the rest of the region

$$Import_t = \max(0, Totalwithdraw_t - Injection_t)$$

Step 2: Calculate the average emissions rate of the rest of the WECC/EI and the imported emissions; Using the notation on the right, and denote the emissions of the rest of the system as X_t, we have:

$$ImportedEmission_t = \frac{X_t}{A_t + D_t} * Import_t$$

Step 3: Calculate the average emissions rate of the grid supply. Denote the emissions of California/PJM as Y_t. Part of Y_t is from 24/7 resources (e.g., residual emissions from gas natural gas w/90% CO_2 capture rate), which is denoted as Z_t. For 24x7 consumers, the grid supply emissions rate is:

$$GridSupplyEmissionRate_t = \frac{Y_t - Z_t + ImportedEmission_t}{B_t - C_t + E_t + Import_t}$$

For California/PJM, the system emissions rate is:

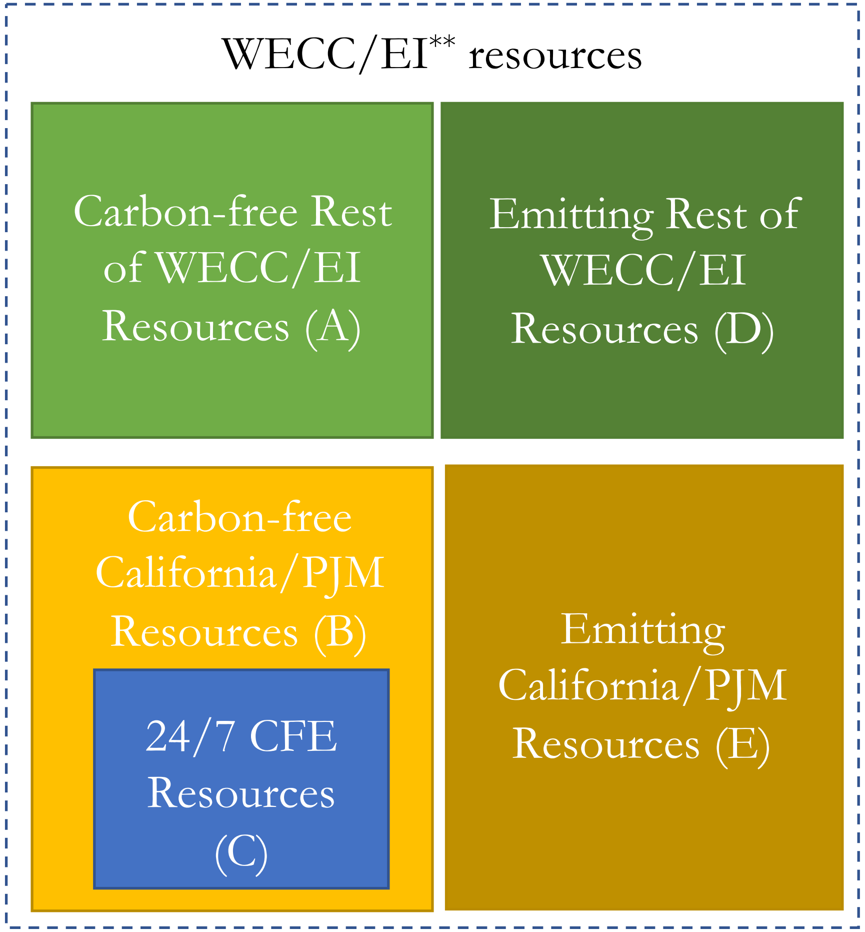
$$SystemLoadEmissionRate_t = \frac{Y_t + ImportedEmission_t}{B_t + E_t + Import_t}$$

Step 4: Calculate total CO_2 emissions for 24/7 participating customers for that hour:

$$Emission_t = GridSupply_t * GridSupplyEmissionRate_t + Z_t$$

The total CO2 emissions for the whole grid system (California/PJM) in that hour is:

$$SystemLoadEmission_t = Load_t * SystemLoadEmissionRate_t$$



*Note that this is a process to link the emissions from the supply-side to the demand-side and to allocate the emissions from the system-level to the sub-system-level. Only a long-run average emission is appropriate in this context.

Calculating avoided system-level CO_2 emissions due to 24/7 CFE procurement.

With capacity expansion planning tool like GenX, we are able to estimate emissions at the electricity system level (or regional level such as PJM or California) before and after implementing 24/7 CFE procurement. (See the previous slide for calculation details.) The emissions avoided by 24/7 CFE procurement can thus be calculated as the difference in system-wide emissions in cases with and without 24/7 CFE procurement.

For instance, suppose the emission of the system (California or PJM) is E_1 without any participation of C&I loads in 24/7 CFE procurement (the Reference case), and the emissions in a case with 10% of C&I loads participating in 24/7 CFE procurement is E_2. The emissions avoided by 24/7 procurement is simply ($E_1 - E_2$).

We calculate avoided emission for each case and for each level of participation of C&I loads in 24/7 procurement.

Why not use the marginal emission rate: There is another valid way of estimating system-level avoided emissions using marginal emission rates, or more precisely, the emissions rate of the marginal generating units. This approach is usually applied while evaluating the avoided emissions at an individual project level. However, this approach is only valid when the marginal units of the energy market do not change (much) before and after adding a certain clean energy project. This assumption does not hold if a large amount of CFE enters the system, as we will see in this study. As such we focus on long-run incremental changes related to the introduction of 24/7 CFE procurement to the system.

Cost calculations: system costs, load and generation settlements, and costs for 24/7 participating consumers

The cost of electricity supply for LSEs (load serving entities) and profit for generation companies (GenCos) rely on the settlement calculation included in GenX. Here is a brief summary. Check the GenX documentation for details.

LSEs cost is the net of the following items:

- Energy payment.
- Capacity payment/Resource adequacy payment.
- Renewable/Clean Energy Credit payment for RPS/CES compliance.
- Non-served energy cost (opportunity cost of voluntary and involuntary demand curtailment).
- Allocated CO_2 revenue: GenX assumes by default that CO_2 allowance revenue (if any) are transferred back to consumers.
- Allocated transmission cost and congestion revenue: LSEs are assumed to receive congestion revenues (e.g. from congestion revenue right auctions or financial transmission rights) and pay the cost of transmission expansion.

GenCo profit is the net of the following items:

- Energy revenue.
- Energy charging cost (storage only).
- Capacity revenue.
- Renewable/Clean Energy Credit revenue.
- Annualized Capex
- Fixed operation and maintenance cost (FOM)
- Variable operation and maintenance cost (VOM)
- Fuel cost
- Carbon tax or allowance payment

Electricity costs for 24/7 participating C&I consumers: the cost is the LSE Cost for participating demand + the profit from the GenCos that supply 24/7 customers. This implicitly assumes 24/7 participating C&I load captures any generator rents, shared with the C&I loads as either lower PPA prices or via ownership of generation in the 24/7 portfolio. If generators maintain bargaining power, they may retain some portion of this rent, increasing costs for 24/7 participating loads.

The system cost of the region is the net of all LSE cost and GenCo's profit in that region. If the system is isolated, every thing will be canceled out except Annualized Capex, FOM, VOM, Fuel Cost, and Non-Served Energy Cost. At the scale of an individual grid region, net revenues from exports/imports are also included in system costs.

Experimental Design and Key Assumptions

Experimental Design (for PJM and WECC)

For both PJM/WECC		Reference	100% Annual MWh matching scenario: C&I load procure CFE resources such that the annual MWh procured = annual demand	24/7 Hourly Matching Scenarios (80% to 100% CFE target with 2% steps)
	C&I Demand Participation Rate	0%	10%	10%
Available Tech-nology	Current Technologies	1 case	1 case	11 cases
	Advanced Technologies, No Combustion	1 case	1 case	11 cases
	Advanced Technologies, Full Portfolio	1 case	1 case	11 cases

100% Annual Matching case: In this case, the participating customers aim to procure a portfolio such that the total MWh generation from the portfolio = annual energy consumption of the participating customers. Grid supply cleanness is ignored. Emissions/cost calculations are the same as for 24/7 participation load, and the only difference is the grid supply, CFE score and hourly excess generation are calculated *ex post*.

- For instance, without actively considering if the CFE generation matches with the hourly demand, a consumer might sign a PPA with a solar farm generating 100 GWh/yr because their annual load is 100 GWh/yr. The excess and grid supply can be calculated by contrasting the actual hourly generation of this solar farm and the hourly electricity consumption of that consumer, and the associated CFE score computed for each hour.

Available Technology:

- Current Technologies: Wind, solar, battery storage + conventional geothermal (WECC only).
- Advanced Technologies, No Combustion: Current Tech. + long-duration metal-air storage + advanced nuclear (excluding California) + near-field enhanced geothermal (California only).
- Advanced Technologies, Full Portfolio: Above + natural gas combined cycle gas turbine (CCGT) with CCS (90% post-combustion CO_2 capture rate) + CCGT with zero-carbon fuel (ZCF, e.g., hydrogen, synthetic methane, biomethane, ammonia). Note that, technically, CCGT w/ 90% CCS is not carbon-free, but we include it here as it is the CCS technology that is closest to mature compared to other CCS technologies like Allam Cycle.

Sensitivities: 5% and 25% participation rate, high natural gas price, system-wide 80% Clean Electricity Standard, and no 45Q support for CCS.

Key Methodology assumptions

Assumption 1 (A1): A group of electricity consumers (e.g., 10% of commercial and industrial [C&I] load) form an alliance and sign contracts with clean power plants so that their aggregated hourly consumption can be matched on an hour-by-hour basis with clean generation to achieve an annual hourly carbon-free electricity (CFE) matching target (CFE score).

A2: A set of CFE resources are available in the model for 24/7 participating loads to procure (distinct from and incremental to general resources available to meet general grid needs). These 24/7 CFE candidates share the development potential with resources that are available for general grid needs. This assumption also means that 24/7 participating loads do not contract with any resources already online as of 2021.

- For instance, suppose a candidate project area can accommodate up to 500 MW of solar panels. If a solar farm for 24/7 CFE procurement uses 300 MW, a solar farm for general grid needs can at most be 200 MW; vice versa.

A3: The 24/7 procurement is conducted by signing power purchase agreements (PPA) and these PPA contracts cover every product type of the contracted CFE resource, including energy, capacity, and renewable/clean energy credits. As a result, total revenue earned by the CFE resources (e.g., energy and capacity) and the cost of building/operating the CFE resources are passed to the 24/7 participating load alliance. This also implies 24/7 participating C&I load captures any generator rents, shared with the C&I loads as either lower PPA prices or via ownership of generation in the 24/7 portfolio. If generators maintain bargaining power, they may retain some portion of this rent, increasing costs for 24/7 participating loads.

A4: 24/7 participating loads must also meet existing RPS/CES rules. Furthermore, through PPA, 24/7 participating loads obtain and completely retire renewable/clean energy credits generated by contracted CFEs to satisfy their RPS/CES obligations and do not resell any excess credits to other parties (e.g. general loads).

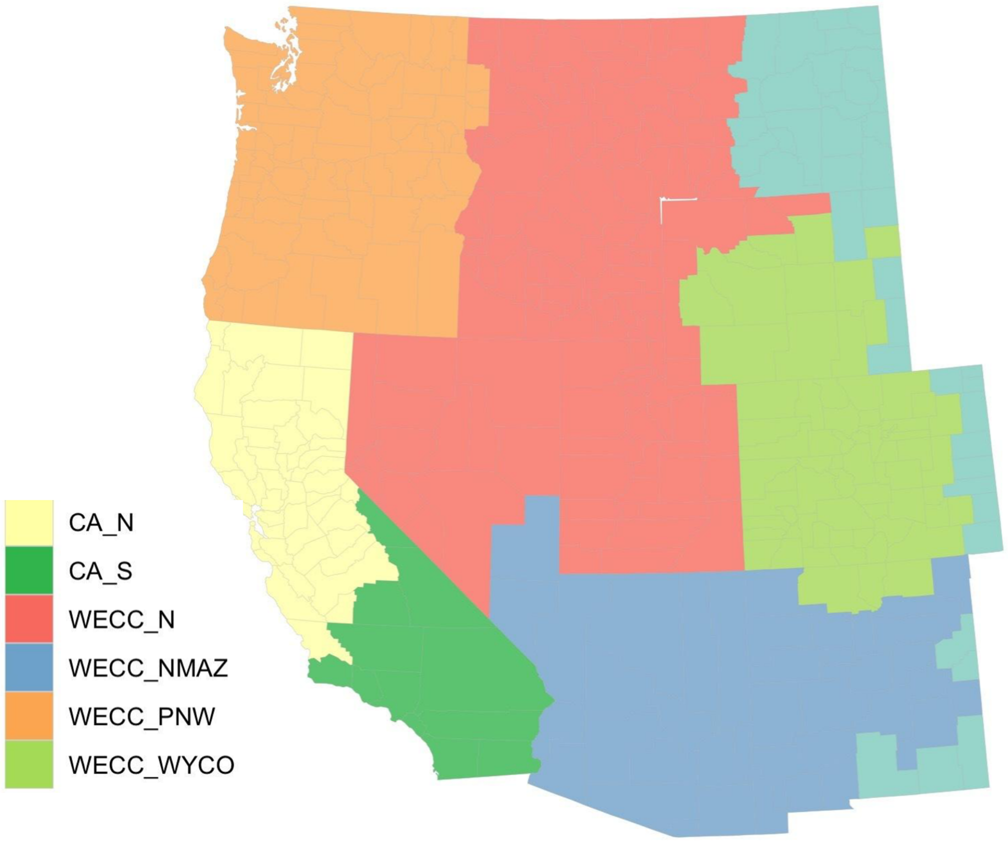
- For instance, suppose California requires a 60% RPS in 2030 and the annual energy consumption of 24/7 participating loads (i.e., the alliance, see A1) is 20 TWh. Per this assumption, 12 TWh of the procured CFE needs to be renewable (60%). Even if the procured renewable energy is 13 TWh, 24/7 participants do not sell the excess credits (1 TWh) to the rest of California. Instead, the 24/7 participants file the RPS compliance report by retiring 13 TWh renewable credits, outperforming the RPS requirement. This practice ensures "additionality" of the procured CFE above and beyond policy obligations.

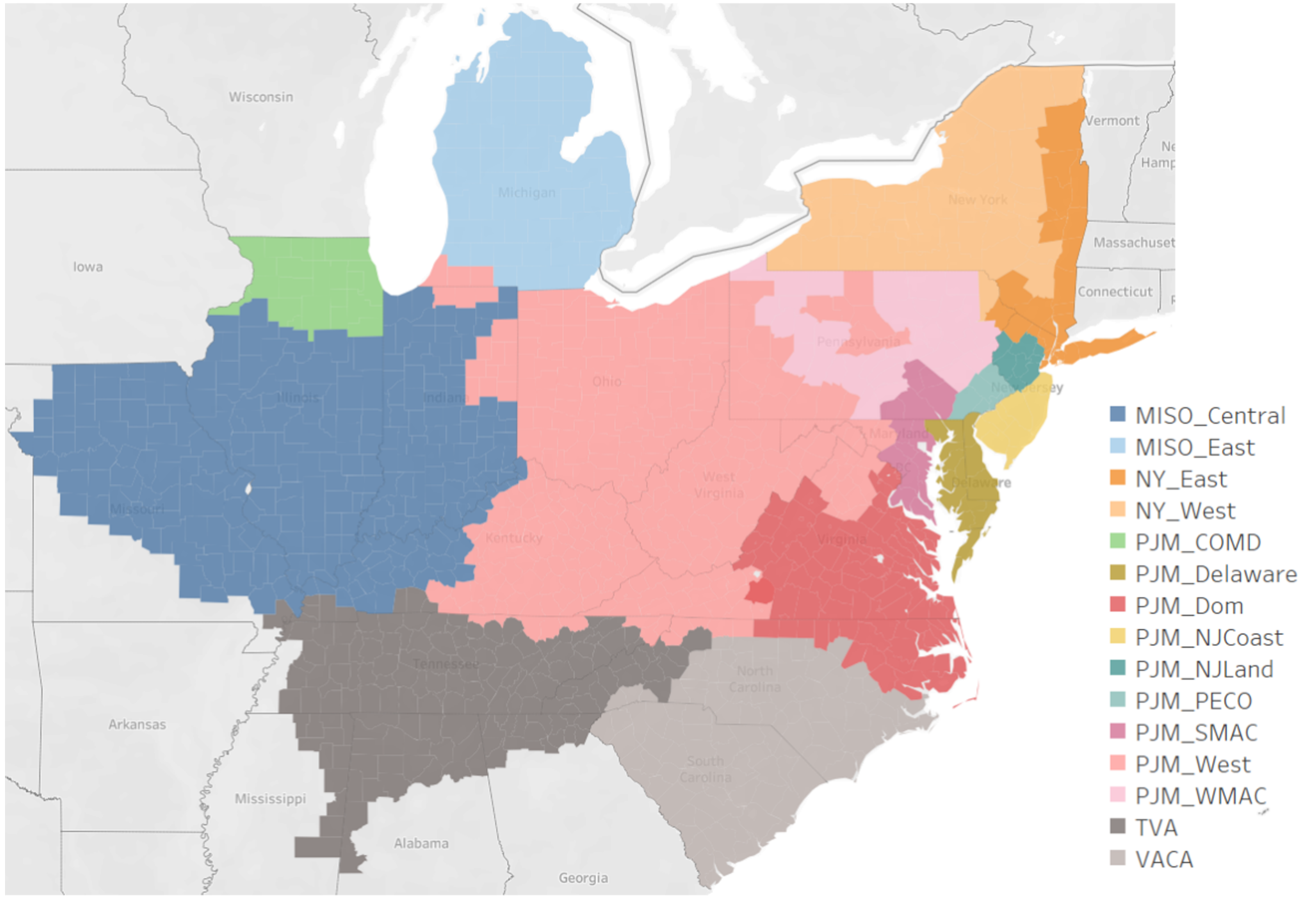
A5: The annual sum of generation in any hour that is in excess of 24/7 participating customer's demand in that hour is limited to 80 percentage points less than the annual CFE target for the case.

- That is, if the CFE target is 100%, the annual limit on hourly excess generation is equal to 20% of annual 24/7 participating demand; if the CFE target is 90%, the limit on excess generation is 10% of annual demand; no hourly excess generation is permitted at 80% CFE.
- See Slide 22, Constraint 3 for implementation of this limit.

System maps (California and PJM)

In this study, we investigate the impact of 24/7 CFE procurement on two systems: California (Left), and PJM (Right). Both of the system are embedded in larger interconnections, namely the Western Electricity Coordinating Council grid (WECC, left) and a portion of the Eastern Interconnection (EI, right).*





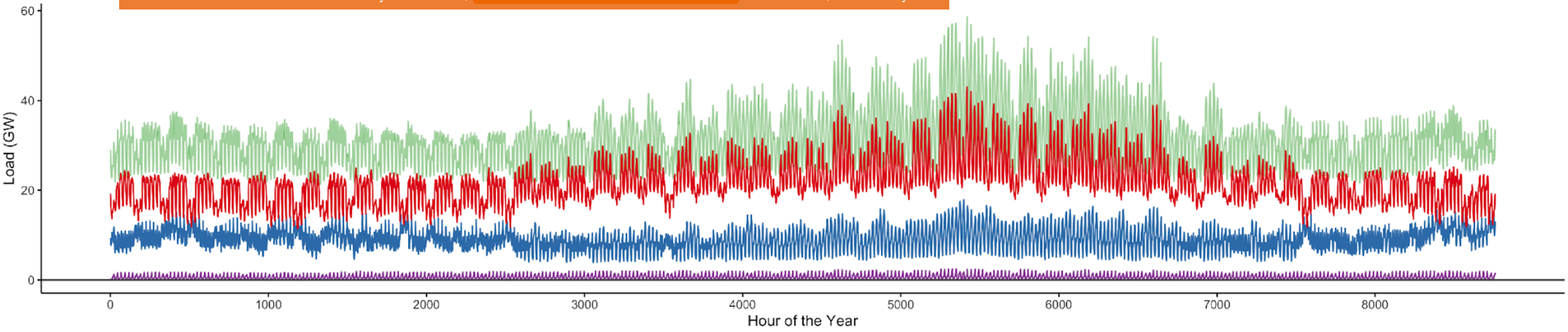
- 6-zone network: based on EPA-IPM; 2 zones in California
- 15-zone network: based on EPA-IPM; 9 zones in PJM

*In this study, we cover the neighboring regions of PJM in EI, namely, NYISO, part of MISO,, and part of SERC, including TVA, NC and SC. See the map above.

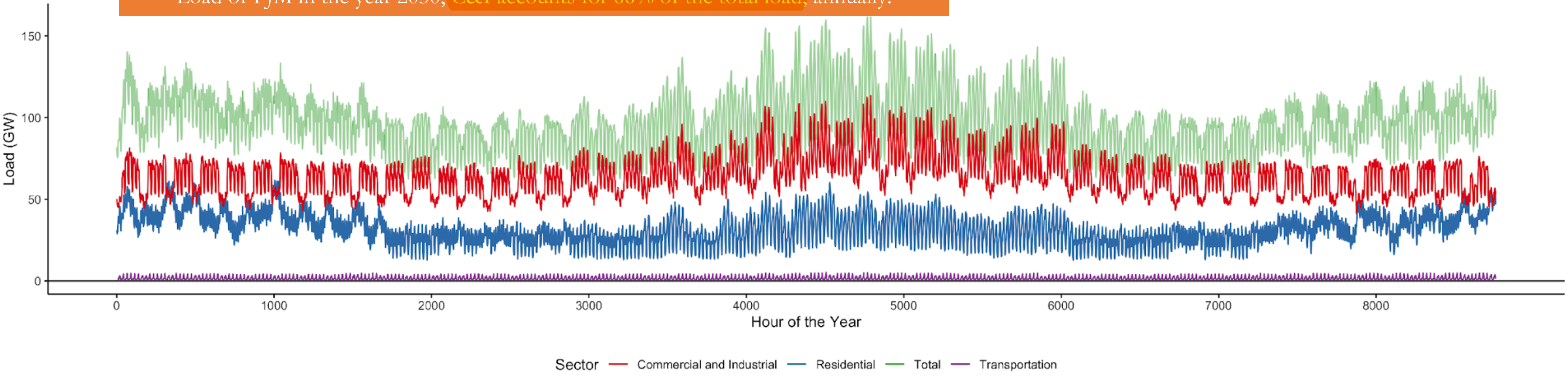
Regions and inter-regional transmission constraints represent single regions or aggregations of regions from the EPA IPM model. See U.S. Environmental Protection Agency, 2021, "Power Sector Modeling." https://www.epa.gov/airmarkets/epas-power-sector-modeling-platform-v6-using-ipm-summer-2021-reference-case

The C&I and total load profiles of PJM and California in 2030

Load of California in the year 2030, C&I accounts for 69% of the total load, annually.



Load of PJM in the year 2030, C&I accounts for 66% of the total load, annually.



Summary of key data assumptions

Data Assumptions:

- Single period optimization reflecting expansion from 2021-2030 and optimized to meet demand in the year 2030
- Data populated by open-sourced power system data compiler, *PowerGenome*: https://github.com/PowerGenome/PowerGenome
- Existing Generation Data: EIA 860m @ Nov. 2020
- PJM: Wind and solar candidate project areas (CPA, by 4km x 4 km) grouped into 171 resource clusters in the study region, from Princeton Net-Zero America (NZA) study (doi:10.5281/zenodo.4628261).
- WECC: Wind and solar CPA (4km x 4 km) grouped into 135 resource clusters in the study region, from Princeton REPEAT Project (doi:10.5281/zenodo.4726433). Additionally, 2.7 GW of geothermal hydro-flash potential is available in WECC, of which 1.7 is available to California based on DOE Geothermal Vision Study.
- Climate year: 2012 (note: impact of Hurricane Sandy on PJM profile removed via interpolation)
- Capital cost: NREL ATB 2020 + Regional Multiplier: EIA AEO 2020;
- Fuel cost: EIA AEO 2020's 2030 fuel projection + 2019 monthly variation from EIA.
- Load: per unit time-series calculated from NREL's Electrification Future Study; stock values from Princeton's NZA. Reference Scenario is used (no Rapid Electrification)
- State RPS policy: as codified in 2020
- Federal Policy: Solar and Offshore wind ITC, 45Q of CCS as codified in December 2020.

Key cost assumptions - California

Technology Group	Technology	2030 CAPEX ($/kW)/CAPEX ($/MWh)	Annualized CAPEX + Interconnection Cost + FOM + Pipeline cost for CCS ($/per MW-year)	Annualized CAPEX (per MWh-year)	VOM ($/MWh)	Heat Rate (MMBTU /MWh)	Capacity Factor	Round-Trip Efficiency and Duration Limit	Total Potential (GW)	Original Cost Assumption Reference (data processed by PowerGenome)
Current Technology	Solar	1,016	66-116k	-	0	-	30-31%	-	235	NREL ATB 2020
	Onshore Wind	1,536	187k – 262k	-	0	-	26-38%	-	27	NREL ATB 2020
	Offshore Wind (Floating)	3,286	389k – 393k	-	0	-	50-55%	-	10	NREL ATB 2020
	Battery	198/228	22k	19k	0.15	-	-	85% (1-10 hours)	No Limit	NREL ATB 2020
	Geothermal (Binary Hydro-flash)	4,700	501k – 519k	-	0	-	-	-	1.7	NREL ATB 2020 (Low Scenario)
Advanced Technology	Long-duration Storage – Metal Air	1,200/12	132k	0.9k	0	-	-	42% (100-200 hours)	No Limit	Baik et al., 2021.
	Near Field Geothermal (Flash)	4,760	480k-549k	-	0	-	-	-	0.4	NREL ATB 2020 (Low Scenario);
Advanced Technology, Combustion	Combined Cycle with ZCF	983	72k-76k	-	1.63	6.27	-	-	No Limit	Same as Combined Cycles in NREL ATB, but use zero carbon fuel
	Natural Gas Combined Cycle w/90%CCS	2,577	180-185k	-	5.89	7.52	-	-	No Limit	NREL ATB 2020; Injection cost is $12/metric ton for Northern California, $21/metric ton for Southern California before 45Q.

- NREL (National Renewable Energy Laboratory). 2020. "2020 Annual Technology Baseline." Golden, CO: National Renewable Energy Laboratory. https://atb.nrel.gov/.
- Carbon Injection cost calculated from NTEL 2017, Cost inflated to 2020 US$. National Energy Technology Laboratory. 2017. "FE/NETL CO2 Saline Storage Cost Model." U.S. Department of Energy. Last Update: Sep 2017 (Version 3) https://www.netl.doe.gov/research/energy-analysis/search-publications/vuedetails?id=2403
- CO2 Pipeline cost calculated from Net Zero America Study: Larson et al. 2021, "Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report Summary." Princeton University, Princeton, NJ. Last Update Oct 2021: https://netzeroamerica.princeton.edu/img/Princeton%20NZA%20FINAL%20REPORT%20SUMMARY%20(29Oct2021).pdf
- Baik et al. 2021. "What is different about different net-zero carbon electricity systems?" Energy and Climate Change, Volume 2, 100046, DOI: 10.1016/j.egycc.2021.100046

Key cost assumptions - PJM

Technology Group	Technology	2030 CAPEX ($/kW)/CAPEX ($/MWh)	Annualized CAPEX + Interconnection Cost + FOM + Pipeline cost for CCS ($/ MW-year)	Annualized CAPEX ($/MWh-year)	VOM ($/MWh)	Heat Rate (MMBTU /MWh)	Capacity Factor	Round-Trip Efficiency and Duration Limit	Total Potential (GW)	Original Cost Assumption Reference (data processed by PowerGenome)
Current Technology	Solar	1,016	63k-82k	-	0	-	26-27%	-	187	NREL ATB 2020
	Onshore Wind	1,536	130k – 175k	-	0	-	26-56%	-	36	NREL ATB 2020
	Offshore Wind (Fixed)	2,295	237k – 261k	-	0	-	44%-46%	-	76	NREL ATB 2020
	Battery	198/228	21k	18k	0.15	-	-	85% (1-10 hours)	No Limit	NREL ATB 2020
Advanced Technology	Long-duration Storage – Metal Air	1,200/12	132k	0.9k	0	-	-	42% (100-200 hours)	No Limit	Baik et al., 2021.
	Advanced Nuclear	7,138	424k-497k	-	2.39	10.46	-	-	No Limit	NREL ATB 2020
Advanced Technology Combustion	Combined Cycle with ZCF	983	59k-72k	-	1.63	6.27	-	-	No Limit	Same as Combined Cycles in NREL ATB, but use zero carbon fuel
	Natural Gas Combined Cycle w/90%CCS	2,577	174k-190k	-	5.89	7.52	-	-	Only in Western PJM and ComED	NREL ATB 2020; Injection cost is $18/metric ton, before 45Q

- NREL (National Renewable Energy Laboratory). 2020. "2020 Annual Technology Baseline." Golden, CO: National Renewable Energy Laboratory. https://atb.nrel.gov/.
- Carbon Injection cost calculated from NTEL 2017, Cost inflated to 2020 US$. National Energy Technology Laboratory. 2017. “FE/NETL CO2 Saline Storage Cost Model.” U.S. Department of Energy. Last Update: Sep 2017 (Version 3) https://www.netl.doe.gov/research/energy-analysis/search-publications/vuedetails?id=2403
- CO2 Pipeline cost calculated from Net Zero America Study: Larson et al. 2021, “Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report Summary.” Princeton University, Princeton, NJ. Last Update Oct 2021: https://netzeroamerica.princeton.edu/img/Princeton%20NZA%20FINAL%20REPORT%20SUMMARY%20(29Oct2021).pdf
- Baik et al. 2021. “What is different about different net-zero carbon electricity systems?” Energy and Climate Change, Volume 2, 100046, DOI: 10.1016/j.egycc.2021.100046

Natural Gas Fuel Price (Tables show system average, inputs also varied by model zones)

- 2030 annual average natural gas price projection calculated form AEO 2021: EIA (U.S. Energy Information Administration), 2021, "Annual Energy Outlook 2021." https://www.eia.gov/outlooks/aeo/
- Monthly factor (monthly multiplier to the annual average) calculated from EIA's 2019 natural gas price report. EIA (U.S. Energy Information Administration), 2021, "Natural Gas Prices." https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_m.htm

Default Natural Gas Price, based on AEO 2021's reference

Month	California	PJM
Jan.	5.16	4.80
Feb.	4.70	3.87
Mar.	4.45	3.85
Apr.	3.71	3.23
May	3.54	3.11
Jun.	3.31	2.90
Jul.	3.25	2.89
Aug.	3.10	2.72
Sep.	3.33	2.79
Oct.	3.20	2.50
Nov.	3.82	3.28
Dev.	3.78	3.22

High Natural Gas Price, based on AEO 2021's low resource

Month	California	PJM
Jan.	6.96	6.61
Feb.	6.34	5.34
Mar.	6.01	5.29
Apr.	5.01	4.43
May	4.77	4.27
Jun.	4.47	3.99
Jul.	4.39	3.97
Aug.	4.18	3.74
Sep.	4.49	3.83
Oct.	4.32	3.43
Nov.	5.16	4.50
Dev.	5.11	4.41

Demand flexibility (shiftable demand) assumptions

Demand flexibility (time shiftable demand) can be activated to modify the C&I load, making the C&I load easier to be matched with carbon-free electricity supply. If the participation rate of C&I customers in 24/7 procurement is 10% of total C&I load, then we assume 10% of the activated demand flexibility in a given hour will be used to modify the 24/7 participating load (e.g. demand flexibility is activated proportionately across the whole C&I load).

The subsector-wise demand profiles are calculated with the load time-series in NREL's EFS study and modified with the Princeton *Net-Zero America* study's vehicle stock values for 2030 (under the E+ or high electrification scenario).

- NREL's EFS study: NREL (National Renewable Energy Laboratory), 2018. "Electrification Futures Study – Demand-Side Scenarios." https://www.nrel.gov/docs/fy18osti/71500.pdf
- Princeton's NZA study: Larson et al. 2021, "Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report Summary." Princeton University, Princeton, NJ. Last Update Oct 2021: https://netzeroamerica.princeton.edu/img/Princeton%20NZA%20FINAL%20REPORT%20SUMMARY%20(29Oct2021).pdf

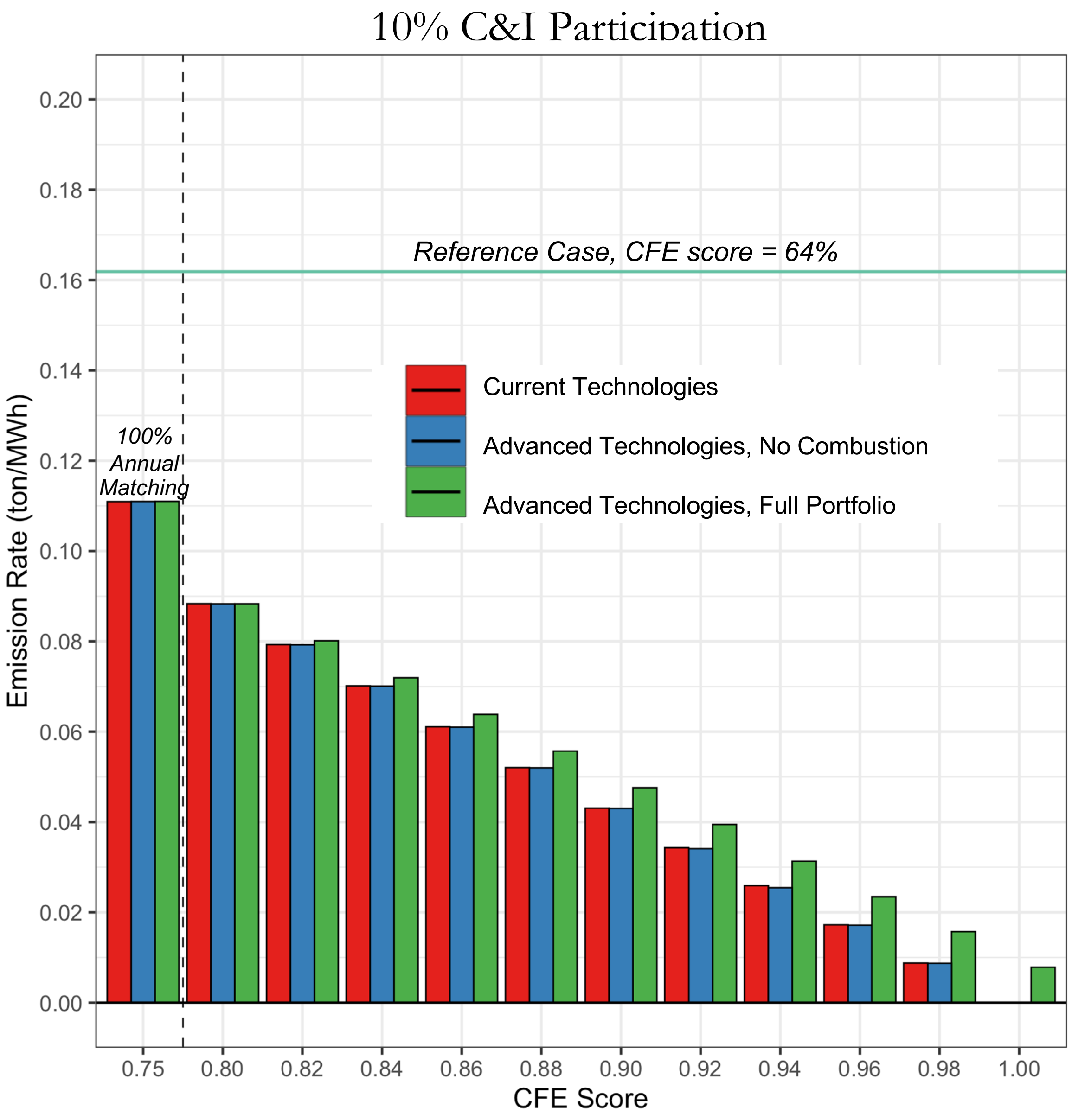
GenX currently only models flexible demand by delaying consumption. The amount of shiftable demand in 2030 is shown below (based on NREL's EFS, Table 5.1).

Subsector	Fraction of subsector demand that is considered flexible	Maximum delay in consumption (Hours)
Commercial Space Heating and Cooling	13%	2
Commercial Water Heating	11%	4
Residential Space Heating and Cooling	13%	2
Residential Water Heating	11%	4
Light-Duty Vehicles	67%	5

In addition, 6.7% of total regional demand in both systems is available as voluntary price-responsive demand curtailment (aka demand response) at an opportunity cost of $400/MWh for the first 0.3% of load, $1,100/MWh for the next 2.4% of load and $1,800/MWh for the next 4% of load (based on analysis of price-responsive bids in PJM market). This price responsive demand curtailment does not modify the 24/7 participating C&I customer demand profile however.

Results: California

Emissions rate of 24/7 participating C&I – California



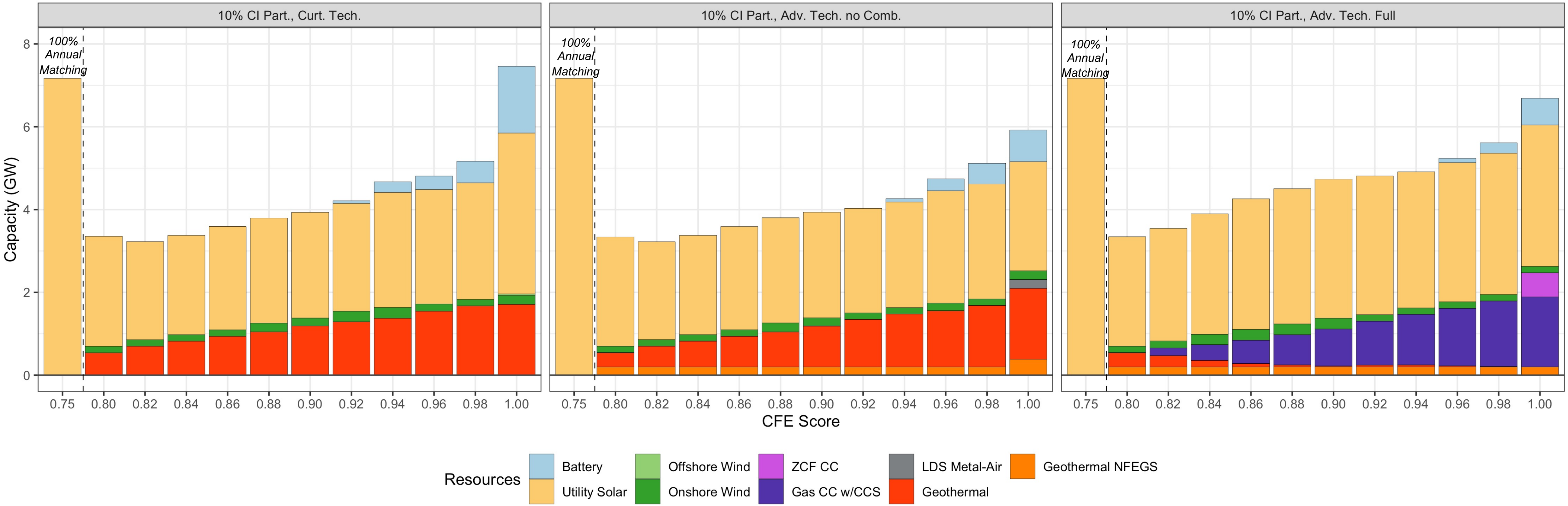
California has a reasonably clean-grid: without procuring any resources, 24/7 participants start with 64% CFE score purely from grid purchases.

Without actively matching the CFE with the load, 100% annual matching with renewable energy can achieve 75% CFE.

24/7 purchasing results in a lower emissions rate associated with C&I electricity use than 100% annual matching, even at relatively low CFE targets (e.g., 80%); the emissions rate falls to zero (or near-zero w/CCS) as CFE increases to 100%.

Note: Differences in emissions between green (adv. tech, full portfolio) and red/blue (current tech/adv. tech, no combustion) are due to residual emissions from NGCC w/CCS (assuming 90% CO_2 capture rate). Emissions could be eliminated at incrementally higher cost.

24/7 Resource Portfolio Capacity – California



Procurement of energy storage and clean firm resources increases as CFE score increases, indicating greater impact on sectoral transformation goals.

- At this level of participation (10% of C&I load), 100% annual matching is met in California at least cost by procuring solar PV only.
- 24/7 participating load purchases a much more diverse portfolio than 100% annual matching, including a mix of solar, wind, storage, and clean firm resources.
- *Current techs*: Geothermal is procured when current techs alone are permitted; at higher C&I participation, solar and energy storage play a larger role as available conventional geothermal and quality wind capacity is maxed out.
- *Advanced techs, no combustion*: Lower-cost near-field enhanced geothermal energy systems (NFEGS) are included in 24/7 portfolios, and at 100% CFE, long duration metal-air storage (LDS) complements geothermal and reduces Lithium-ion battery storage and solar PV capacity.
- *Advanced techs, full portfolio:* If low-carbon combustion technologies are allowed, natural gas w/CCS and zero-carbon fuel plants will substitute for geothermal & LDS, although near-field EGS remains in the portfolio. However, the built-out of natural gas w/CCS is strongly dependent on natural gas price and the existence of current tax incentives for carbon capture and storage (45Q) and may trade off with geothermal under different cost assumptions; see Sensitivity Analysis, Slides 78-81.

24/7 Resource Portfolio Capacity – California

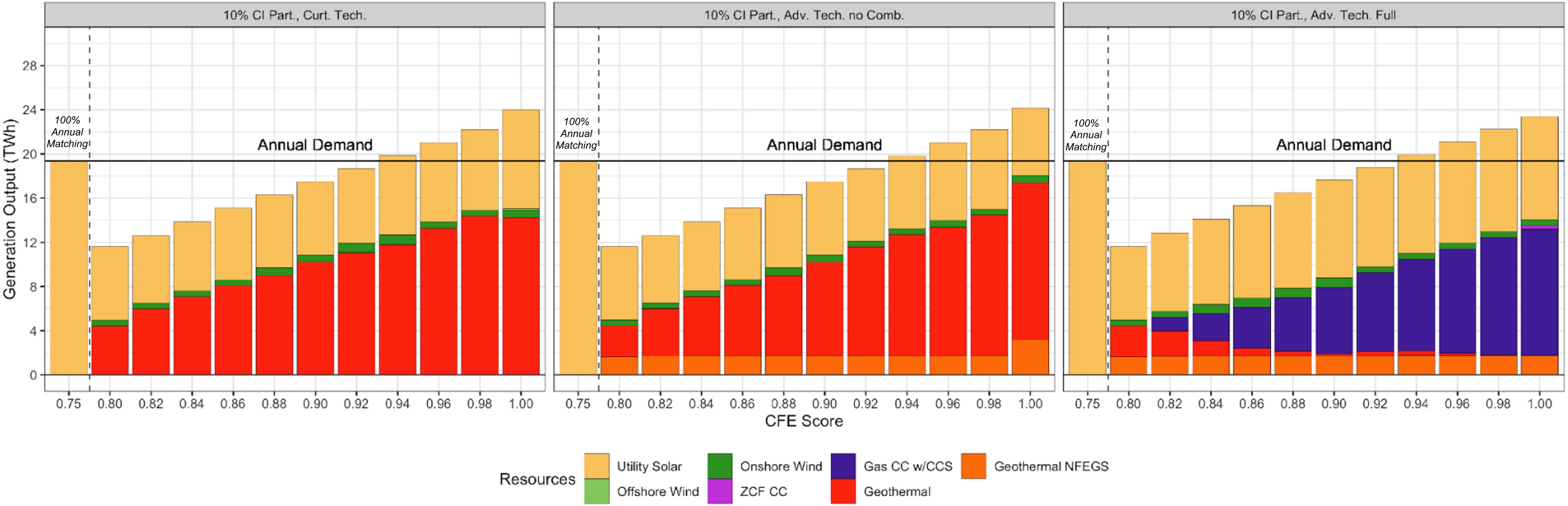
100% Annual Matching – Capacity Deployed (GW)

100% Annual	Offshore Wind	Onshore Wind	Utility Solar	Geothermal	Battery	Battery (Duration)	Geothermal NFEGS	LDS Metal-Air	LDS Metal-Air (Duration)	Gas CC w/CCS	ZCF CC
10% CI Part., Curt. Tech.	0	0	7.2	0	0	0	0	0	0	0	0
10% CI Part., Adv. Tech. no Comb.	0	0	7.2	0	0	0	0	0	0	0	0
10% CI Part., Adv. Tech. Full	0	0	7.2	0	0	0	0	0	0	0	0

24/7 CFE Procurement – Capacity Deployed (GW)

88% CFE	Offshore Wind	Onshore Wind	Utility Solar	Geothermal	Battery	Battery (Duration)	Geothermal NFEGS	LDS Metal-Air	LDS Metal-Air (Duration)	Gas CC w/CCS	ZCF CC
10% CI Part., Curt. Tech.	0	0.2	2.5	1	0	0	0	0	0	0	0
10% CI Part., Adv. Tech. no Comb.	0	0.2	2.5	0.8	0	0	0.2	0	0	0	0
10% CI Part., Adv. Tech. Full	0	0.3	3.3	0	0	0	0.2	0	0	0.7	0
98% CFE	**Offshore Wind**	**Onshore Wind**	**Utility Solar**	**Geothermal**	**Battery**	**Battery (Duration)**	**Geothermal NFEGS**	**LDS Metal-Air**	**LDS Metal-Air (Duration)**	**Gas CC w/CCS**	**ZCF CC**
10% CI Part., Curt. Tech.	0	0.2	2.8	1.7	0.5	4.6	0	0	0	0	0
10% CI Part., Adv. Tech. no Comb.	0	0.2	2.8	1.5	0.5	4.5	0.2	0	0	0	0
10% CI Part., Adv. Tech. Full	0	0.2	3.4	0	0.3	3.1	0.2	0	0	1.6	0
100% CFE	**Offshore Wind**	**Onshore Wind**	**Utility Solar**	**Geothermal**	**Battery**	**Battery (Duration)**	**Geothermal NFEGS**	**LDS Metal-Air**	**LDS Metal-Air (Duration)**	**Gas CC w/CCS**	**ZCF CC**
10% CI Part., Curt. Tech.	0	0.2	3.9	1.7	1.6	6.3	0	0	0	0	0
10% CI Part., Adv. Tech. no Comb.	0	0.2	2.6	1.7	0.8	4	0.4	0.2	106.5	0	0
10% CI Part., Adv. Tech. Full	0	0.2	3.4	0	0.6	3.4	0.2	0	0	1.7	0.6

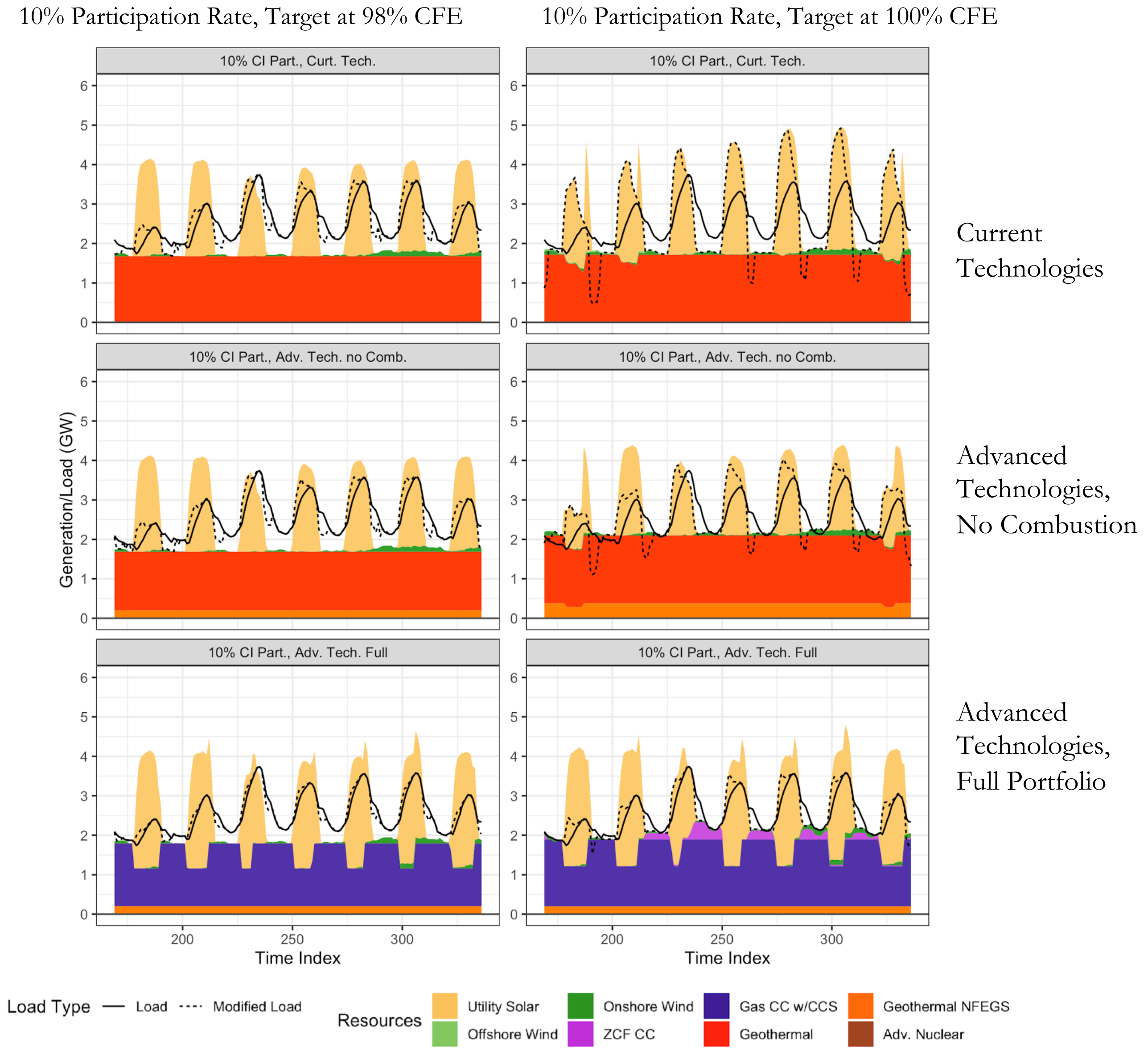
24/7 Resource Portfolio Output – California



Generation from clean firm resources increases as CFE score increases, while solar contribution remains relatively constant.

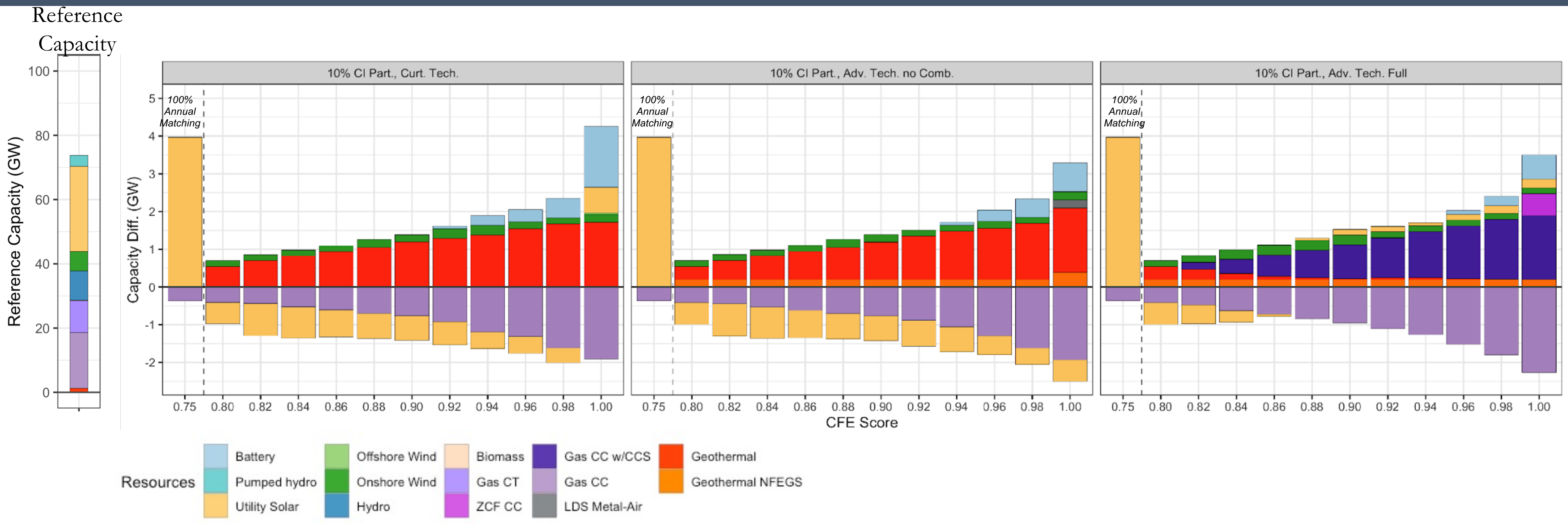
- 24/7 contracted CFE starts to generate more annual energy than 100% annual matching when target is higher than 94% (note that excess generation is not credited towards CFE score and annual excess generation is constrained to <80 percentage points less than the annual CFE target per year, e.g. 10% limit for 90% CFE, 20% for 100% CFE).
- Note that, between the range of 88-94% CFE, 24/7 participating C&I load procures less energy than 100% annual matching, as it relies on grid CFE contributions, but reduces more systemwide emission than the 100% annual matching (see Slide 46) due to the timing effect (see Slides 47-48).
- Clean firm generation – geothermal energy, and in the advanced tech, full portfolio case, natural gas w/CCS – supplies a growing share of the annual 24/7 generation portfolio as the CFE target reaches higher levels, while solar maintains a roughly constant contribution to the annual energy portfolio. Solar PV consistently meets a similar share of daytime demand, while clean firm generation progressively substitutes for grid supply as more stringent CFE targets are required.

Example of hourly generation and demand profiles: 98% and 100% CFE score – California



- Storage resources and flexible demand are used to modify demand to align with contracted solar production.
- Inclusion of clean firm resources in the Advanced Technologies cases (geothermal, natural gas w/CCS and zero carbon fuel, if allowed) reduce storage operations and demand flexibility activations (i.e., dashed modified demand lines are closer to the solid original demand lines).
- Geothermal operates consistently in day and night due to low marginal costs while gas w/CCS (given higher fuel costs) reduces output during daytime hours, permitting greater use of solar PV.
- For 100% CFE, grid supply is not permitted (as the grid supply is not 100% clean) requiring procured generation to completely cover the modified demand profile represented by the dashed lines. Zero-carbon fueled CC's play a key role in filling this final gap between supply and demand and their availability thus lowers costs of the Adv. Tech. Full Portfolio cases. Excess generation also increases as CFE score increases.

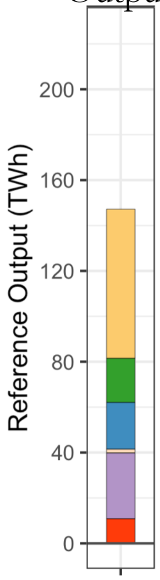
System Level Total Capacity – California

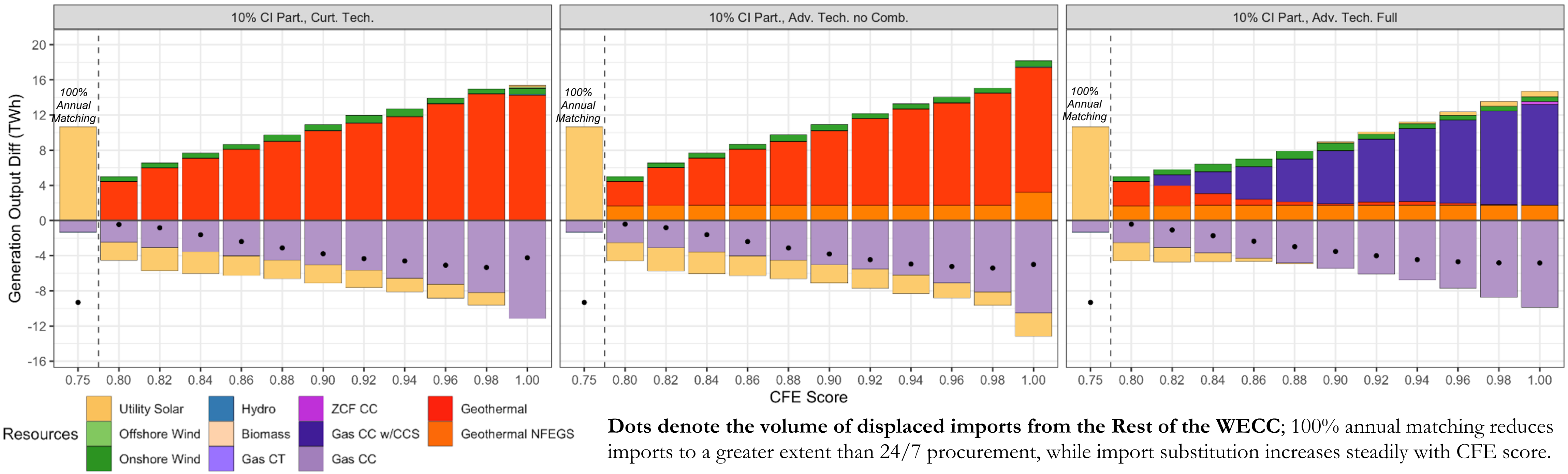


24/7 procurement of clean firm generation drives much greater retirement of natural gas-fired power plant capacity.

- 100% annual matching results in about 4 gigawatts of additional solar PV capacity and reduces natural gas combined cycle capacity by only 400 MW due to the relatively low capacity substitution value of solar in the California system (e.g. ~12.5%).
- Although solar also appears in the 24/7 portfolio, 24/7 CFE procurement can reduce the total solar capacity in the system in many cases as geothermal capacity procured for the 24/7 portfolio substitutes for solar PV to meet the system-wide Renewable Portfolio Standard requirements. (When 24/7 portfolios rely on non-RPS qualifying natural gas w/CCS capacity, solar capacity is unchanged at the system level).
- The 24/7 purchase of clean firm generation sufficient to meet participating customer's peak demand causes the system to avoid significantly more construction of NGCC capacity than 100% annual matching. Clean firm capacity from geothermal and gas w/CCS substitutes for NGCC capacity roughly one-for-one.

Reference Output





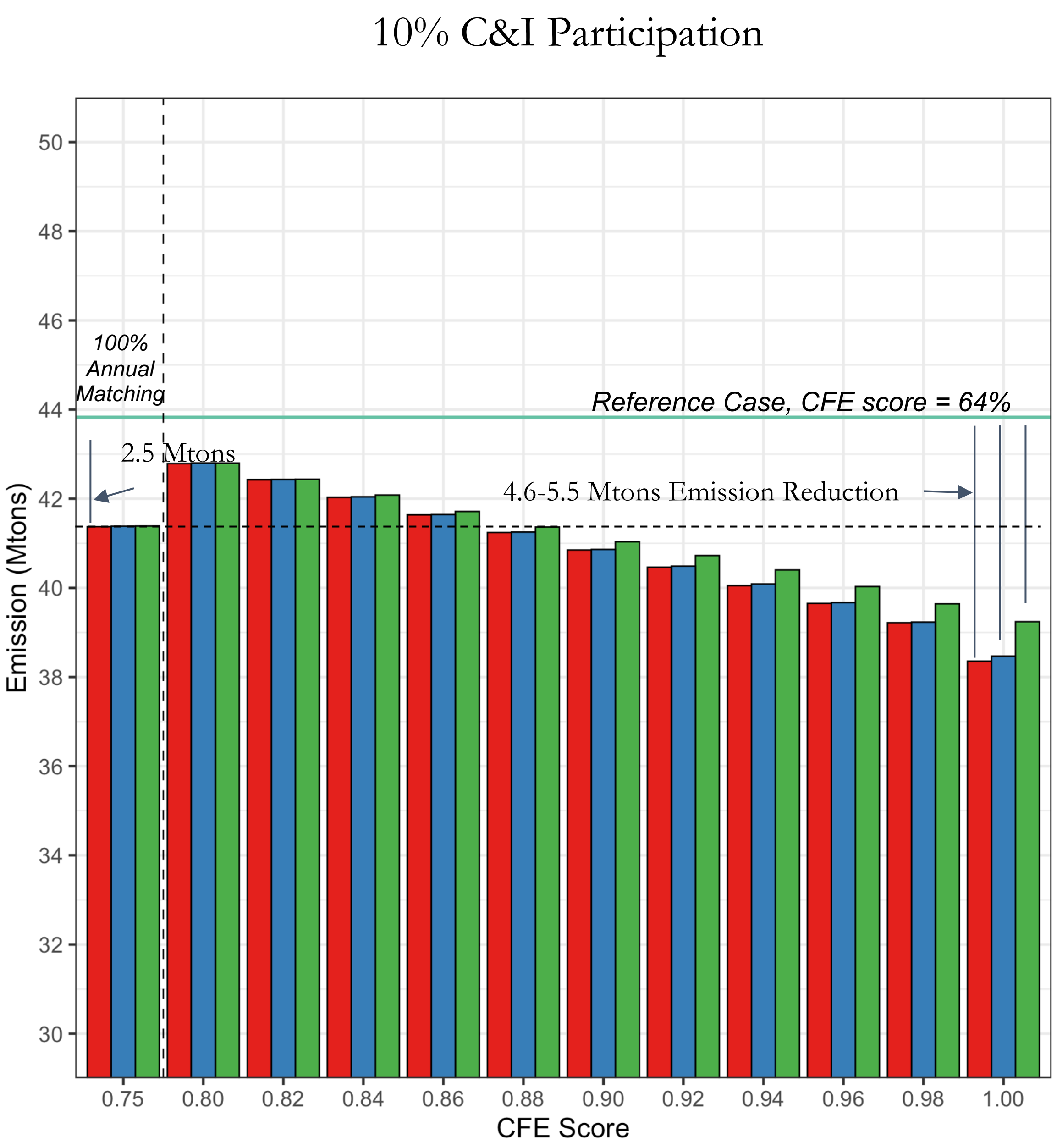
Dots denote the volume of displaced imports from the Rest of the WECC; 100% annual matching reduces imports to a greater extent than 24/7 procurement, while import substitution increases steadily with CFE score.

24/7 CFE procurement can reduce NGCC capacity and generation in California to a greater extent than 100% Annual Matching.

Displaced NGCC Capacity and Generation

Reference California NGCC Capacity = 17.4 GW California NGCC Generation = 29.1 TWh		100% Annual Matching (*ex post* CFE = 75%)		24/7 Hourly Matching (CFE Target = 88%)		24/7 Hourly Matching (CFE Target = 100%)	
		Capacity (GW)	Output (TWh)	Capacity (GW)	Output (TWh)	Capacity (GW)	Output (TWh)
Available Tech.	Current Tech.	0.4	1.3	0.7	5.8	1.9	11.2
	Advanced Tech., No Combustion	0.4	1.3	0.7	5.5	1.9	10.5
	Advanced Tech., Full Portfolio	0.4	1.3	0.8	6.1	2.3	9.9

System level CO_2 emissions – California (including imported emissions)



100% Annual Matching can deliver greater system-level CO_2 emissions reductions than lower CFE scores (e.g. less than 88% CFE in California under current policies). 100% Annual Matching reduces emissions in California by 2.5 million metric tons (Mtons) CO_2 per year (at 10% C&I participation).

Beyond 88% CFE, 24/7 portfolios reduce system-level emissions in California to a greater extent than 100% annual matching.

C&I customers procuring 100% hourly CFE lowers system-wide emissions by 4.6-5.5 million metric tons (Mtons) per year, with 10% C&I participation rate.

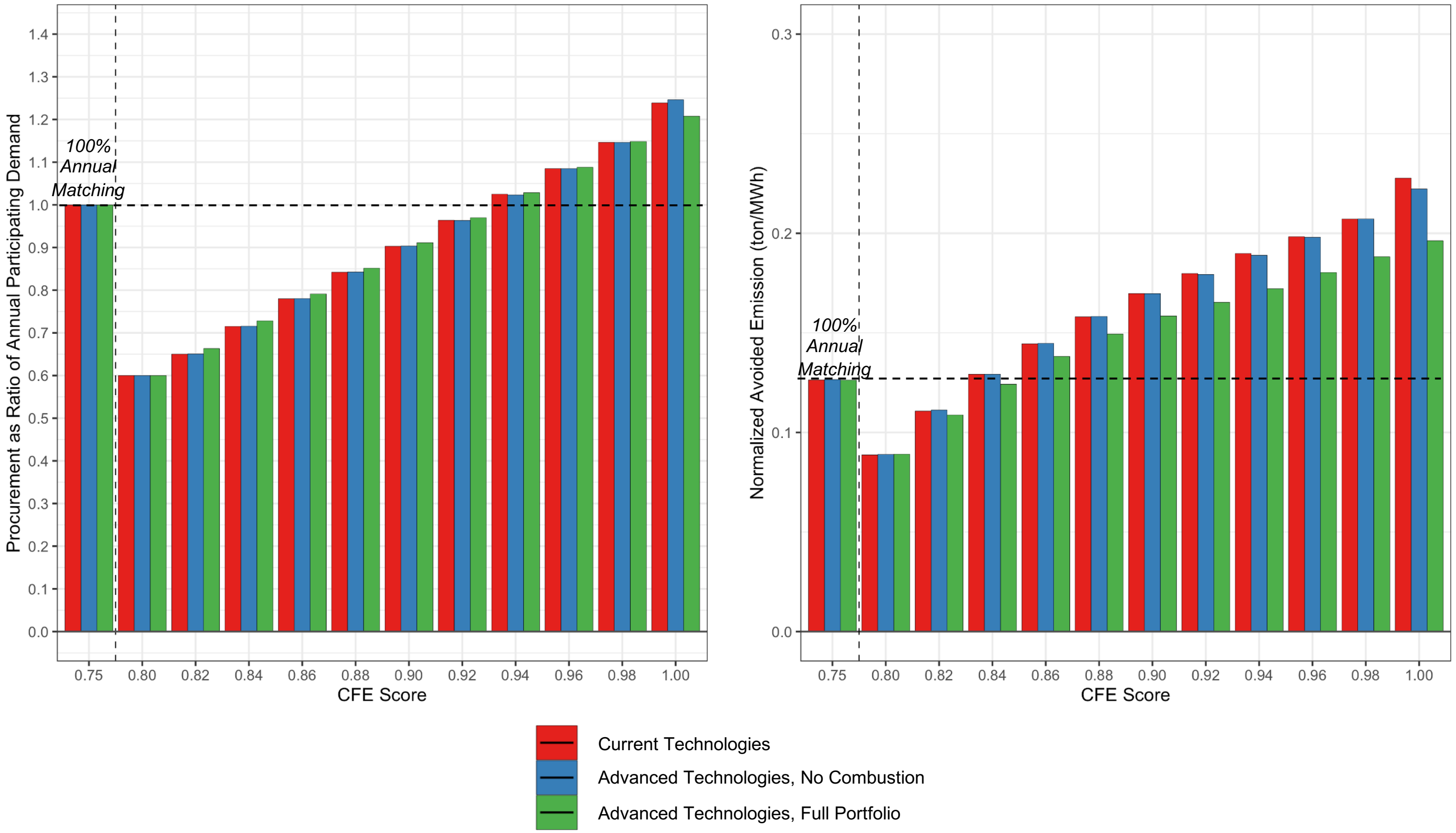
- This reduces emissions by 11% to 13% relative to the Reference case.
- 100% CFE achieves 84%-120% greater emissions reductions than 100% Annual Matching.

The magnitude of emissions reductions is sensitive to the magnitude of C&I participation (see Sensitivity Analysis, Slide 71)

Explaining differences in system-level emissions outcomes - California

(a) Total volume of procured carbon-free electricity – California, 10% Participation Rate

(b) Normalized avoided emissions per MWh of procured electricity – California, 10% Participation Rate



Observed emissions reductions can be explained by two distinct mechanisms or effects:

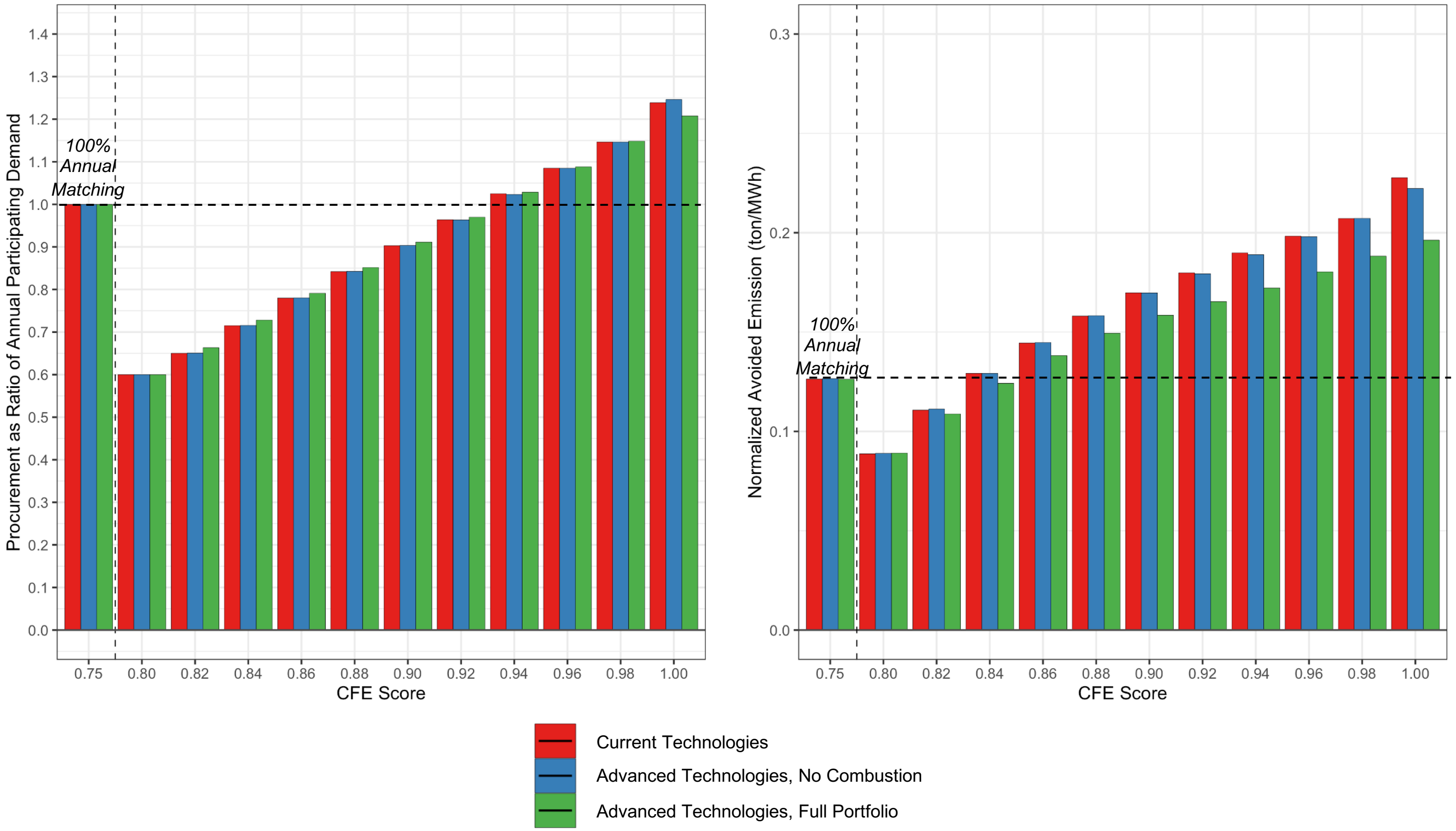
1. **A volume effect**: higher volume of clean energy procurement drives less emitting grid-supplied generation (e.g. more MWh = more emissions reductions)
2. **A timing effect**: better alignment of procured generation with demand can increase displacement of emitting grid-supplied generation by concentrating more generation in periods with less system-wide wind and solar production and thus higher emissions rates (e.g. more MWh at the right times = more emissions reductions).

In this slide, we isolate both factors by calculating the total volume of generation procured by participating C&I customers (figure at left, panel (a)) and calculate the normalized avoided emission (figure at left, panel (b)) by dividing system-level emission reduction by the total MWh procured. This second metric could also be considered the long-run marginal emission reduction rate of CFE procurement.

Explaining differences in system-level emissions outcomes - California

(a) Total volume of procured carbon-free electricity – California, 10% Participation Rate

(b) Normalized avoided emissions per MWh of procured electricity – California, 10% Participation Rate



- At lower CFE scores (<94%), 24/7 portfolios procure less MWh than 100% annual matching, as they rely on grid supplied CFE for a portion of the CFE target.
- Additionally, at low CFE scores, emissions reductions per MWh are lower for 24/7 procurement, indicating that the cheapest carbon-free electricity to supply 24/7 portfolios in California (e.g. solar PV) is correlated with periods of lower system-wide emissions.
- As CFE scores increase, avoided emissions per MWh increases, as procured CFE supply better matches C&I demand patterns and more of the 24/7 portfolio produces at times of higher emissions rates (e.g. the 24/7 portfolio becomes less correlated with system-wide CFE generation); at >84% CFE in California, 24/7 procurement has greater emissions reduction per MWh procured.
- Due to the combination of timing effect and volume effect, 24/7 portfolios drive greater emissions reductions at CFE >88% (see Slide 46), despite the fact that the total volume procured remains lower than 100% annual matching.

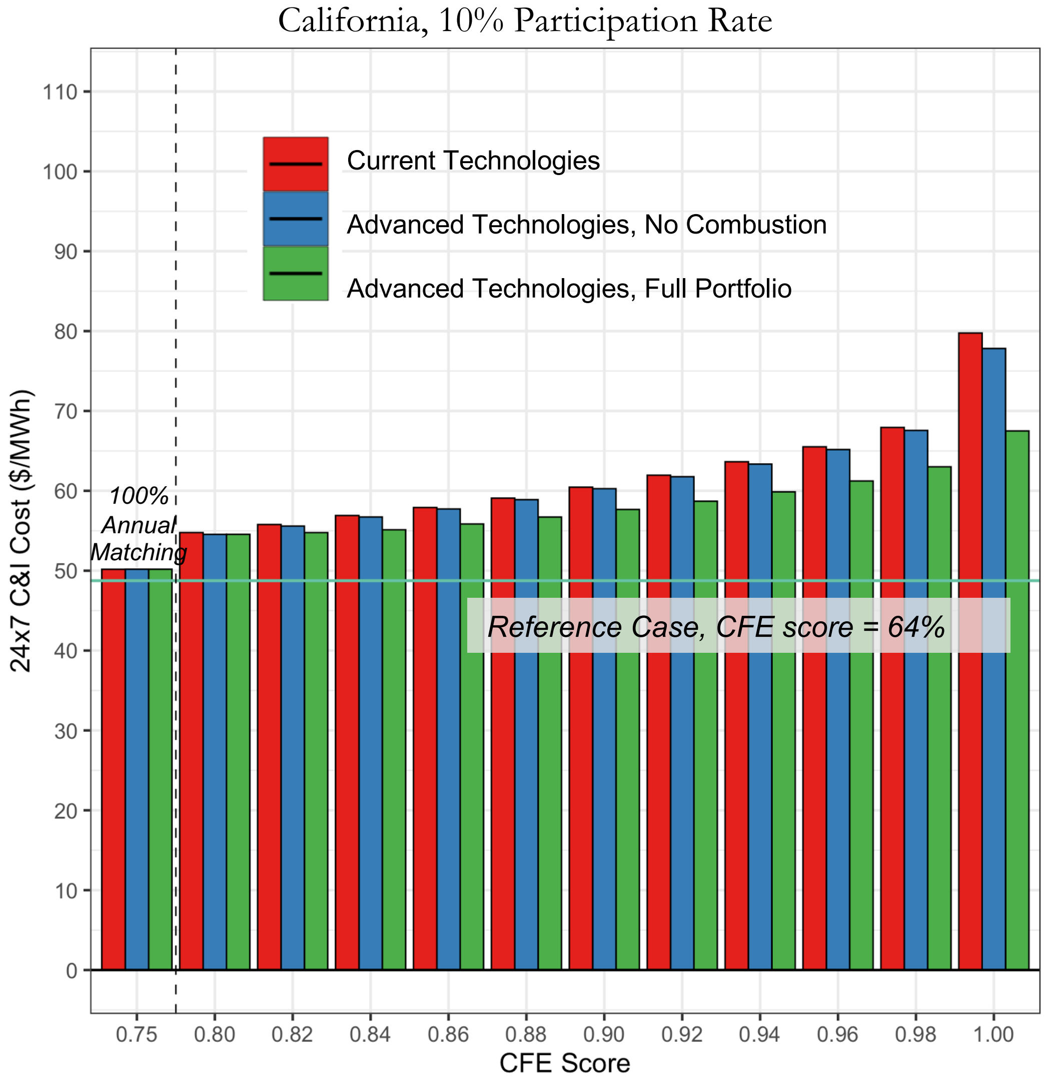
Summary of avoided emissions - California

Avoided Emission (Mtons/year)

Reference Participating Load Emission = 3.1 Mton/year Rest of California Emission = 39.8 Mton/year California Emission = 42.9 Mton/year		100% Annual Matching (*ex post* CFE = 75%)			24/7 Hourly Matching (Target CFE = 88%)			24/7 Hourly Matching (Target CFE = 100%)		
		Participating Load	Rest of the California Load	Total	Participating Load	Rest of the California Load	Total	Participating Load	Rest of the California Load	Total
Available Technology	Current Technologies	1.0	1.5	2.5	2.1	0.5	2.6	3.1	2.3	5.5
	Advanced Technologies, No Combustion	1.0	1.5	2.5	2.1	0.5	2.6	3.1	2.2	5.4
	Advanced Technologies, Full Portfolio	1.0	1.5	2.5	2.1	0.4	2.5	3.0	1.6	4.6

24/7 matching can drive deeper emissions reductions than 100% annual matching if the target is high enough (e.g., 88% or greater);

Cost for 24/7 participating C&I consumers – California



Note: The presence of 45Q subsidy for CCS lowers costs in the full portfolio case, but the policy support does not explain the full reduction in cost relative to more restricted portfolios. See Sensitivity slide 81 which illustrates significant cost reductions in the Advanced Technologies, Full Portfolio case without 45Q.

24/7 procurement can deliver lower emissions rates for participating C&I customers, drive greater emissions reductions (at CFE ≥88%) and help transform electricity systems via accelerated deployment of clean firm resources. However, greater impact comes at a premium cost relative to 100% annual matching due to the added challenge of matching hourly demand.

That cost premium is reduced when a full portfolio of advanced technologies are available, particularly at 100% CFE. This is because:

- With current technologies (limited to wind, solar, batteries, and conventional geothermal in California), marginal value from additional wind and solar falls rapidly without increased storage deployment, raising the cost of reaching higher CFE scores and/or increasing participating share of C&I customers (see Sensitivity slide 77).
- With advanced technologies (e.g., near-field geothermal, long-duration storage, CCS, zero-carbon fuel), this effect is moderated due to higher system value of these technologies, and costs increase much more modestly as share of participating C&I customers increases (see Sensitivity slide 77).
- Absent a full portfolio of clean firm resources, the cost of 100% CFE can be significantly greater than 98% CFE. 100% CFE cannot rely on grid supply in any time periods. Meeting these final periods of demand is most cost effective with a clean firm resource that has a low fixed cost / high variable cost, which is only present in the advanced tech, full portfolio (e.g. zero-carbon fuel combined cycle plants). Meeting this final increment of demand with geothermal (or another high fixed cost, low-variable cost resource) is significantly more costly.

Summary of cost for 24/7 participating C&I consumers – California

C&I Cost Increase Compared to the Reference in California (2020US$/MWh)

Reference Reference California Participating C&I Cost = $48.7/MWh		100% Annual Matching (*ex post* CFE = 75%)	24/7 Hourly Matching (Target CFE = 88%)	24/7 Hourly Matching (Target CFE = 98%)	24/7 Hourly Matching (Target CFE = 100%)
Available Technology	Current Technologies	1.4 (+3%)	10.3 (+21%)	19.2 (+39%)	31.0 (+64%)
	Advanced Technologies, No Combustion	1.4 (+3%)	10.1 (+21%)	18.9 (+39%)	29.1 (+60%)
	Advanced Technologies, Full Portfolio	1.4 (+3%)	8.0 (+16%)	14.3 (+29%)	18.8 (+39%)

24/7 CFE drives deeper emissions reductions and sectoral transformation, but comes at a cost premium relative to 100% annual matching

Note: Our result indicate that the additional cost of 24/7 procurement is internalized by participants; i.e., participating loads are responsible for paying ~100% of the incremental system costs resulting from 24/7 procurement, with no cost shifting to non-participating customers.

Explaining costs of 24/7 procurement

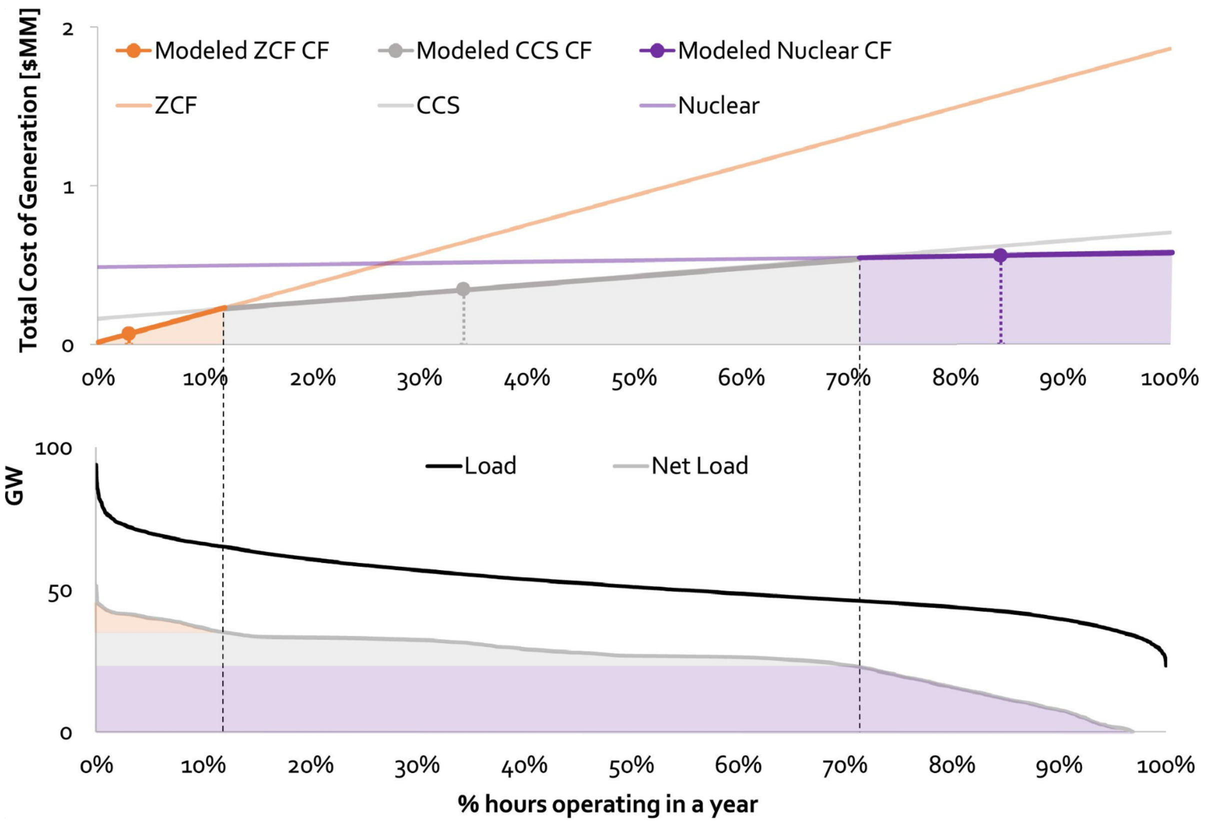


Fig. 3 from Baik et al. (2021), reproduced for explanatory purposes. The total cost of three different types of clean firm resources as a function of annual utilization rates (top) and the net load served by the clean firm resources in a 2045 scenario for California with availability of renewable energy, storage, nuclear, natural gas combined cycle w/CCS, and zero-carbon fuel (ZCF) gas combustion plants. The total cost curves reflect variation in fixed costs (the intercept) and variable/marginal costs (the slope). The net load curve is the load (demand) net of wind, solar, and hydro generation and storage charging and discharging.

As in prior systems-level deep decarbonization studies (see e.g. Baik et al. (2021), "What's different about different net-zero carbon electricity systems," *Energy & Climate Change*, https://doi.org/10.1016/j.egycc.2021.100046), modeling of 24/7 CFE procurement illustrates **the importance of a complete portfolio of clean firm resources to cost-effectively reach high CFE** (especially 100%).

Storage and demand flexibility can reshape C&I demand to better align with variable generation, but there are economic limits to this approach. Availability of clean firm resources that can be operated any time of the year and for as long as required makes 24/7 load matching easier and more affordable.

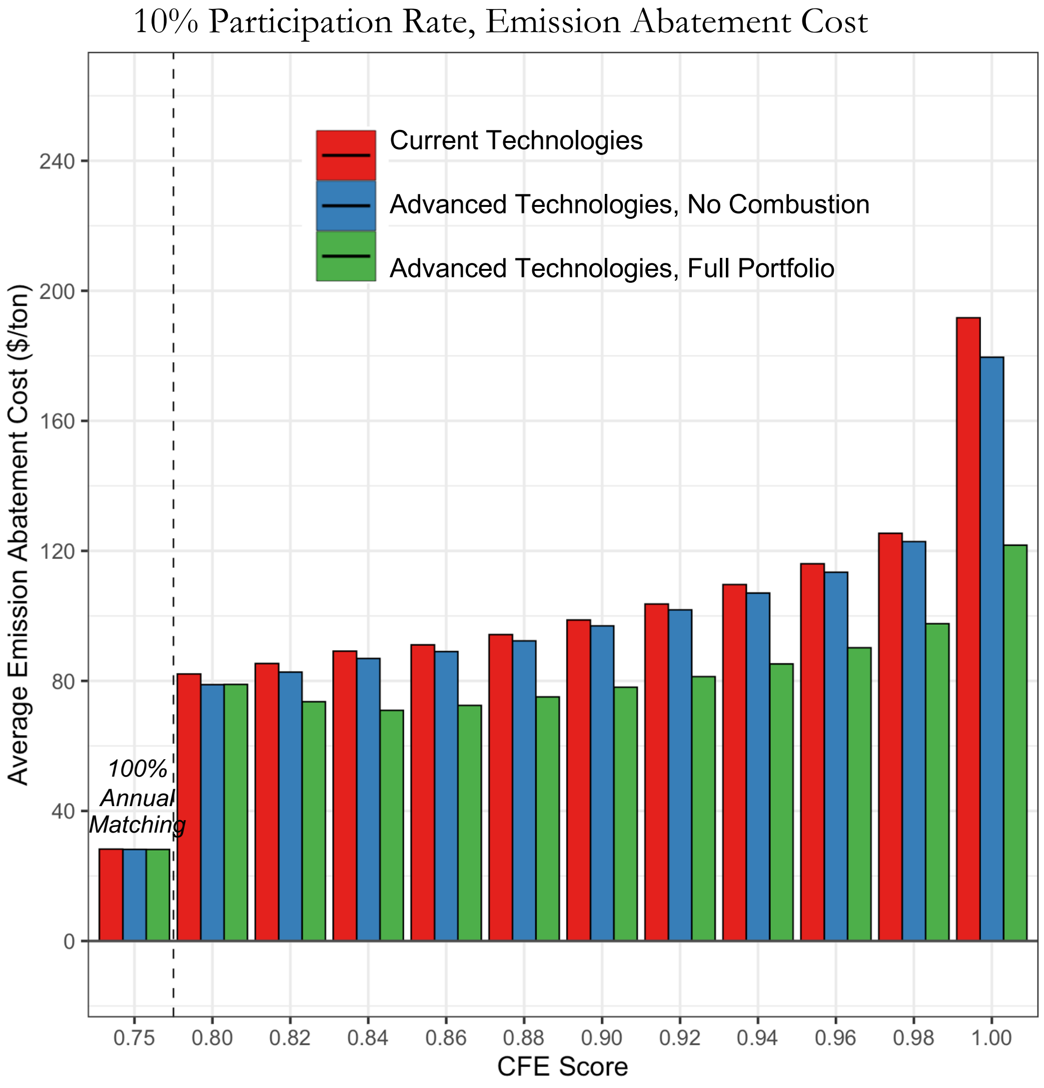
As the figure at left illustrates, different clean firm resources are each the most cost-effective when operating for different amounts of time over a year. The lowest cost 100% CFE portfolios thus include a range of clean firm resources with different ratios of fixed costs and variable costs that allow each resource to occupy a specific operating niche in matching hourly participating net demand.

In **Current Technology** cases, the only available clean firm resource in California is conventional geothermal, with high fixed / low variable costs making it ill-suited to operate at low utilization rates, raising the cost of high CFE cases.

Adding long-duration storage in the **Advanced Technology, No Combustion** cases helps address less frequent needs for carbon-free electricity output, but this case still lacks a complete range of clean firm resources.

The **Advanced Technology, Full Portfolio** cases add natural gas w/CCS (with moderate fixed and variable costs) and zero-carbon fuel (ZCF) power plants (with lower fixed and high variable costs) to the portfolio, completing the full portfolio of resources ideally suited to a range of utilization rates needed to match participating demand 24/7. This significantly lowers costs at high CFE cases.

Abatement Cost as a Function of CFE Score – California



- While 24/7 procurement can deliver greater emissions reductions than 100% annual matching, it does so at a higher average abatement cost ($/ton of CO_2 emissions reduced), due to the added cost of procuring clean firm or long duration energy storage technologies to match hourly demand.
- Note again that the presence of a full suite of clean firm options, including geothermal (with high fixed / low variable costs) as well as combustion technologies with lower fixed costs / higher variable costs permits a more cost-effective 24/7 portfolio and lower average abatement costs (green vs red/blue bars).
- By driving early deployment of clean firm and long duration energy storage technologies, 24/7 procurement can drive experience curves and cost reductions for these nascent technologies, lowering the cost of emissions abatement for follow-on actors, making 100% carbon-free electricity more affordable for the electricity system as a whole.

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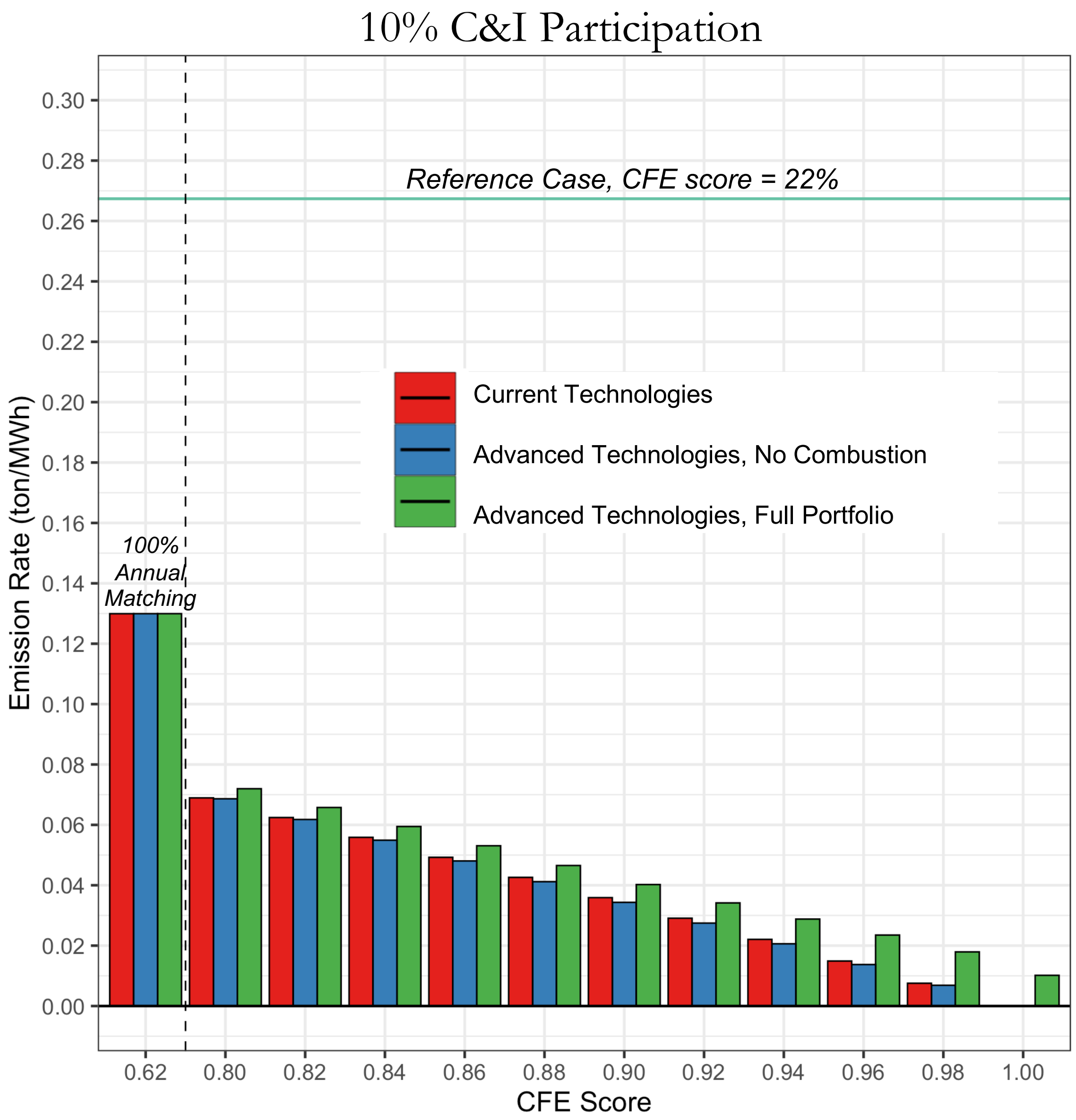
Results: PJM

Emissions rate of 24/7 participating C&I – PJM



PJM has a much lower modeled carbon-free electricity share than California in 2030. Without procuring any resources, 24/7 participants start with 22% CFE score* (vs. 64% CFE in California).

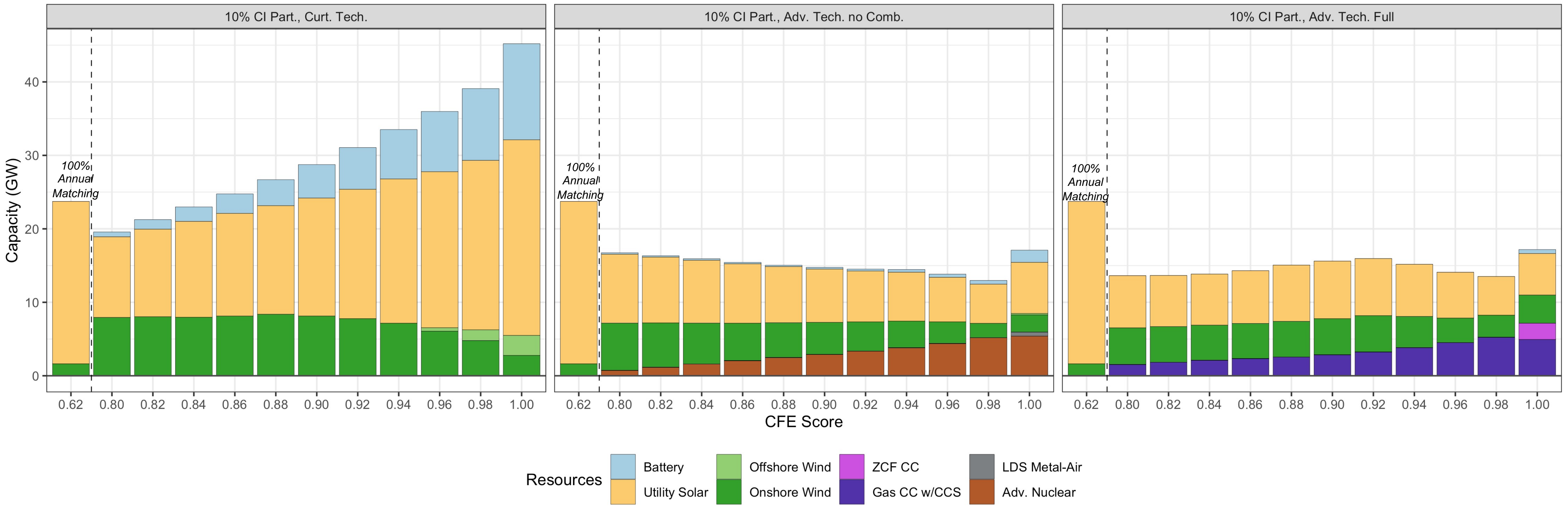
Without actively matching the CFE with the load, 100% annual matching can achieve 62% CFE (again lower than the 75% CFE in California).

As in California, under current policies, 24/7 purchasing achieves much lower emissions rate than 100% annual matching, even at a relatively low CFE targets (e.g., 80% or greater); emissions rates fall to zero (or near-zero in cases w/CCS) as CFE score increases.

Differences between green (adv. tech, full portfolio) and red/blue (current tech/adv. tech, no combustion) are primarily due to residual emissions from NGCC w/CCS (assuming 90% CO_2 capture rate).

*As we will see later in this report, under the current policy and the pressure of currently low natural gas price (thus low energy price because of the marginal pricing scheme of PJM), our modeling estimates it is cost-effective for PJM nuclear without ZEC support to retire in 2030, and PJM coal to completely exit the market. More NGCC enters the market to fill the gap, lowering the clean energy share of the grid supply, compared to today (~40%)

24/7 Resource Portfolio Capacity – PJM



As in California, energy storage and clean firm capacity increase as CFE score increases, indicating greater impact on sectoral transformation goals.

- In PJM, 100% annual matching is met at least cost by procuring a smaller share of onshore wind in addition to solar PV (assuming 10% participation of C&I customers).
- As in California, 24/7 participating load purchases a much more diverse portfolio than 100% annual matching, including a mix of solar, wind, storage, and clean firm resources.
- *Current techs*: PJM lacks access to conventional geothermal and thus any clean firm capacity under current technologies; higher CFE score drives larger solar & storage capacity; at >96% CFE, offshore wind enters the portfolio to diversify the temporal profile of procured resources.
- *Advanced techs, no combustion*: Advanced nuclear capacity increases as CFE score increases, substantially reducing variable renewable energy and Lithium-ion battery storage capacity. A small amount of long duration metal-air storage (LDS) enters the portfolio if the CFE target is 100%.
- *Advanced techs, full portfolio:* If low-carbon combustion technologies are allowed, natural gas w/CCS and zero-carbon fuel plants will substitute for advanced nuclear & LDS. However, the built-out of natural gas w/CCS can be dependent on natural gas price and the existence of current tax incentives for carbon capture and storage (45Q); see Sensitivity Analysis, Slides 78-81.

24/7 Resource Portfolio Capacity – PJM

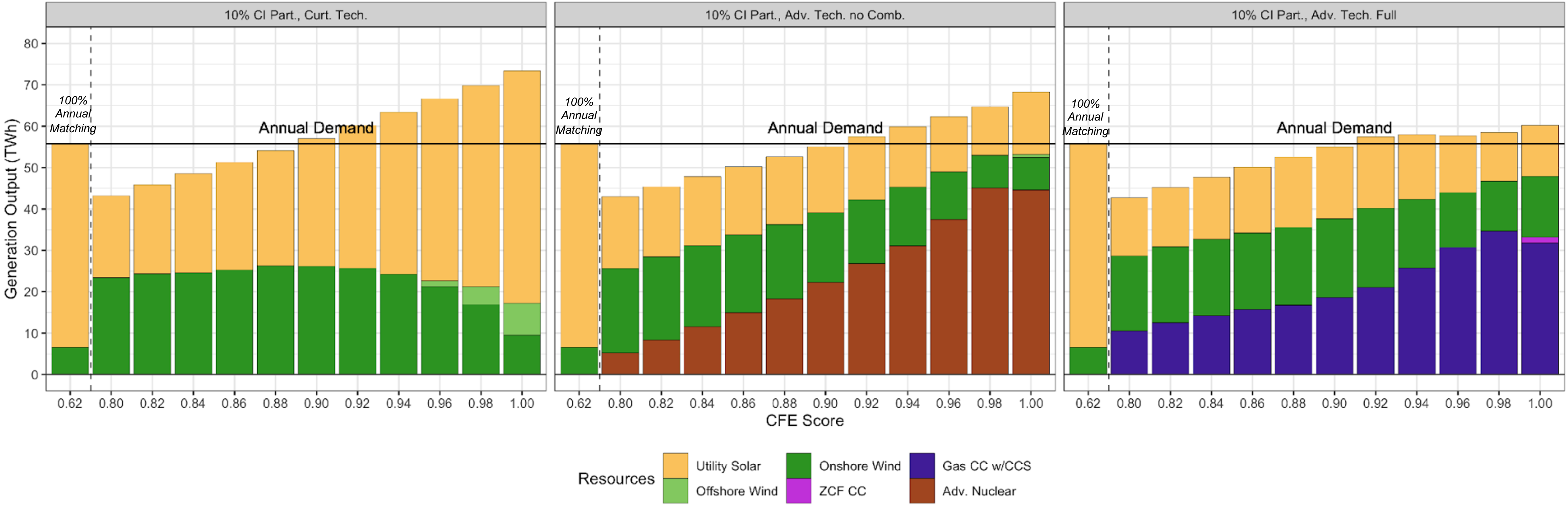
100% Annual Matching – Capacity Deployed (GW)

100% Annual	Offshore Wind	Onshore Wind	Utility Solar	Geothermal	Battery	Battery (Duration)	Geothermal NFEGS	LDS Metal-Air	LDS Metal-Air (Duration)	Gas CC w/CCS	ZCF CC
10% CI Part., Curt. Tech.	0	1.6	22.1	0	0	0	0	0	0	0	0
10% CI Part., Adv. Tech. no Comb.	0	1.6	22.1	0	0	0	0	0	0	0	0
10% CI Part., Adv. Tech. Full	0	1.6	22.1	0	0	0	0	0	0	0	0

24/7 CFE Procurement – Capacity Deployed (GW)

88% CFE	Offshore Wind	Onshore Wind	Utility Solar	Geothermal	Battery	Battery (Duration)	Geothermal NFEGS	LDS Metal-Air	LDS Metal-Air (Duration)	Gas CC w/CCS	ZCF CC
10% CI Part., Curt. Tech.	0	7.8	17.6	5.7	5.6	0	0	0	0	0	0
10% CI Part., Adv. Tech. no Comb.	0	4	6.9	0.3	3.7	3.4	0	0	0	0	0
10% CI Part., Adv. Tech. Full	0	5	7.8	0	0	0	0	0	3.2	0	0
98% CFE	**Offshore Wind**	**Onshore Wind**	**Utility Solar**	**Geothermal**	**Battery**	**Battery (Duration)**	**Geothermal NFEGS**	**LDS Metal-Air**	**LDS Metal-Air (Duration)**	**Gas CC w/CCS**	**ZCF CC**
10% CI Part., Curt. Tech.	1.5	4.8	23.1	9.8	6.2	0	0	0	0	0	1.5
10% CI Part., Adv. Tech. no Comb.	0	2	5.3	0.5	4.2	5.2	0	0	0	0	0
10% CI Part., Adv. Tech. Full	0	3	5.3	0	0	0	0	0	5.2	0	0
100% CFE	**Offshore Wind**	**Onshore Wind**	**Utility Solar**	**Geothermal**	**Battery**	**Battery (Duration)**	**Geothermal NFEGS**	**LDS Metal-Air**	**LDS Metal-Air (Duration)**	**Gas CC w/CCS**	**ZCF CC**
10% CI Part., Curt. Tech.	2.7	2.8	26.6	13.1	6.9	0	0	0	0	0	2.7
10% CI Part., Adv. Tech. no Comb.	0.2	2.3	6.9	1.7	3.6	5.4	0.5	108	0	0	0.2
10% CI Part., Adv. Tech. Full	0	3.8	5.6	0.5	2.8	0	0	0	4.9	2.2	0

24/7 Resource Portfolio Output – PJM

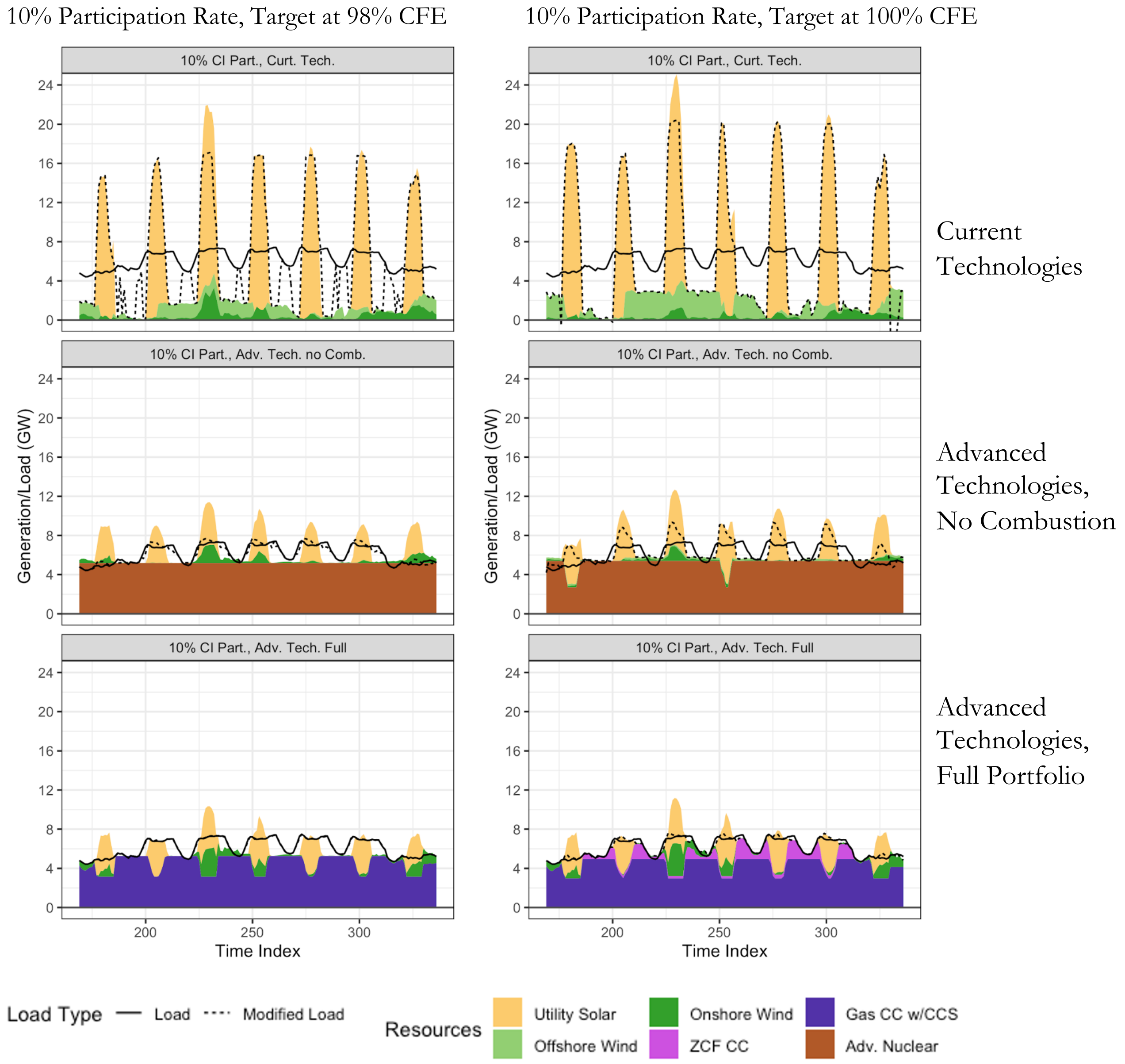


Generation in PJM is more evenly split between solar and wind and in Advanced Technology cases features a large share of adv. nuclear or gas w/CCS

In Current Technologies cases, the total generation surpasses 100% annual matching and total annual demand for participating customers for any CFE >88%.

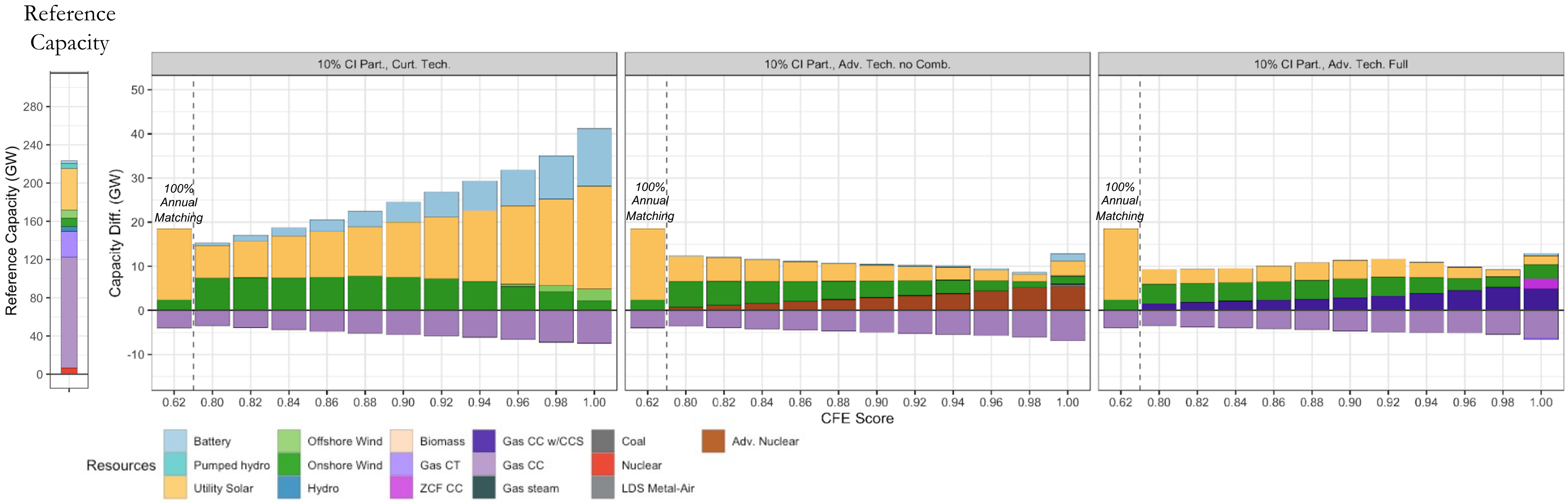
Advanced Technology portfolios with clean firm generation (advanced nuclear or natural gas w/CCS) more closely match participating demand with less excess generation.

Example of hourly generation and demand profiles: 98% and 100% 24/7 score – PJM



- As in California, storage resources and flexible demand are used to modify demand to align with contracted solar production
- Absent any clean firm option in the Current Technologies case (e.g. the geothermal present in California), significant storage capacity is required to utilize large excess peak solar generation and shift this output to evening periods.
- Clean firm capacities (nuclear, natural gas w/CCS and zero carbon fuel, if allowed) significantly reduce storage operations and demand flexibility activations (i.e., dashed modified demand lines are closer to the solid original demand lines).
- Gas w/CCS and ZCF power plants have better flexibility and higher marginal costs than advanced nuclear plants; they therefore ramp up/down more frequently to closely match participating demand and reduce excess generation.
- For 100% CFE, grid supply is not permitted (as the grid supply is not 100% clean) requiring procured generation to completely cover the modified demand profile represented by the dashed lines. Zero-carbon fueled CC's play a key role in filling this final gap between supply and demand and their availability thus lowers costs of the Adv. Tech. Full Portfolio cases.

System Level Total Capacity – PJM



24/7 portfolios retire more natural gas capacity, but the capacity value of wind and solar is higher in PJM than California due to lower system penetration

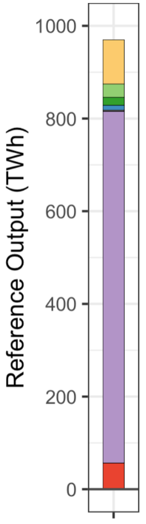
Reference: under current policies and the pressure of currently low natural gas prices, our modeling estimates that it is economic to retire PJM nuclear capacity that does not receive state policy support (e.g. ZECs) by 2030 and for PJM coal to completely exit the market. More NGCC capacity enters to fill the gap.

100% annual matching in PJM includes procurement of about 18 GW of solar and wind and reduces NGCC capacity by 4 GW, reflecting an average capacity substitution value of 22% (10 percentage points higher than California due to the lower system penetration of wind & solar in PJM and the blend of solar and wind in the portfolio).

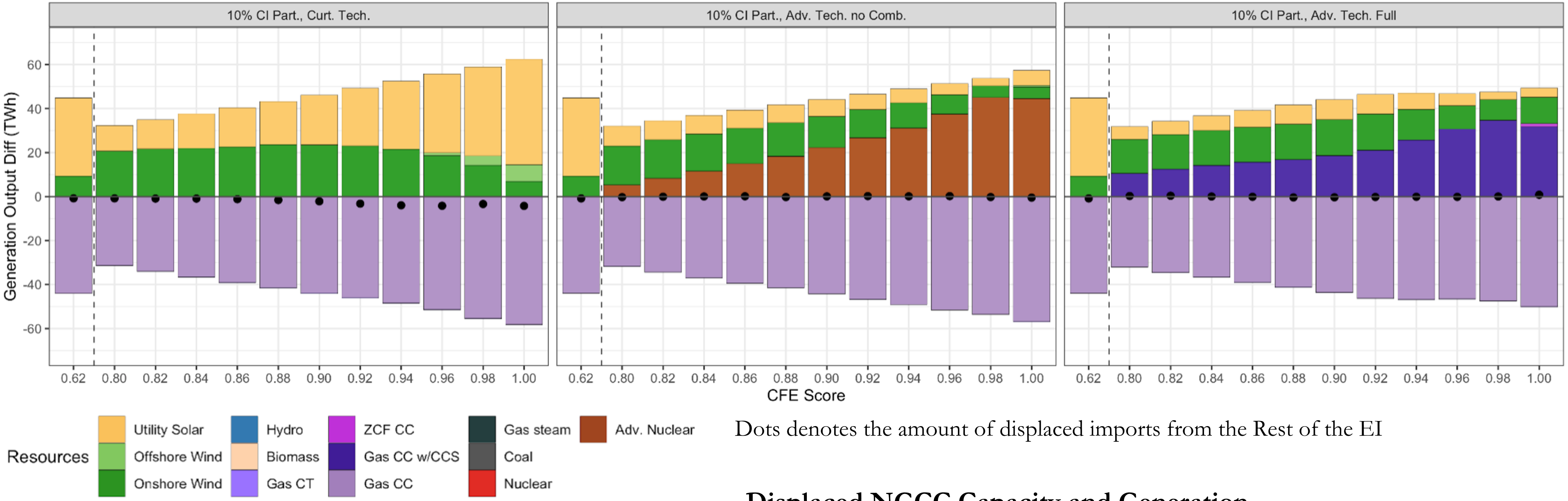
The purchase of additional clean firm generation in the 24/7 portfolios can reduce NGCC capacity while meeting system reliability needs, with roughly one-for-one substitution of clean firm and NGCC capacity.

System Level Total Generation – PJM

Reference Output



Reference: under current policies, the load-weighted average RPS of the whole PJM is about 20% in 2030 and CFE score is 22%. PJM generation is mostly from natural gas.



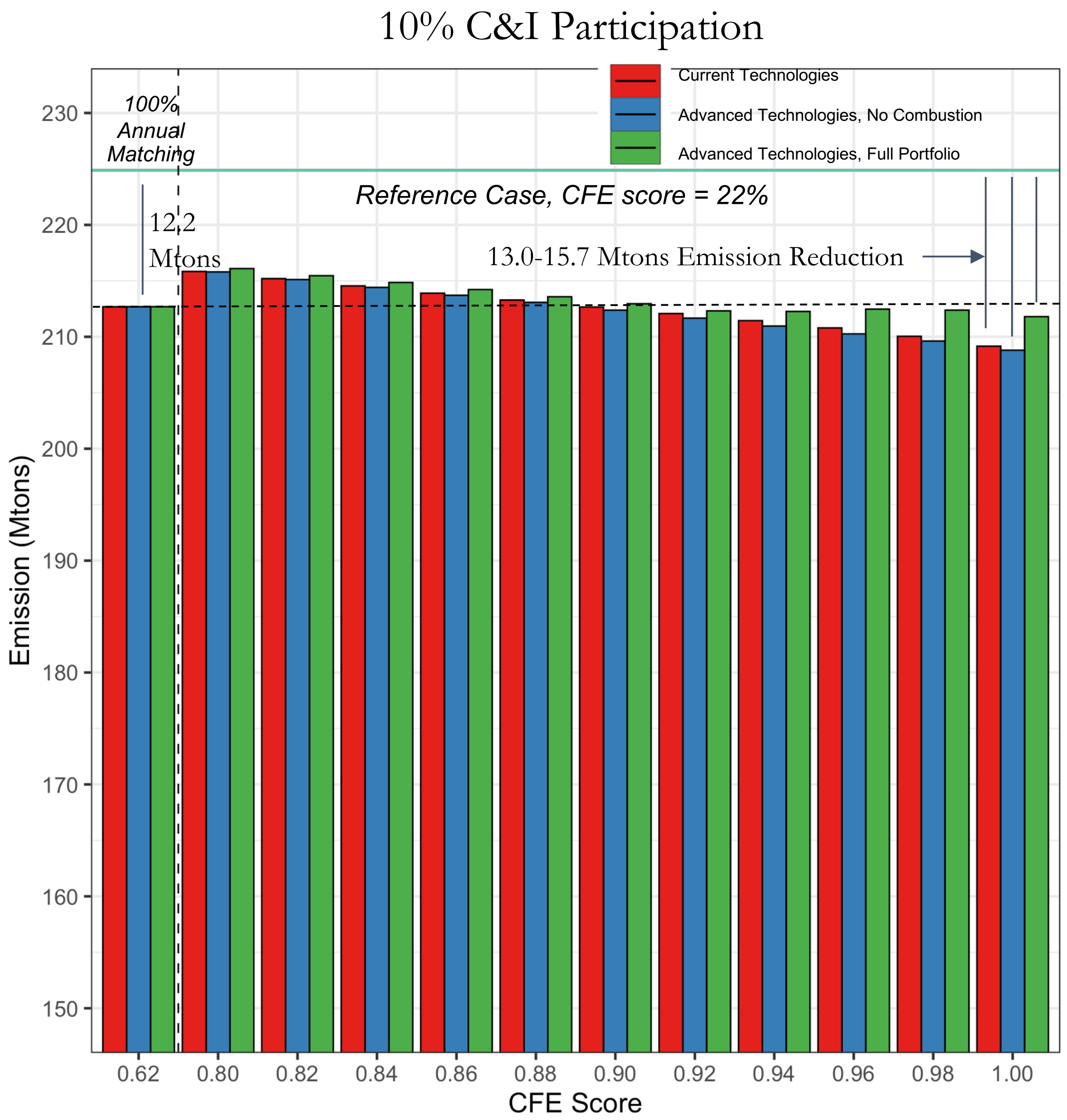
Dots denotes the amount of displaced imports from the Rest of the EI

24/7 CFE procurement can reduce NGCC capacity and generation in PJM to a greater extent than 100% Annual Matching.

Displaced NGCC Capacity and Generation

Reference PJM NGCC Capacity = 116 GW PJM NGCC Generation = 759 TWh		100% Annual Matching (*ex post* CFE = 62%)		24/7 Hourly Matching (CFE Target = 92%)		24/7 Hourly Matching (CFE Target = 100%)	
		Capacity (GW)	Output (TWh)	Capacity (GW)	Output (TWh)	Capacity (GW)	Output (TWh)
Available Tech.	Current Tech.	4.0	44.0	5.8	45.9	7.5	58.1
	Advanced Tech., No Combustion	4.0	44.0	5.2	46.7	6.9	56.7
	Advanced Tech., Full Portfolio	4.0	44.0	4.9	46.2	6.2	50.0

System level CO_2 emissions – PJM (including imported emissions)



In the PJM system, solar and wind penetration levels are lower and gas-fired generators are the marginal supply during more hours of the year. This makes the **volume effect** (see Slide 47) a more powerful driver of overall emissions abatement than in California.

Due to less variation in hourly marginal emissions rates in the PJM system, the **timing effect** is less pronounced.

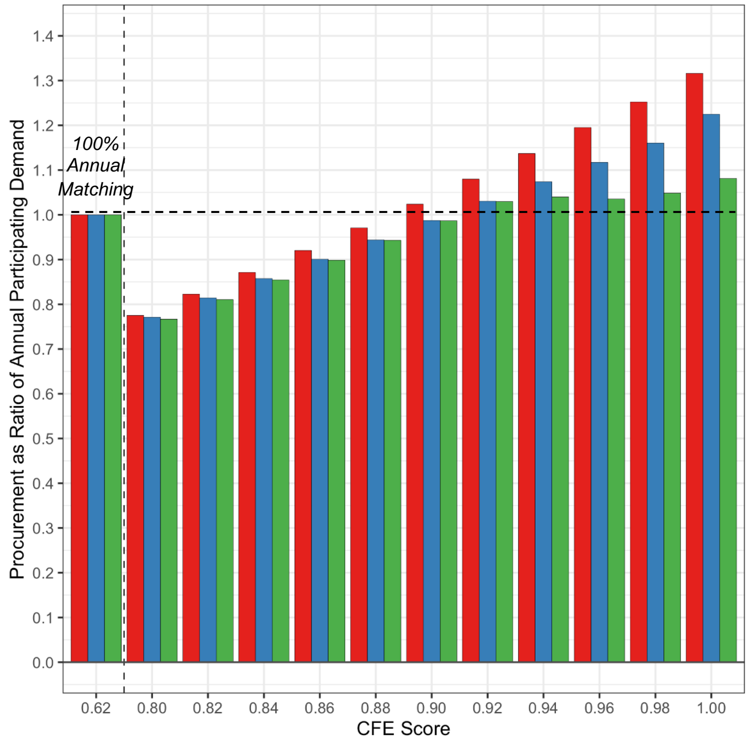
24/7 procurement drives greater system-level emissions reductions than 100% annual matching for CFE scores ≥92%.

C&I customers procuring 100% 24/7 CFE lowers system-wide emissions by 13.1-15.7 Mtons per year, with 10% C&I participation rate.

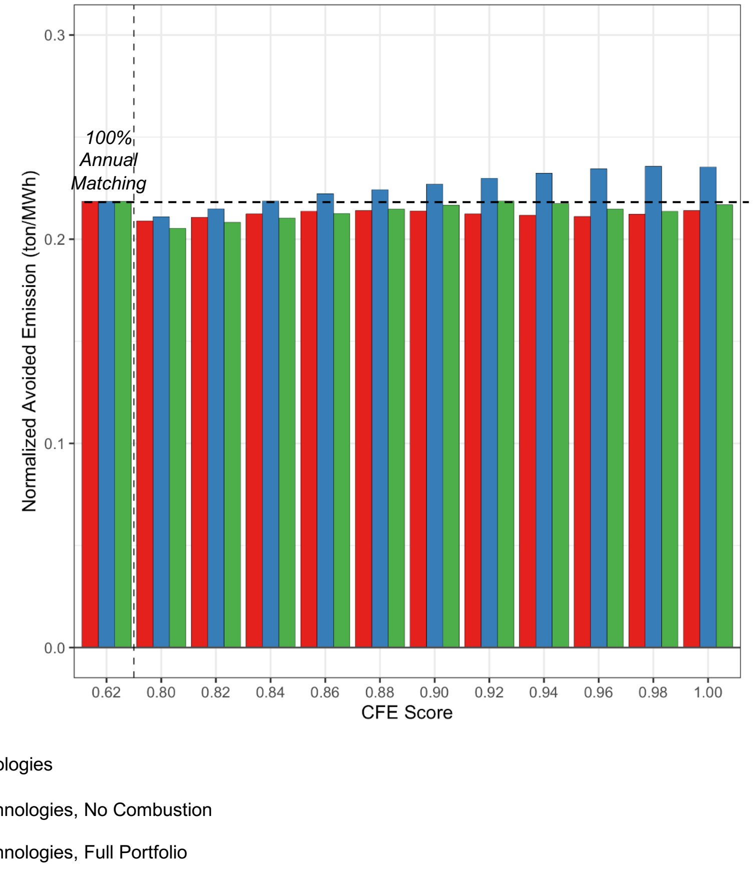
- This reduces emissions by 6% to 7% of the Reference case.
- 100% CFE achieves 7%-29% greater emissions reductions than 100% annual matching.

Explaining differences in system-level emissions outcomes - PJM

(a) Total volume of procured carbon-free electricity –
PJM, 10% Participation Rate



(b) Normalized avoided emissions per MWh of procured electricity –
PJM, 10% Participation Rate



In the PJM system, solar and wind penetration levels are lower and gas-fired generators are the marginal supply during more hours of the year. This makes the **volume effect** (see Slide 47) a more powerful driver of overall emissions abatement than in California: e.g. generating more total MWh can reduce gas generation and associated emissions more (see figure at left, panel (a)).

Due to less variation in hourly marginal emissions rates in the PJM system, the **timing effect** is less pronounced (e.g. normalized avoided emissions per MWh in figure at left, panel (b) increase only modestly as CFE increases).

These results highlight that procurement and operation of a portfolio optimized to reduce CO_2 emissions may differ from a portfolio optimized to align with participating demand, unless participating demand profiles and marginal emissions rates are highly correlated.

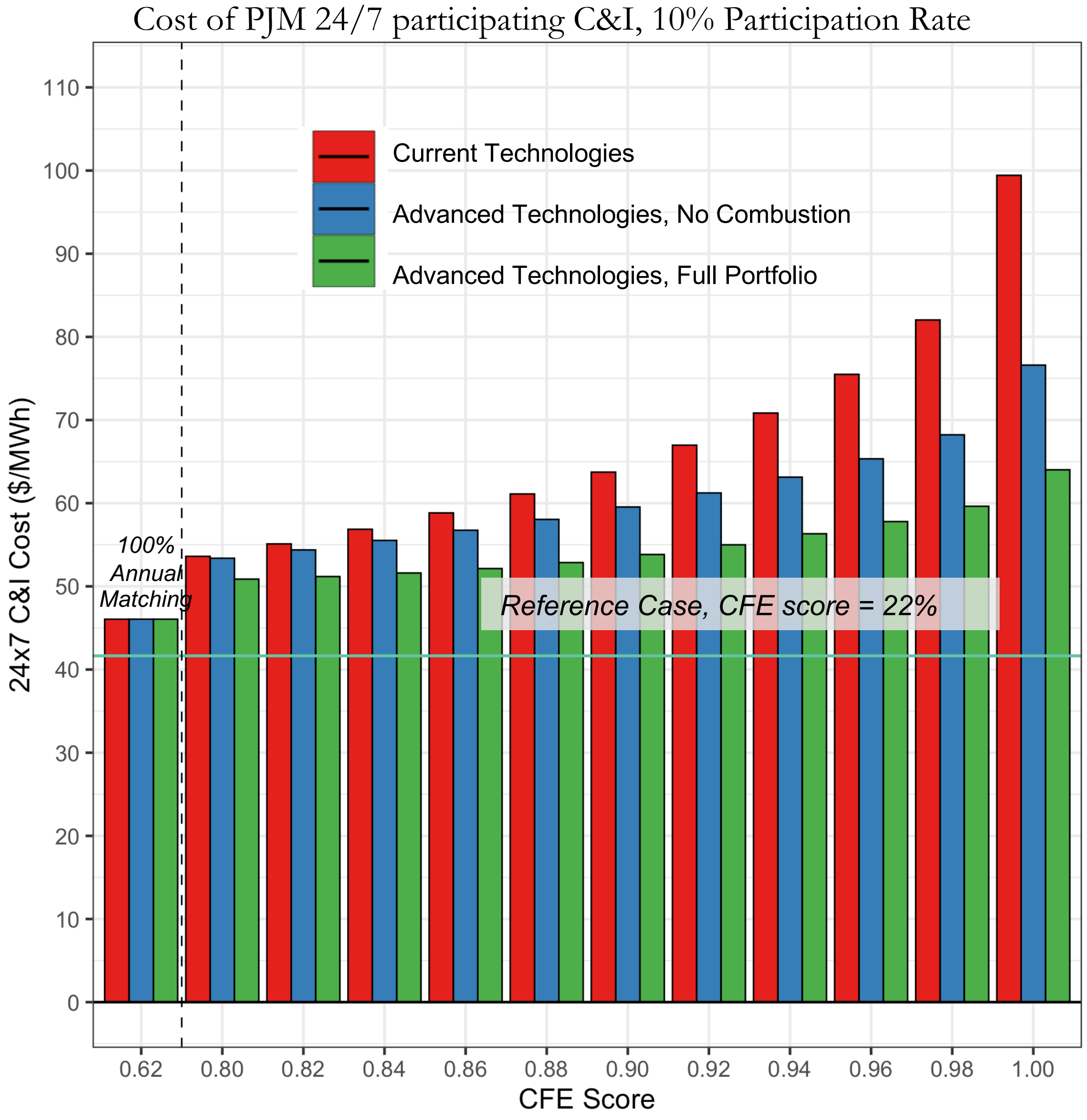
Summary of avoided emissions - PJM

Avoided Emission (Mtons/year)

Reference Participating Load Emission = 14.9 Mton/year Rest of California Emission = 207.9 Mton/year California Emission = 222.8 Mton/year		100% Annual Matching (*ex post* CFE = 62%)			24/7 Hourly Matching (Target CFE = 92%)			24/7 Hourly Matching (Target CFE = 100%)		
		Participating Load	Rest of the PJM Load	Total	Participating Load	Rest of the PJM Load	Total	Participating Load	Rest of the PJM Load	Total
Available Technology	Current Technologies	7.7	4.5	12.2	13.3	-0.5	12.8	14.9	0.8	15.7
	Advanced Technologies, No Combustion	7.7	4.5	12.2	13.4	-0.2	13.2	14.9	1.2	16.1
	Advanced Technologies, Full Portfolio	7.7	4.5	12.2	13.0	-0.5	12.6	14.3	-1.3	13.1

24/7 matching can drive deeper emissions reductions than 100% annual matching if the target is high enough (e.g., 92% or greater);

Cost for 24/7 participating C&I consumers – PJM



24/7 procurement can deliver lower emissions rates for participating C&I customers, drive greater emissions reductions (at CFE ≥92%) and help transform electricity systems via accelerated deployment of clean firm resources. As in California, greater impact of 24/7 procurement in PJM comes at a premium cost relative to 100% annual matching, particularly when procurement is limited to currently mature technologies.

Costs for participating customers are reduced with a more expansive portfolio of advanced technologies including clean firm generation. This is because:

- The current technologies portfolio in PJM is limited to wind, solar and batteries, with no geothermal as in California, leaving no clean firm options. This results in an even more pronounced increase in marginal costs of achieving higher CFE, as increasing CFE requires larger and larger storage capacity to permit greater use of wind and solar, raising portfolio costs.
- With advanced clean firm technologies (e.g., advanced nuclear, long-duration storage, CCS, zero-carbon fuel), this effect is moderated due to higher system value of these technologies, and costs increase much more modestly as share of participating C&I customers increases.
- The Advanced Technology, No Combustion case adds clean firm capacity to the mix, but only advanced nuclear with high fixed and low variable costs, which makes it techno-economically suited to high utilization rates. Adding NGCC w/CCS and ZCF in the Full Portfolio case provides a broader range of resources suited to varying utilization rates, further lowering costs.
- Cost premiums for 24/7 CFE also decrease as the overall system becomes cleaner (see Sensitivities, slide 83).

Summary of cost for 24/7 participating C&I consumers – PJM

C&I Cost Increase Compared to the Reference in PJM (2020US$/MWh)

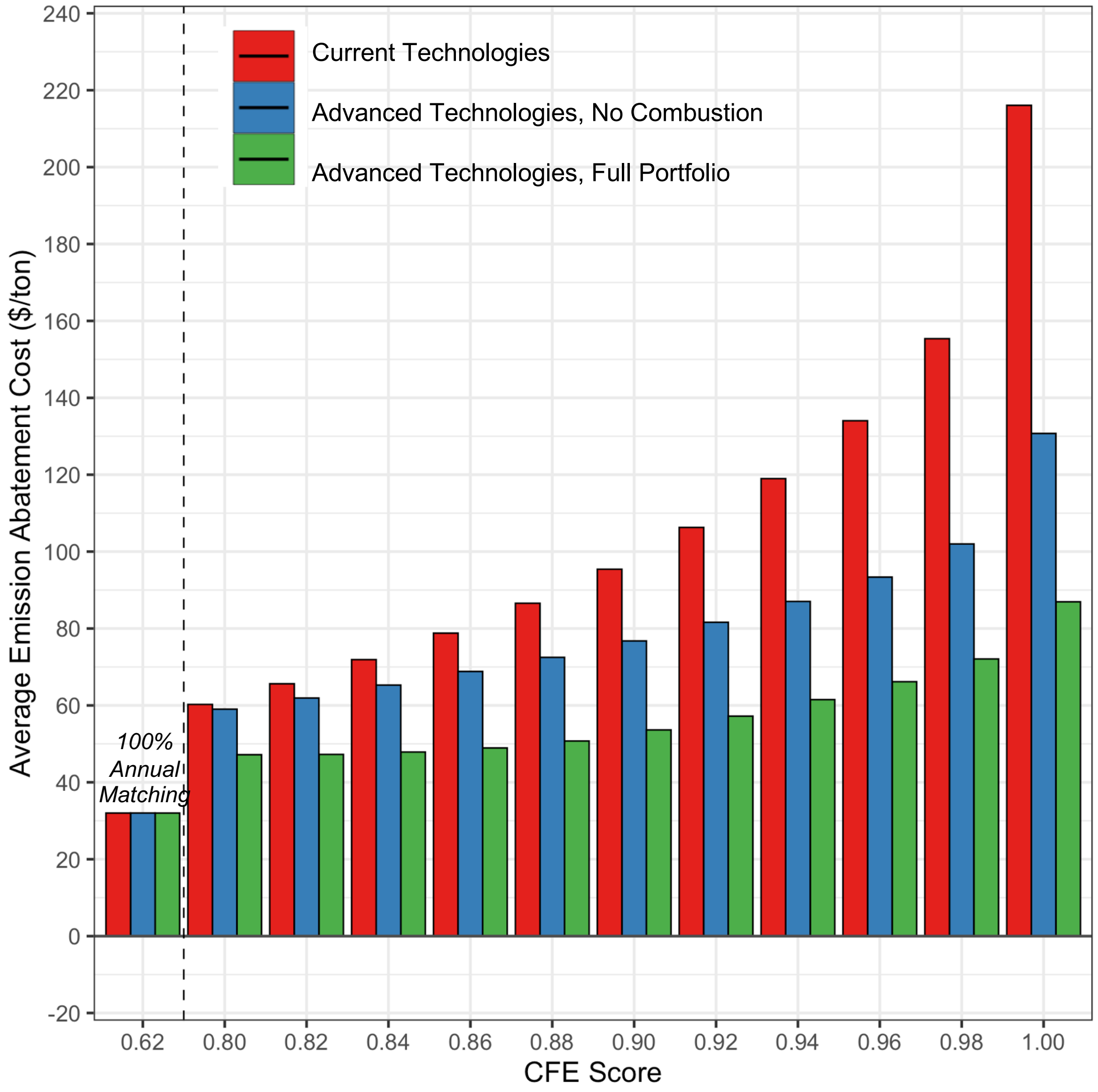
Reference Reference PJM Participating C&I Cost = $41.7/MWh		100% Annual Matching (*ex post* CFE = 62%)	24/7 Hourly Matching (Target CFE = 92%)	24/7 Hourly Matching (Target CFE = 98%)	24/7 Hourly Matching (Target CFE = 100%)
Available Technology	Current Technologies	4.4 (+10%)	25.3 (+61%)	40.3 (+97%)	57.8 (+139%)
	Advanced Technologies, No Combustion	4.4 (+10%)	19.6 (+47%)	26.5 (+64%)	35.0 (+84%)
	Advanced Technologies, Full Portfolio	4.4 (+10%)	13.3 (+32%)	17.9 (+43%)	22.4 (+54%)

24/7 CFE delivers greater emissions reductions and sectoral transformation, but comes at a cost premium relative to 100% annual matching

Note: Our result indicate that the additional cost of 24/7 procurement is internalized by participants; i.e., participating loads are responsible for paying ~100% of the incremental system costs resulting from 24/7 procurement, with no cost shifting to non-participating customers.

Abatement cost as a function of CFE score - PJM

10% Participation Rate, Cost of 24/7 participating C&I

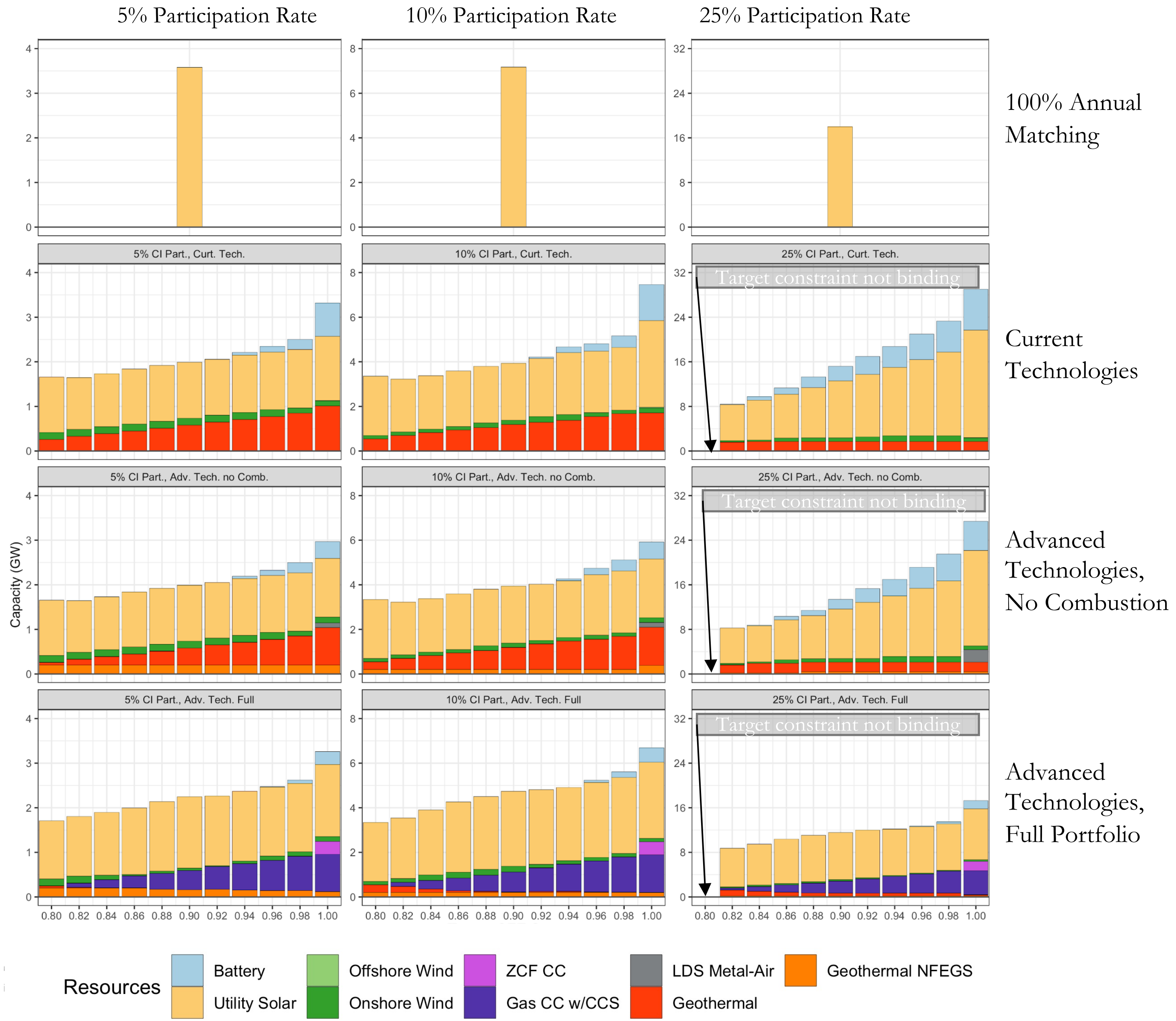


- While 24/7 procurement can deliver greater emissions reductions than 100% annual matching, it does so at a higher average abatement cost ($/ton of CO_2 emissions reduced), due to the added cost of meeting hourly demand
- This cost is particularly pronounced in the Current Technologies case, where PJM lacks any available clean firm resources.
- Procuring clean firm generation or long duration energy storage technologies can significantly lower marginal abatement costs, particularly at higher CFE scores.
- As in California, 24/7 procurement can drive experience curves and cost reductions for these nascent technologies, making 100% carbon-free electricity more affordable for the electricity system as a whole.

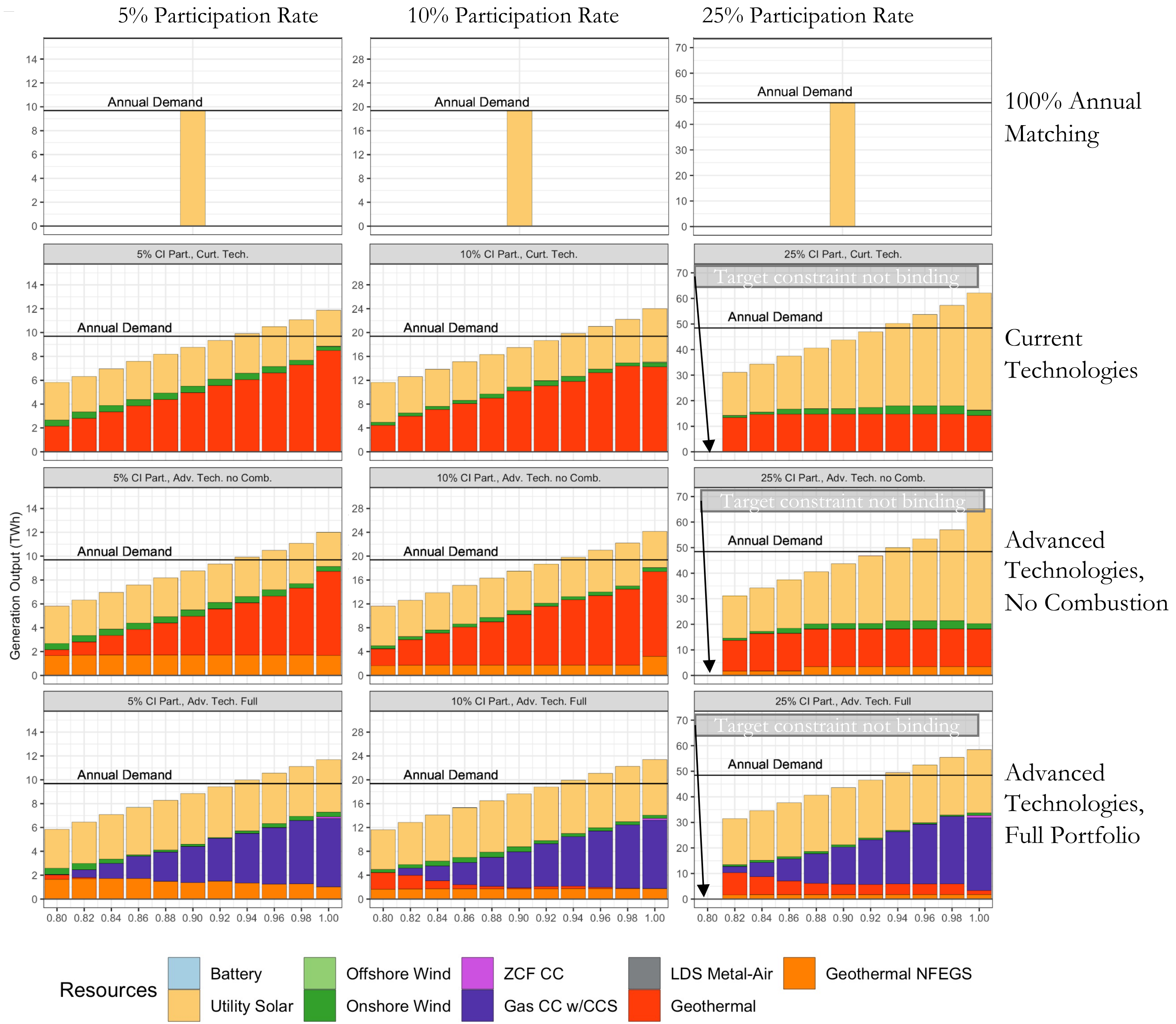
Sensitivity Analysis 1 – C&I participation rate (California)

This analysis shows that in California, limited availability of geothermal resources results in higher costs and greater reliance on solar and storage in the Current Technologies and Advanced Technologies, No Combustion cases. When the full portfolio of clean firm resources is available, natural gas w/CCS and zero-carbon fuel plants supplement geothermal and results are no longer sensitive to C&I participation rate.

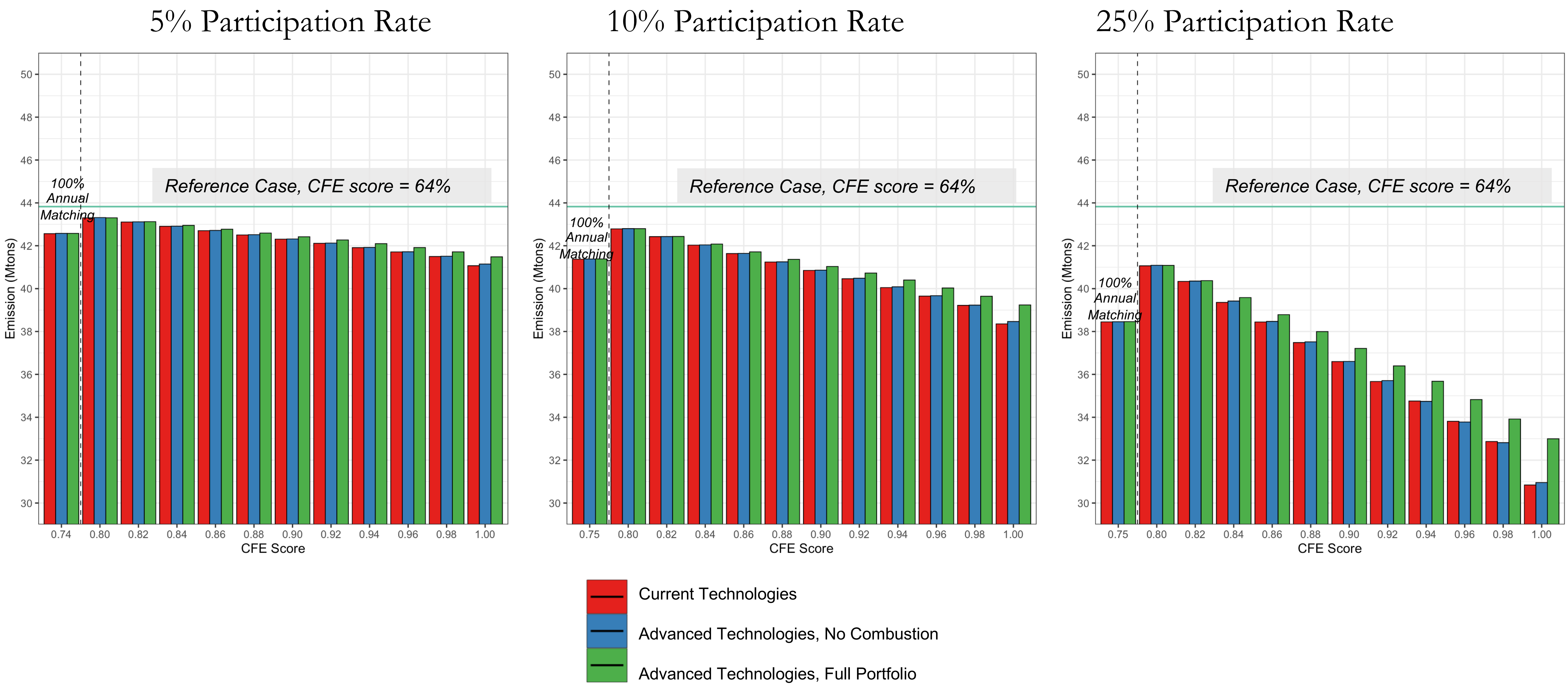
24/7 Resource Portfolio Capacity – California with different participation rate



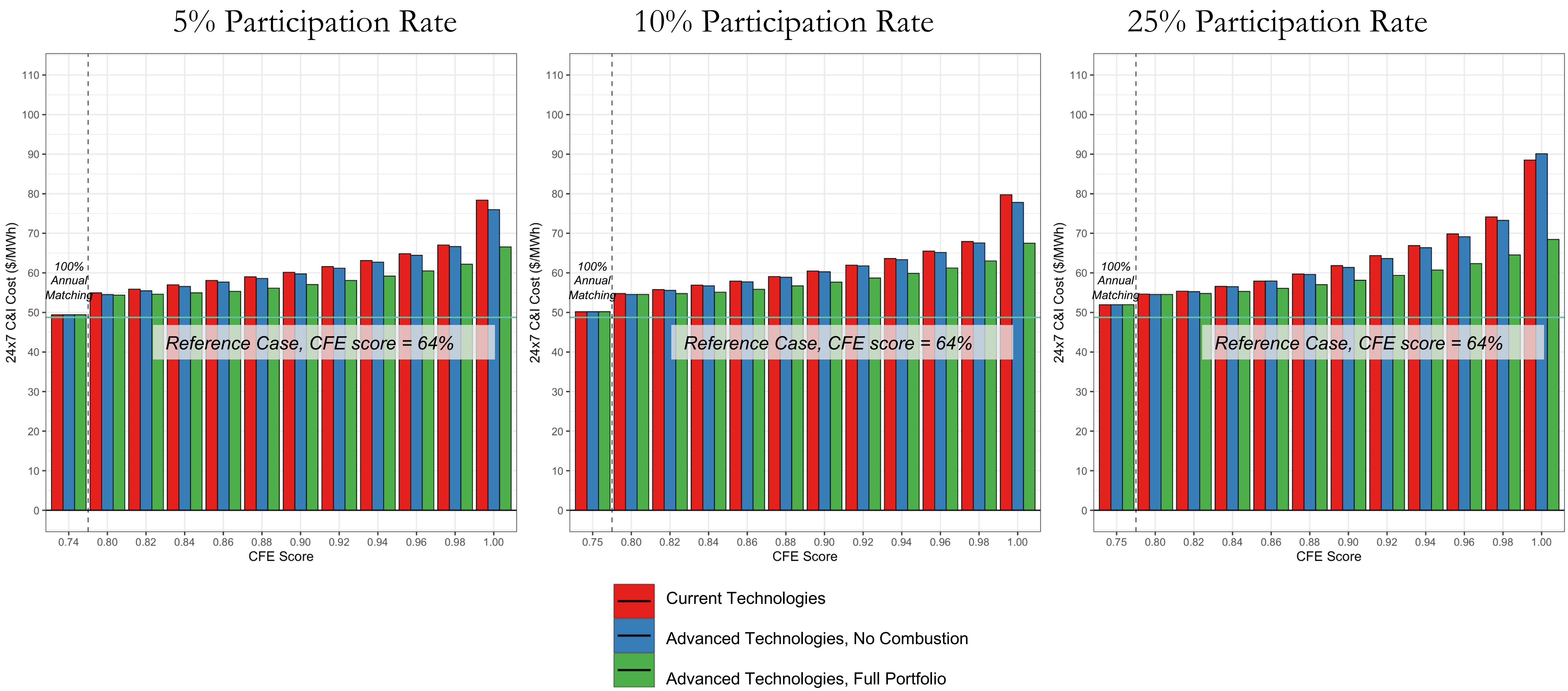
24/7 Resource Portfolio Generation – California with different participation rates



Impact on system-level emissions – California with different participation rates



Impact on Participating C&I Cost – California with different participation rates



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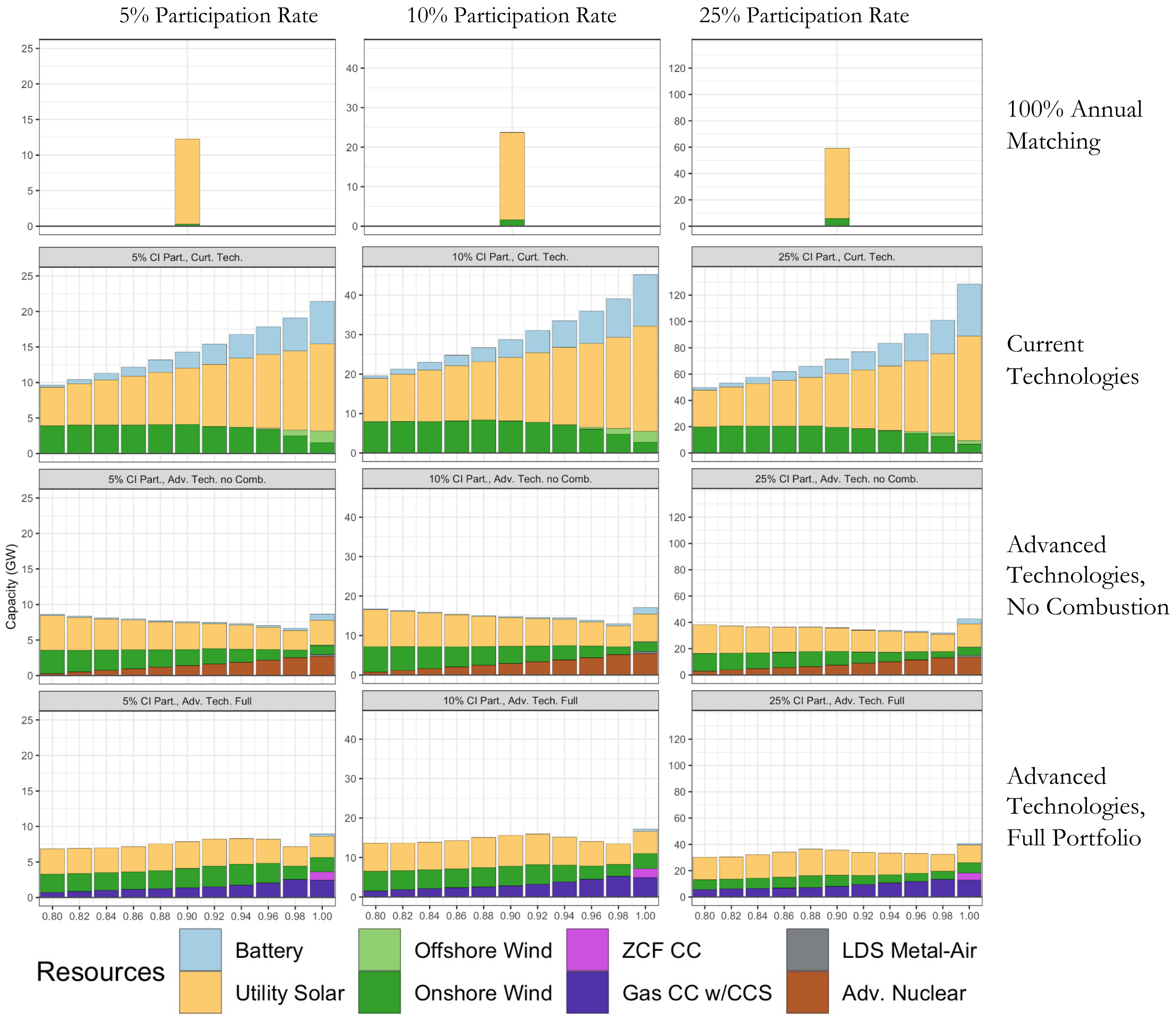
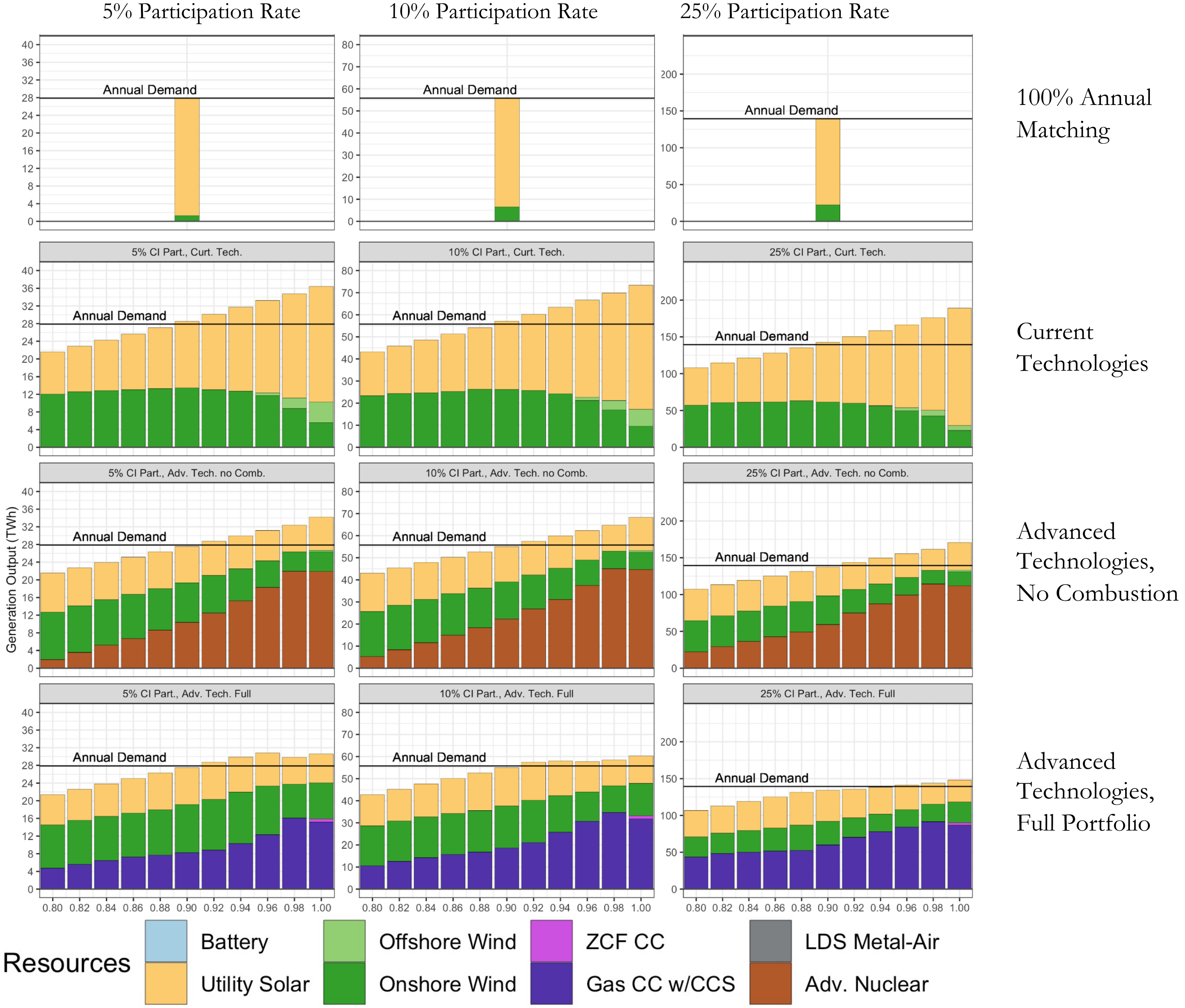
Sensitivity Analysis 2 – C&I participation rate (PJM)

This analysis shows that (a) the composition of the 24/7 procurement and (b) the trends as CFE increases are not particularly sensitive to the participation rate, while (c) the overall magnitude of impacts is proportionate to the participation rate. This analysis also shows that the cost for 24/7 participants increases slightly at higher participation rates for Current Technologies only but is insensitive to participate rate when clean firm resources are available in Advanced Technology Cases.

24/7 Resource Portfolio Capacity – PJM with different participation rate

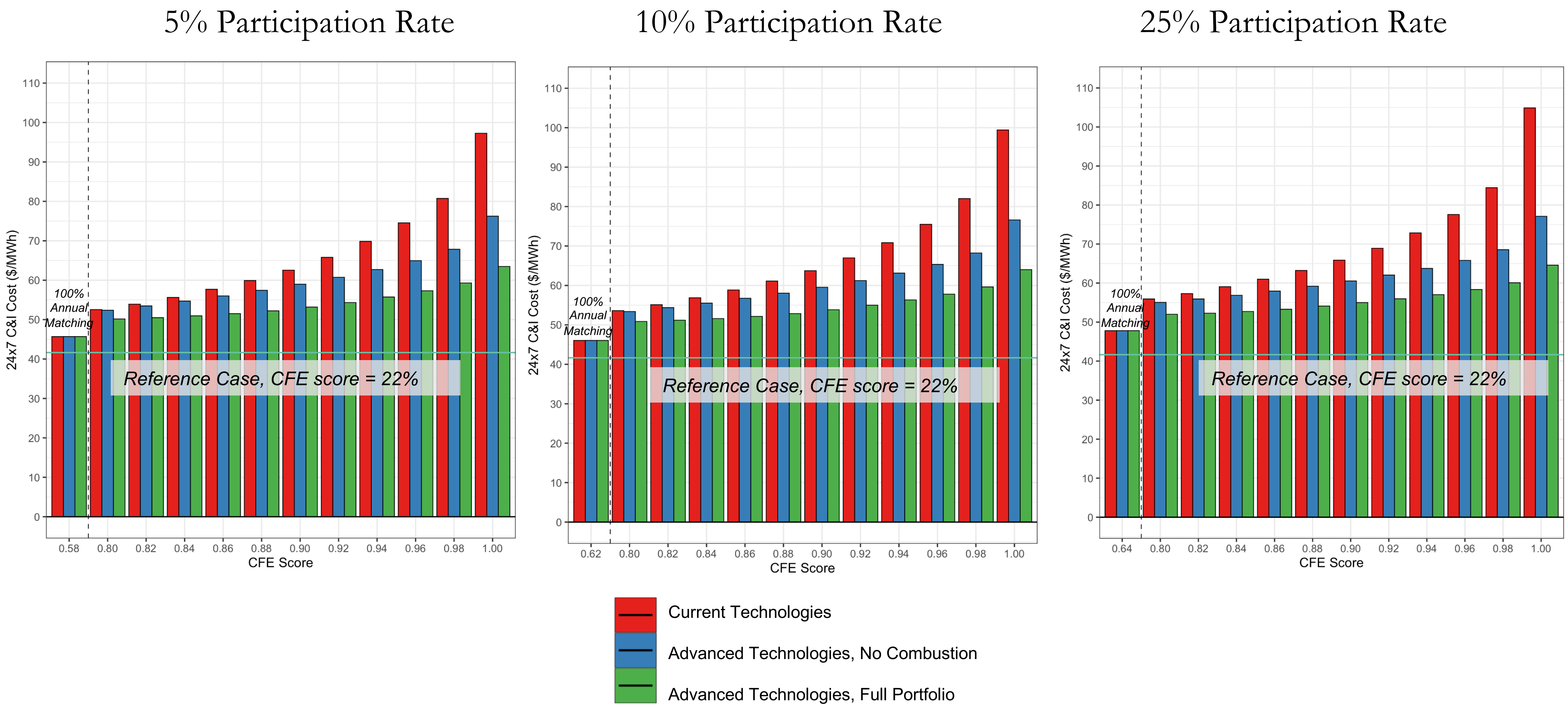


24/7 Resource Portfolio Generation – PJM with different participation rates



Impact on system-level emissions – PJM with different participation rates

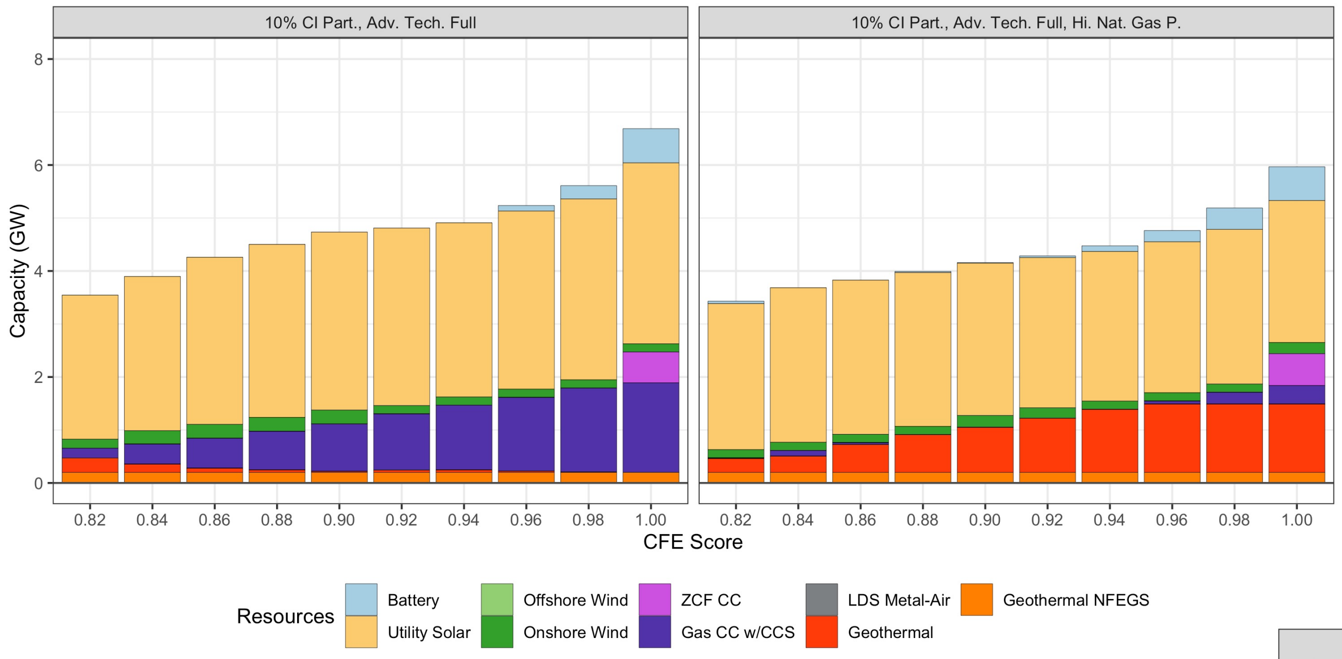
Impact on Participating C&I Cost – PJM with different participation rates



Sensitivity Analysis 3 – Natural gas price

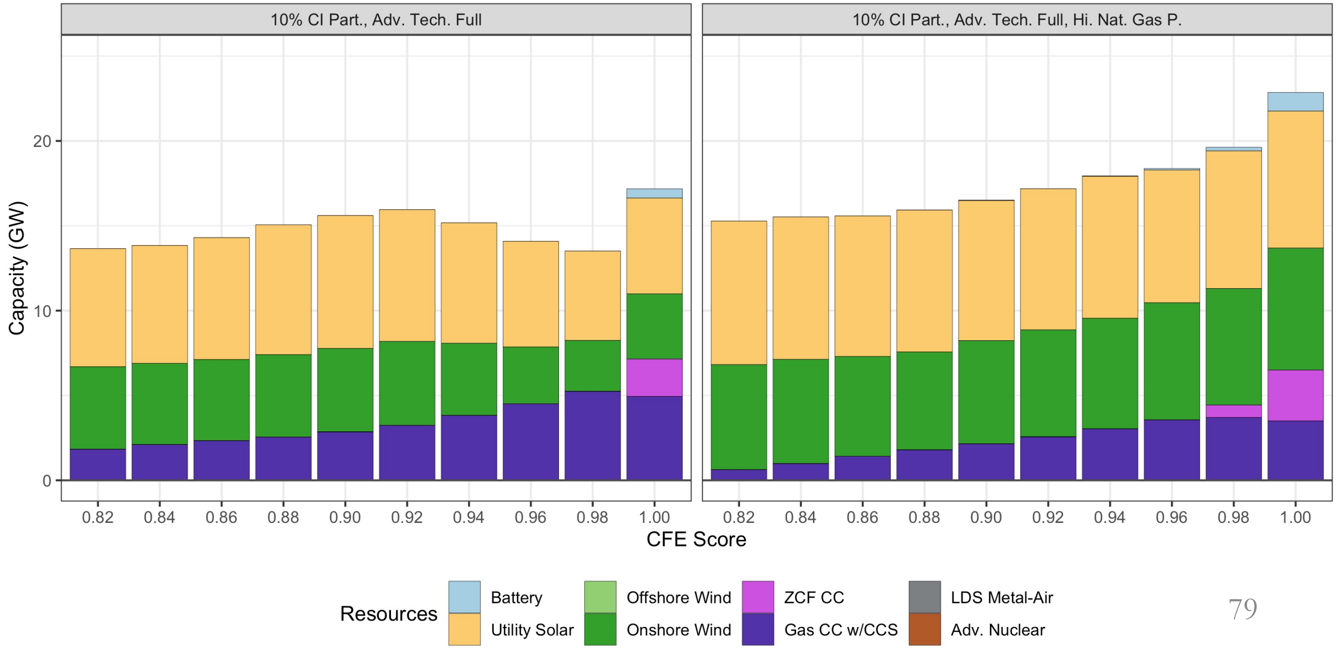
This analysis shows that natural gas combined cycle w/CCS deployment in the 24/7 portfolio is sensitive to the natural gas price, highlighting that the optimal 24/7 portfolio depends on the relative cost of the various available clean firm technologies.

Full portfolio composition is sensitive to relative costs of clean firm technologies



California (Left): if natural gas prices are higher, much less CCS will be built, and instead, more geothermal will be developed.

PJM (right): if natural gas prices are higher, much less CCS will be built, and instead, more variable renewable energy (particularly wind) and storage will be built. Combined cycle burning zero-carbon fuel (ZCF) will also be selected at a lower CFE target.

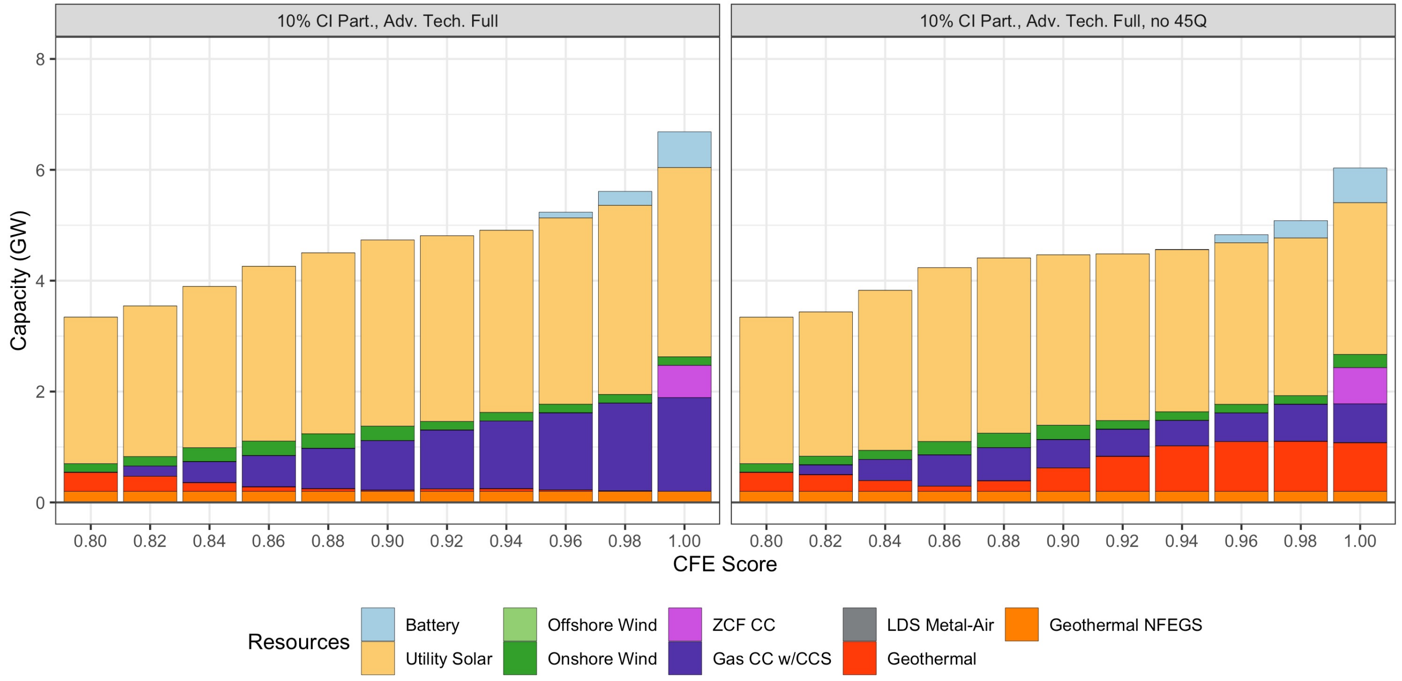


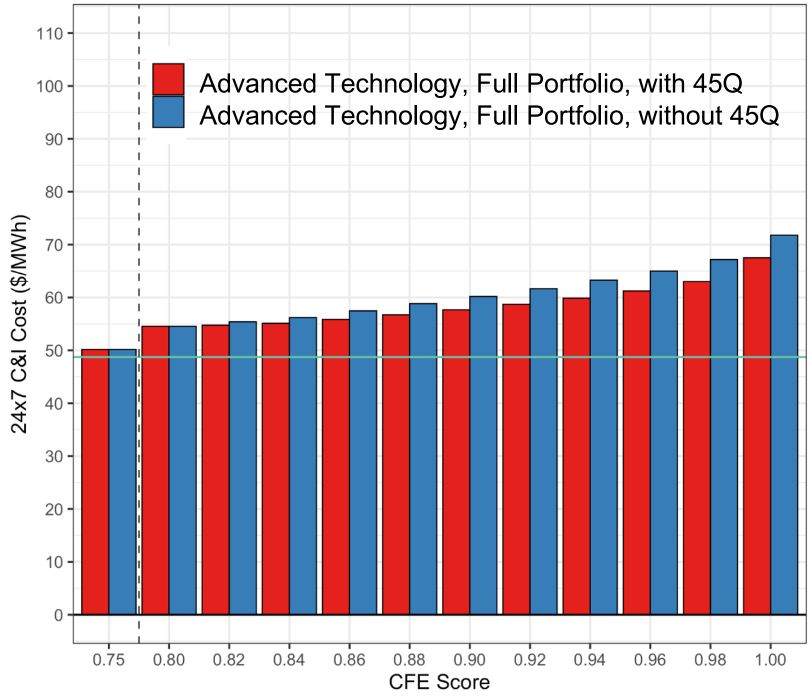
Sensitivity Analysis – 4
Technology support policies

This analysis shows that natural gas combined cycle w/CCS deployment in the 24/7 portfolio is sensitive to policy support from the 45Q tax credit, highlighting that the optimal 24/7 portfolio is impacted by technology support policies (e.g. production and investment tax credits, carbon prices, RPS policies, etc.). With Congress currently considering substantial changes to federal energy policy and subsidies, these results could change significantly under a different policy regime.

Portfolio and cost is sensitive to the presence of policy support for advanced technologies, e.g., 45Q to CCS

California results:





The 24/7 portfolio is sensitive to inclusion of the current $50/ton subsidy for CO_2 captured and stored offered by the federal 45Q tax credit.

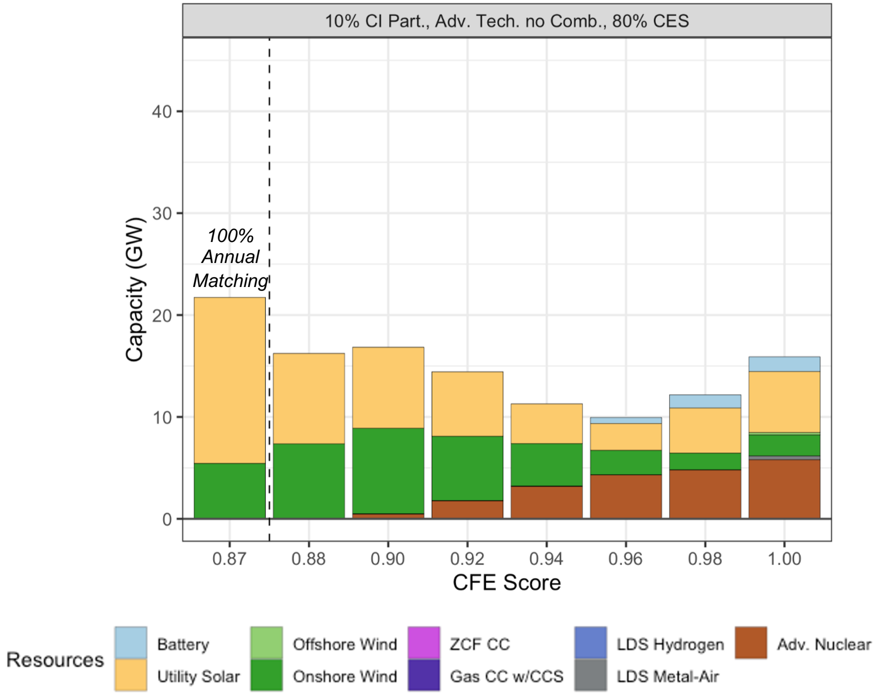
Without 45Q, 24/7 portfolios in California include a greater share of geothermal (and in 100% CFE cases, a smaller increase in wind and zero-carbon fuel combustion).

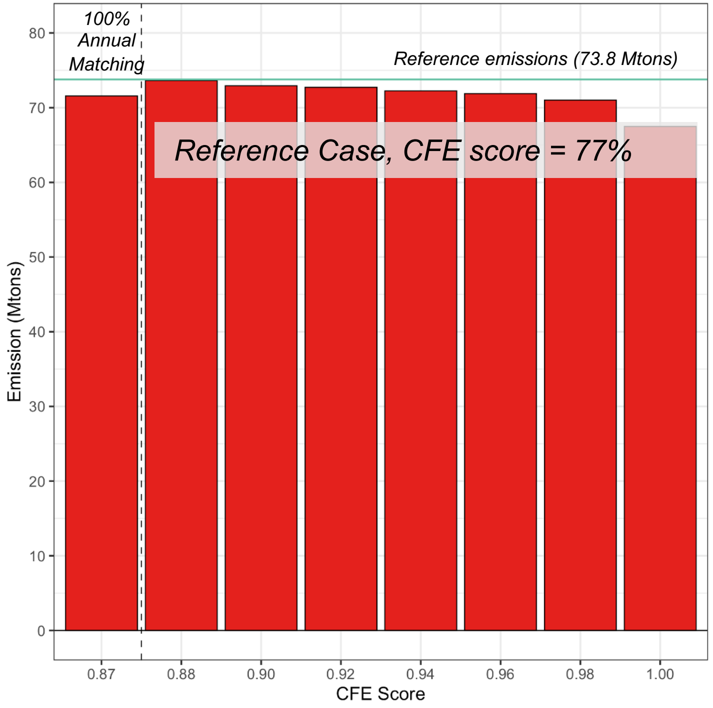
In general, policy supports for clean firm and long duration storage resources makes the cost for 24/7 CFE procurement lower, but the inclusion of 45Q does not account for all of the improvement in cost from including a full set of clean firm resources in the Advanced Tech, Full Portfolio case (relative to more constrained 24/7 portfolios).

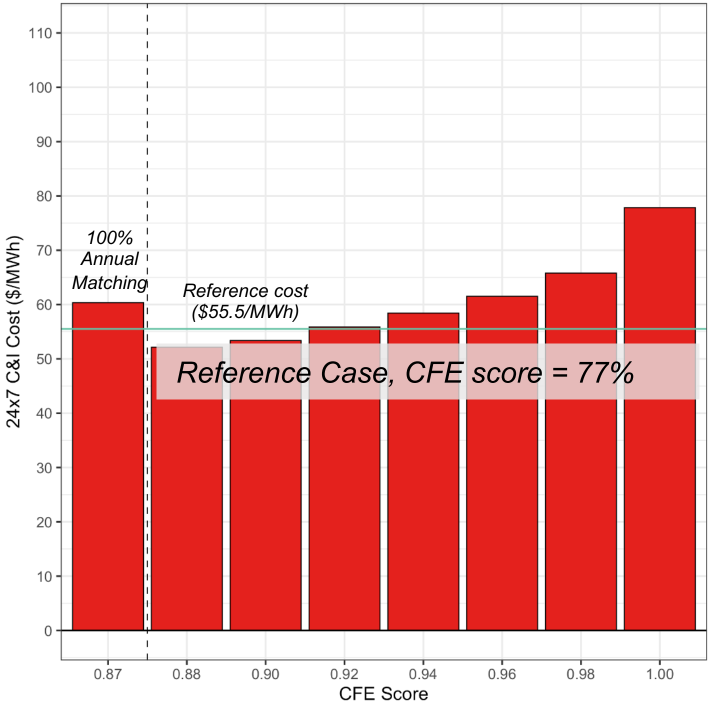
Sensitivity Analysis 5 – Higher clean energy standards

This analysis shows that under a higher clean energy standard (modeled as a requirement for 80% of electricity to be sourced from qualifying low-carbon sources), it becomes easier for 24/7 participants to meet CFE targets less than 100%, and the cost premium for 24/7 hourly matching is much lower. This is because the system penetration of wind and solar is much higher, raising the relative cost of 100% annual matching, permitting 24/7 customers to rely on grid supply for more of their CFE target (assuming <100% CFE), and making the timing effect a more salient driver of emissions reductions.

PJM results with Advanced Technologies, No Combustion + Federal Clean Energy Standards = 80%







Under a CES policy, the clean energy share in the grid supply becomes much higher, making it easier for the 24/7 participants to rely on the grid supply to meet most of CFE targets <100%. As a result the CFE target constraint starts binding only when the CFE target is high: e.g., under 80% CES in PJM, a CFE target becomes binding at 88% (Case = Advanced Technologies, no Combustion); For California, CFE target constraints starts binding only when 100% hourly matching is required (Case = Advanced Technologies, no Combustion, not shown).

A non-binding CFE target means that the contract signed between 24/7 participants and the procured resource has no additional economical value compared to the contracts that only require unbundled clean energy credits, creating no additional investment incentives. In other words, these procured resources will otherwise be built without specifically entering a contract with the 24/7 participants and simply allocate their carbon-free supply to 24/7 customers rather than the broader market.

The system being much cleaner also means the potential emission reduction driven by 100% Annual Matching and 24/7 hourly matching are both more modest. However, we still observe that 24/7 can cut more emissions more than 100% Annual Matching when the target is high enough (98% in the plots above).

Finally, the reference being much more expensive also means that the 24/7 procurement can sometimes be less expensive than reference or 100% annual matching. In another words, the premium for the participants to implement 24/7 is much less because of the CES.

Limitations and Future Work

In analyzing 24/7 procurement in this study, the model has perfect foresight in projecting hourly participating electricity demand, wind and solar variability, and knowledge of grid CFE hour by hour.

In reality, meeting 24/7 CFE goals will face both long-term uncertainty at procurement or contracting stage and short-term operational uncertainties and price volatility.

We should therefore recognize at least two extra layers of uncertainty not considered in this work:

1. Participating consumers and clean power suppliers need to estimate the demand and generation profiles *ex ante*, *at a higher resolution than the annual capacity factors*. This can involve higher estimation error and performance risk.

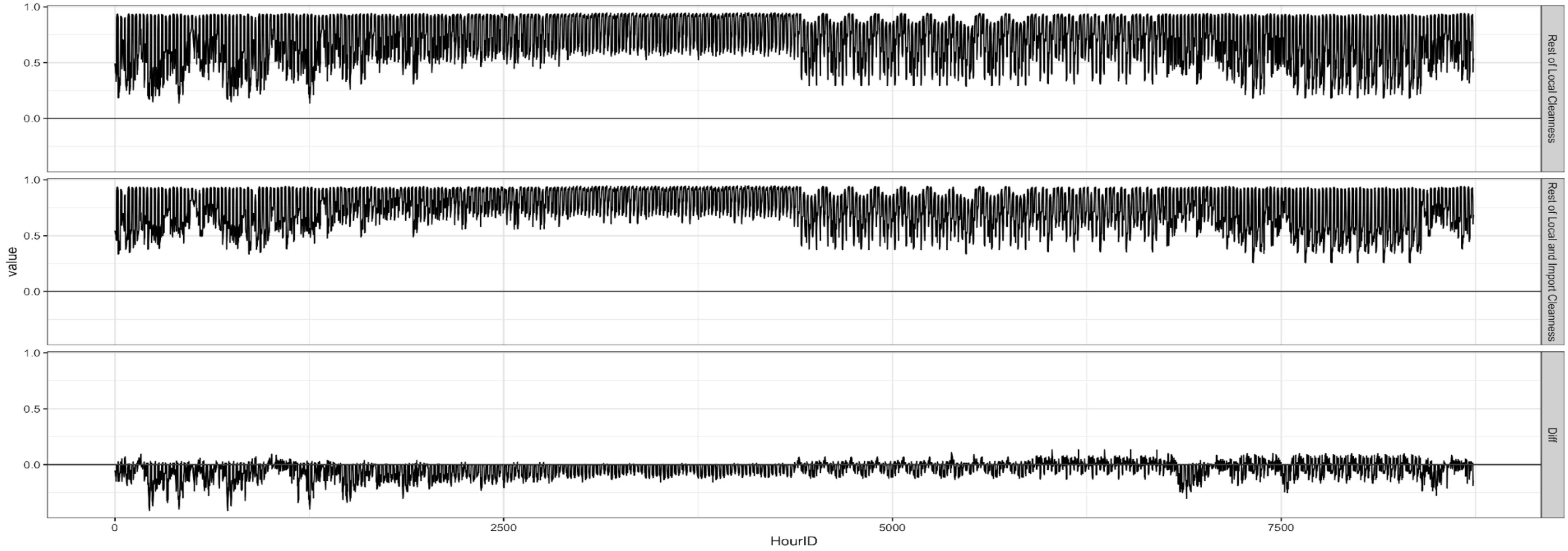
2. For a cost-efficient 24/7 procurement to meet a certain CFE target, participants need to estimate the grid supply CFE: that is, at each hour (or similar resolution), per each MWh grid supply consumption, what share of grid-supplied electricity is clean, and how much can the 24/7 participants rely on this grid supply for their total CFE goals (note at 100% CFE, this is not relevant as grid supply cannot be utilized).

Future work should explore the impact of uncertainty on 24/7 contracting and operations which may increase the challenge as compared to modeling in this study. This work could also consider the differences in price hedging and risk mitigation provided by 24/7 contracting vs 100% annual matching or other strategies (e.g. carbon optimized procurement).

Different methods for calculating grid carbon-free electricity score

Accounting methods can be another source of complexity. For example, whether or not and how to account for imports: e.g., if the California grid is importing, is the grid supply consumed by 24/7 load partially made of imports? And how much of the electricity imports is clean? The figures below show the average CFE score for the California grid supply in 2030 in this study, showing high variability and the impact of imports. Other differences in accounting methods include treatment of marginal vs average emissions rates and other considerations.

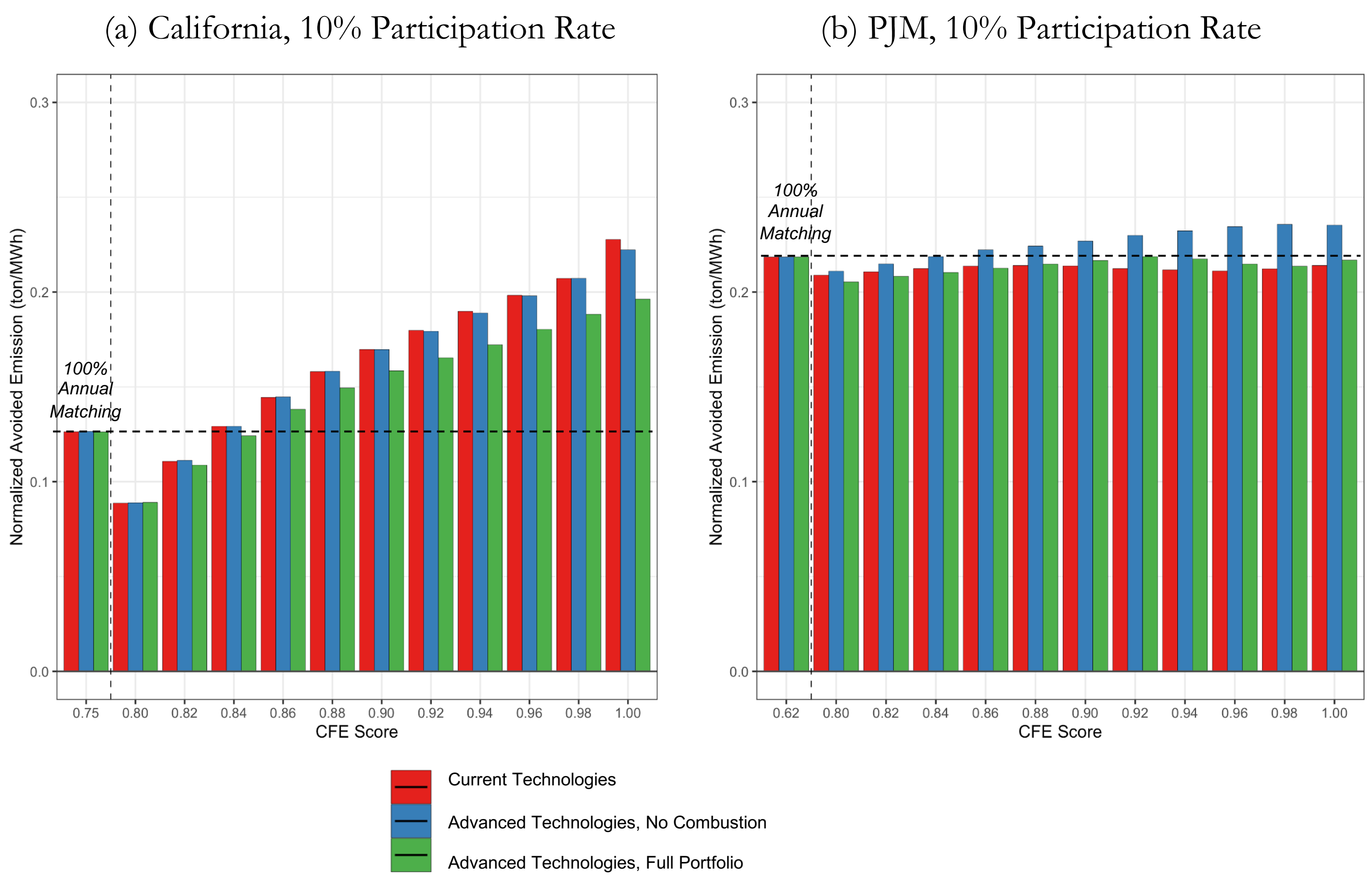
10% C&I Participation rate, hourly matching targeting at 90% CFE score.



Top to bottom: (1) no import consideration, (2) imports are considered in calculation, (3) difference between the two.
This plot shows two facts: California is frequently importing, and California is frequently cleaner compared to the rest of the WECC.

Isolating the volumetric and time-coincidence impact of 24/7 procurement

Normalized avoided emissions per MWh of procured electricity



As a reminder:

- Higher CFE score of 24/7 procurement means less grid supply will be used for meeting the CFE target, and consequently, the hourly generation of the procured resources will follow the C&I load pattern more closely.
- Higher deployment of clean firm dispatchable capacity (e.g., geothermal, advanced nuclear, natural gas combined cycle w/CCS) also means the hourly generation of the procured resource will follow the C&I load pattern more closely.

This study introduces two factors that can contribute to higher avoided emissions from 24/7 procurement:

1. **A volume effect**: higher volume of clean energy procurement drives less emitting grid-supplied generation (e.g. more MWh = more emissions reductions)
2. **A timing effect**: better alignment of procured generation with demand can increase displacement of emitting grid-supplied generation by concentrating more generation in periods with less system-wide wind and solar production and thus higher emissions rates (e.g. more MWh at the right times = more emissions reductions).

We also find significant differences in the relative importance of these two effects in California — where the timing effect is significant and normalized emissions reductions per MWh increase steadily with CFE score (see panel (a)) — and in PJM — where the normalized emissions reduction per MWh increases only modestly as CFE increases, indicating that the timing effect is modest and the volume effect more pertinent.

Future work should more carefully determine when the timing effect becomes most salient, as these circumstances are likely to be where and when 24/7 procurement efforts deliver the greatest reduction in CO_2 emissions, relative to 100% annual matching.

It is also worth modeling and evaluating alternative strategies for maximizing carbon emissions impact from a portfolio of procured resources, as this may differ from 24/7 portfolios optimized to match demand patterns. Costs and benefits of each approach can be compared and contrasted.

Aggregation of participating 24/7 customers and procured resources

In this study, we implicitly assume all participating C&I customers 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.

Much as retail aggregation and multi-lateral wholesale electricity markets reduce costs via aggregation and multi-lateral contracting, this assumption is likely to lead to lower costs of 24/7 procurement and reflects an optimistic possible outcome.

In reality, many C&I customers are likely to pursue hourly matching strategies independently, based on their own specific load profiles. This will necessarily lead to results that are somewhat less efficient than those modeled here.

Future work should evaluating the possible efficiency benefits of multi-lateral vs 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 renewable energy credits or carbon-free electricity attributes that can allow customers to manage imbalances in contracted supply and demand and unlock related cost savings.

Dynamic impacts on experience curves and cost declines from early deployment of advanced technologies

Accelerated deployment of advanced clean firm and long-duration energy storage technologies is one of the principal impacts of 24/7 CFE procurement.

Yet this study makes no attempt to estimate the potential benefits and impacts related to accelerating experience curves, reducing technology risk, driving cost declines, and building financial market experience that this early deployment may entail.

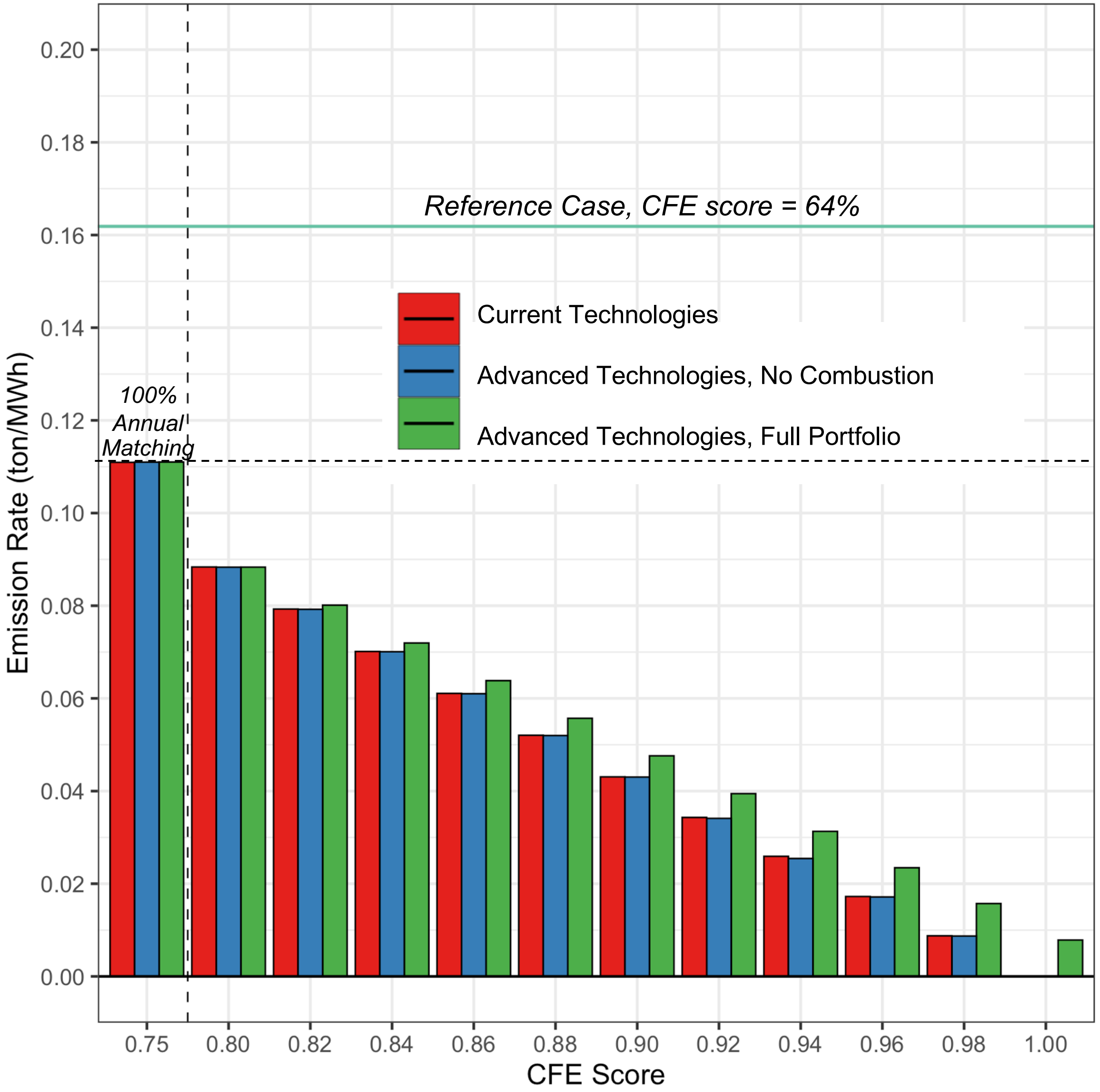
Future work could thus explore the dynamic impacts of 24/7 CFE procurement over time and potential benefits in terms of reduced costs and earlier availability of clean firm and long-duration energy storage technologies for societal as a whole, supporting more cost-effective transitions to 100% carbon-free electricity.

This work could also explore the potential benefits of reducing near-term expansion of emitting natural gas-fired generating capacity, which could make future system-wide deep decarbonization more costly.

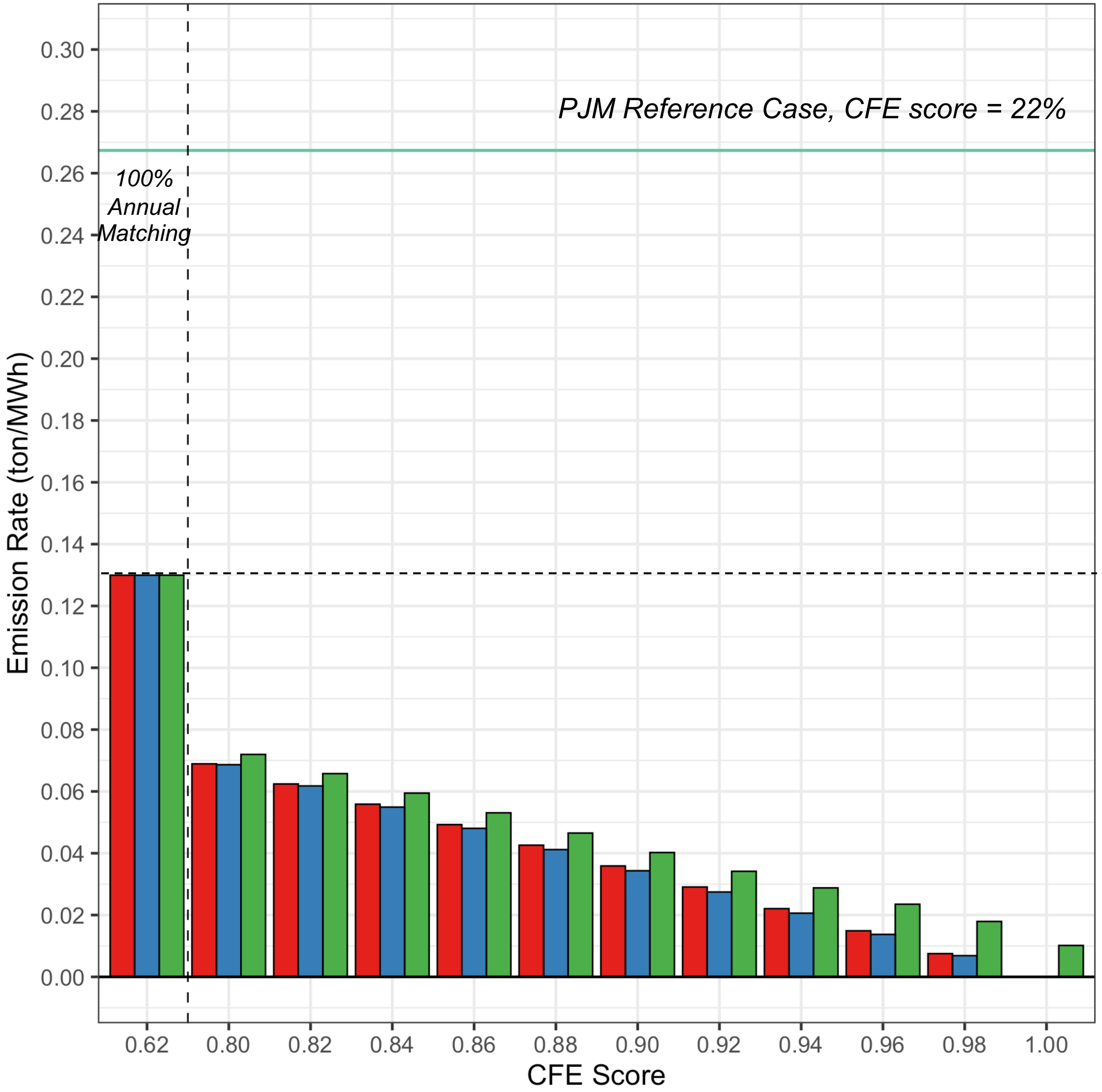
Conclusions and Implications

Conclusions 1: 24/7 CFE procurement can eliminate emissions from a buyer's electricity consumption, going beyond the impact renewable energy to meet 100% of annual volumetric demand

California system emissions, 10% C&I Participation,

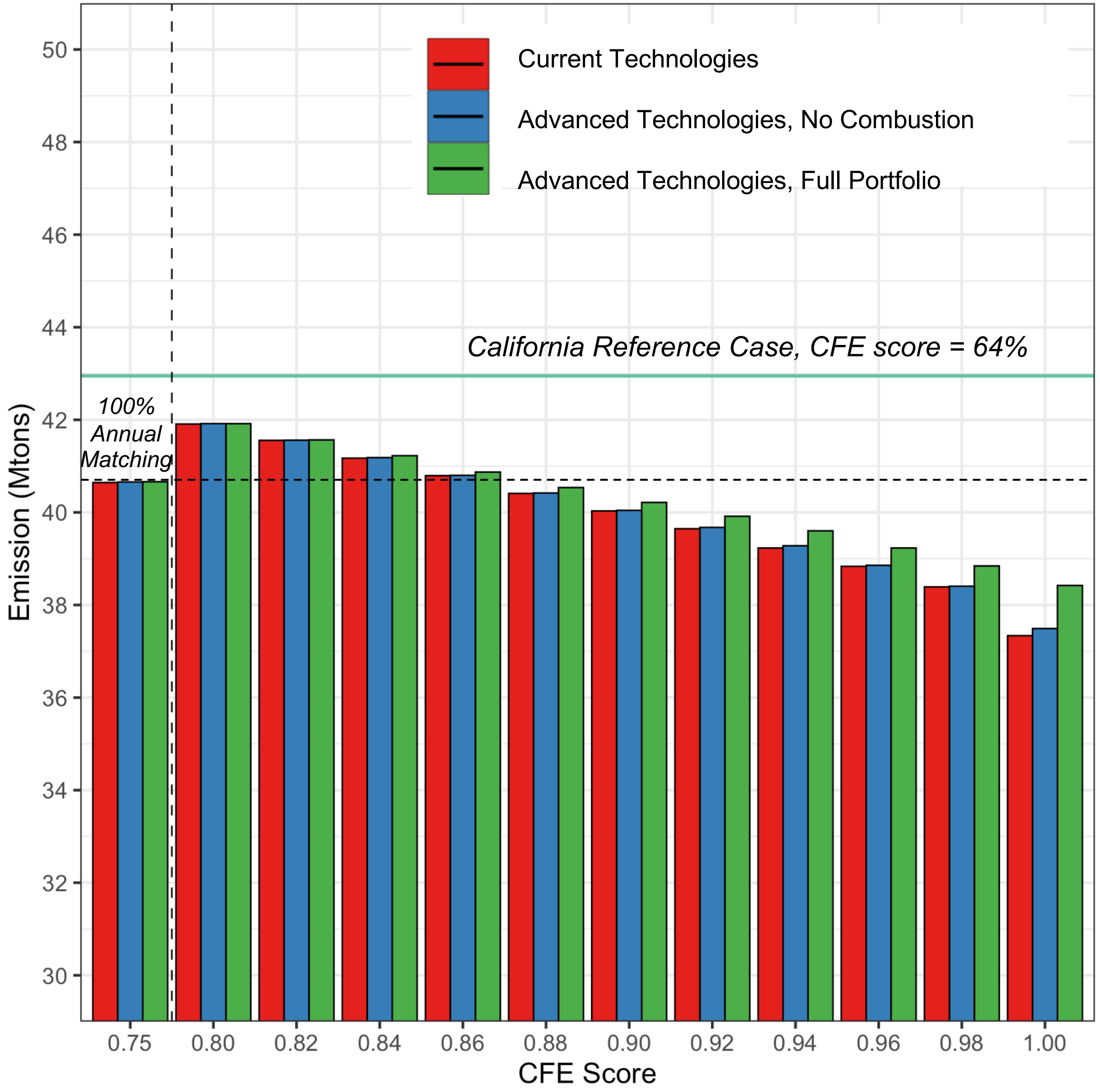


PJM system emissions, 10% C&I Participation

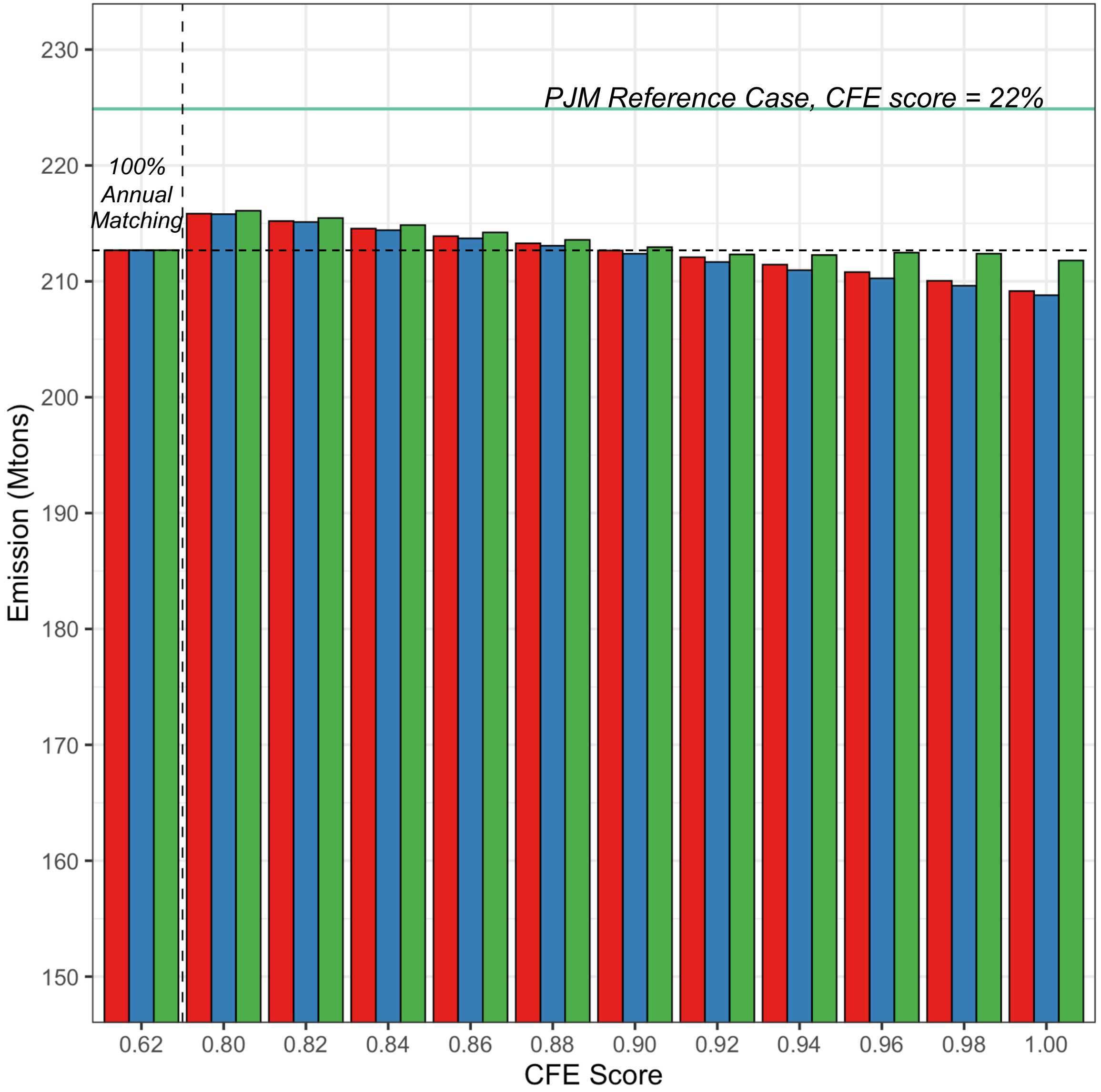


Conclusions 2: 24/7 CFE procurement can drive greater system-level emissions reductions than 100% annual matching if the CFE target is high enough

California system emissions, 10% C&I Participation,



PJM system emissions, 10% C&I Participation

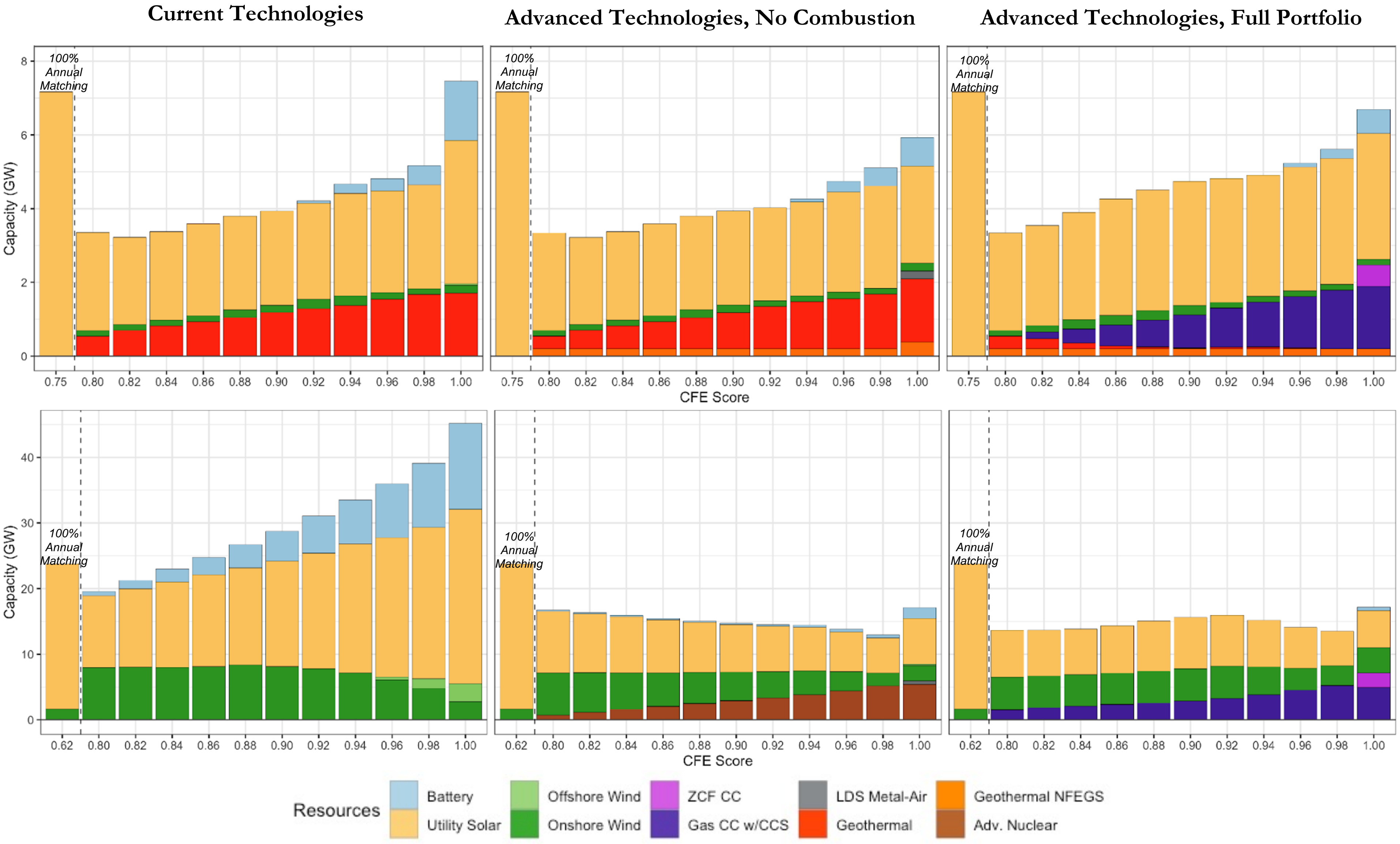


Conclusions 3: 24/7 clean electricity procurement drives deployment of advanced, 'clean firm' generation and/or long-duration energy storage, helping to drive innovation and transform the electricity sector.

Depending on system, cost and performance assumptions, 24/7 portfolios w/100% CFE include geothermal, advanced nuclear, zero-carbon fuel combustion, natural gas power plants w/carbon capture and storage, and/or long duration energy storage. Higher CFE drives greater advanced technology adoption & system transformation

California 24/7 CFE portfolio, 10% C&I Participation Rate

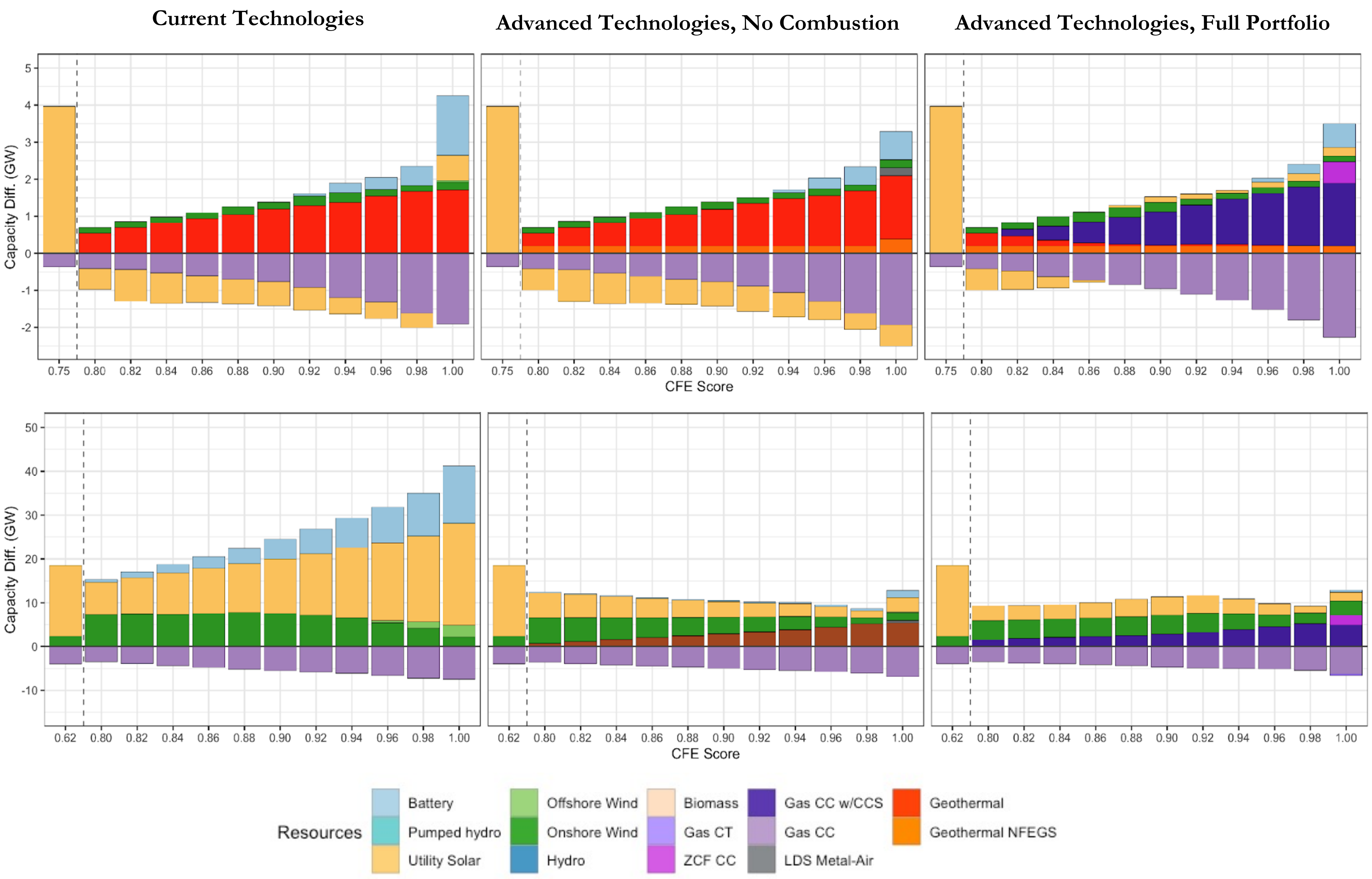
PJM 24/7 CFE portfolio, 10% C&I Participation Rate



Conclusions 4: 24/7 CFE procurement better matches participating demand during periods of limited supply and thus drives significantly more retirement of natural gas generating capacity than 100% annual matching.

California 24/7 CFE portfolio, 10% C&I Participation Rate

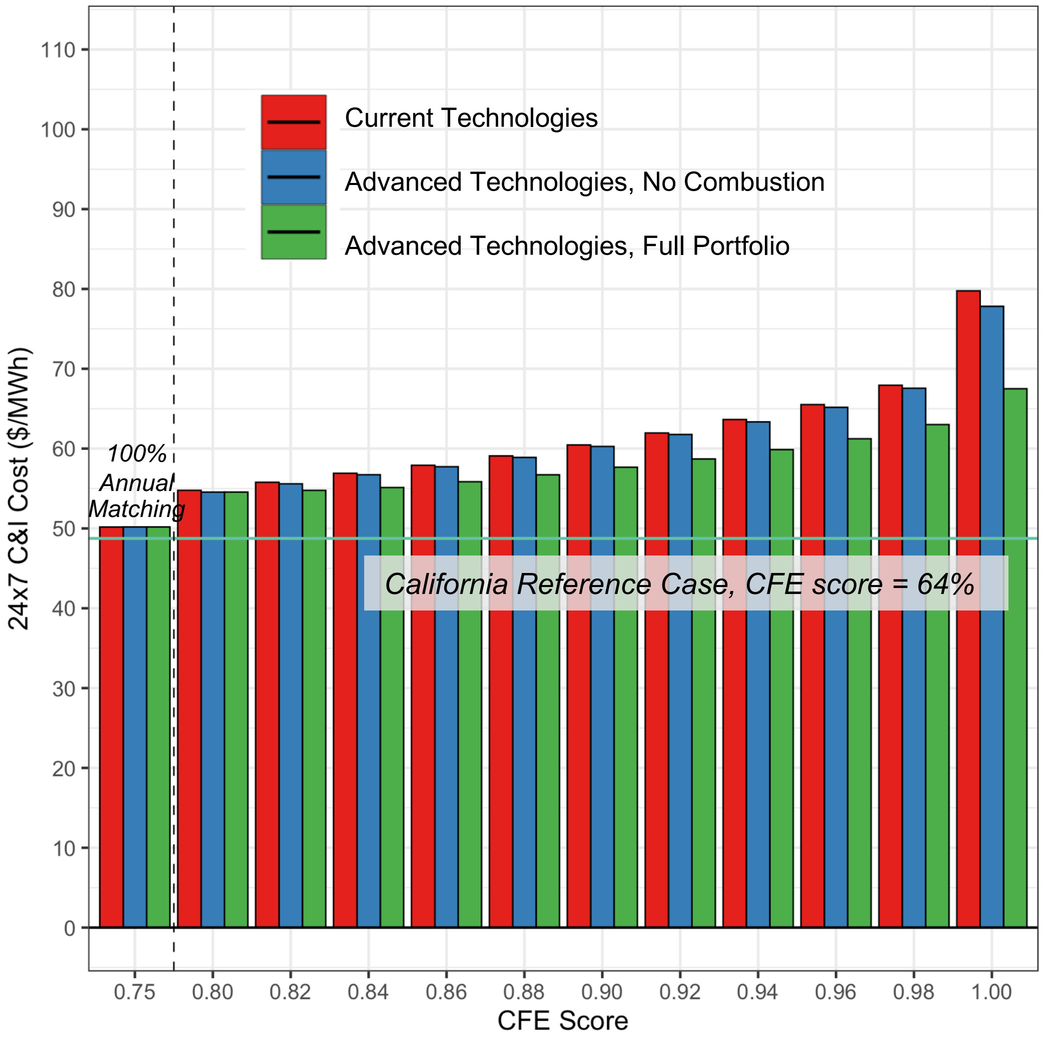
PJM 24/7 CFE portfolio, 10% C&I Participation Rate



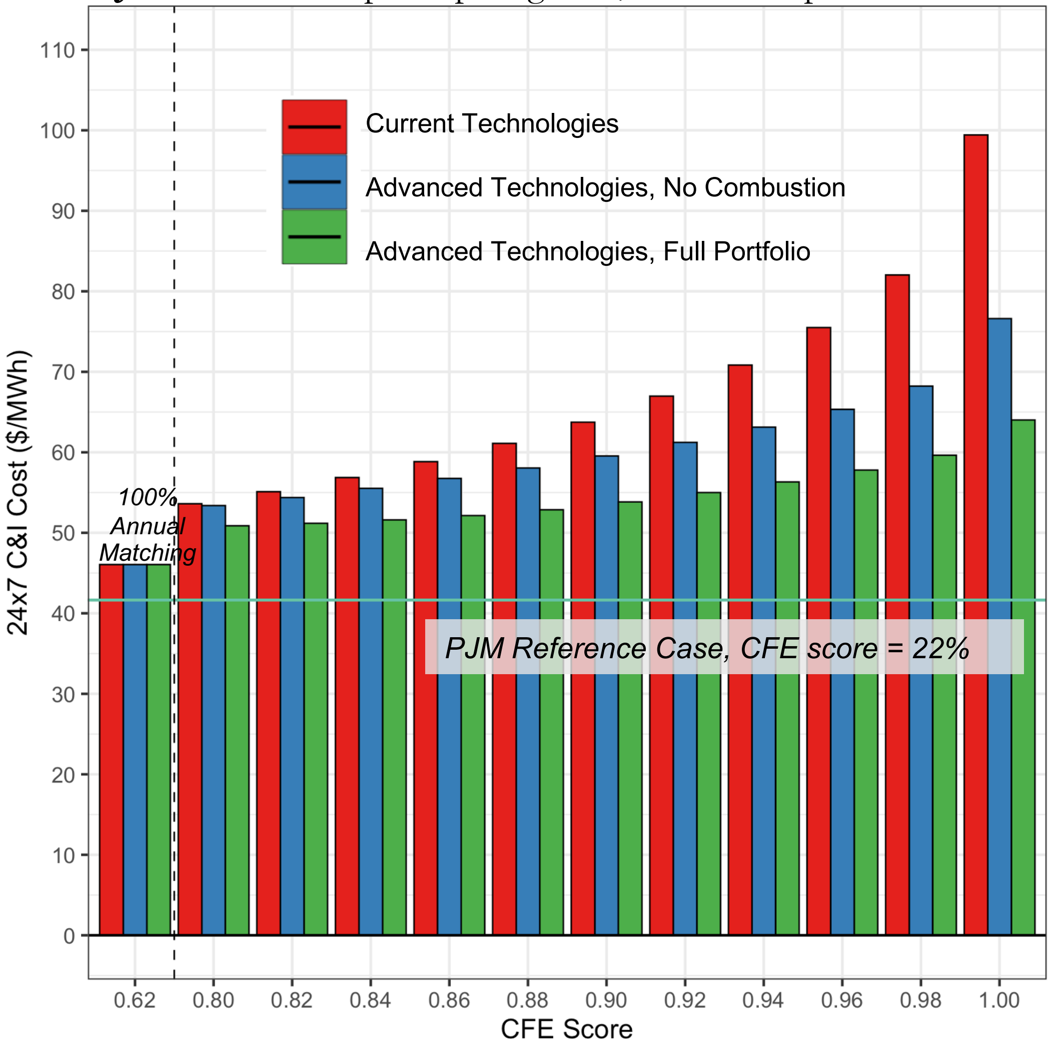
Conclusions 5: 24/7 CFE procurement comes at a more significant cost premium relative to 100% annual matching; cost premium is reduced with full portfolio of clean firm resources and/or pursuing CFE <100%.

The availability of a range of clean firm generation technologies each suitable to different utilization rates makes reaching 100% CFE significantly more affordable, as evidenced by the Advanced Technologies, Full Portfolio cases in this study.

California Cost of 24/7 participating C&I, 10% Participation Rate



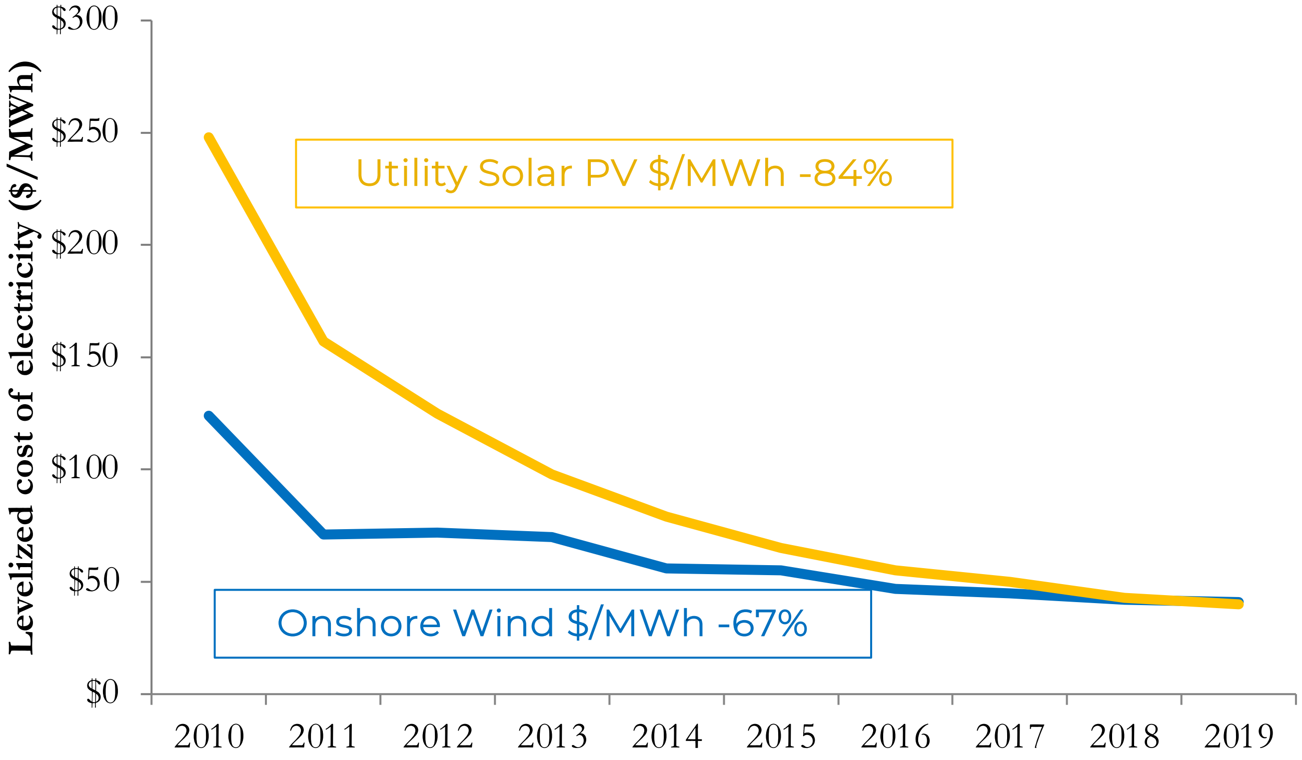
PJM cost of 24/7 participating C&I, 10% Participation Rate



Implications

Voluntary procurement of renewable energy has already had a transformative impact on the cost, financeability, and availability of wind and solar power.

Procuring sufficient renewable energy to match 100% of a consumers annual electricity use remains a powerful first step to accelerate clean energy adoption.



As this study illustrates, 100% annual matching falls short of fully eliminating carbon emissions associated with a buyer's electricity consumption, due to mismatches in variable renewable energy supply and consumer demand profiles.

Data Sources: Wind & solar costs from Lazard (2019), Lazard's Levelized Cost of Energy Analysis – Version 13.0.
Battery pack costs from Bloomberg New Energy Finance (2019), Battery Price Survey.

Implications

The next step on the road to zero emissions can be for corporate, government, and institutional leaders to procure carbon-free electricity to match their hourly electricity demand 24/7, with local resources from their grid region.

As this study demonstrates, 24/7 carbon-free electricity (CFE) procurement presents added challenges and raises electricity costs relative to 100% annual matching, but also enables greater reductions in emissions associated with a buyer's electricity usage.

At the same time, 24/7 procurement drives early deployment of advanced clean firm generation and long-duration energy storage technologies, offering the potential to accelerate innovation, maturity, financeability, and widespread availability of these critical ingredients in the broader societal transition to a 100% carbon-free grid.

Just as 100% annual matching helped transform wind and solar PV from expensive "alternative energy sources" to mainstream, affordable options for the world, 24/7 procurement can have similar transformative impacts on clean firm resources.

Implications

This study indicates that the emissions impact of 24/7 procurement is dependent on the correlation between participating demand profiles and grid-level emissions intensity and the penetration of variable renewable energy in the grid region (as evidenced by differences in California and PJM system outcomes).

As electricity systems transition towards cleaner supply with greater use of variable renewable energy sources, it is likely that leaders in clean energy procurement can increase their emissions impact by shifting to 24/7 procurement (from 100% annual matching). The cost premium for 24/7 CFE procurement also falls as the wider grid becomes cleaner.

However, alternative procurement strategies optimized to maximize generation during periods of high grid carbon intensity rather than match demand may deliver greater overall emissions reductions. The systems-level impact of alternative strategies for increasing the impact for clean electricity procurement should be rigorously evaluated with similar methods as this study and comparative pros/cons considered relative to 24/7 procurement.

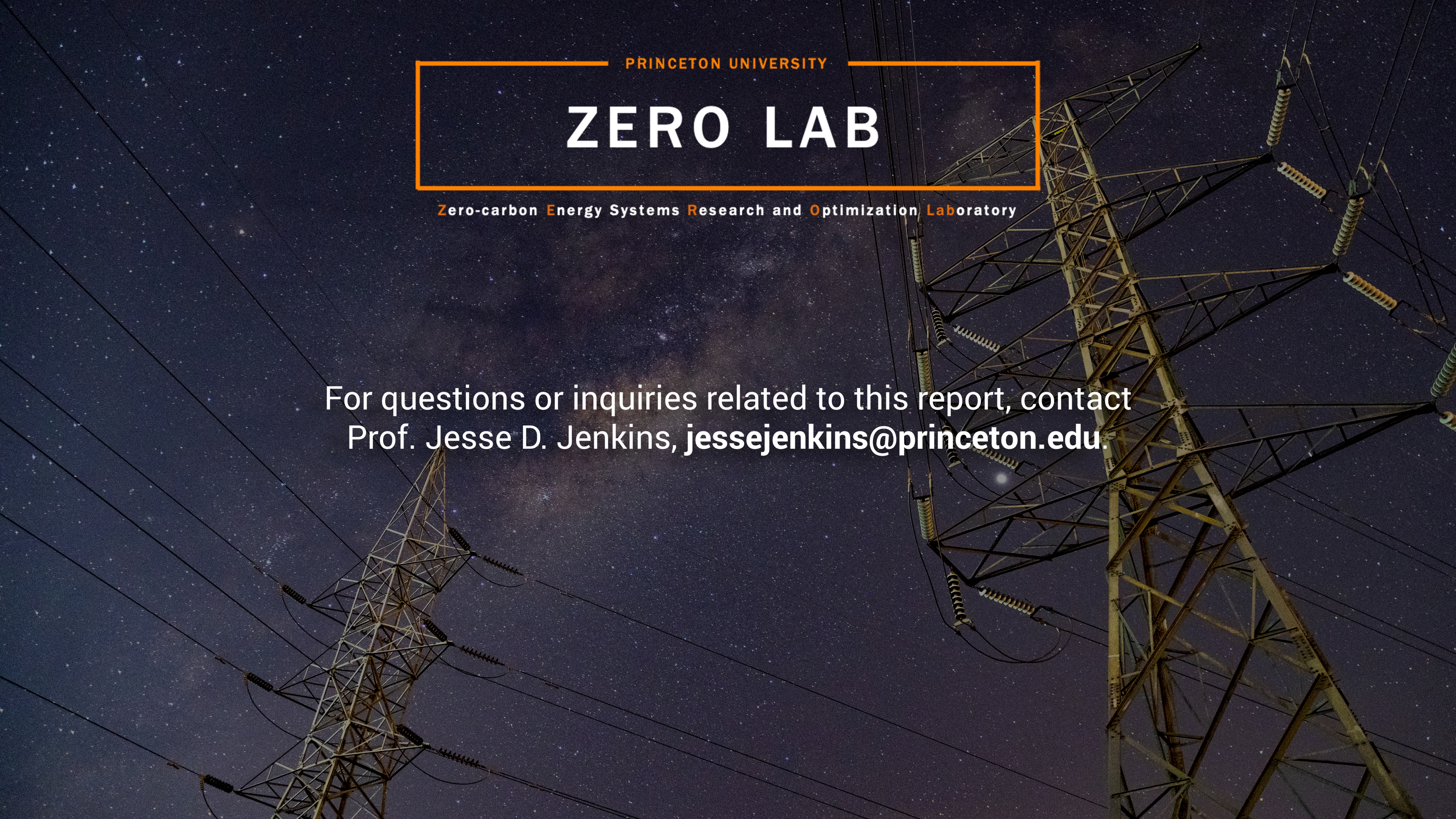
Implications

Finally, it is worth emphasizing that cost premiums born by leaders in 24/7 procurement today can play a pivotal role in reducing the cost of the clean energy transition in the future.

Electricity systems are now at a pivotal point where deployment of clean firm resources and long duration electricity storage is needed this decade to drive maturation and cost reductions and prepare for wider deployment in the 2030s and 2040s. If proactive investment in advanced technologies is not made soon, it is highly likely that these resources will not be prepared to scale when needed to ensure reliability and affordability and reach 100% carbon-free grids.

Of course, voluntary procurement is not the only route to drive early deployment of innovative technologies. Leaders in clean energy procurement can further increase their impact and accelerate the transformation of the electricity sector by working to advance public policies that support deployment and improvement of clean firm power and long-duration storage and by partnering with governments on early commercial demonstration and deployment.

Collectively, these actions will make it easier and cheaper for both voluntary 24/7 carbon-free electricity procurement and society at large to transition to a carbon-free electricity supply.



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ZERO LAB

Zero-carbon Energy Systems Research and Optimization Laboratory

For questions or inquiries related to this report, contact Prof. Jesse D. Jenkins, **jessejenkins@princeton.edu**.