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Electricity System and Market Impacts of Time-based Attribute Trading and 24/7 Carbon-free Electricity Procurement

By Qingyu Xu and Jesse D. Jenkins, Princeton University

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Electricity System and Market Impacts of Time-based Attribute Trading and 24/7 Carbon-free Electricity Procurement

Qingyu Xu[a] and Jesse D. Jenkins[b]

(a) *Post-doctoral Research Scholar, Zero-carbon Energy Systems Research and Optimization Laboratory (ZERO Lab), Andlinger Center for Energy and the Environment*

(b) *Assistant Professor, Department of Mechanical and Aerospace Engineering and the Andlinger Center for Energy and the Environment and Principal Investigator, ZERO Lab*

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

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

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Introduction & Motivations

In November 2021, the Princeton ZERO lab published the first system-level impact analysis of 24/7 Carbon-Free Electricity (CFE) procurement. The study concluded that voluntary procurement of 24/7 CFE incurs an increase in energy costs for participating customers but achieves the following impacts:

- **Promotes Emission Reduction:** 24/7 CFE 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. 24/7 CFE can also drive greater system-level emissions reductions than 100% annual matching if the CFE target is high enough, via expediting the exit of natural gas generating capacity and production from the electricity system.

- **Accelerates Power Sector Transition:** 24/7 CFE 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.

Introduction & Motivations, Cont'd

However, in the previous study, we implicitly assumed all participating customers pool together purchases and manage portfolios in aggregate, and we conjectured that such an assumption could lead to an optimistic estimate of the cost premium of 24/7 CFE.

In reality, without a place or entity that facilitates the multilateral trading of 24/7 CFE, many participants are likely to pursue hourly matching strategies independently based on their own specific load profiles and their own access to clean power. Therefore, we concluded:

An important future work is to explore the possible efficiency benefits of a market structure of multilateral CFE procurement that can allow participants to trade CFE attributes among themselves to manage imbalances in contracted supply and demand.

In this report, we refer this market structure as a time-based energy attribute certificate (T-EAC) trading system.

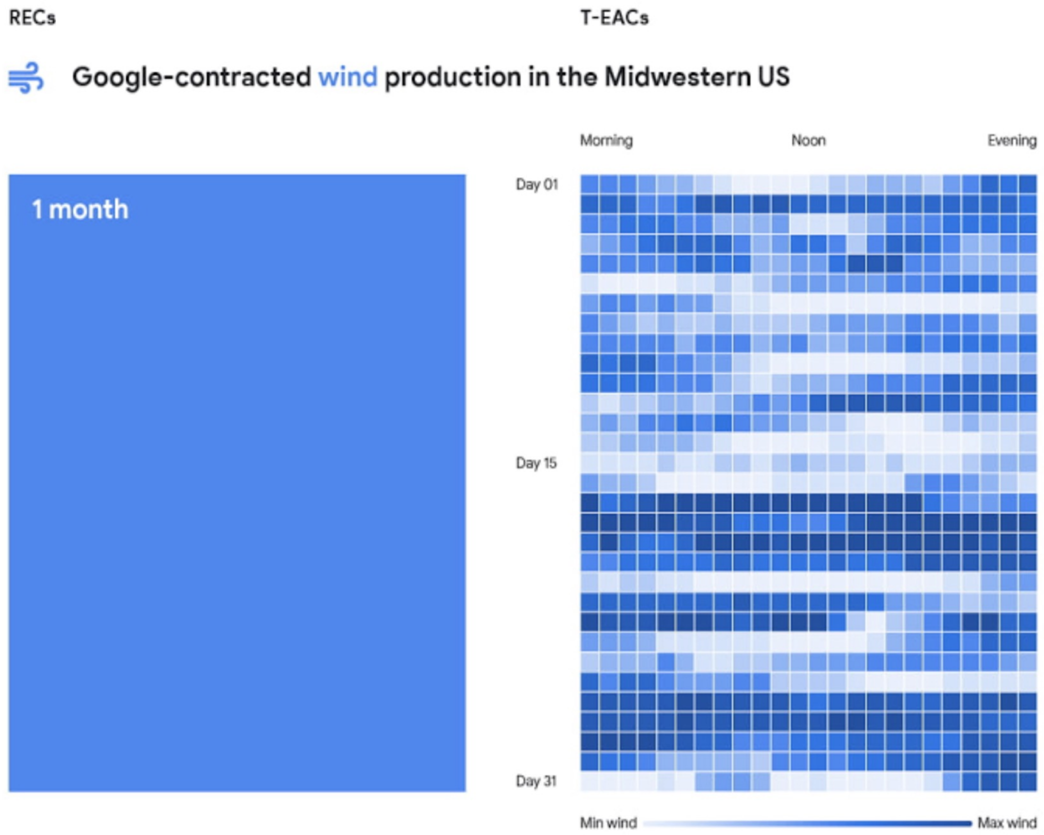
What is a T-EAC?

Time-based energy attribute certificates (T-EACs) are a new, hourly approach for verifying clean energy matching, and they are a critical tool to enable the most cost-effective procurement of 24/7 CFE by all participating customers.

Traditional, volume-focused renewable energy certificates, or RECs, are not adequate for verifying load matching with 24/7 CFE

- ➔ One MWh is valued the same no matter what time of day or month of the year it is produced.
- ➔ RECs are poorly suited to track output from novel clean energy technologies, like battery storage and hydrogen.
- ➔ RECs do not contain data on carbon emissions rates avoided by clean generation.

Ideally, certificate tracking systems would incentivize resources that help fill gaps in the supply of round-the-clock clean power and in the dirtiest grids.



RECs vs. T-EACs associated with Google renewable energy purchasing. RECs indicate how much energy wind or solar farms produce in a month, but not precisely when it is generated. In contrast, each of the 744 hours in a 31-day month has its own T-EAC, with a corresponding amount of electricity produced.

Source: https://cloud.google.com/blog/topics/sustainability/t-eacs-offer-new-approach-to-certifying-clean-energy

The value of having an organized T-EACs market

This study explores the system-level impacts and potential benefits for buyers associated with developing a liquid market for T-EAC trading. The possible benefits include:

- ➔ Improving the economic efficiency, affordability, and accessibility of 24/7 Carbon-free Energy (CFE) Procurement
- ➔ Generating hourly price signals to incentivize clean energy investment and operation when and where it is needed most
- ➔ Helping 24/7 CFE participants hedge against uncertainties like forecast errors.

Methods: In this study, we model T-EAC trading by enhancing the existing 24/7 CFE module implemented in the open-source GenX electricity system planning model to include multiple participants with different load profiles and allow T-EAC trading among them bilaterally/via a pool market. Each participant can meet their CFE target by either procuring capacity directly (like in the previous report) and/or procuring T-EACs from other participants or the market pool.

Caveat: *via carefully designed experiments, this report focuses on exploring why and how T-EAC trading can be beneficial, rather than quantifying what these benefits will be in real life.* ***Quantitative results in this study should thus be taken as examples of the qualitative benefits of T-EAC trading rather than quantitative projections of future benefits.*** *The impact and benefit quantification of a real-life T-EAC exchange may require subsequent empirical analyses.*

Executive Summary

In summary, the study demonstrates that:

- ➔ T-EACs trading can lower the cost of 24/7 CFE procurement, especially for buyers who face limited options for direct procurement from carbon-free generators.
- ➔ A liquid T-EACs exchange creates hourly price signals that can incentivize investment in clean technologies when the grid is dirtiest (e.g., in California, modeled T-EAC prices are highest as the sun sets and generally in nighttime hours.)
- ➔ While modeling in this study assumes perfect foresight for the year, in reality, buyers and sellers face significant uncertainty in matching demand and generation; T-EAC trading can play an important role in diversifying and managing risks associated with these forecast uncertainties.
- ➔ Under the assumption that only new resources qualify to sell T-EACs, as modeled here, T-EACs trading maintains the system-level emissions reduction benefits of 24/7 CFE procurement.
- ➔ The value of T-EACs trading increases as CFE targets approach 100%, helping buyers meet the demand for ‘the last 10%’ of carbon-free generation needed to match their demand 24/7 at lower cost, especially buyers who may have a difficult time directly contracting with clean firm generators.

Key finding 1 (Part 1): T-EAC trading lowers the cost of 24/7 CFE procurement

The cost premium for 24/7 CFE procurement without T-EAC trading (left) **is significantly reduced when trading becomes possible** (right).

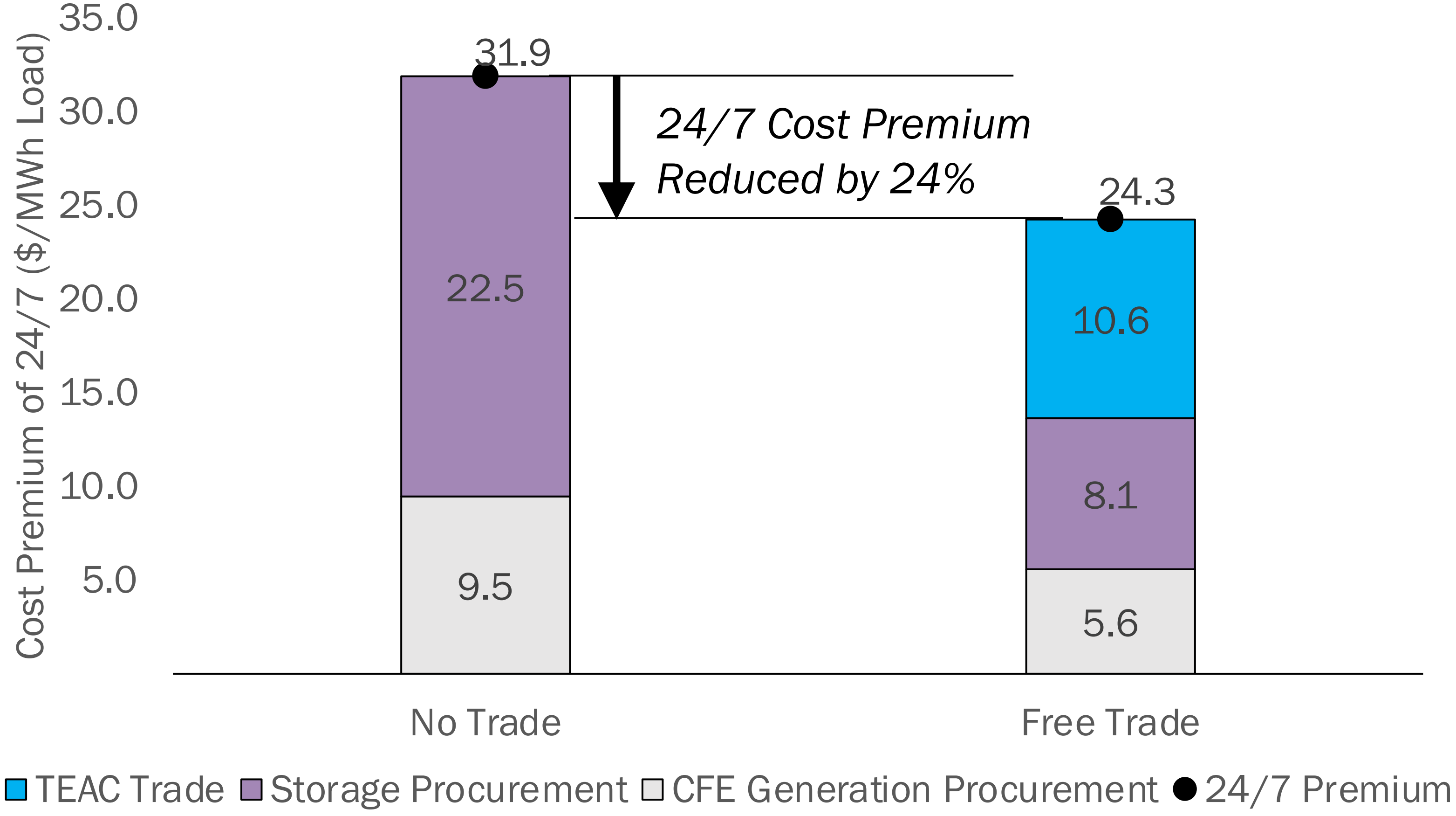


Figure K-1: Cost premium of 24/7 for a California residential participant that only has access to utility-level photovoltaic and onshore wind capacities (CFE Target = 98%). The large amount of CFE introduced by 24/7 procurement also decreases the wholesale energy/capacity payment of participants by $1.3/MWh (not shown).

Key finding 1 (Part 1): T-EAC trading lowers the cost of 24/7 CFE procurement

T-EAC trading promotes the economic efficiency and affordability of 24/7 CFE procurement: Assuming all procured resources are additional, 24/7 CFE buyers can meet the same level of CFE target at a lower cost.

We find three channels for cost savings:

1. **Higher accessibility:** T-EAC trading enables access to cheap, clean energy at times of day with high VRE penetration and creates more options for CFE when VRE is scarce (see next slide for details).
2. **Load aggregation:** the trading allows participants to procure CFE capacities *as if* their different demand profiles were aggregated together, which smooths out demand variations and makes it easier to match electricity demand with 24/7 CFE.
3. **Lower transaction cost:** a centralized exchange reduces the transaction cost that can occur, for example, among secondary bilateral tradings of 24/7 CFE generation.

Key finding 1 (Part 2): T-EAC trading lowers the cost of 24/7 CFE procurement

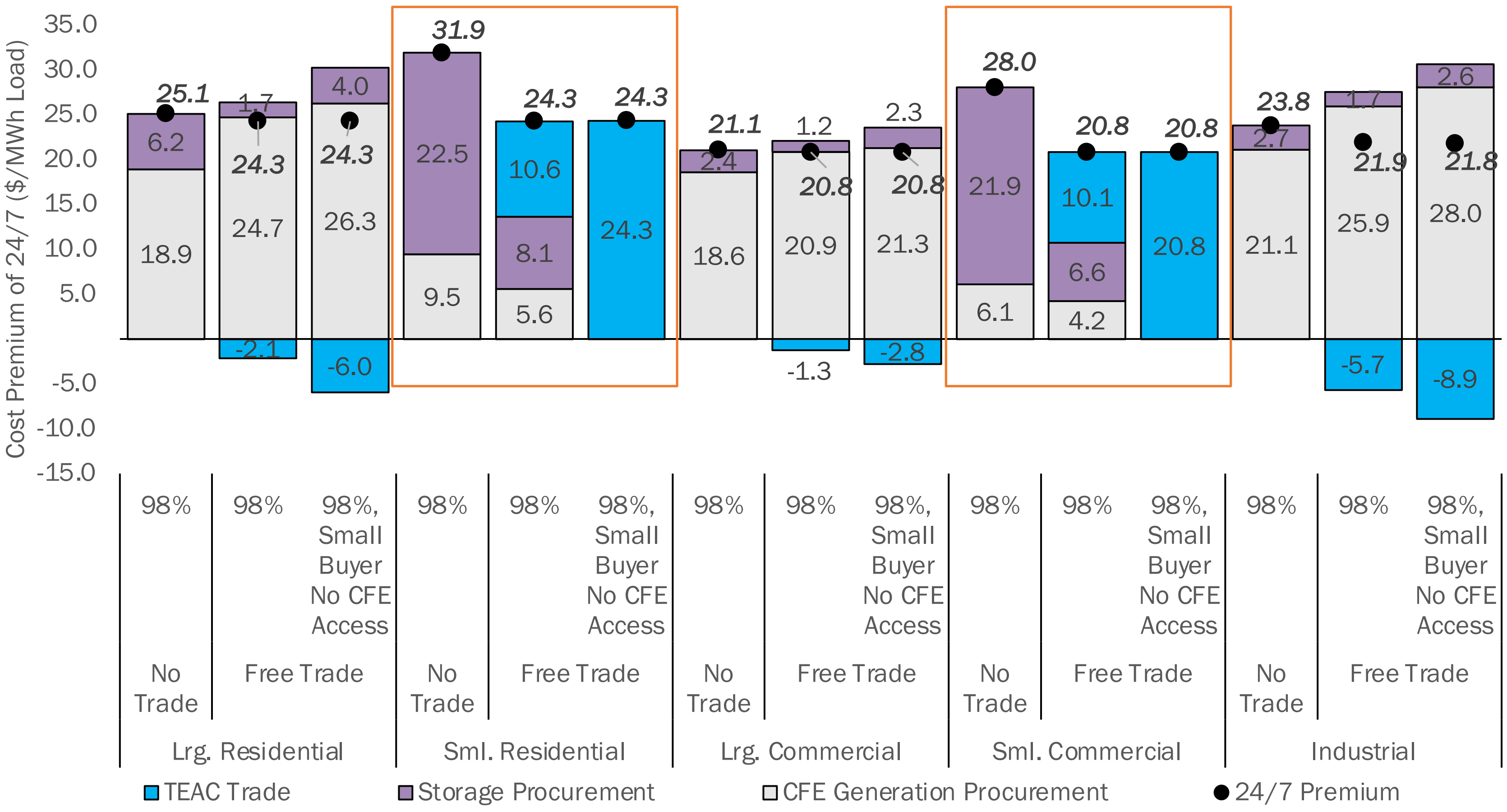


Figure K-2: Cost premium of 98% CFE procurement for five modeled California participants under three scenarios: no T-EAC trading scenario (left columns), and two variants of T-EAC trading scenario (middle and right columns). In all scenarios, large buyers have access to the full spectrum of CFE resources, including both intermittent CFE (wind and solar) and clean firm resources (geothermal and CCS). Small commercial / residential buyers either only have access to solar and wind (left and middle columns) or do not have access to any resource at all (right columns) where they completely rely on T-EAC trading to meet the CFE target. For further explanation about available technologies, see here.

T-EAC trading significantly improves the economic efficiency of 24/7 CFE by reducing the cost premium, especially for resource-constrained (e.g., small) participants that lack access to the full spectrum of CFE resources. Larger buyers also see lower net costs due to revenues from T-EAC sales.

Key finding 1 (Part 2): T-EAC trading lowers the cost of 24/7 CFE procurement

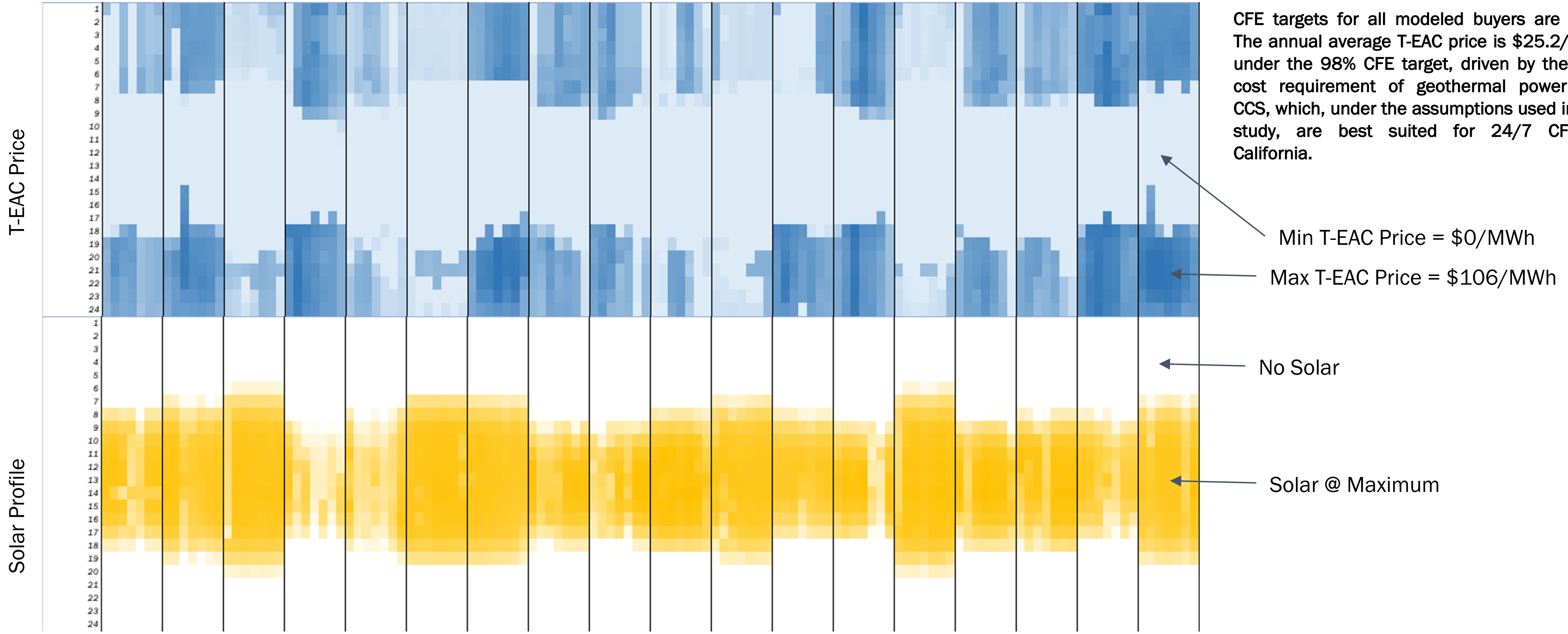
The purchase and trade of T-EACs provide an onramp to participate in 24/7 CFE procurement for a larger pool of buyers/suppliers when a set of prospective 24/7 CFE buyers only have access to partial or even no CFE supply.

The limited access of these potential participants on both the supply- and demand-side includes situations where:

- A potential CFE buyer has difficulties entering into any power purchase agreement (PPA) due to a lack of resources, expertise, or credit rating.
- A potential CFE buyer has limited risk appetite to consider newer clean energy technologies under significant cost uncertainty and lack of financeability.
- A potential CFE buyer (or supplier) has limited information about the existence of a potential counterparty.

This research shows that, in such circumstances, companies who do have access to the full spectrum of CFE resources can procure more, sell T-EACS to other customers at a net profit, and help others join the journey to 24/7 CFE at lower costs (see **Figure K-2**).

Key finding 2: T-EACs provide an hourly price that signals when CFE is most valuable



CFE targets for all modeled buyers are 98%. The annual average T-EAC price is $25.2/MWh under the 98% CFE target, driven by the high cost requirement of geothermal power and CCS, which, under the assumptions used in this study, are best suited for 24/7 CFE in California.

Figure K-3: T-EAC prices from the exchange (top) and California solar profile (bottom) over eighteen representative weeks. CFE targets for all modeled buyers are 98%. Because of the large amount of existing solar power in California, the demand for T-EACs in the daytime is scare, driving diurnal T-EAC prices down. The nocturnal T-EAC prices are high because grid-supplied clean power is comparatively scarce during the night. Because California T-EAC prices are close to zero in most hours, to recover the cost requirement of 24/7 CFE, the non-zero T-EAC prices are high. This will be different across markets depending on the variability of clean energy and correlation with demand.

Key finding 2: T-EACs provide an hourly price that signals when CFE is most valuable

We find a centralized T-EAC trading house or multilateral exchange can generate hourly differentiated T-EAC prices (Figure K-3) that signal when CFE would be the most valuable, incentivizing optimal investment and operational decisions for carbon-free resources. **Bidding from the demand side, rather than from the supply side, will be more important in the T-EAC price formation.** The T-EAC price will be determined by:

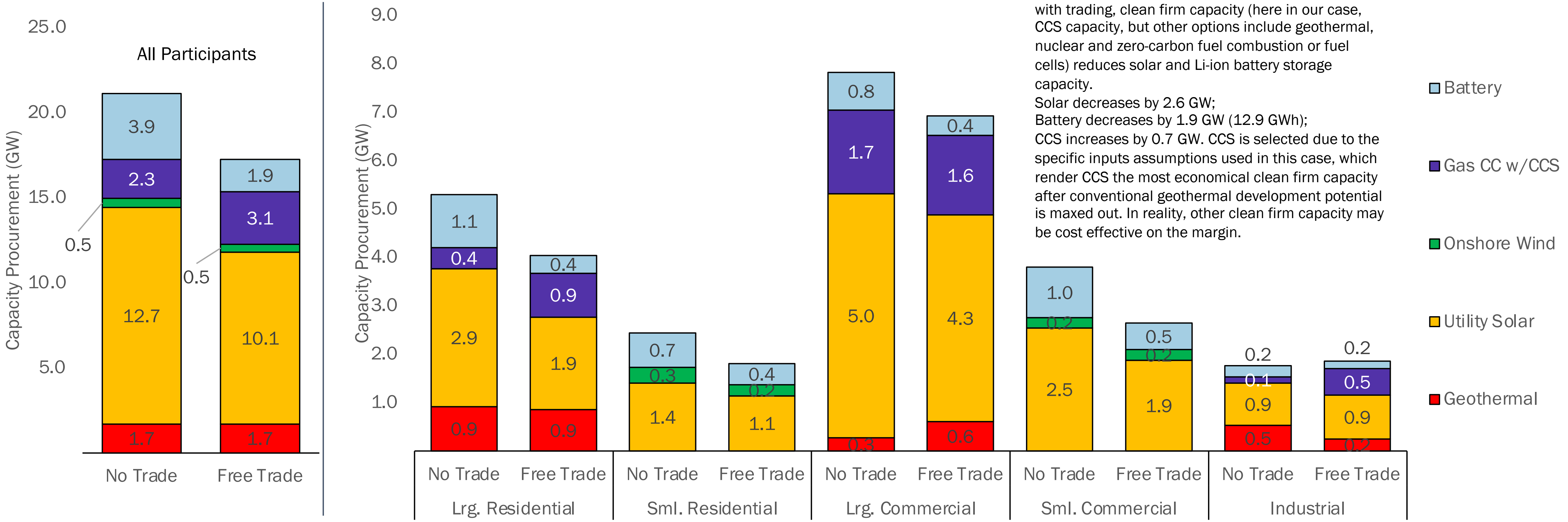
Demand-side: Participants' hourly differentiated maximum willingness to pay for T-EACs and the opportunity cost of operating storage/activating demand response to modify participants' load to follow CFE generation schedule. In our core case, 43% of T-EAC prices are set in this way.

Supply-side: The additional revenue requirement from CFE (above and beyond the energy market earnings) to recoup variable costs can also set hourly T-EAC prices. In our core case, 7% of T-EAC prices are set in this way.

Consequently, T-EAC prices will rise when available CFE is relatively scarce, and either clean power from the grid supply is used to meet the CFE target, or storage assets are operated (or demand response is activated) to modify demand to follow the CFE generation, or additional T-EAC revenues are needed to operate the marginal CFE resources.

In contrast, T-EAC prices will be low when CFE is ample and supplied by low-marginal-cost resources like wind or solar PV. Prices for T-EACs can fall to zero when available CFE exceeds demand from 24/7 buyers. In our core case, 50% of T-EAC prices are set at zero or close to zero because of the CFE oversupply in sunny hours.

Key finding 3: T-EAC trading reduces the total procurement of CFE capacity



The net impact:
with trading, clean firm capacity (here in our case, CCS capacity, but other options include geothermal, nuclear and zero-carbon fuel combustion or fuel cells) reduces solar and Li-ion battery storage capacity.
Solar decreases by 2.6 GW;
Battery decreases by 1.9 GW (12.9 GWh);
CCS increases by 0.7 GW. CCS is selected due to the specific inputs assumptions used in this case, which render CCS the most economical clean firm capacity after conventional geothermal development potential is maxed out. In reality, other clean firm capacity may be cost effective on the margin.

Figure K-4: Capacity procurement of the five modeled California 24/7 participants with or without T-EAC trading. CFE Score Target = 98% for all participants.

Key finding 3: T-EAC trading reduces the total procurement of CFE capacity

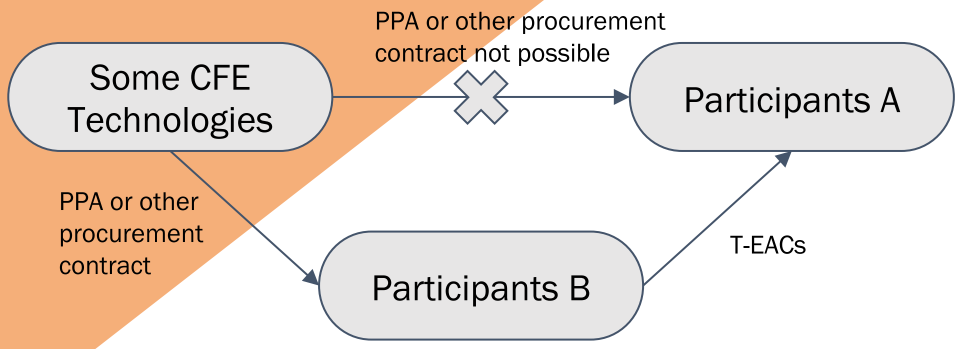


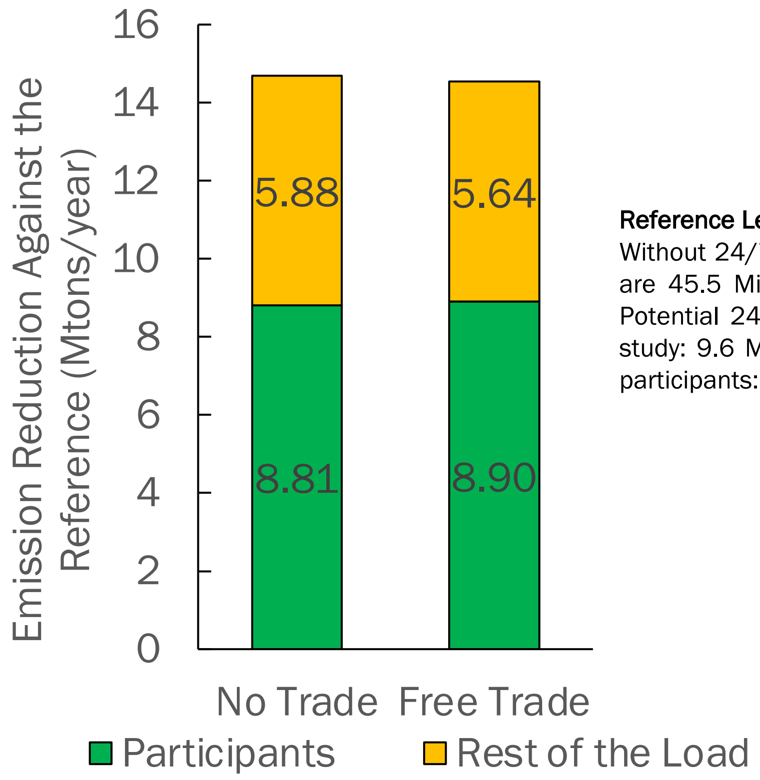
Figure K-5: Diagram demonstrating how T-EAC trading indirectly provides resource-constrained participants access to a broader range of resources.

T-EAC trading *indirectly* provides resource-constrained participants access to the full spectrum of CFE technologies (see slide here) such as capital-intensive clean firm resources (e.g., geothermal and CCS) that they may otherwise be unable to contract directly with. In our cases:

- With trading, it will be more economical for participants with access to a full spectrum of technologies to procure more clean firm capacity and then sell the T-EACs to resource-constrained participants, enabling these participants to meet the target more affordably.
- For the resource-constrained participants, it costs less to procure T-EACs from other CFE buyers with excess clean firm capacity than to procure battery storage and excess solar to meet high CFE targets, where batteries are used to modify the demand to follow wind and solar.

The net impact of T-EAC trading is thus less overall procurement of CFE capacity, particularly of battery storage and variable renewable resources.

Key finding 4: T-EAC trading does not result in significantly different system-level emissions reductions



Reference Level:
Without 24/7, California load-side emissions are 45.5 Million metric tons/year in 2030. Potential 24/7 participants assumed in our study: 9.6 Million Metric tons (Mtons); Non-participants: 35.9 Mtons.

Figure K-6: Emission reduction of 24/7 (sum of all participants) with and without T-EAC trading. CFE Score Target = 98% for all participants.

Our test setting assumes the total amount of participants are fixed, and all participants require additionality of new resources to meet their CFE target. Under this setting, we find that the T-EAC trading does not significantly impact the system-level greenhouse gas emission impact of 24/7 CFE (see **Figure K-6**), even though it reduces the total procured CFE capacity.

However, T-EAC trading will reduce the cost premium for 24/7 CFE procurement (see Key Finding 1), and consequently, it has potential to attract *more* participants to join the 24/7 CFE campaign. Therefore, if one assumes T-EAC trading induces higher overall 24/7 CFE procurement, the impact on emissions will be more beneficial than presented here.

Summary of Methods

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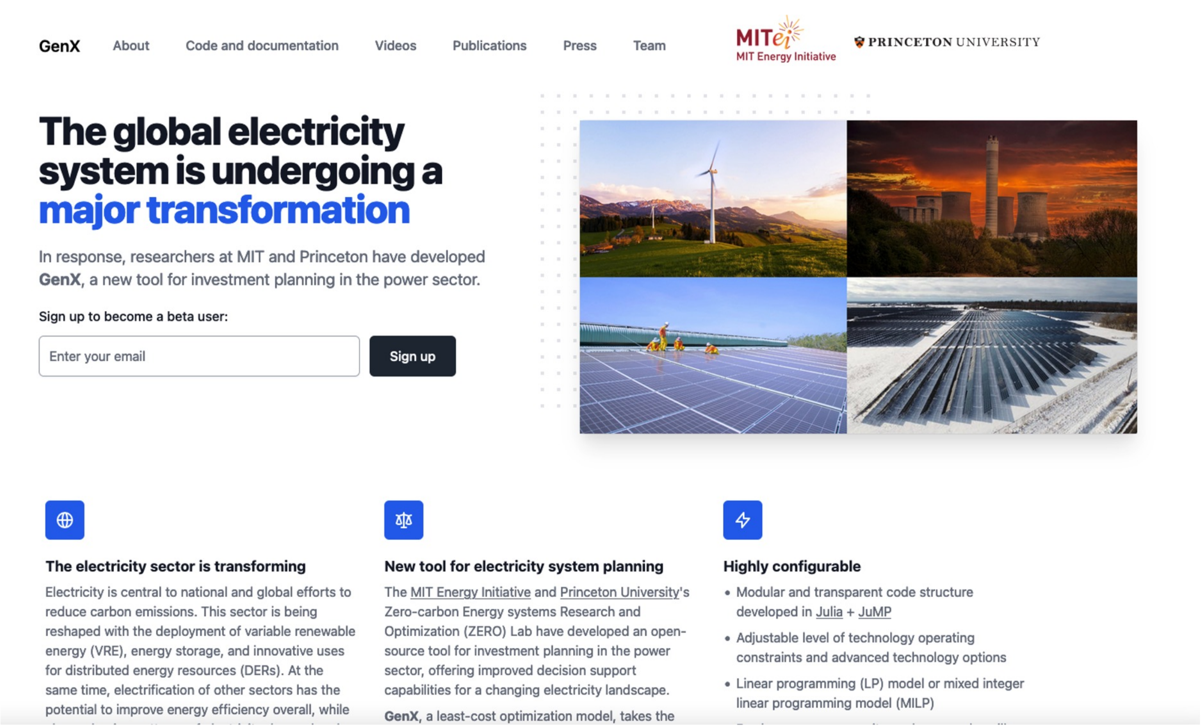
GenX: an electricity system planning tool

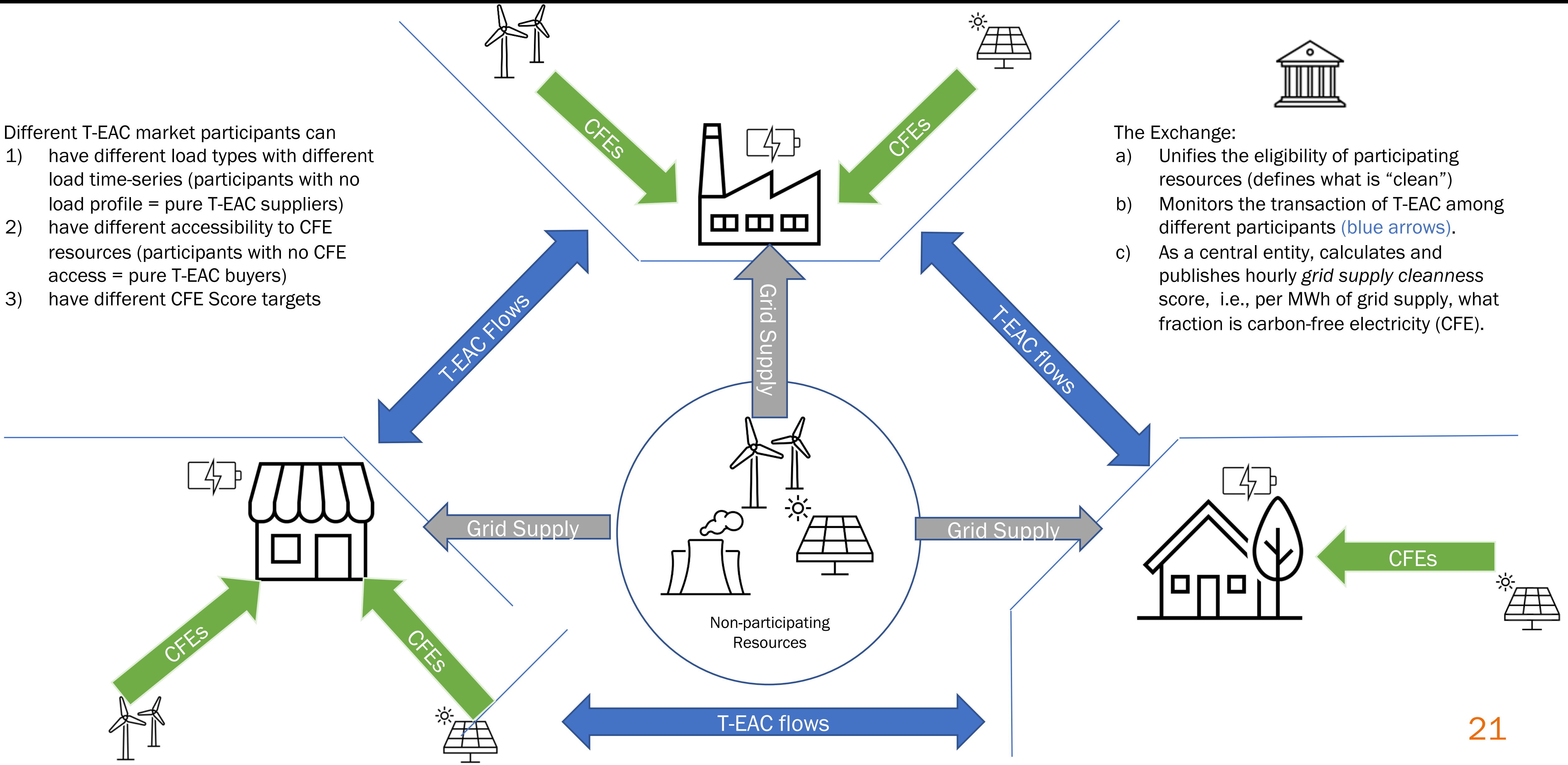
- ➔ Open-sourced & highly configurable
- ➔ Optimization based (LP or MILP)
- ➔ Objective:
  - ◆ Minimize system cost (equivalent to maximizing welfare w/opportunity cost of price elastic demand curtailment)
- ➔ Decision variables:
  - ◆ Generation / storage / inter-regional transmission expansion, retirement,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



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

Modeling T-EAC trading (bilateral T-EAC transaction modeling)

Different T-EAC market participants can
1) have different load types with different load time-series (participants with no load profile = pure T-EAC suppliers)
2) have different accessibility to CFE resources (participants with no CFE access = pure T-EAC buyers)
3) have different CFE Score targets



The Exchange:
a) Unifies the eligibility of participating resources (defines what is "clean")
b) Monitors the transaction of T-EAC among different participants (blue arrows).
c) As a central entity, calculates and publishes hourly *grid supply cleanness* score, i.e., per MWh of grid supply, what fraction is carbon-free electricity (CFE).

Modeling T-EAC Trading (bilateral T-EAC transaction modeling)

Updated GenX-24/7 module, i is the index of participants, j is i's alias, t is the index of hours

Load Modification: Participants procure/operate storage capacities and activate demand response to modify the load to match with T-EACs.	$ModifiedDemand_{i,t} = Demand_{i,t} + DRUp_{i,t} - DRDown_{i,t} + StorageCharge_{i,t} - StorageDischarge_{i,t}$
Hourly matching: Participants decide how much T-EAC do they need.	$ModifiedDemand_{i,t} + Excess_{i,t} = GridSupply_{i,t} + NeededTEAC_{i,t}$
Excess limit	$\sum_t Excess_{i,t} \leq ExcessLimit \times \sum_t ModifiedDemand_{i,t}$
CFE Score Target	$\sum_t (GridSupplyCleanness_t \times GridSupply_{i,t} + NeededTEAC_{i,t}) \geq CFETarget \times \sum_t ModifiedDemand_{i,t}$
T-EAC Exchange and Market Clearing: Participants either get T-EAC from the CFE capacity they procured or from other participants. The shadow price of this constraint is the T-EAC price.	$NeededTEAC_{i,t} = ContractedCFEGeneration_{i,t} - \sum_{i \neq j} TEACSell_{i,j,t} + \sum_{i \neq j} TEACBuy_{i,j,t}$ *$TEACSell_{i,j,t}$ is non-negative variable for the T-EAC sale from participants i to j;* *$TEACBuy_{i,j,t}$ is non-negative variable for the T-EAC procurement of participants i from j.*
Transaction Cost (add to objective function)	GenX Objective += $TransactionCost \times \sum_{t,i,j}(TEACSell_{i,j,t} + TEACBuy_{i,j,t})$

Experimental Design and Key Assumptions

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Experimental Design: Default Settings

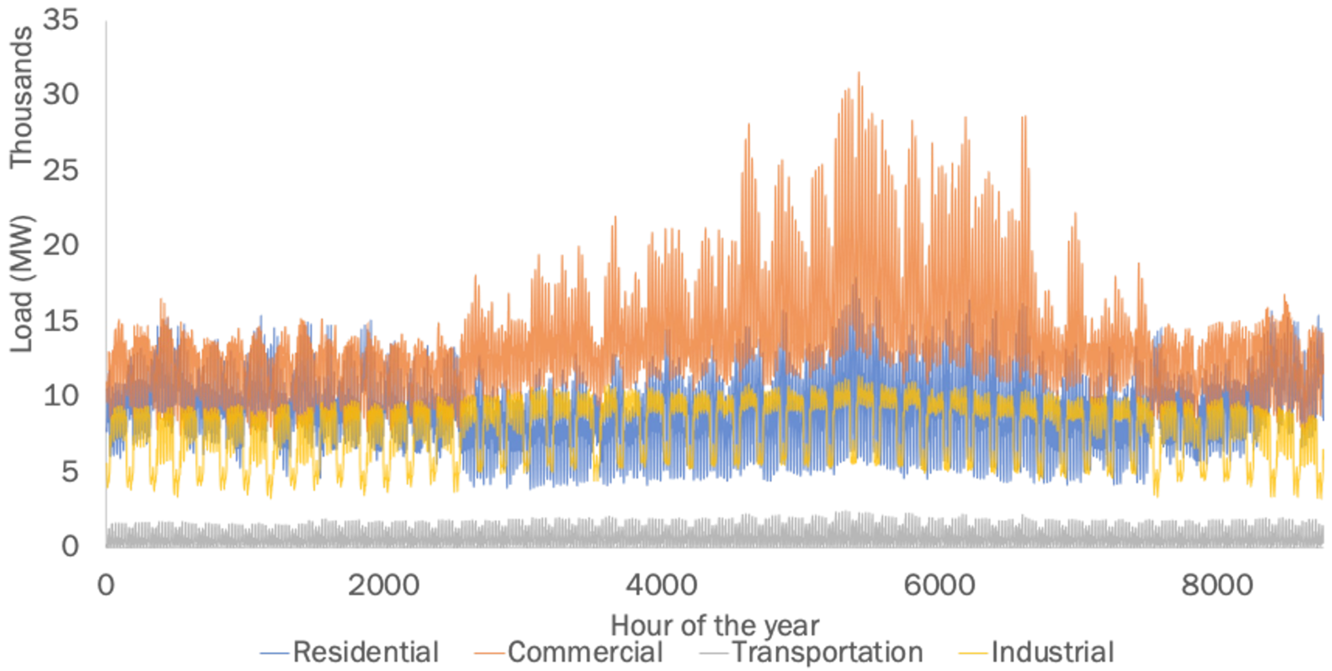

Figure 1: California's electricity demand profiles in 2030. The total amount of electricity demand is 274 TWh, with residential = 79 TWh, commercial = 120 TWh, industrial = 69 TWh and transportation = 6 TWh. The data is based on Princeton's *Net-Zero America* study (2021) and NREL's *Electrification Futures Study* (2018).

The test system is set in California. There are five groups of participants modeled, varied by size, time-series, and resource accessibility

Participants	Load Type	Size	CFE Resource Accessibility
1	Residential*	20% of CA Res. Load	Full
2	Residential*	5% of CA Res. Load	Constrained
3	Commercial	20% of CA Com. Load	Full
4	Commercial	5% of CA Com. Load	Constrained
5	Industrial	10% of CA Ind. Load	Full

The default CFE Score Target = 98% for all participants.
* Residential refers to a pass-through cost from their retailer or aggregator.

Experimental Design: Resource Accessibility Justification

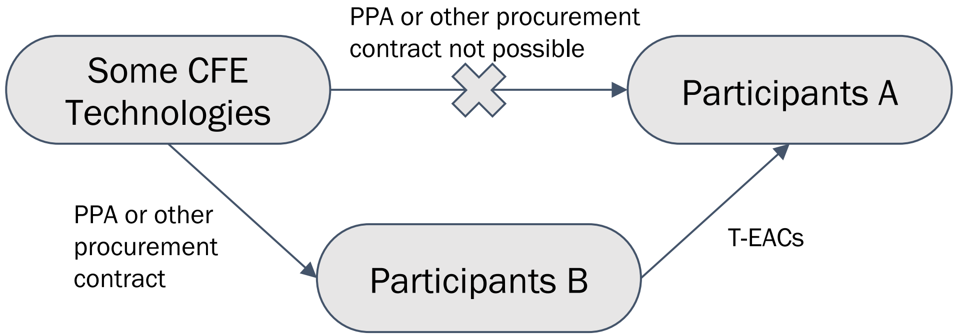

Figure 2: Diagram demonstrating how T-EAC trading gives resource-constrained participants access to a broader range of resources.

We model different levels of CFE Resource Accessibility:

- *(Default) Constrained*: Onshore Wind, Solar, Lithium-Ion Battery,
- *(Default) Full:* Above + floating offshore wind, geothermal (conventional/near-field hydro-flash), long-duration storage (metal-air and hydrogen), natural gas combined cycle with post-combustion carbon capture and sequestration (NGCC with CCS), and combined cycles burning zero-carbon fuel (e.g., hydrogen, biomass, ammonia, etc.)
- *(Sensitivity) None:* T-EACs only

The design of different resource accessibilities is to approximate the fact that:

- ❑ Small participant groups may face difficulties to finance capital intensive generation technologies, such as offshore wind, geothermal, and advanced technologies like NGCC with CCS, at the scale needed for a PPA
- ❑ Advanced technologies carry more risk and small participants likely do not have resources to do full due diligence
- ❑ (Sensitivity of no Resource Access) Doing any PPA requires careful consideration and a thoughtful energy strategy, which may not be available to small participants, to account for:
  - ➔ Analyzing energy market options, finding projects, and negotiating proposals (requires understanding of power markets, price forecasts, benchmarking prices via tenders, etc.)
  - ➔ Financing: OPEX, internal business approvals, and understanding accounting treatment
  - ➔ Assessing regulatory risk
  - ➔ Managing financial risks

	Unbundled RECs	**PPAs**
Economics	Low cost	Economical
Risk	Low risk (but no upside)	Financial risks
Scale	Any	Minimum threshold (>10 MW usually)
Complexity	Low	High
Impact	Historically low, but can change with granularity	High

Experimental Design

Caveat: via carefully designed experiments, this report focuses on ***exploring*** why and how a T-EAC exchange can be beneficial, rather than ***quantifying*** these benefits will be in real-life. **Quantitative results in this study should thus be taken as examples of the qualitative benefits of T-EAC trading, rather than quantitative projections of future benefits.** The impact and benefit quantification of a real-life T-EAC exchange may require subsequent empirical analyses.

Experiment 1
(Efficiency improvement):
We run the model without T-EAC trading and again with free T-EAC trading (e,g, no transaction cost for T-EAC trades). A comparison of the procured CFE and the cost premium of 24/7 CFE reveals the economic benefit of a centralized, liquid T-EAC exchange with limited-to-no transaction costs.

Experiment 2
(Transaction cost-savings):
We run the model with free T-EAC trading and again with different levels of transaction cost ($0-$5/MWh) as a proxy of the potential transaction costs for bilateral T-EAC contracts without a centralized Exchange. The total amount of T-EAC transaction cost can be interpreted as the potential cost-savings from establishing a centralized, liquid Exchange.

Experiment 3
(Risk hedging functionality):
We first run the model without T-EAC trading and fix the procured 24/7 CFE capacities. With the fixed amount of CFE capacities, we artificially introduce some forecast errors to the wind/solar time-series and re-run the model without T-EAC trading and again with free T-EAC trading. The difference between the cases reveals the ability for T-EACS to hedge risk from forecast error.

Sensitivity: for Experiment 1, we also model a high natural gas price case.

Summary of key data assumptions

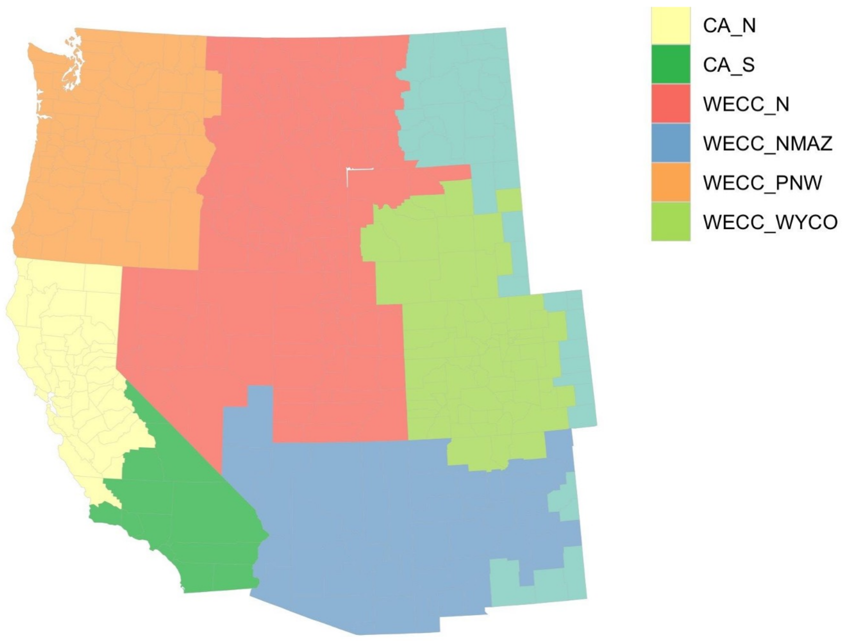

Figure 3: Six-zone WECC system map of this study. there are two zones in California. Regions and inter-regional transmission constraints represent single regions or aggregations of regions from the EPA IPM model. See U.S. Environmental Protection Agency's Power System Modeling Platform, IPM (2021).

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 @ Dec. 2021
- WECC: Wind and solar CPA (4km x 4 km) grouped into 315 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
- Capital cost: NREL *Annual Technology Baseline (ATB)* 2021 + Regional Multiplier: EIA *Annual Energy Outlook (AEO)* 2020;
- Fuel cost: EIA *AEO* 2021'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 *Net-Zero America* study (E+ scenario). 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 (excludes *Inflation Reduction Act*)

Key cost assumptions

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)
Solar	980	72k - 139k	-	0	-	30-31%	-	235	NREL ATB 2021
Onshore Wind	1,185	157k – 281k	-	0	-	26-38%	-	82	NREL ATB 2021
Battery	216/204	24k	22k	0.15	-	-	85% (1-10 hours)	No Limit	NREL ATB 2021
Offshore Wind (Floating)	2,946	367k-372k	-	0	-	50-55%	-	13	NREL ATB 2021
Geothermal (Binary Hydro-flash)	5,648	401k-462k	-	0	-	-	-	1.7	NREL ATB 2021 (Advanced Scenario)
Long-duration Storage – Metal Air	1,200/12	98k	0.6k	0	-	-	42% (100-200 hours)	No Limit	Baik et al., 2021.
Long-duration Storage – Hydrogen	1339/1	128k	0.05k	4.5	-	-	27% (200-800 hours)	No Limit	Baik et al., 2021.
Near Field Geothermal (Flash)	11,611	746k-871k	-	0	-	-	-	0.4	NREL ATB 2021 (Advanced Scenario)
Combined Cycle with ZCF	1,036	103k-108k	-	1.76	6.36	-	-	No Limit	Same as Combined Cycles in NREL ATB, but use zero carbon fuel
Natural Gas Combined Cycle w/100%CCS	2,709	255k-260k	-	6.3	7.53	-	-	No Limit	NREL ATB 2021 + Feron et al 2019; Injection cost is $12/metric ton for Northern California, $21/metric ton for Southern California before 45Q.

- NREL (National Renewable Energy Laboratory). 2021. "2021 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
- Foron et al. 2019. “Towards Zero Emissions from Fossil Fuel Power Stations.” International Journal of Greenhouse Gas Control, Volume 87, 188-202, DOI: 10.1016/j.ijggc.2019.05.0189

Natural Gas Fuel Price

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

Month	California
Jan.	5.16
Feb.	4.70
Mar.	4.45
Apr.	3.71
May	3.54
Jun.	3.31
Jul.	3.25
Aug.	3.10
Sep.	3.33
Oct.	3.20
Nov.	3.82
Dev.	3.78

- *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*

Main Results: Exploring the Impact of T-EAC Trading

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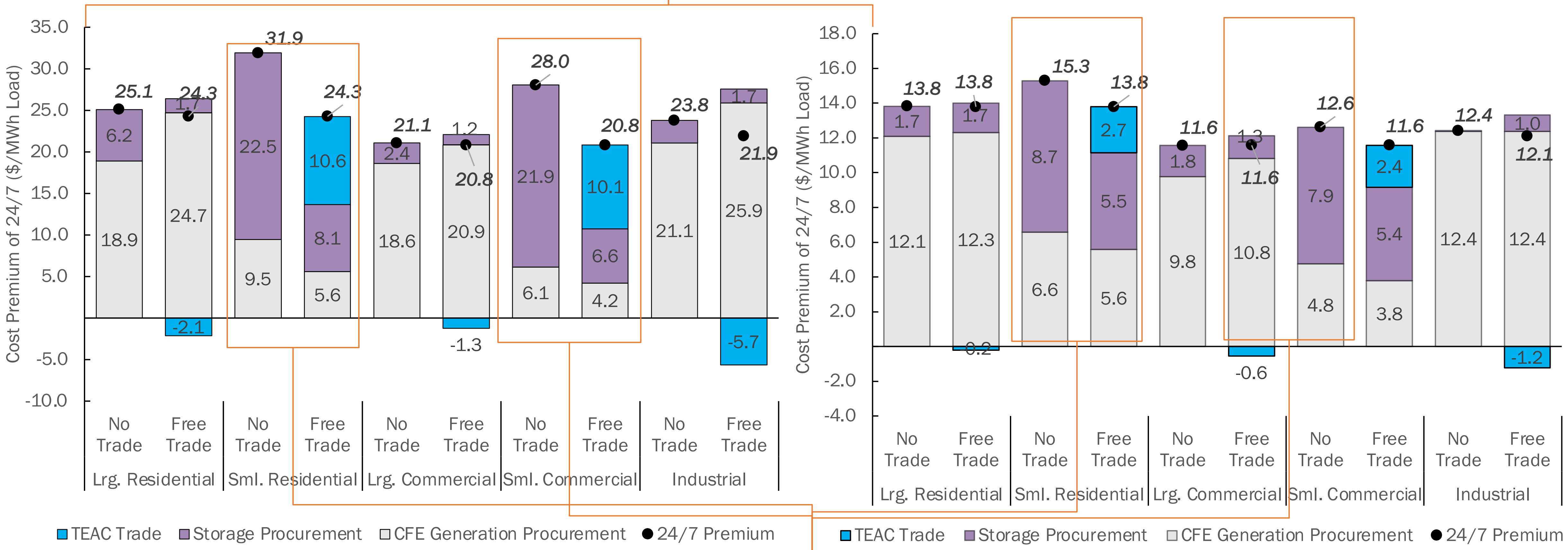
Result 1: T-EACs trading increases participants' access to CFE resources and decreases the cost premium required by 24/7 CFE

24/7 cost premium and savings from T-EAC trading are both larger if participants have higher CFE Score Targets



T-EAC trading reduces 24/7 cost premium, especially of resource-constrained participants. The cost reduction increases when CFE Score target is high

Figure 4: Cost premium of 24/7 CFE procurement for five modeled California participants, CFE score target = 90% (right) and 98% (left). CFE Generation Procurement: cost premium 24/7 participants pay to procure CFE capacities. Storage Procurement: net cost (capex + operation cost - revenue from other markets) 24/7 participants pay to procure the storage facilities. T-EAC Trade: T-EAC payment to (or revenue from) other participants. Because of large amount of CFE injected into the grid, market prices of other product like energy and capacity also change; the net impact (roughly unchanged given a CFE target) is -$0.8/MWh load (CFE Target = 90%) and -$1.3/MWh (CFE Target = 98%).

Result 1: T-EACs trading increases participants' access to CFE resources and decreases the cost premium required by 24/7 CFE

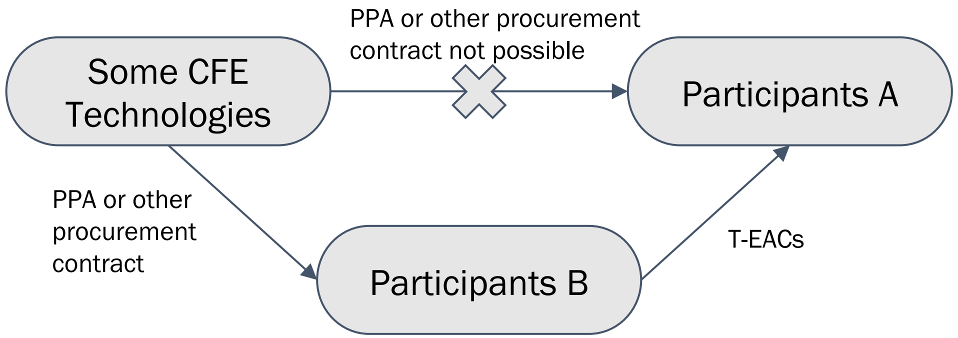


Figure 2: Diagram demonstrating how T-EAC trading gives resource-constrained participants access to a broader range of resources.

If organized T-EAC trading becomes possible, it would be an economical choice for participants with access to a full range of clean firm technologies to procure more capacity (and pay more), and then sell T-EACs to those who have limited access and earn revenue from T-EAC trading.

It is clear that the T-EAC trading reduces the cost premium of participants that have limited access to CFE technologies (**Figure 4**). The primary source of the cost saving is the avoided overpayment to battery storage facilities which participants use to modify load to follow wind and solar profiles with less difficulty.

With trading, the large consumers and small consumers with the same load type (e.g., commercial ones) have the same level of cost premium, even though the compositions of the cost premium are different. The net impact is that the T-EAC trading allows resource-constrained participants to meet their CFE target *as if* a full spectrum of technologies are available to them.

Notably, the cost-saving introduced by the T-EAC trading increases as the CFE score target increases, suggesting that T-EACs trading helps solve for the 'last 10%' of 24/7 CFE more efficiently by reducing costs.

Result 2: A centralized, organized T-EAC Exchange reduces transaction costs associated with "matching" T-EAC buyers/suppliers.

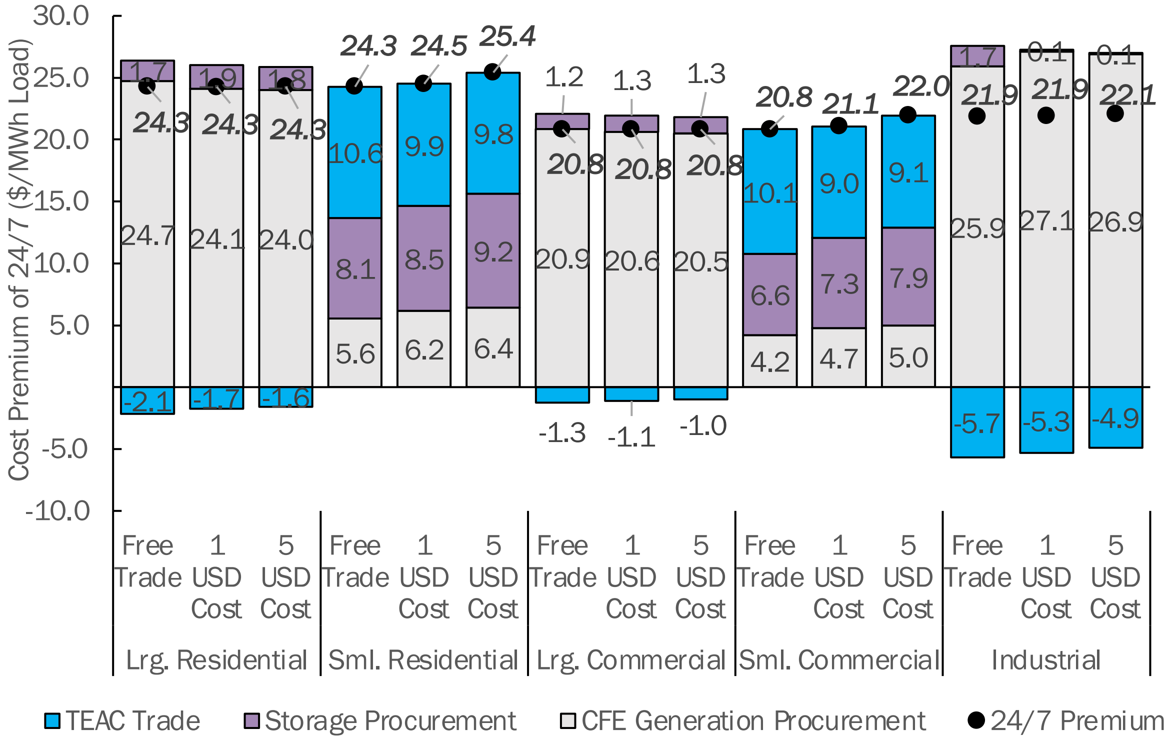


Figure 5: Cost premium for 24/7 CFE procurement for five modeled California participants with different levels of transaction cost, CFE score target = 98%. We assume under a centralized, organized T-EACs exchange, the cost of exchange transaction is negligible. When transaction cost is non-zero, an extra amount of transaction cost to "brokers" would occur, see Table 1.

Table 1: Total exchange volume and total transaction payment under different transaction cost assumptions. CFE score target = 98% for all players.

Transaction Cost	Exchange Volume	Total Transaction payment
~$0/MWh	3.06 TWh	~$0
$1/MWh	2.45 TWh	$2.45 Million
$5/MWh	2.31 TWh	$11.54 Million

A centralized, organized T-EAC exchange can lower the transaction costs that otherwise will be paid for "matching" a T-EAC supplier with a T-EAC consumer. Under our test setting, the total cost saving can be millions of dollars annually. The lower transaction cost also encourages a higher volume of trading and ultimately leads to lower cost premium of 24/7 (left).

Result 3: T-EACs Exchange serves as a risk hedging function

Table 2: Distance from the CFE Target after the introduction of forecast error via normal distribution with a mean = -10% and standard deviation = 10% .

Participants Group	Distance From the Target without T-EAC trading	$ penalty if evaluated at the Maximum Observed T-EAC price = $106/MWh (if there is trading)
Lrg. Residential	48,942 MWh (0.30% of load)	$5.19 Million ($0.32/MWh of load)
Sml. Residential	35,818 MWh (0.89% of load)	$3.80 Million ($0.89/MWh of load)
Lrg. Commercial	102,002 MWh (0.41% of load)	$10.81 Million ($0.43/MWh of load)
Sml. Commercial	67,955 MWh (1.10% of load)	$7.20 Million ($1.09/MWh of load)
Industrial	17,140 MWh (0.25% of load	$1.81 Million ($0.26/MWh of load)

In this experiment, we fix the capacity procurement without T-EAC trading and everyone targets a CFE score of 98%. We then artificially introduce a forecast error to the wind and solar time-series. Then we ran the model with and without T-EAC trading. The results show that:

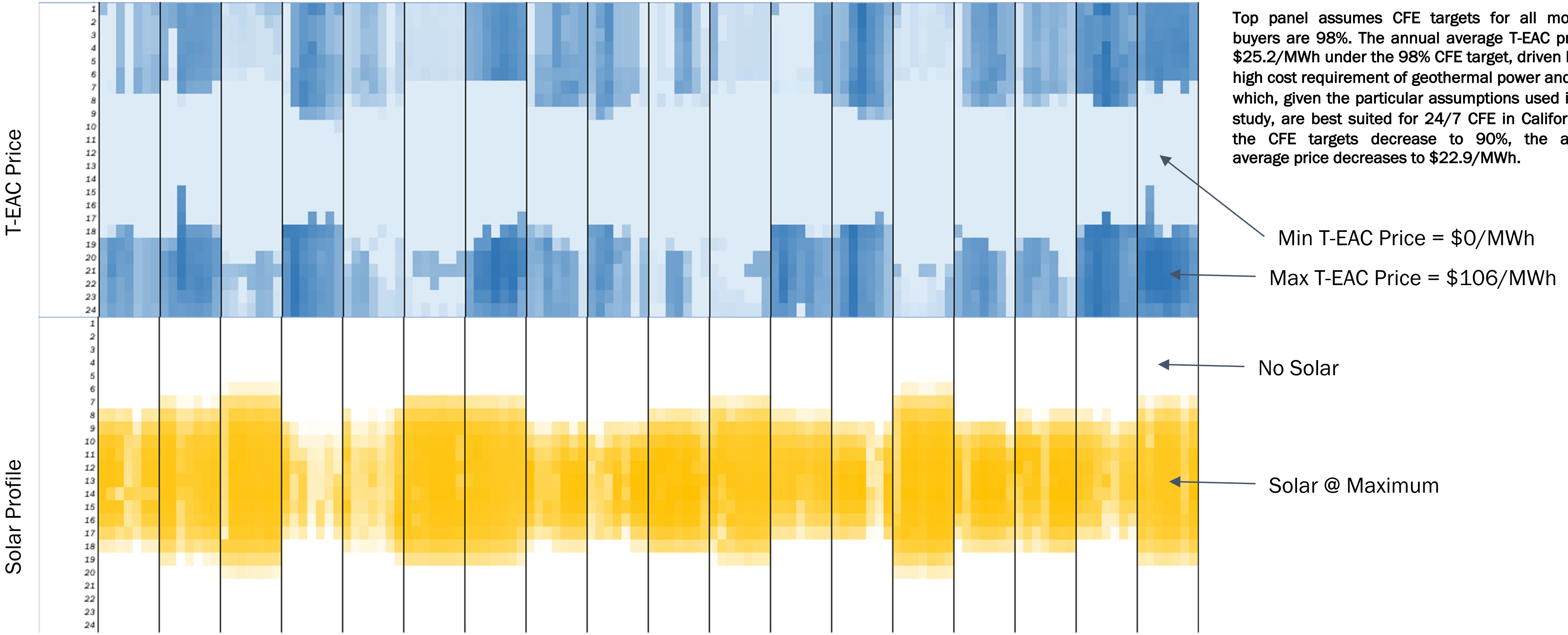
- Without T-EAC trading, the buyers will miss the CFE target, and the distance to the target is shown in **Table 2**.
- With trading, however, by exchanging T-EACs among the buyers *ex-post*, the CFE targets are still met: T-EAC trading hedges against the forecast error of wind and solar.

Although the resulted hedging benefit of the T-EAC exchange is small in our setting, it can be significantly larger in reality for several reasons:

1) We only consider one type of forecast error (wind and solar) in our analysis; there are other source of uncertainty that is important to 24/7, including the forecast errors of hourly demand and the cleanness of the grid supply,

2) The introduced error in this experiment is relatively small because we don't completely switch to another set of time series.

Result 4: Hourly Price T-EACs signal when T-EACs are most valuable



Top panel assumes CFE targets for all modeled buyers are 98%. The annual average T-EAC price is $25.2/MWh under the 98% CFE target, driven by the high cost requirement of geothermal power and CCS, which, given the particular assumptions used in this study, are best suited for 24/7 CFE in California. If the CFE targets decrease to 90%, the annual average price decreases to $22.9/MWh.

Figure 6: T-EAC prices from the exchange (top) and California solar profile (bottom) over eighteen representative weeks. CFE targets for all modeled buyers are 98%. Because of the large amount of existing solar power in California, the demand for T-EACs in the daytime is scare, driving diurnal T-EAC prices down. The nocturnal T-EAC prices are high because grid-supplied clean power is comparatively scarce during the night. Because California T-EAC prices are close to zero in most hours, to recover the cost requirement of 24/7 CFE, the non-zero T-EAC prices are high. This will be different across markets depending on the variability of clean energy and correlation with demand.

Result 4: Hourly Price T-EACs signal when T-EACs are most valuable

We find the T-EAC trading can generate hourly differentiated T-EAC prices. In deregulated electricity markets, locational marginal prices (LMPs) reflect when the electricity is most valuable. Likewise, T-EAC prices signal when additional carbon-free generation would be the most valuable, incentivizing optimal investment decisions for 24/7 CFE. The T-EAC price will be determined by:

Demand-side: Participants' hourly differentiated maximum willingness to pay for T-EACs and the opportunity cost of operating storage/activating demand response to modify participants' load to follow CFE generation schedule. In our core case.

Supply-side: The additional revenue requirement from CFE (above and beyond the energy market earnings) to recoup variable costs can also set hourly T-EAC prices.

Consequently, T-EAC prices will rise when available CFE is relatively scarce, and either clean power from the grid supply is used to meet the CFE target, or storage assets are operated (or demand response is activated) to modify demand to follow the CFE generation, or additional T-EAC revenues are needed to operate the marginal CFE resources.

In contrast, T-EAC prices will be low when CFE is ample and supplied by low-marginal-cost resources like wind or solar PV. T-EAC prices can fall to zero when available CFE exceeds demand from 24/7 buyers.

Result 4: Hourly Price T-EACs signal when T-EACs are most valuable

Unlike the LMPs that are usually set by the marginal cost of the supply side, our observations show that T-EAC prices will be frequently (43% of the hours) set by the demand side bids, either at the hourly differentiated maximum willingness to pay for the T-EACs, or the opportunity cost of operating storage for load modification. This indicates that in the T-EACs market, where T-EACs supply are primarily zero-marginal-cost resources, bidding from the demand-side will become much more important in price formation than it is in the current deregulated energy market -- accurately revealing T-EAC's value primarily depends on T-EAC buyers' bid offers.

Hourly maximum willingness to pay for T-EACs:

In our study, the CFE score target constraint (see here) will produce an annual shadow price ($/MWh), representing the system marginal cost for 1 MWh incremental demand of participants CFE score target. The underlying costs include the annualized capex, operation and maintenance costs, and fuel costs of the incrementally needed CFE capacity. In addition, it also includes the cost to procure some grid-supply that presumably includes some clean power. This shadow price can also be interpreted as the **annual** maximum willingness to pay for 1 MWh incremental demand of CFE given a certain target.

Our results show that this annual maximum willingness to pay for CFE, say *X*, becomes differentiated on an hourly basis based on the grid-supply cleanness to form the **hourly maximum willingness to pay for T-EACs.** At a certain hour *t*, suppose participants recognize that per MWh grid supply, *M* MWh is carbon-free. Our results show that the maximum willingness to pay for T-EAC is: **$(1\text{-}M_t) \bullet X$.** In reality, this highlights that the price of the buying offer should be hourly differentiated, even though the CFE score target is annual. When grid supply is needed, the T-EAC price will be at **$(1\text{-}M_t) \bullet X$.** Specifically, when CFE targets are 98% for all buyers and trading is allowed, 30% of T-EAC prices (~2600 hours) are set at this level.

Result 4: Hourly Price T-EACs signal when T-EACs are most valuable

Opportunity cost of storage operation:

Our result also demonstrate that the T-EAC buyers can also bid the opportunity cost of storage operation in the T-EAC trading system, when storage is operated to modify the participants' demand to follow the CFE generation schedule. The underlying cost includes the value of stored energy (i.e., cost to charge in advance or possible benefit to discharge at a later time) offset by the energy price of the current hour.

Specifically, when CFE targets are 98% for all buyers and trading is allowed, 13% of T-EAC prices (~1100 hours) are set by the opportunity cost of storage operation.

Finally, because of the large amount of solar power in the portfolio, 50% of T-EAC prices are close to zero because of CFE oversupply in those hours. Therefore only during the remaining 7% of the hours, T-EACs prices are determined by the supply-side and set at the marginal cost of CFE generation minus the hourly energy market price – e.g. the additional hourly revenue that must be earned by CFE to justify dispatch in that hour. Supply-side bids thus only set hourly prices when CFE generators have non-zero marginal costs that exceed the hourly electricity market clearing price.

Result 5: With a T-EAC Exchange, participants would actively buy/sell T-EACs to meet the CFE score target.

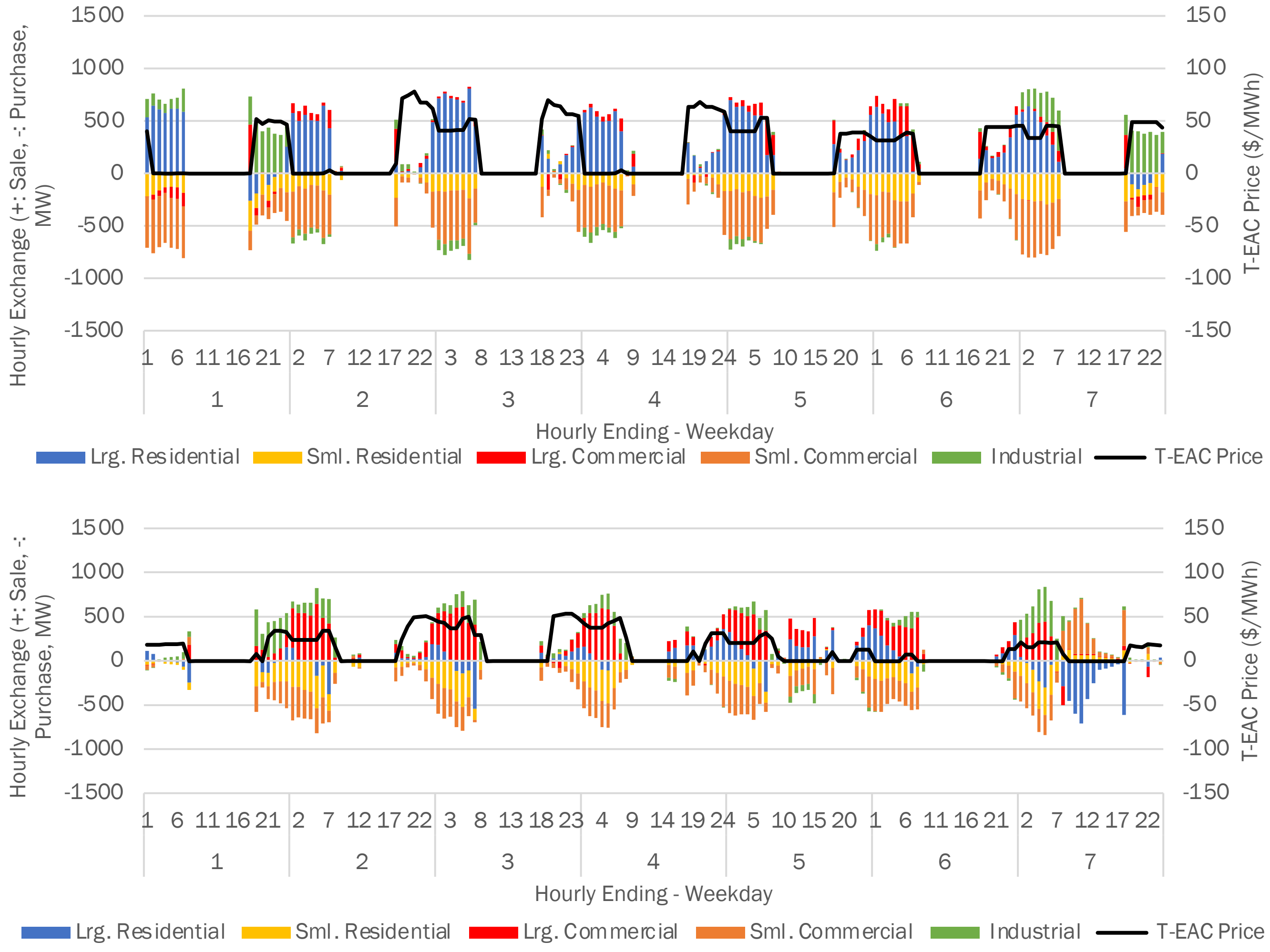
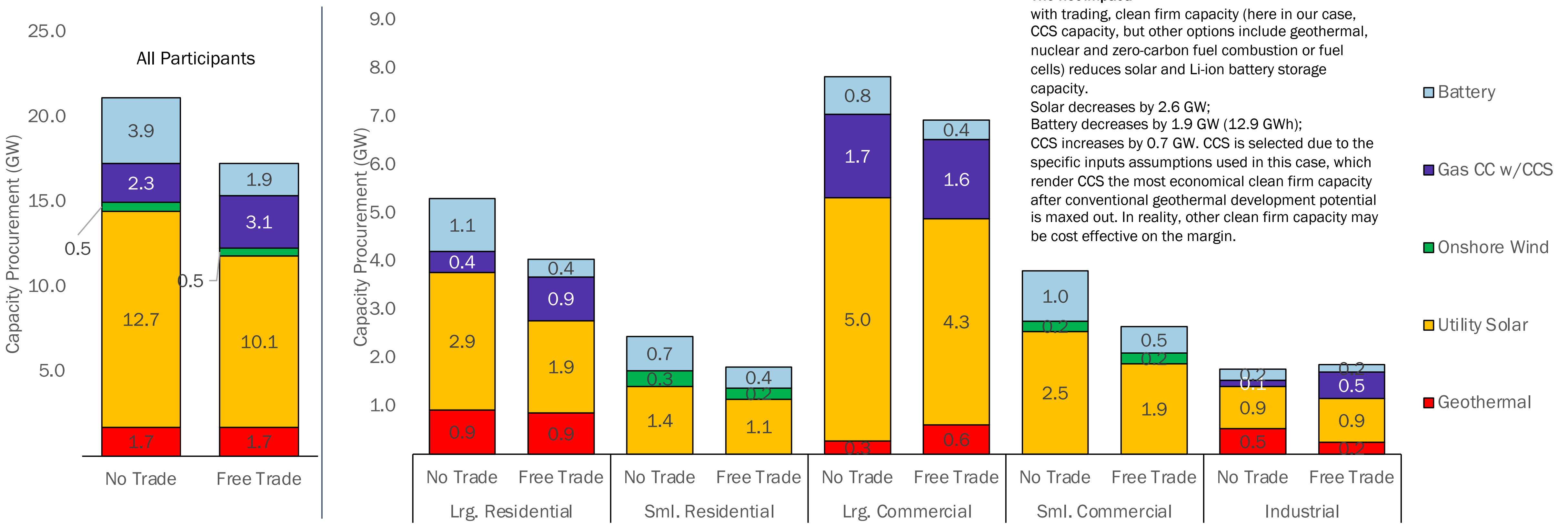


Figure 7: T-EAC exchange among the participants and the T-EAC prices. Two example weeks are selected. Note that with only a few exceptions, the exchange volume tends to be low when the T-EAC prices are low and the exchange volume tends to be high when T-EAC prices are high.

We find the participants would actively buy/sell T-EACs with each other to meet the CFE score target if there is a T-EAC exchange. With only a few exceptions, the exchange volume tends to be low when the T-EAC prices are low and the exchange volume tends to be high when T-EAC prices are high.

Most notably, even though a participant can be a net buyer or net seller of T-EACs, none of the participants is a "pure" buyer or seller: every one of the participants buys or sells at some hour of the year.

Result 6: T-EAC trading reduces the over-procurement of CFE capacities; buyers can potentially buy capacity to make revenue from the T-EAC trading



The net impact:
with trading, clean firm capacity (here in our case, CCS capacity, but other options include geothermal, nuclear and zero-carbon fuel combustion or fuel cells) reduces solar and Li-ion battery storage capacity.
Solar decreases by 2.6 GW;
Battery decreases by 1.9 GW (12.9 GWh);
CCS increases by 0.7 GW. CCS is selected due to the specific inputs assumptions used in this case, which render CCS the most economical clean firm capacity after conventional geothermal development potential is maxed out. In reality, other clean firm capacity may be cost effective on the margin.

Figure 8: Capacity procurement of the five modeled California 24/7 participants with or without T-EAC trading. CFE Score Target = 98% for all participants.

Result 6: T-EAC trading reduces the over-procurement of CFE capacities; buyers can potentially buy capacity to make revenue from the T-EAC trading

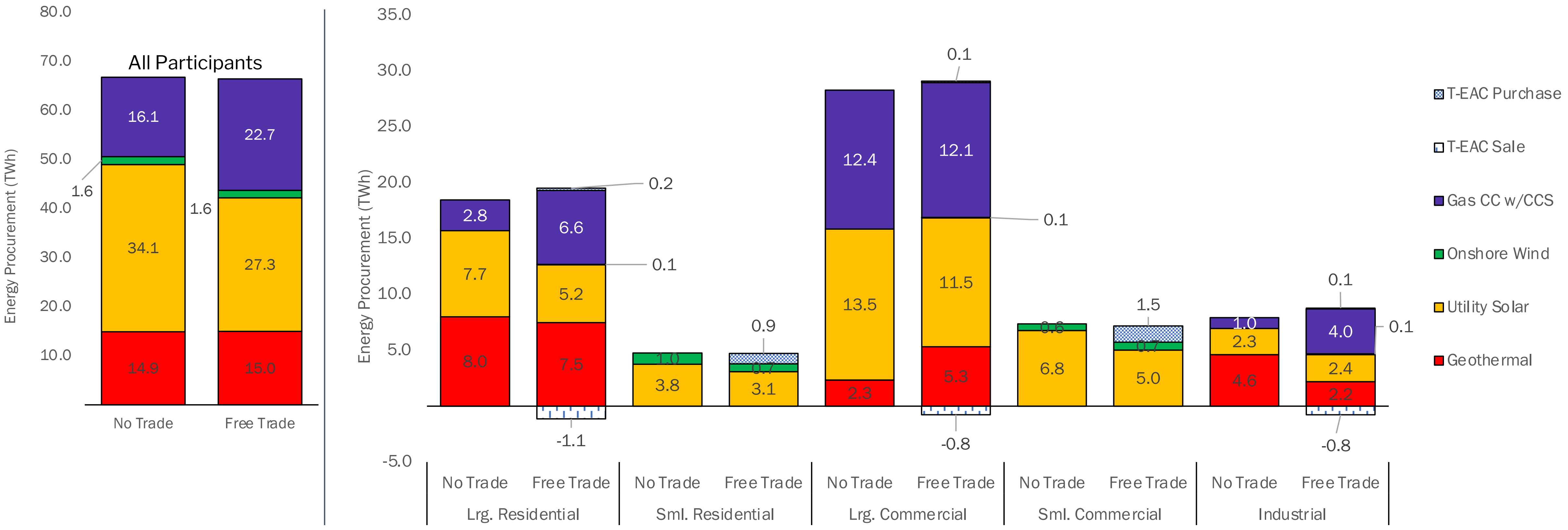


Figure 9: Energy procurement and purchase or sale of T-EACs of the five modeled California 24/7 participants with or without T-EAC trading, the CFE Score target = 98%. With trading, the resource-unconstrained participants procure more CCS power (6.6 TWh) and sell the T-EACs to the resource-constrained participants, reducing the intermittent CFE generation that would be otherwise procured by (6.8 TWh of solar, 0.1 TWh of Wind, the difference of 0.3 TWh is avoided storage loss). Also, note that, even the large residential or commercial participants are net T-EAC exporter, they occasionally procure T-EACs.

Result 6: T-EAC trading reduces the over procurement of CFE capacities

T-EAC trading *indirectly* gives resource-constrained participants access to the full spectrum of CFE technologies (see slide here) such as capital-intensive clean firm resources (e.g., geothermal and CCS) that they may otherwise be unable to contract directly with. In our cases:

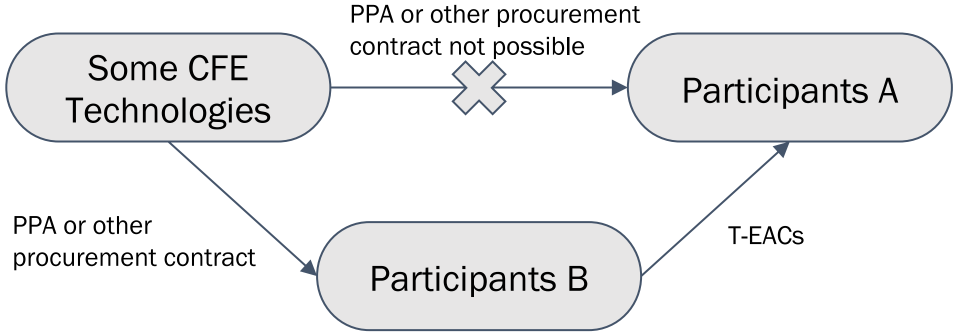


Figure 2: Diagram demonstrating how T-EAC trading gives resource-constrained participants access to a broader range of resources.

- With trading, it will be more economical for participants with access to a full spectrum of technologies to procure more clean firm capacity and then sell the T-EACs to resource-constrained participants for them to meet the target more easily.
- For the resource-constrained participants, it costs less to procure T-EACs from other CFE buyers with excess clean firm capacity than to procure battery storage and excess solar to meet high CFE targets, where batteries are used to modify the demand to follow wind and solar.

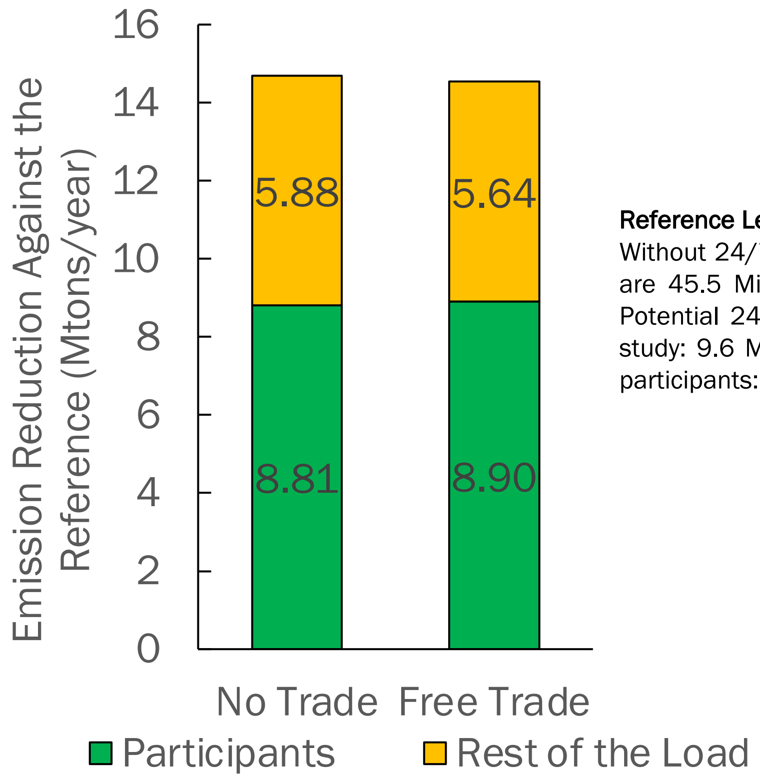
The net impact of T-EAC trading is thus less overall procurement of CFE capacity, especially of battery storage and variable renewable resources.

Result 6: T-EAC exchange reduces the over procurement of CFE capacities

Note that some buyers can procure more because of the allowed trading; they over-procure (more than needed to meet their own CFE target) to participate in and earn additional revenues in the trading market. The revenue of selling T-EAC is more than the cost of purchasing more capacity.

However, T-EAC trading allows participants to meet each CFE target differently. As aforementioned, even though a participant can be a net importer (e.g., commercial participants), or net exporter (e.g., industrial participants), it is rare for participants to be a "pure" importer or exporter: most participants import or export at some hour of the year. (See an example time series here).

Result 7: T-EAC trading does not result in significantly different emissions reduction



Reference Level:
Without 24/7, California load-side emissions are 45.5 Million metric tons/year in 2030. Potential 24/7 participants assumed in our study: 9.6 Million Metric tons (Mtons); Non-participants: 35.9 Mtons.

Figure 10: Emission reduction of 24/7 (sum of all participants) with and without T-EAC trading. CFE Score Target = 98% for all participants.

Our test setting assumes the total amount of participants is fixed, and all participants require additionality of new resources to meet their CFE target. Under this setting, we find that the T-EAC trading does not significantly impact the system-level greenhouse gas emission impact of 24/7 CFE (Figure 10), even though it reduces the total procured CFE capacity.

However, T-EAC trading will reduce the cost premium for 24/7 CFE procurement, and consequently, it has the potential to attract *more* participants to join the 24/7 CFE campaign. Therefore, if one assumes T-EAC trading induces higher overall 24/7 CFE procurement, the impact on emissions will be more beneficial than presented here.

Conclusions and Implications

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Conclusions and Implications

In summary, this study demonstrates that:

- ➔ T-EACs trading can lower the cost of 24/7 CFE procurement, especially for buyers who face limited options for direct procurement from carbon-free generators
- ➔ A liquid T-EACs exchange creates hourly price signals that can incentivize investment in clean technologies when the grid is dirtiest (e.g., in California, modeled T-EAC prices are highest as the sun sets, and generally in nighttime hours)
- ➔ While modeling in this study assumes perfect foresight for the year, in reality, buyers and sellers face significant uncertainty in matching demand and generation; T-EACs trading can play an important role in diversifying and managing risks associated with these forecast uncertainties
- ➔ Under the assumption that only new resources qualify to sell T-EACs, as modeled here, T-EACs trading maintains the system-level emissions reduction benefits of 24/7 CFE procurement
- ➔ The value of T-EACs trading increases as CFE targets approach 100%, helping buyers meet demand for 'the last 10%' of carbon-free generation needed to match their demand 24/7 at lower cost, especially buyers who may have a difficult time directly contracting with clean firm generators

Future work

We encourage future research to explore the outstanding questions:

- ➔ **Risk hedging function of T-EAC trading:** The stylized risk hedging quantification experiment in this study can be enhanced to be more realistic by (1) introducing significantly different wind, solar, and load time-series and (2) non-deterministic modeling, for example, stochastic programming modeling with first-stage decisions (CFE capacity procurement), and second-stage recourse decisions (T-EAC trading).

- ➔ **New participants:** In this study, we assume the demand of 24/7 CFE is fixed with no new participants. Given trading reduces 24/7 CFE's cost premium, this assumption likely underestimates the impact of T-EAC trading by ignoring the possibility that the lower cost premium could attract new participants. In a future study, this assumption should altered, for example by introducing a maximum budget constraint for CFE procurement for different participants and allowing the CFE score to be endogenously determined by the cost of procurement in order to enable a more realistic quantification of T-EAC trading's impact.

Future work, cont'd

- **T-EAC trading beyond 24/7 CFE:** T-EAC trading is not necessarily limited to enabling 24/7 CFE procurement. Participants can also trade T-EAC to optimize the CO_2 emissions reduction caused by voluntary procurement, that is, to procure T-EACs when the marginal emission rate of the system is high. The establishment of a single T-EAC trading system can enable both 24/7 CFE participants and carbon offset maximizers and the benefit of such a general trading system should be quantified.

- **Impact of T-EAC trading on new technologies:** This study shows indicative T-EAC pricing, but does not dig into how these new revenue streams may help the economics for new technologies. Future research could address this by running sensitivities on supply-demand dynamics and the downstream implications on different carbon-free technologies.

Appendix

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Appendix: High Natural gas price sensitivity – Cost Premium and procurement for 24/7 CFE

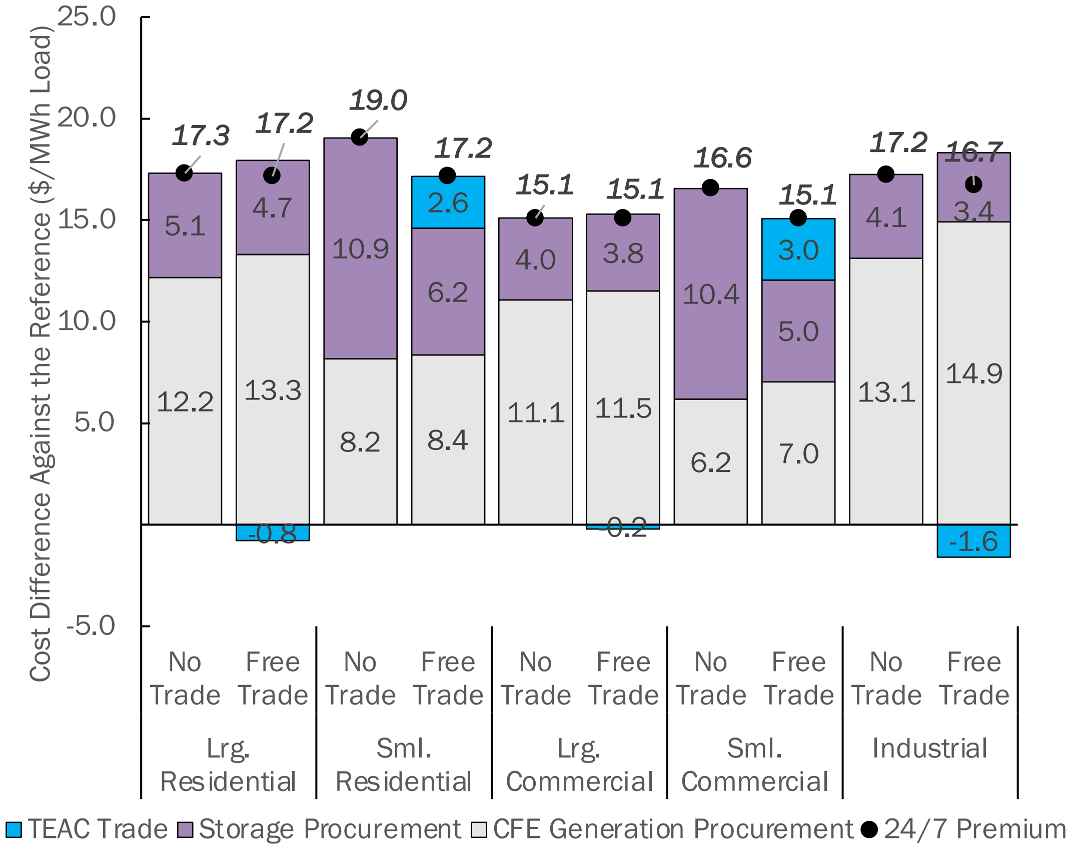


Figure A-1: Cost premium of 24/7 for five modeled California participants, CFE score target = 98%, under the high natural gas price. High natural gas prices (and thus high electricity prices) reduce the premium required for the 24/7 CFE as well as the benefit of establishing the T-EAC Exchange for resource-constrained participants.

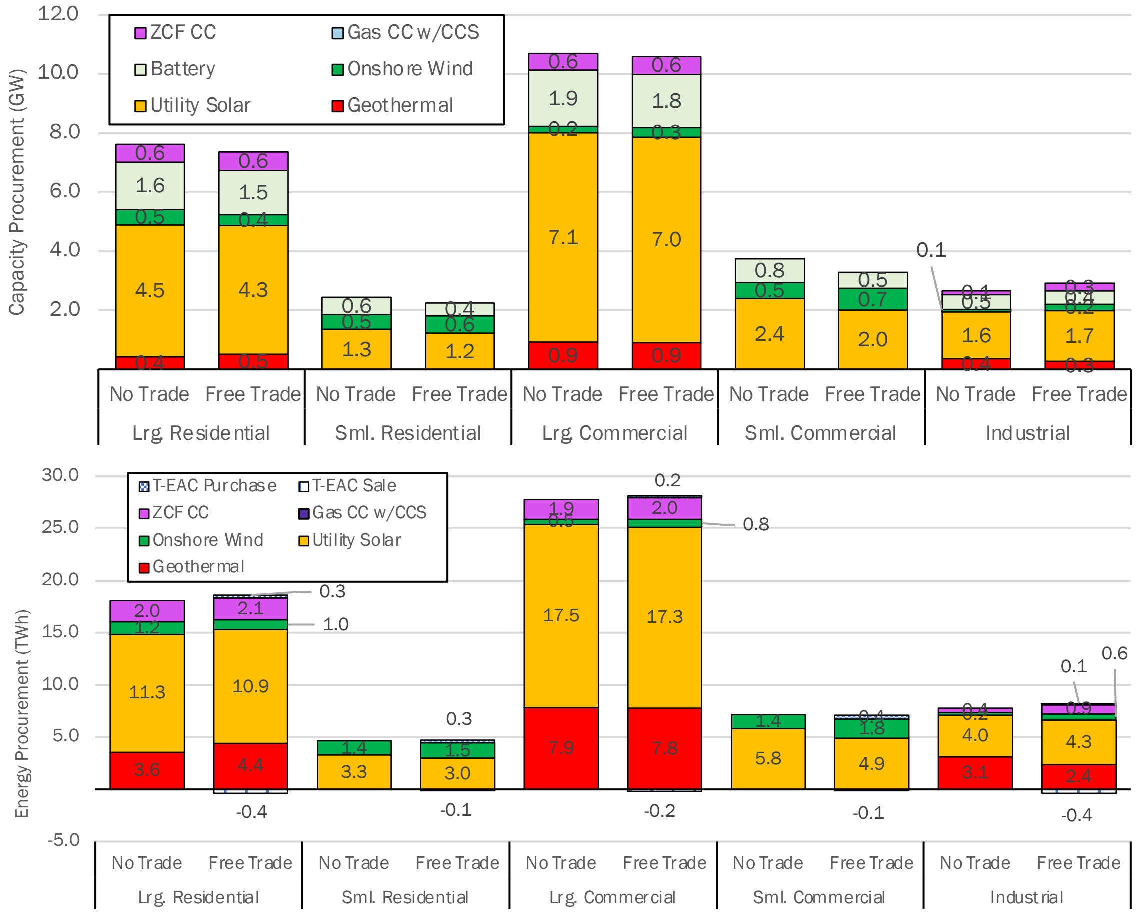


Figure A-2: Capacity and Energy Procurement of five modeled California participants, CFE score target = 98%, under the high natural gas price. High natural gas price makes NGCC with CCS much less economical, and the participants switch to combined cycle plants that burn zero-carbon fuel ($14/MMBTU).

Appendix: Small Participants can achieve their CFE targets by completely relying on the T-EAC procurement from the T-EAC Market

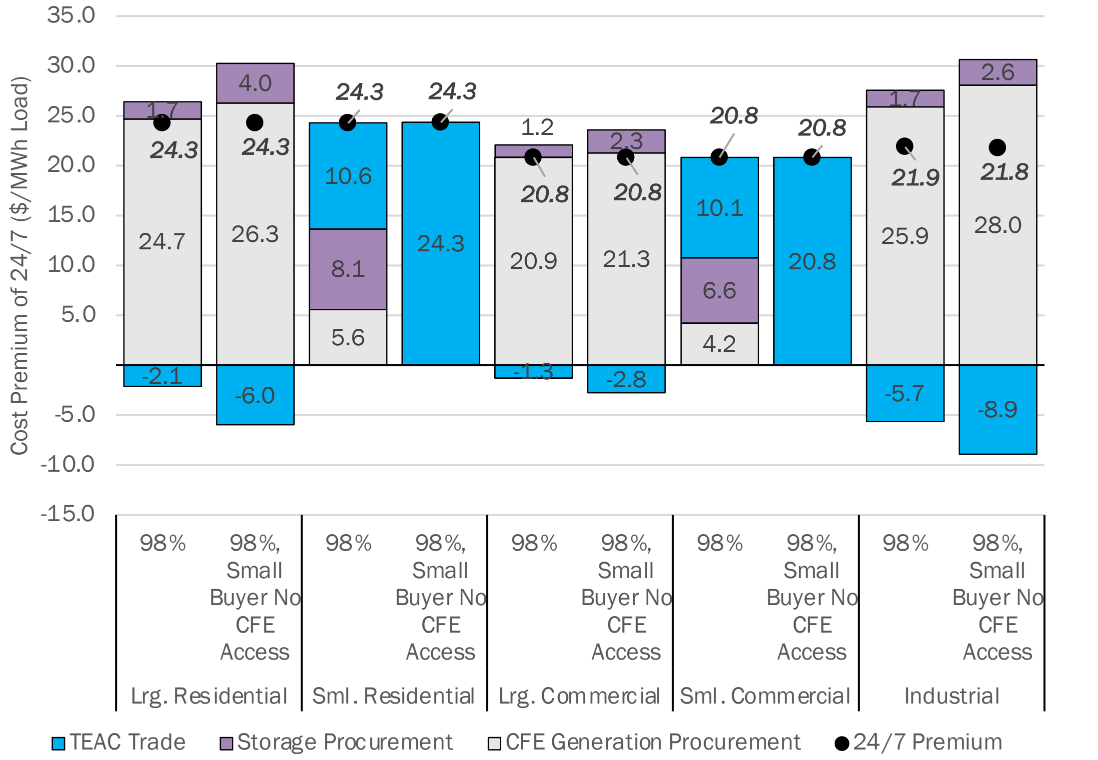


Figure A-3: Cost premium of 24/7 for five modeled California participants, CFE score target = 98%, if the small participants have no access to any resources and therefore have to completely rely on T-EAC trading to meet their CFE score targets.

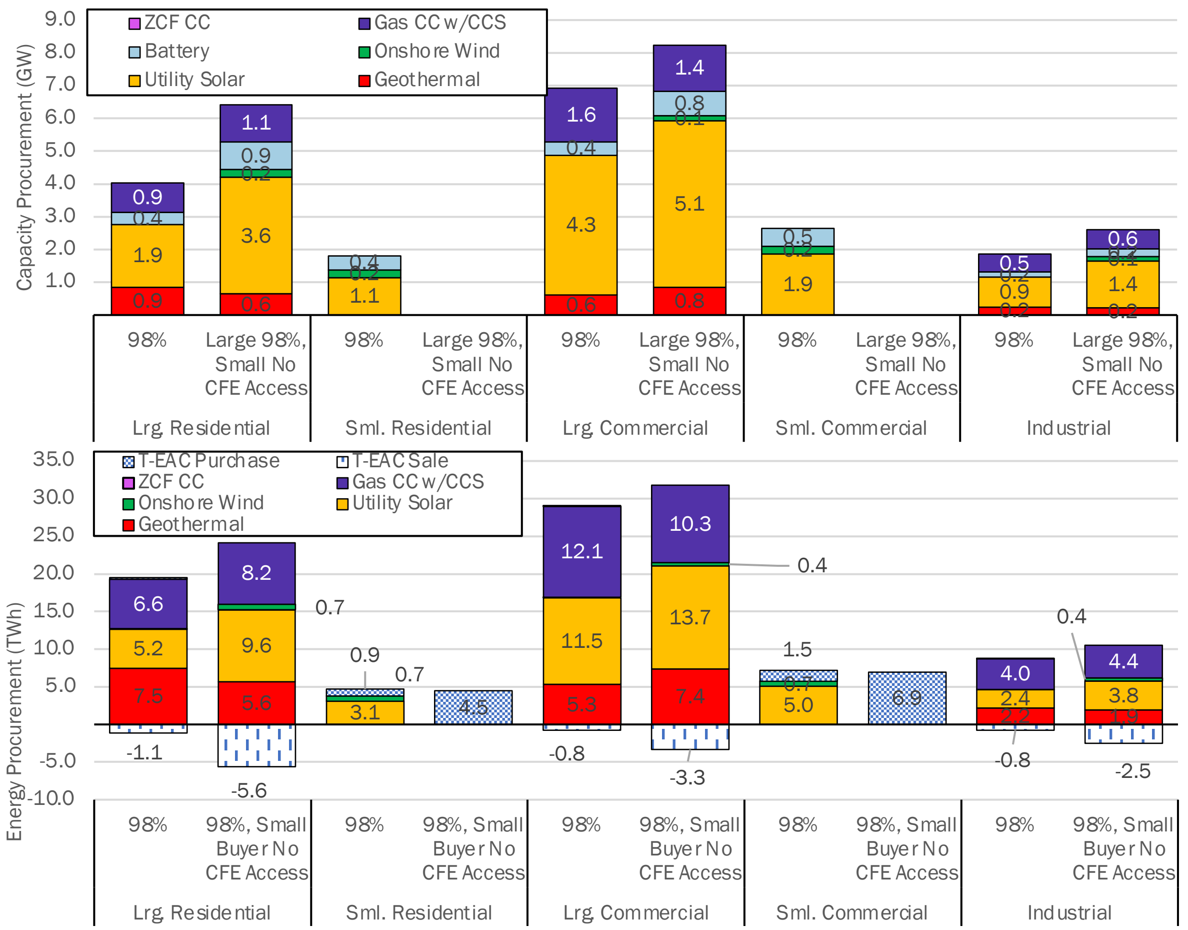


Figure A-4: Capacity and Energy Procurement of five modeled California participants, CFE score target = 98%; if the small participants have no access to any resources and therefore have to completely rely on T-EAC trading to meet their CFE score targets. Small buyers' willingness to pay to procure more T-EACs from other participants will incentivize those have access to resources to procure more CFE capacity and storage, so that they can sell the excess T-EACs.

Appendix: T-EAC exchange "indirectly" opens access to clean firm capacity for the resource-constrained buyers, and this is the primary source of the economic benefit

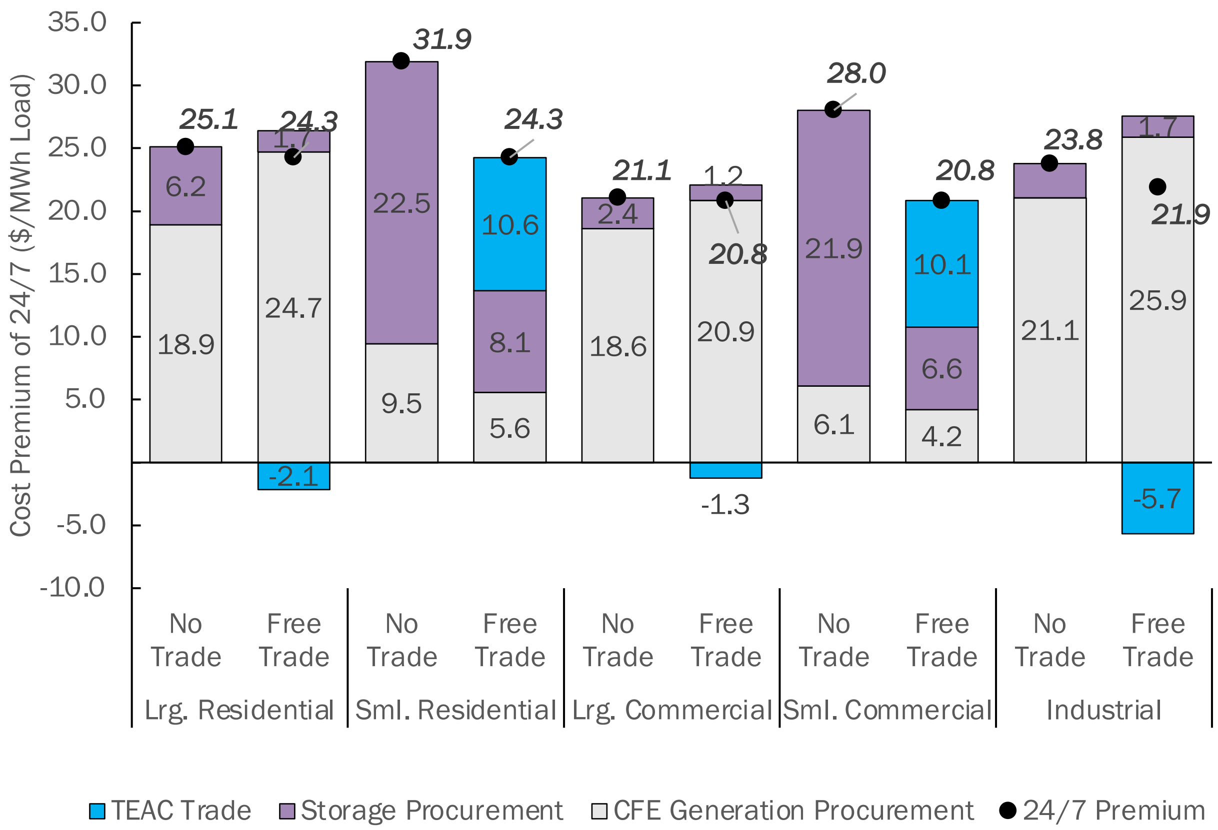


Figure A-5: Cost premium of 24/7 for five modeled California participants, CFE score target = 98% (same as Figure 3)

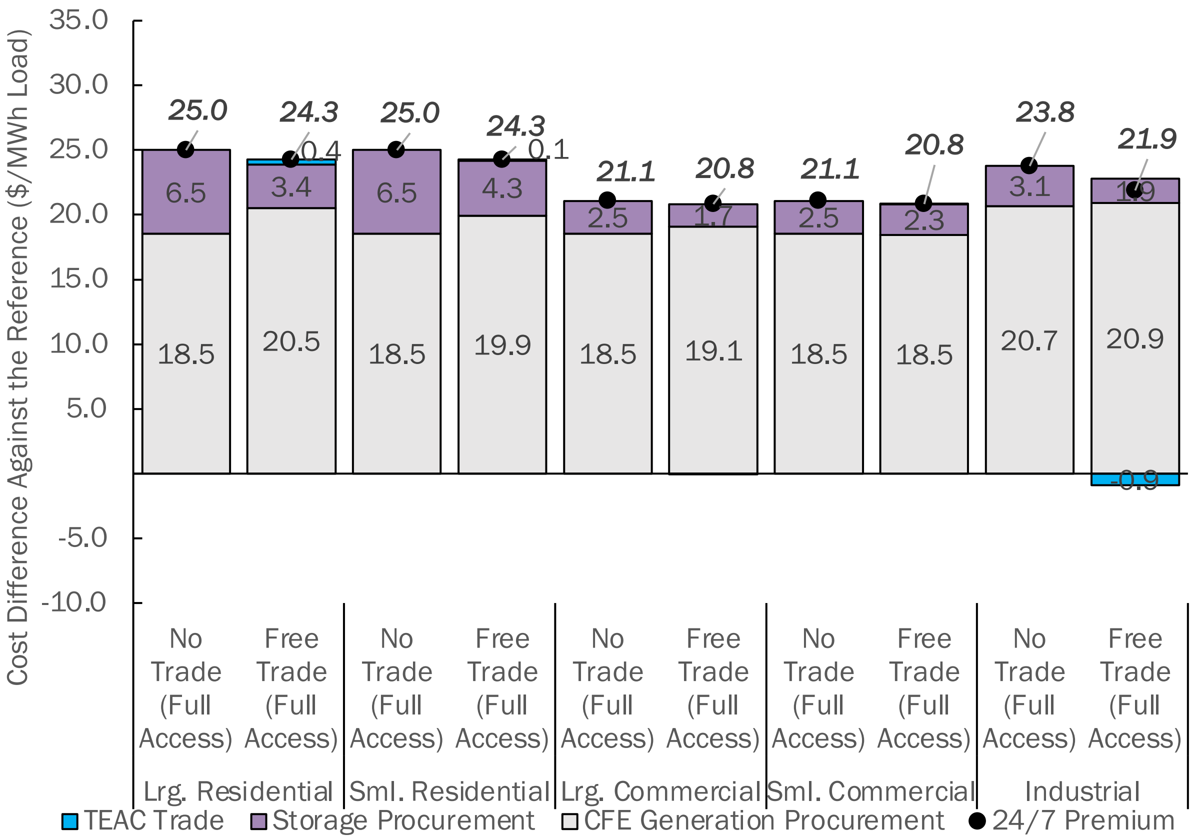
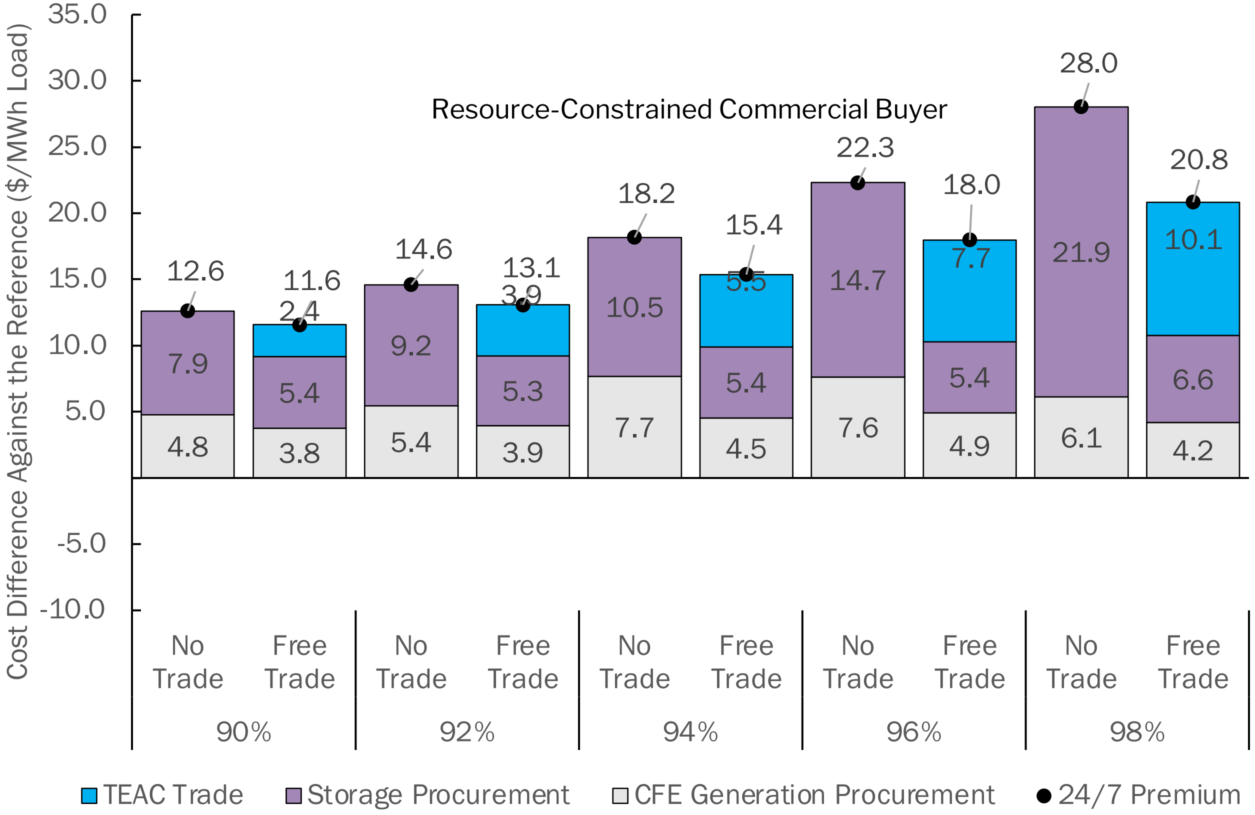


Figure A-6: Cost premium of 24/7 for five modeled California participants, CFE score target = 98%, if small buyers also have access to the full spectrum of CFE technologies. It is noteworthy that, compared to Figure A-5, the efficiency improvement of T-EAC Exchange is almost gone, reinforcing our conclusion that the primary source of T-EAC's cost savings is that it increases "accessibility".

Appendix: The higher the CFE target, the higher the benefit of T-EAC trading



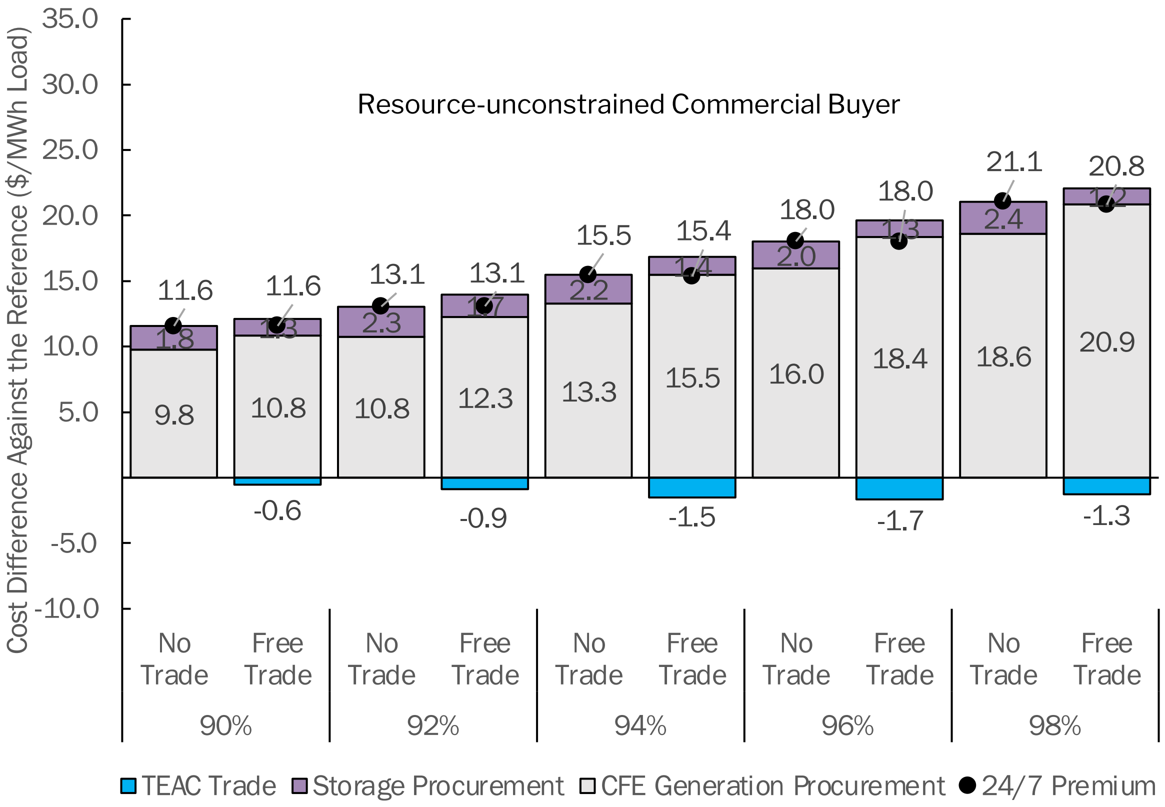


Figure A-7: Cost premium of 24/7 for resource-constrained commercial buyers (left) and commercial buyers with full access to the technologies (right). It is clear that the higher the target, the higher benefit a T-EAC exchange can provide to resource-constrained participants. The cost savings of T-EAC Exchange to buyers with full access to technologies are negligible. Increasing CFE score target also introduces higher CFE injection into the system, lowering other payments of these buyers by a range from -$0.7-$1.0/MWh. However, these impacts are almost the same for all buyers, with and without trading, so they are not shown in the figure.

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

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