Progress and Challenges in Changing California's Electricity Supply Mix

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Two Major Challenges

- Transition from vertically-integrated geographic monopoly regime to wholesale market regime started in 1998 in California
  - Historically, vertically-integrated geographic monopoly was responsible for all generation, transmission, distribution, and retail sales of electricity in service territory
    - Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electric
- Significant intermittent renewable resources implies paradigm shift in market and system operation
  - Historically, system operators forecasted demand and adjusted (dispatched) supply, primarily thermal generation resources
  - Intermittent renewables and new sources of flexible demand (such as electric vehicles) implies with operators increasingly “forecasting” supply and “dispatching” demand

Vertically Integrated Monopoly

In vertically-integrated geographic monopoly regime, single entity (utility) is responsible for ensuring that demand is met under all possible future system conditions

- Regulator penalizes monopoly for supply shortfalls

In wholesale market regime no single entity is responsible for ensuring system demand is met under all possible system conditions

- Independent System Operator (ISO) can only operate market with resources offered into market
- Generation unit owners can only supply energy from the generation units they control
- Retailers can only purchase the energy that generation unit owners supply to wholesale market

Unique feature of electricity—Customer only gets reliable supply of electricity with desired *voltage and frequency* if other customers in distribution grid do too

- Intermittent supply and transmission network constraints makes this extremely challenging in wholesale market regime

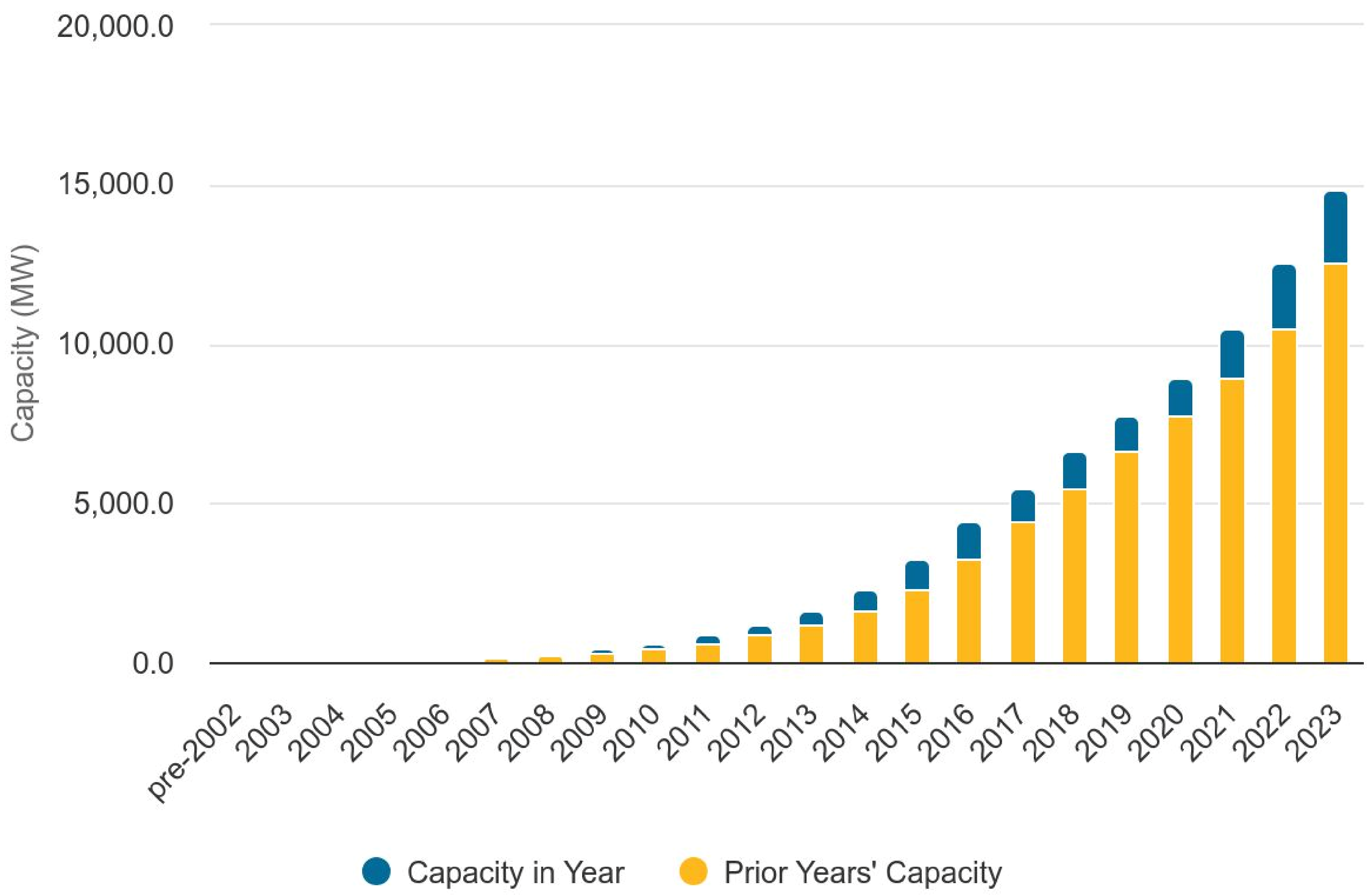
Large Shares of Renewables

- Paradigm shift in market and system operation primarily because of three features of renewable resources
  - Electricity must be produced where underlying resource—wind, solar, and water—exists
    - Cannot move raw energy, like natural gas, coal, and fuel oil, and produce electricity near load center
  - Electricity can only be produced when underlying renewable resource is available
    - Intermittent generation resources are not dispatchable
  - Hourly output of intermittent resources highly contemporaneously correlated across locations
    - Wolak, Frank A. "Level versus variability trade-offs in wind and solar generation investments: The case of California." *The Energy Journal* 37, no. 2_suppl (2016): 1-36.

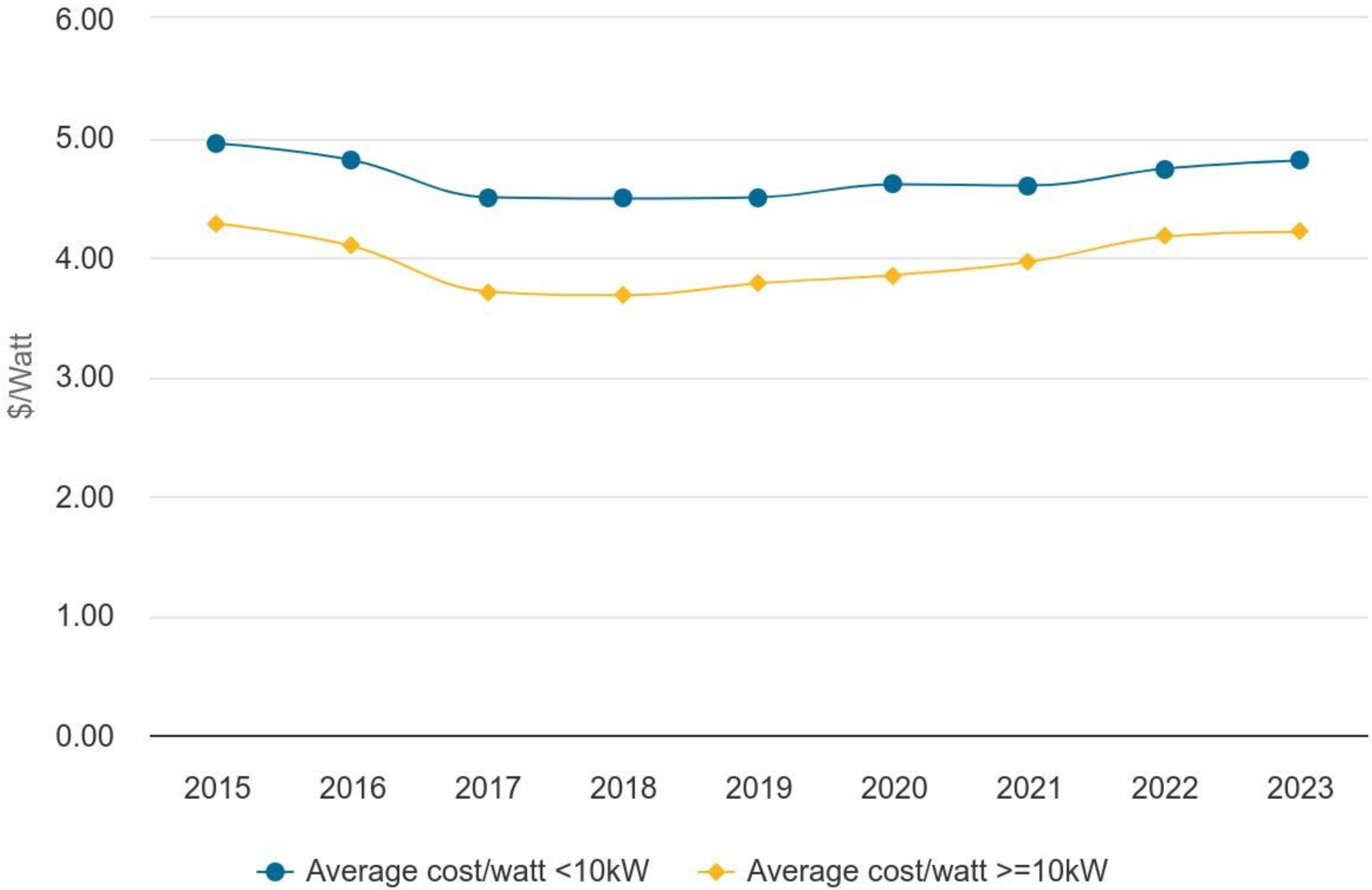
CA’s Clean Energy Goals

- California Solar Initiative (CSI) provided $2.167 billion to support to installing solar PV capacity in local distribution network
    - On-site residential, commercial, educational solar PV capacity
    - Distributed Generation (DG) capacity typically installed behind customer’s meter
- California has 33% Renewables Portfolio Standard (RPS) by 2020 and 60% RPS by 2030
    - RPS percentage of annual retail energy consumption (net of behind the meter DG consumption) much come from qualified renewables resources
- California has 100% clean energy goal by 2045
    - Renewable and zero-carbon energy resources supply 100 percent of retail sales (net of behind the meter DG consumption)

CA Distributed Solar PV Capacity



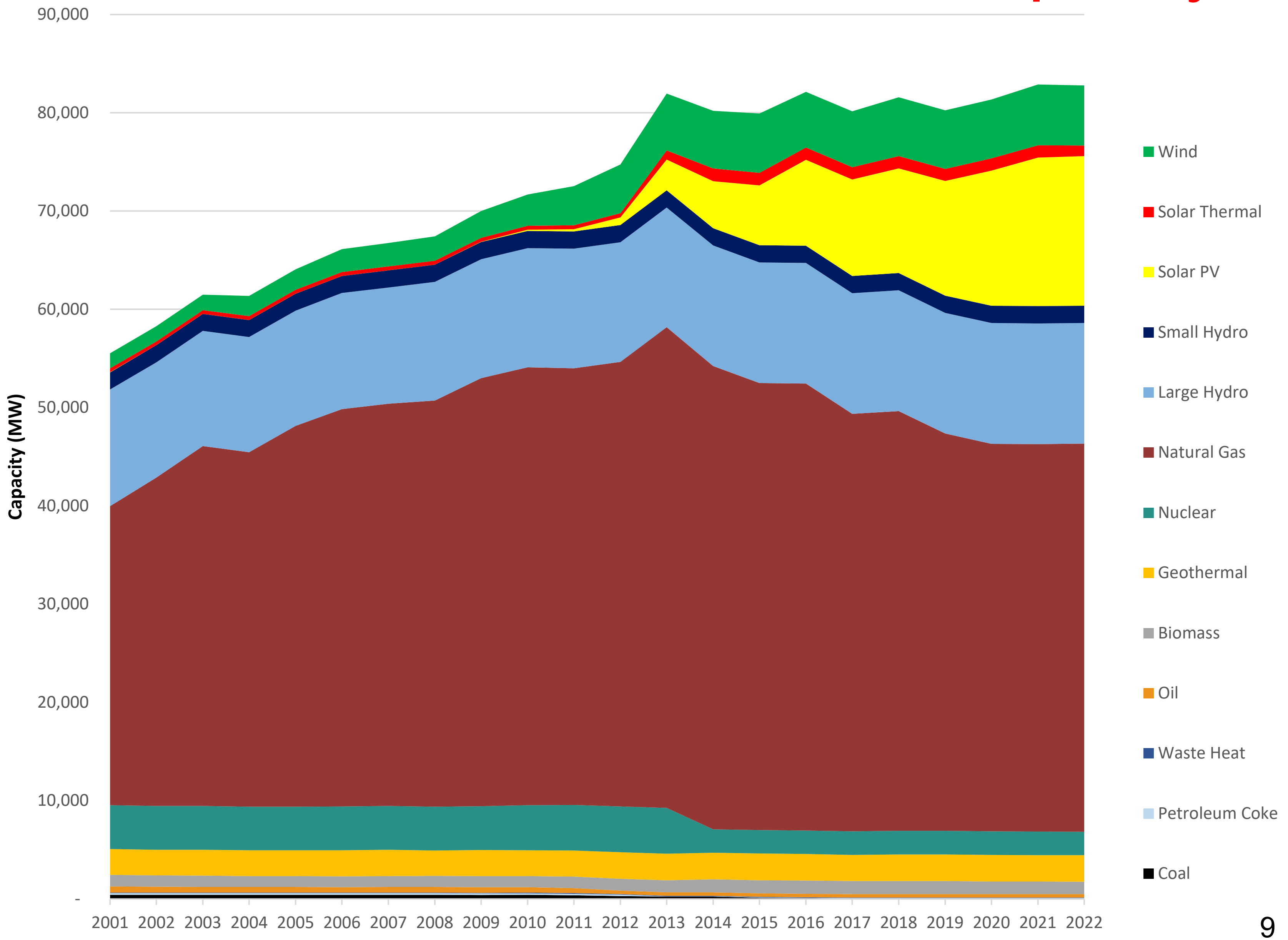
CA Distributed Solar PV Cost per Watt



Share of CA Electricity Demand Accounted for by Distributed Solar

- Impossible to know this number precisely because DG solar systems are typically installed behind the customer's meter in CA
  - Can only measure customer's net consumption
    - Actual consumption less rooftop solar system production
- California's annual *metered generation* from utility-scale sources in 2022 was 287,220 gigawatt-hours (GWh)
  - Includes 83,960 GWh of imports from neighboring states
- Using a 0.16 average fleetwide capacity factor for rooftop solar applied to 15,000 MW of rooftop solar systems yields 21,024 GWh annually
  - Roughly 7.5 percent of metered generation utility-scale sources

CA's Grid Scale Generation Capacity



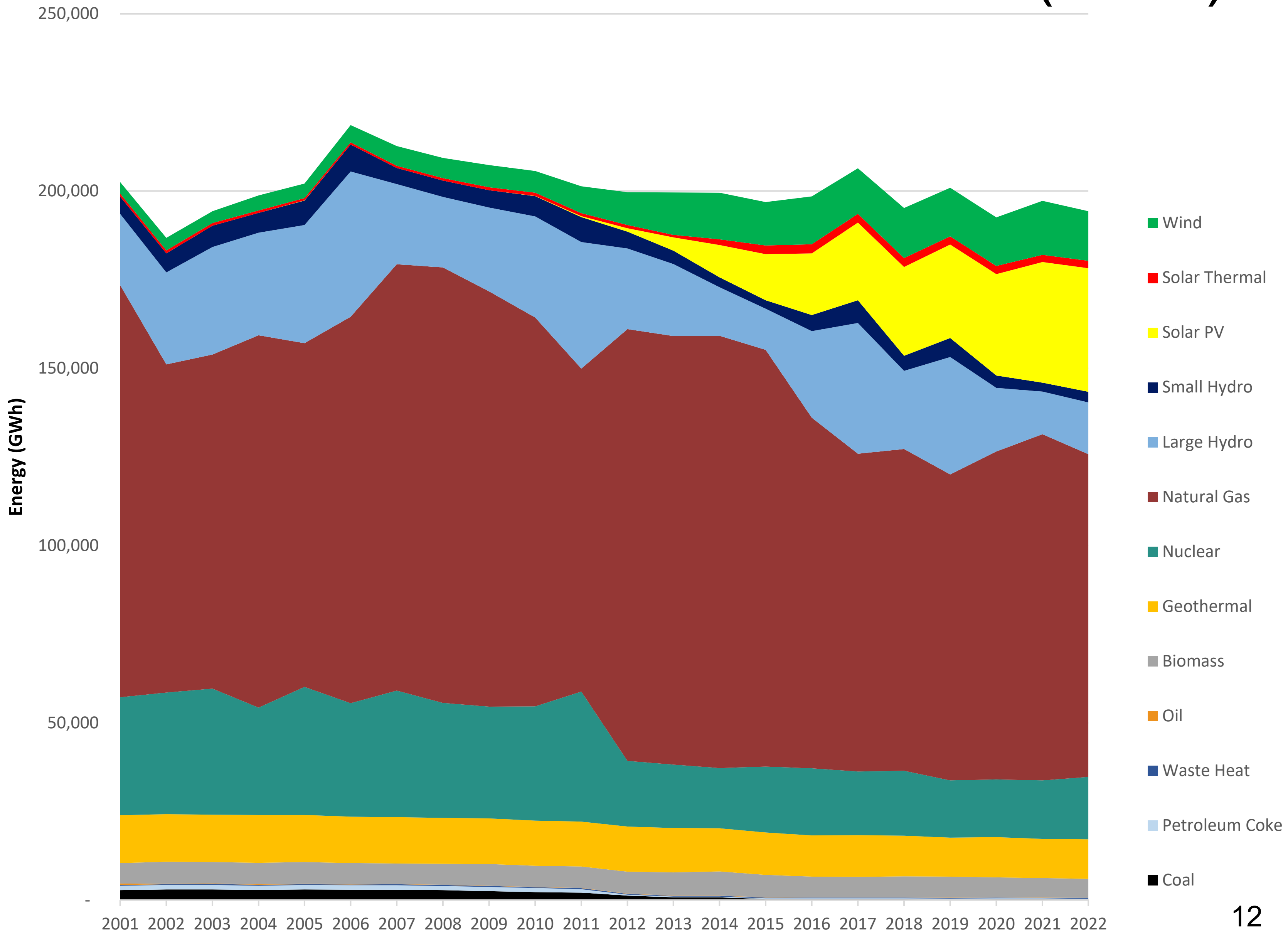
Generation Capacity Change 2013 to 2022

- Between 2013, first of year of the 33% RPS compliance period, and 2022 California reduced
  - Natural gas fired-generation capacity by 9,500 MW
  - Nuclear generation capacity by 2,250 MW—San Onofre Nuclear Generation Station (SONGS) was retired
  - Total reduction of ~11,750 MW in dispatchable capacity
- Dispatchable generation replaced with an additional
  - 12,000 MW of solar photovoltaic generation capacity
  - 150 MW solar thermal generation capacity
  - 330 MW wind generation capacity
  - Total increase of ~12,480 MW in intermittent capacity

Generation Unit Capacity Factors

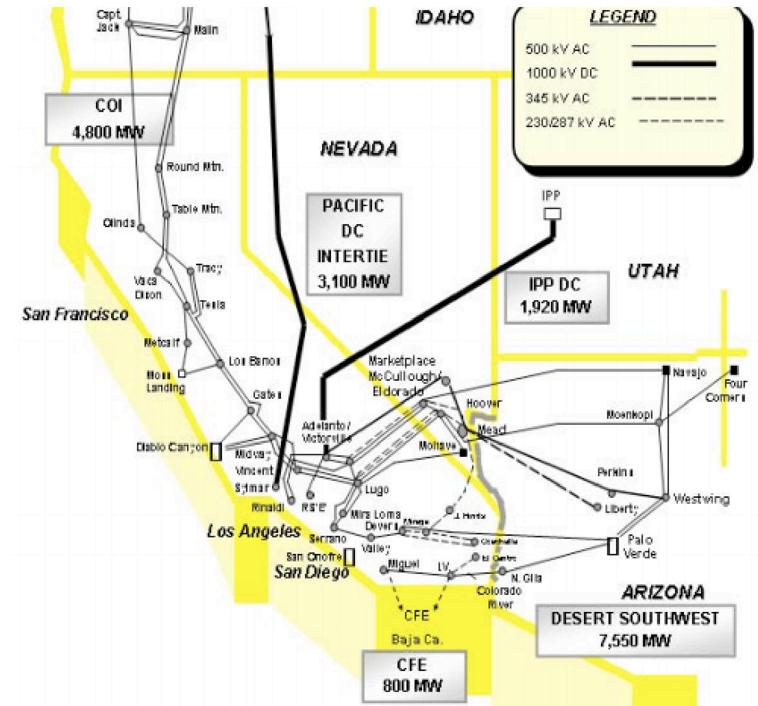
- Capacity Factor = (Annual Generation in Megawatt-hours (MWh))/(Capacity (in MW) x 8760 Hours)
  - Average annual capacity factor of wind units in California is between ~0.20 to ~0.30
  - Average annual capacity factor of solar PV units in California is between ~0.20 to ~0.30
- Capacity factor of Diablo Canyon nuclear unit in California is between 0.90 and 0.95
  - Unit size is ~1140 MW
- Capacity factors for combined cycle natural gas and coal units can be as high as 0.90
  - Unit sizes in the range of 300 to 500 MW
- Conclusion--Much less ability to produce grid scale energy in California in 2013 versus 2022 due to reduction in dispatchable generation capacity in state

CA's Annual Grid Scale Generation (GWh)

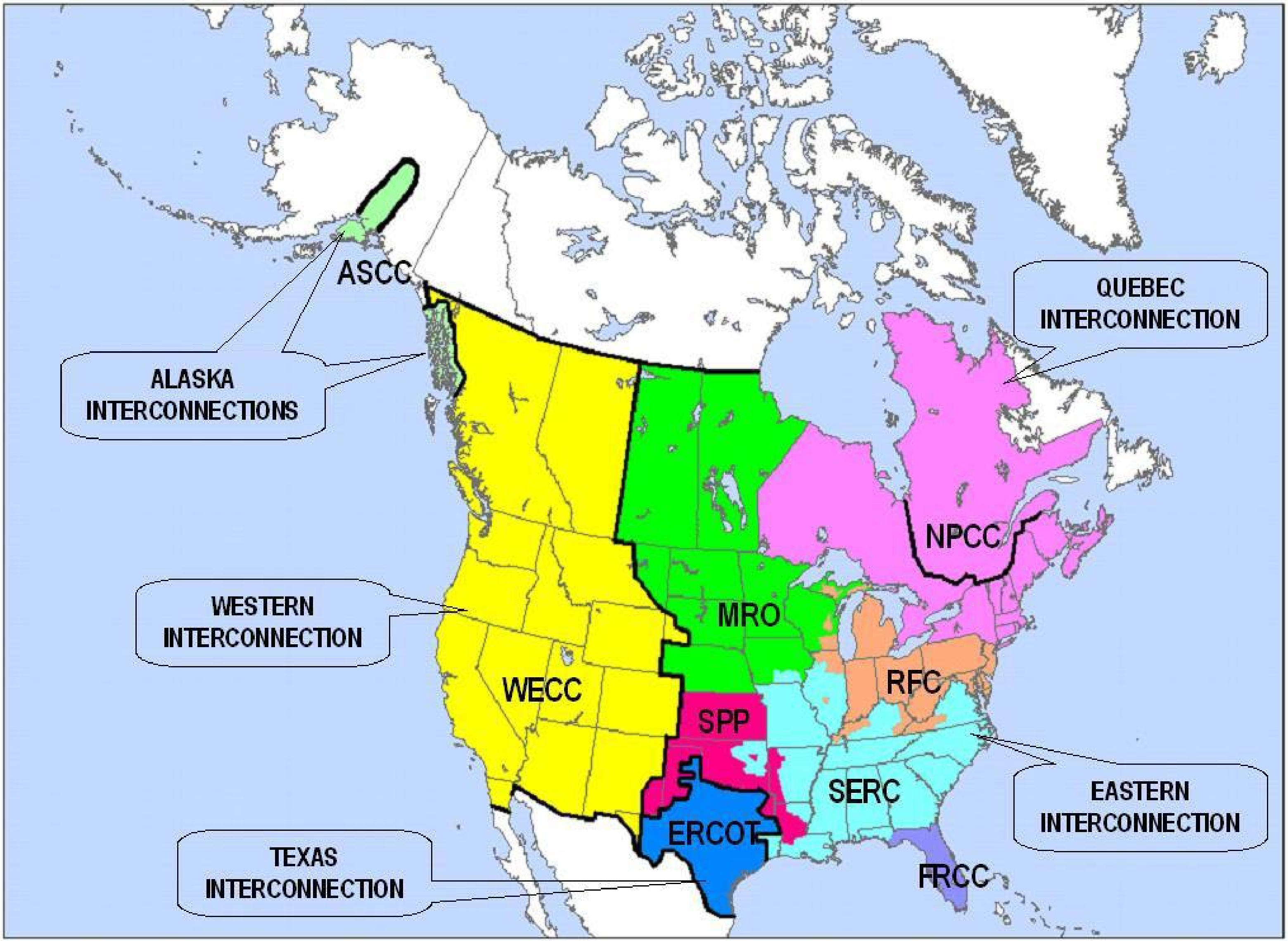


California's Import Dependence

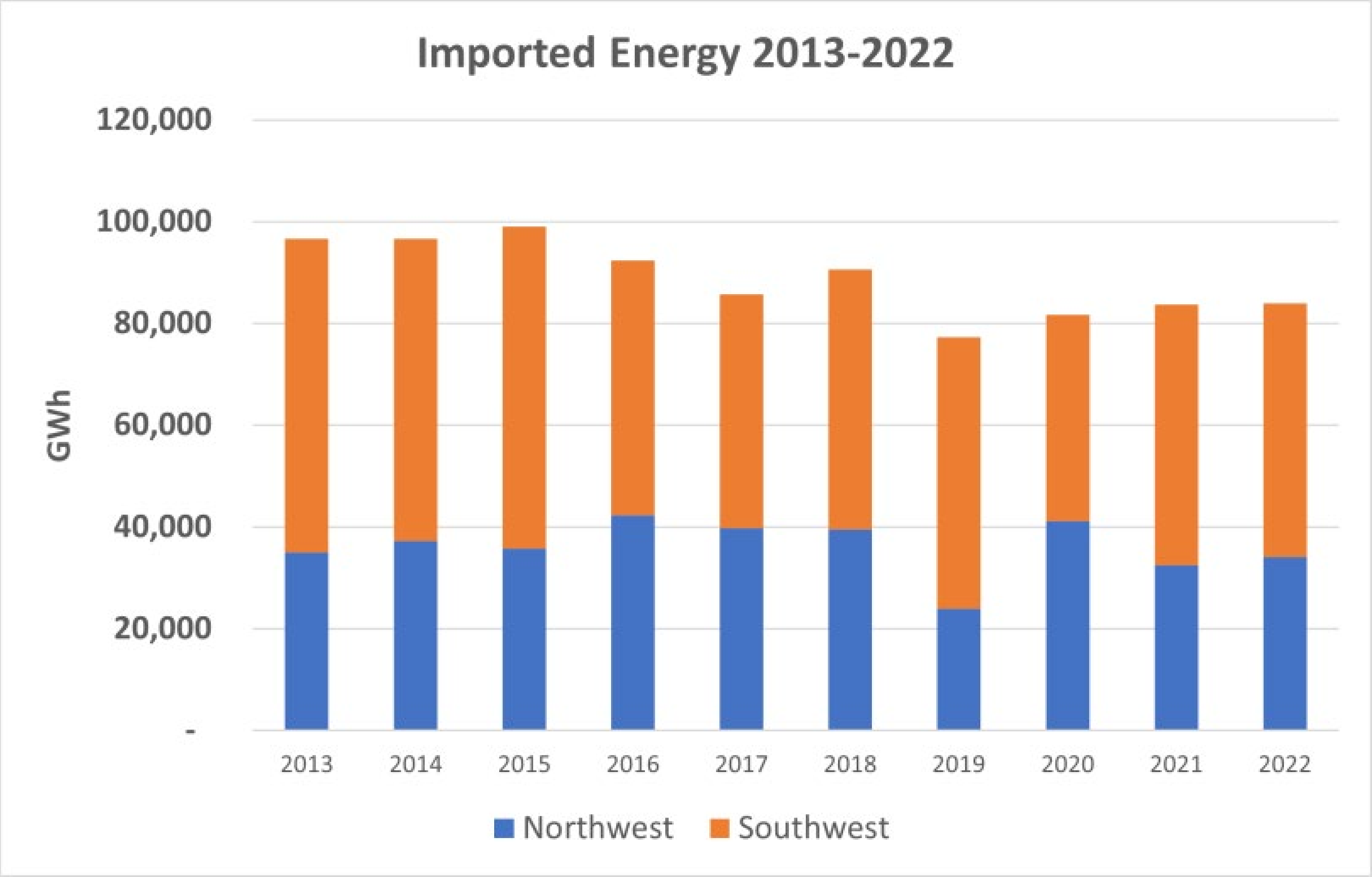
- More than 18,000 MW of transfer capacity between California and neighboring states
    - Significant import potential
- Neighboring states have priority access to electricity produced by generation units owned by utilities in their states
    - Implication: When temperatures in the western US are uniformly high, California may not receive sufficient imports without advance purchases of energy
- California is part of Western Electricity Coordinating Council (WECC) that comprises all states and Canadian provinces west of Continental Divide



North America's Interconnections



CA’s Net Electricity Imports (GWh)



Consumer Cost of CA Policies

- According to US Department of Energy, Energy Information Administration (DOE/EIA)
  - Average retail prices in California in 2022 (P(retail))
    - Residential 25.64 cents/KWh
    - Overall 22.33 cents/KWh
  - Average retail prices in Texas in 2022 (P(retail))
    - Residential 13.76 cents/KWh
    - Overall 10.16 cents/KWh
- Average retail prices in California are more than double those in Texas
  - Both states obtain roughly the same fraction of electricity consumption (~25 percent) from grid scale wind and solar resources
  - Both states produce the majority of dispatchable energy from natural gas fired generation units and consequently have very similar annual average **short-term wholesale prices**

It’s Not About Short-Term Prices

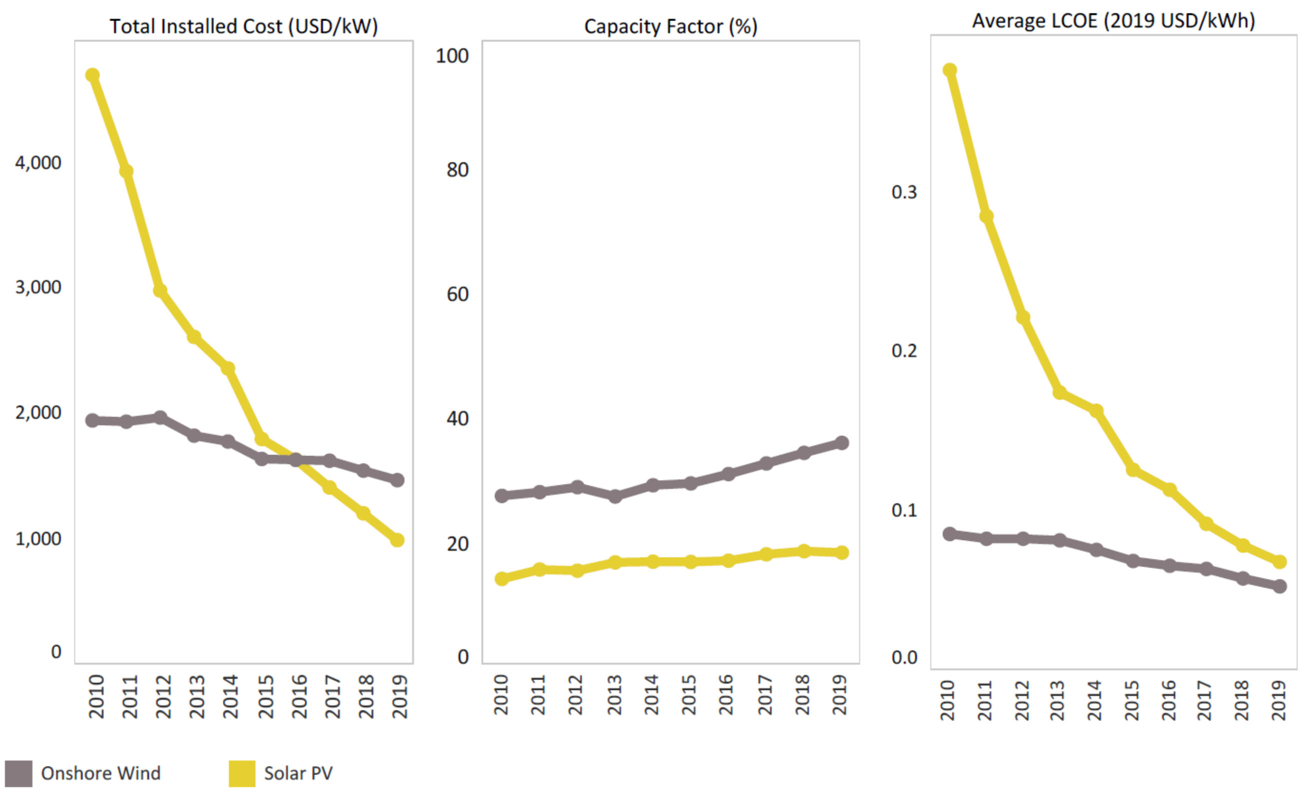
- P(retail) = P(Forward) + P(Net Short-Term + A/S) + P(Transmission) + P(Distribution) + Other
- Difference in average retail prices between Texas and California primarily due to two factors
  - P(Forward) in each market determined by when these purchases were made and for investments in generation technologies
    - Recall that P(Net Short-Term + A/S) very similar in each market
  - “Other” = Additional costs paid by retail electricity consumers
    - Other = Retailing margin, energy efficiency programs, above-market cost of Renewables Portfolio Standard (RPS) energy, low-income energy programs, distributed generation (rooftop solar) support and grid-scale and distributed storage support mechanisms
- These two factors are major reasons why P(retail) in California is much higher than that in Texas
  - Impossible to determine precisely how much is due to P(forward) differences and “Other “cost differences
    - Note that “Other” costs are largely due to state policies

Forward Energy Cost Differences

Until very recently grid scale solar photovoltaic generation capacity was significantly more expensive on a $/kW installed basis than grid scale wind generation capacity

- Above-market costs of renewable energy in California (Other costs) much higher

This also explains California's early investment in wind generation capacity



Note: All LCOE values are calculated based on project level data for total installed costs and capacity factors from the IRENA Renewable Cost Database, with other assumptions necessary for LCOE detailed in the source link below, notably an assumption of a weighted-average cost of capital of 7.5% real in the OECD and China and 10% elsewhere.

Source: IRENA (2020), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi
https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019

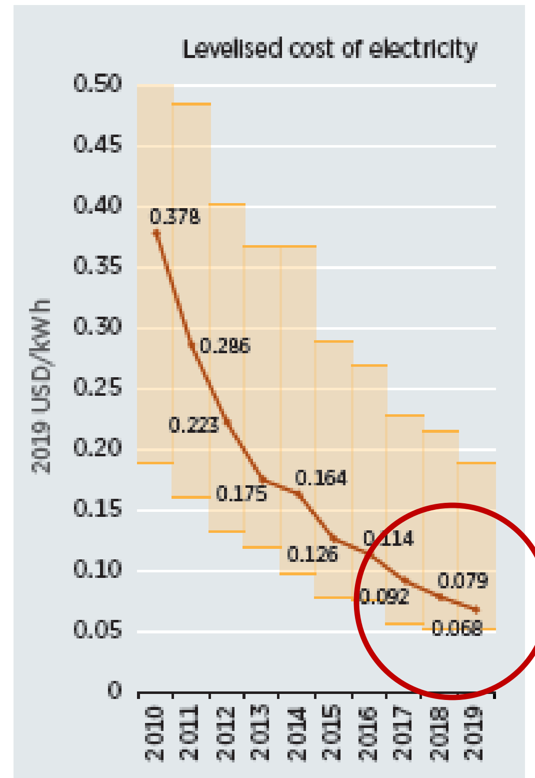
Distributed Solar versus Utility Scale Solar Levelized Cost of Energy (LCOE)

Distributed Solar

Sector	Market	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
		2019 USD/kWh									
Residential	Australia	0.319	0.258	0.187	0.163	0.154	0.106	0.098	0.089	0.082	0.075
	Brazil				0.261	0.244	0.232	0.187	0.155	0.125	0.111
	China			0.162	0.144	0.139	0.107	0.103	0.096	0.079	0.067
	France		0.712	0.516	0.435	0.330	0.201	0.188	0.174	0.161	0.149
	Germany	0.301	0.261	0.204	0.185	0.174	0.144	0.141	0.138	0.144	0.138
	India				0.132	0.128	0.093	0.085	0.074	0.067	0.063
	Italy	0.405	0.360	0.248	0.228	0.162	0.137	0.128	0.121	0.113	0.109
	Japan	0.455	0.450	0.393	0.298	0.250	0.224	0.202	0.188	0.169	0.163
	Malaysia				0.185	0.185	0.161	0.151	0.127	0.109	0.095
	Republic of Korea				0.224	0.225	0.170	0.164	0.141	0.130	0.125
	South Africa				0.200	0.180	0.156	0.148	0.134	0.119	0.102
	Spain				0.181	0.158	0.122	0.116	0.109	0.106	0.104
	Switzerland				0.304	0.274	0.259	0.246	0.225	0.205	0.188
	Thailand				0.250	0.201	0.183	0.179	0.159	0.137	0.106
	United Kingdom				0.327	0.342	0.302	0.274	0.276	0.268	0.265
	California (US)	0.306	0.290	0.253	0.222	0.210	0.213	0.207	0.187	0.179	0.171
	Other US states	0.304	0.280	0.230	0.202	0.203	0.202	0.178	0.162	0.157	0.155

Source: IRENA, Renewable Power Generation Costs in 2020

Utility-Scale Solar



Utility Scale Solar has LCOE that is ~1/3 of LCOE of Distributed Solar

Utility Scale LCOE Advantage Due to Economies to Scale, Location Choice, Tracking

California Solar Initiative (CSI)

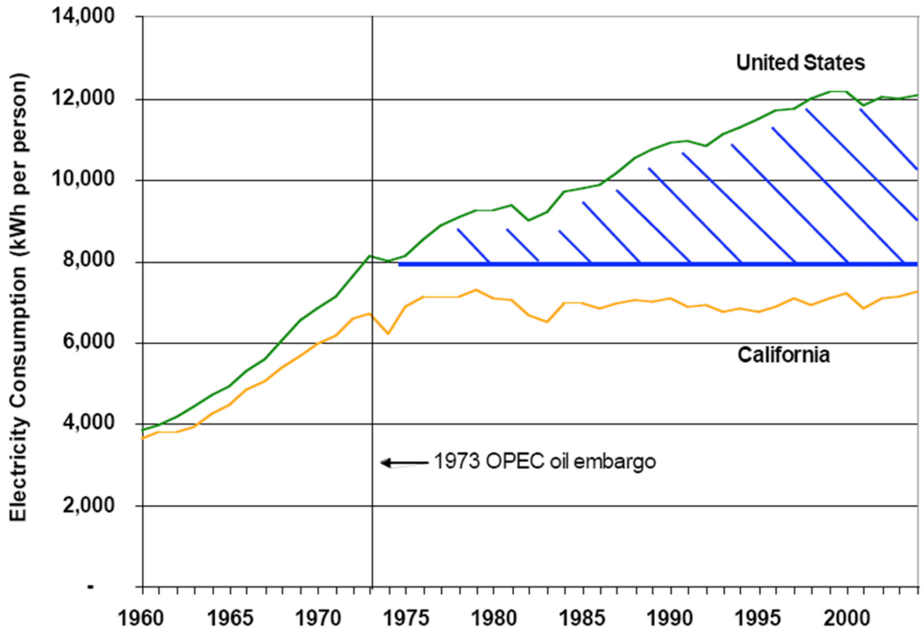
- Significant rooftop (distributed) solar capacity in a geographic region requires upgrades to local distribution network
- Between 2004 and 2020 average distribution network prices for three large investor-owned utilities in California more than doubled
  - ~4 cents/KWh to ~8 cents/KWh
- P(Distribution) increased faster in California regions with greater geographic density of rooftop solar installations
  - Wolak, F.A. (2020) "Evidence from California on the Economic Impact of Inefficient Distribution Network Pricing and a Framework for a Proposed Solution" (on web-site)
- Texas has little distributed solar capacity, so few, if any, distribution network upgrades required for this reason
  - P(Distribution) unaffected by this factor in ERCOT

California Storage Mandate

- In October 2013, the CPUC adopted a 1,325 MW energy storage procurement mandate for the state's three investor-owned utilities by 2024
  - Divided between transmission connected, distribution level and customer-sited storage
  - Funded by surcharge on customer bills
- Texas does not have a storage mandate
  - High offer cap on wholesale market and volatile short-term prices helps make storage investments economic without ratepayer support
- Increases "Other" cost in California relative to Texas

California's Energy Efficiency Programs

- More then $1 billion annually to support energy efficiency investments in California
  - Financed by higher retail prices
- Texas has a much smaller energy efficiency programs
- Increases "Other" cost in California versus Texas



The "Rosenfeld Diagram"

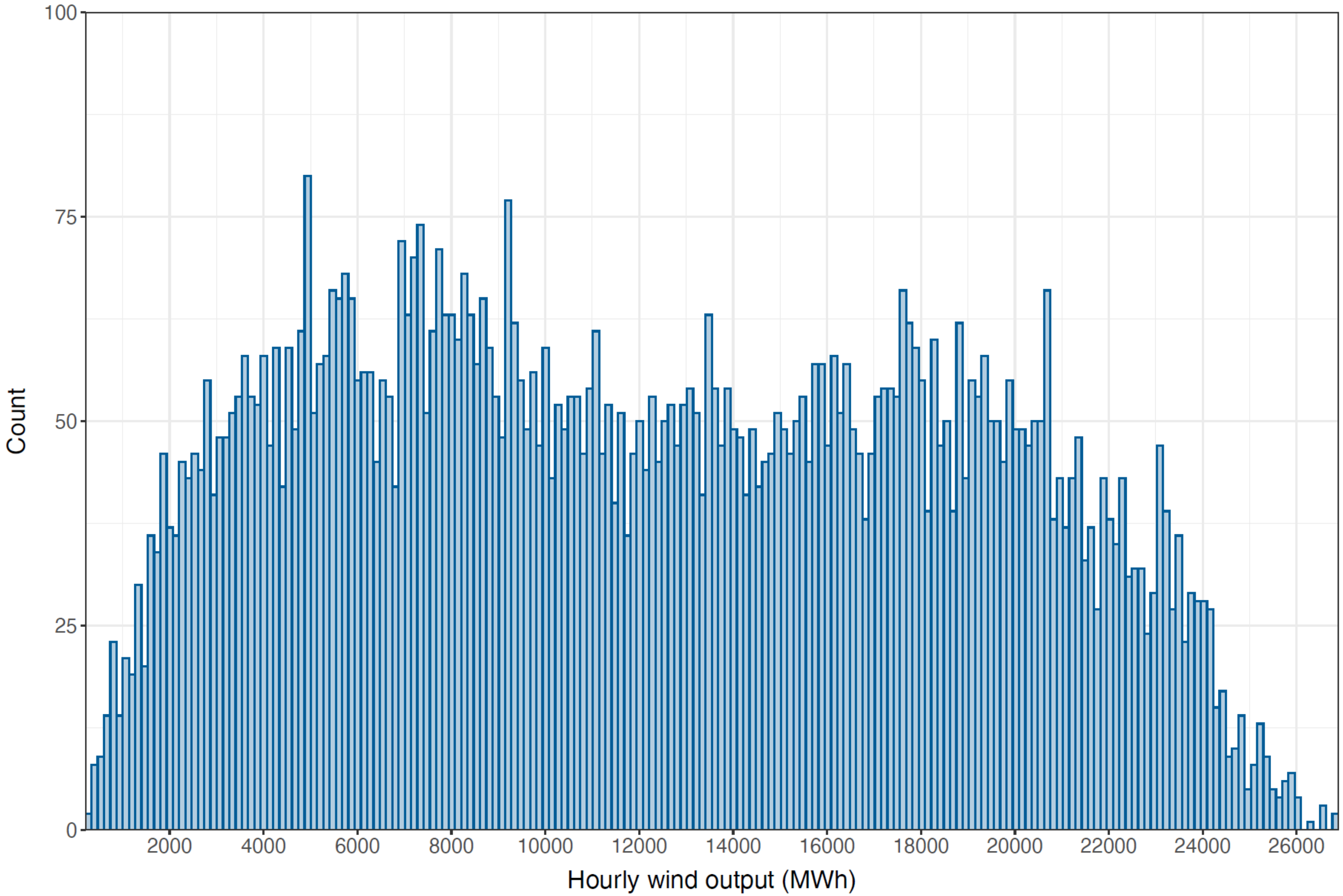
Summary of Reasons for Retail Price Differences

- California was early adopter of renewables, so had much larger above-market costs of renewables than Texas
  - Not particularly rich wind resources in California relative to Texas
    - Lower LCOE of wind in ERCOT versus California
      - Higher capacity factor and lower up-front cost in ERCOT versus CA
    - No significant grid scale solar in ERCOT until 2020
    - For more discussion of CAISO versus ERCOT capacity mix
      - Wolak, (2022) "Long-Term Resource Adequacy in Wholesale Electricity Markets with Significant Intermittent Renewables" (on web-site)
  - California focused on solar (larger forward energy costs than TX)
    - Recall role of fixed-price forward contracts in getting renewables built
- CSI provided significant financial support for distributed solar
  - Large "Other costs" that do not exist in Texas
  - Geographically concentrated distributed solar investments requires investments in distribution network—P(Distribution) increases in CA
- California has many state programs supported by retail electricity prices relative to Texas--Higher "Other" costs
  - Energy efficiency programs, low-income energy programs, distributed solar generation (versus grid scale solar) and storage support mechanisms

Benefits of Geography

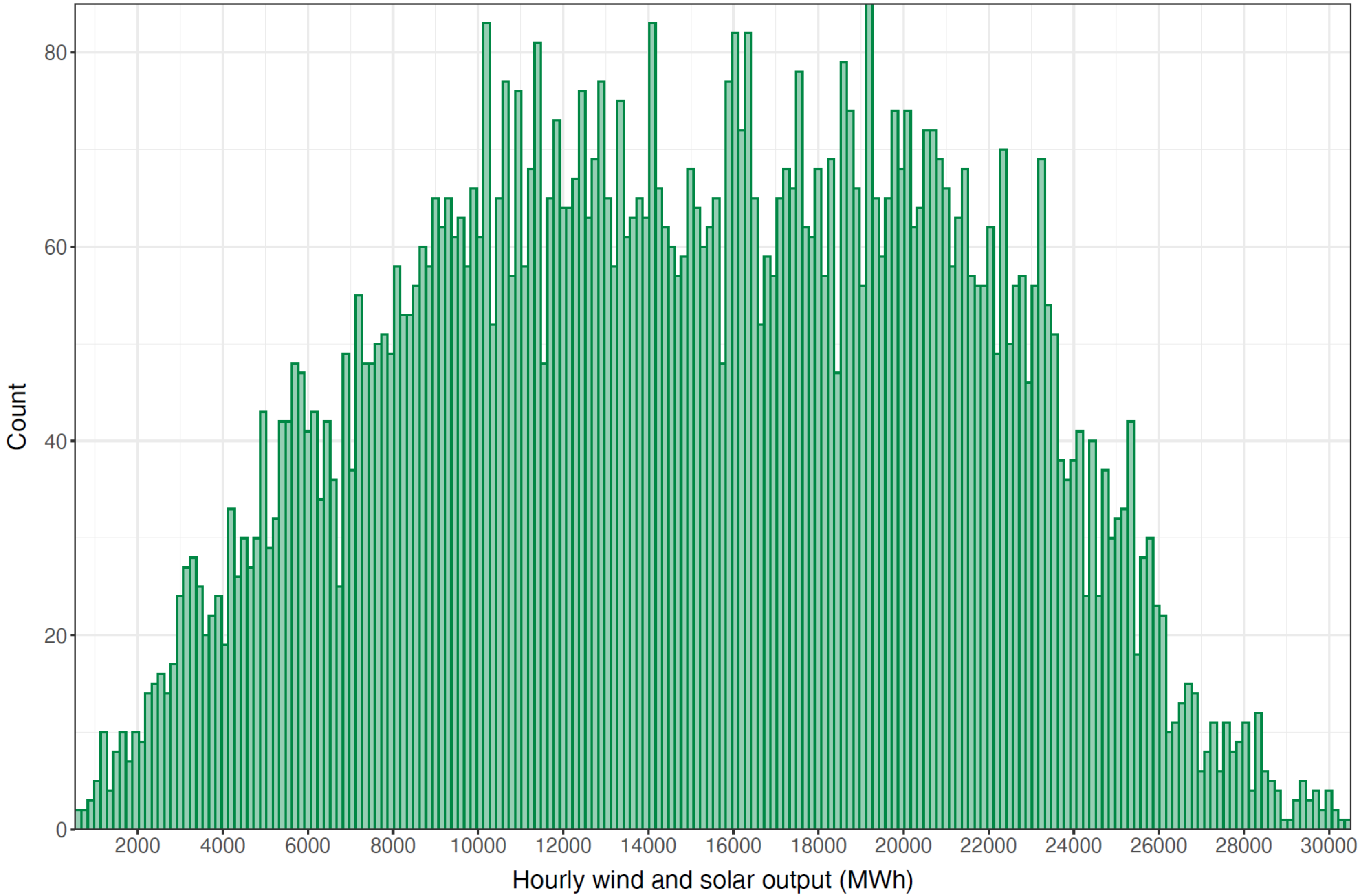
- California is thin state east-west
  - Sunny day in state, high solar output
  - Windy day in state, high wind generation
    - Wolak, Frank A. "Level versus variability trade-offs in wind and solar generation investments: The case of California." *The Energy Journal* 37, no. 2_suppl (2016): 1-36.
- Texas is much wider east-west
  - Almost same distance north-south as east-west
  - West Texas is located in rich wind belt of United States

Histogram of Hourly Wind Output in ERCOT for 2022



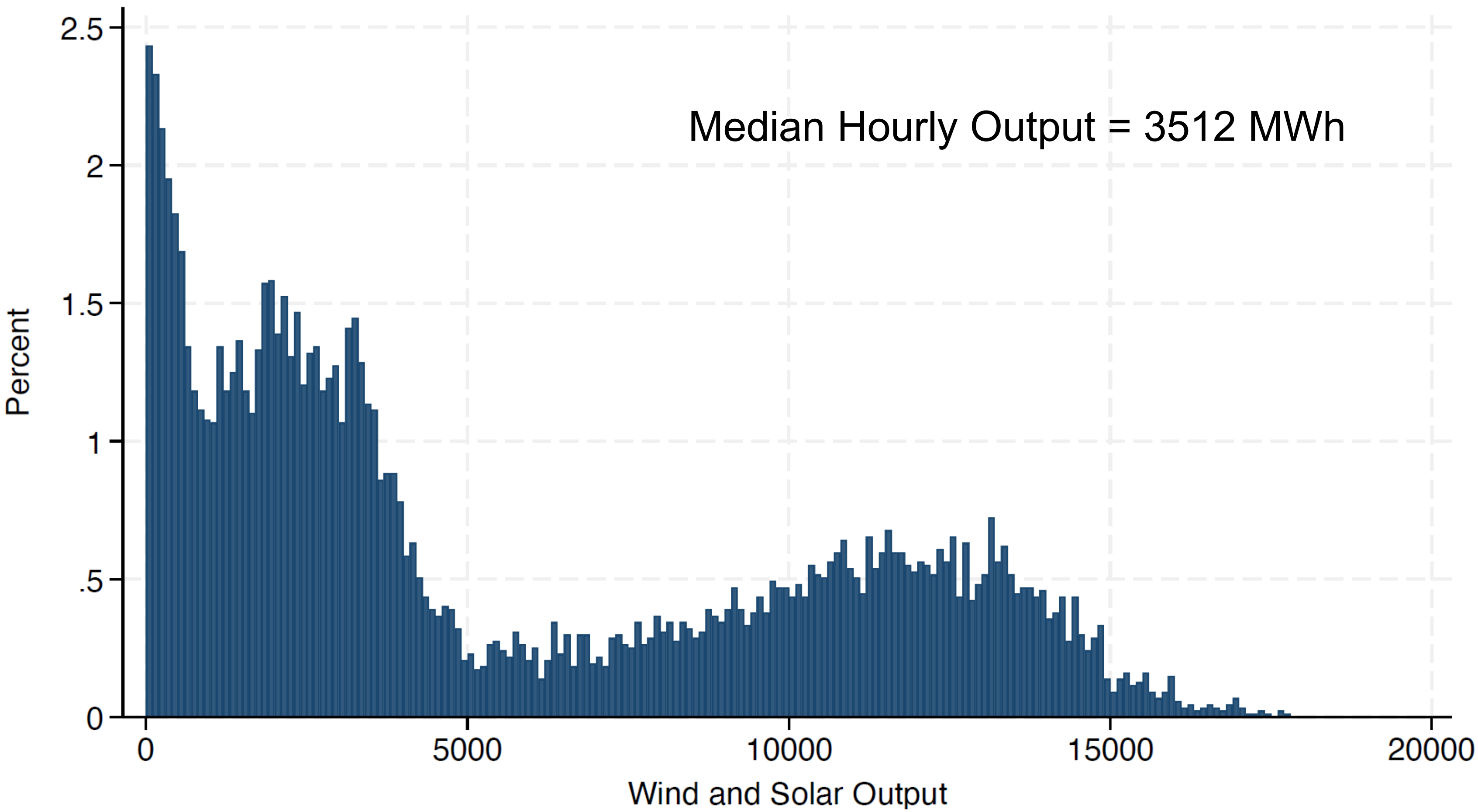
Texas had 37 GW of Wind Capacity in 2022

Hourly Wind and Solar Output in ERCOT for 2022



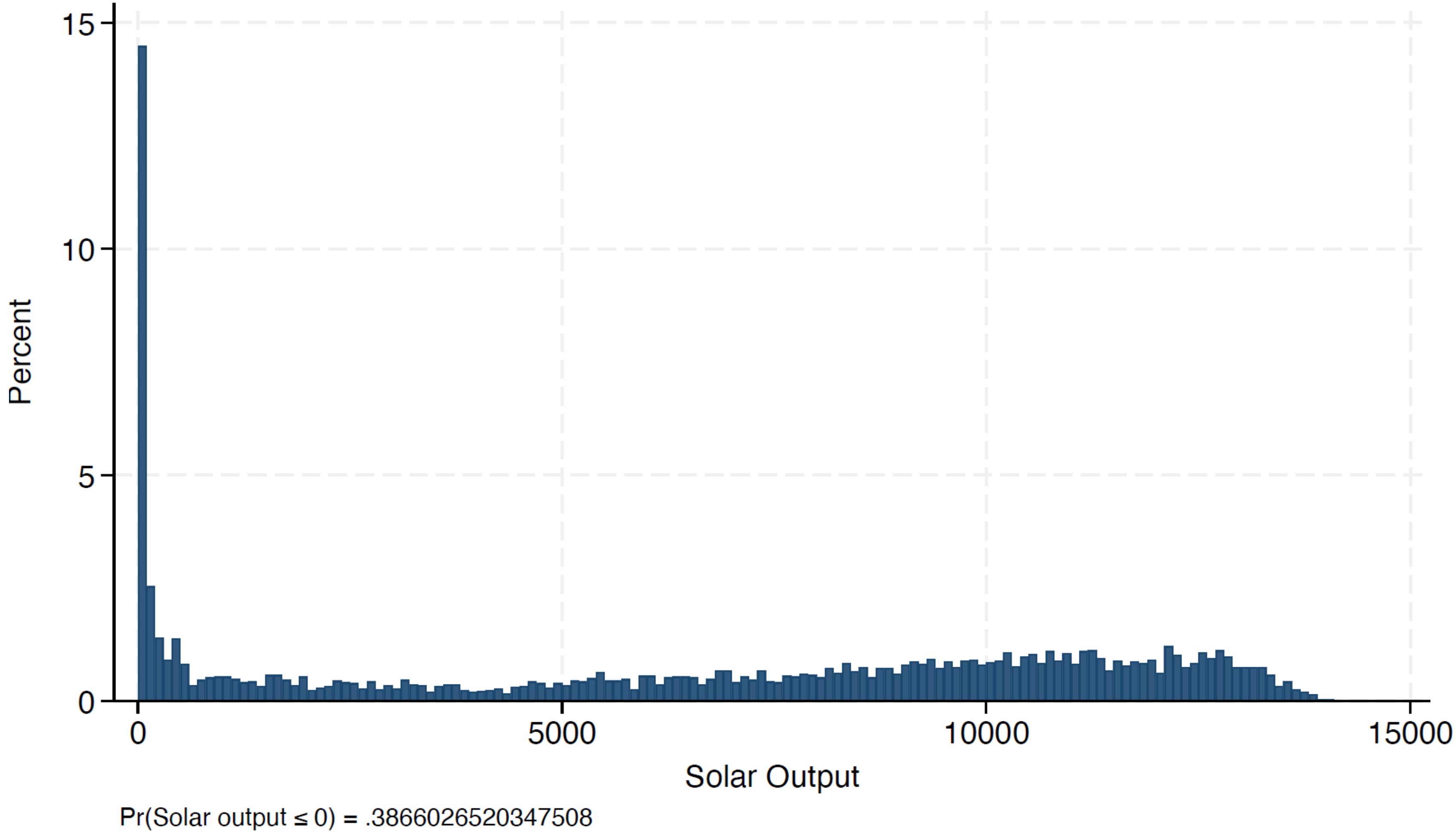
37 GW Wind and 12 GW of Solar PV Capacity in 2022

Histogram of Hourly Solar and Wind Output in California in 2023 (MWh)



~18 GW of Solar PV and ~7 GW of Wind Capacity in 2023

Histogram of Hourly Solar Output in California in 2023 (MWh)



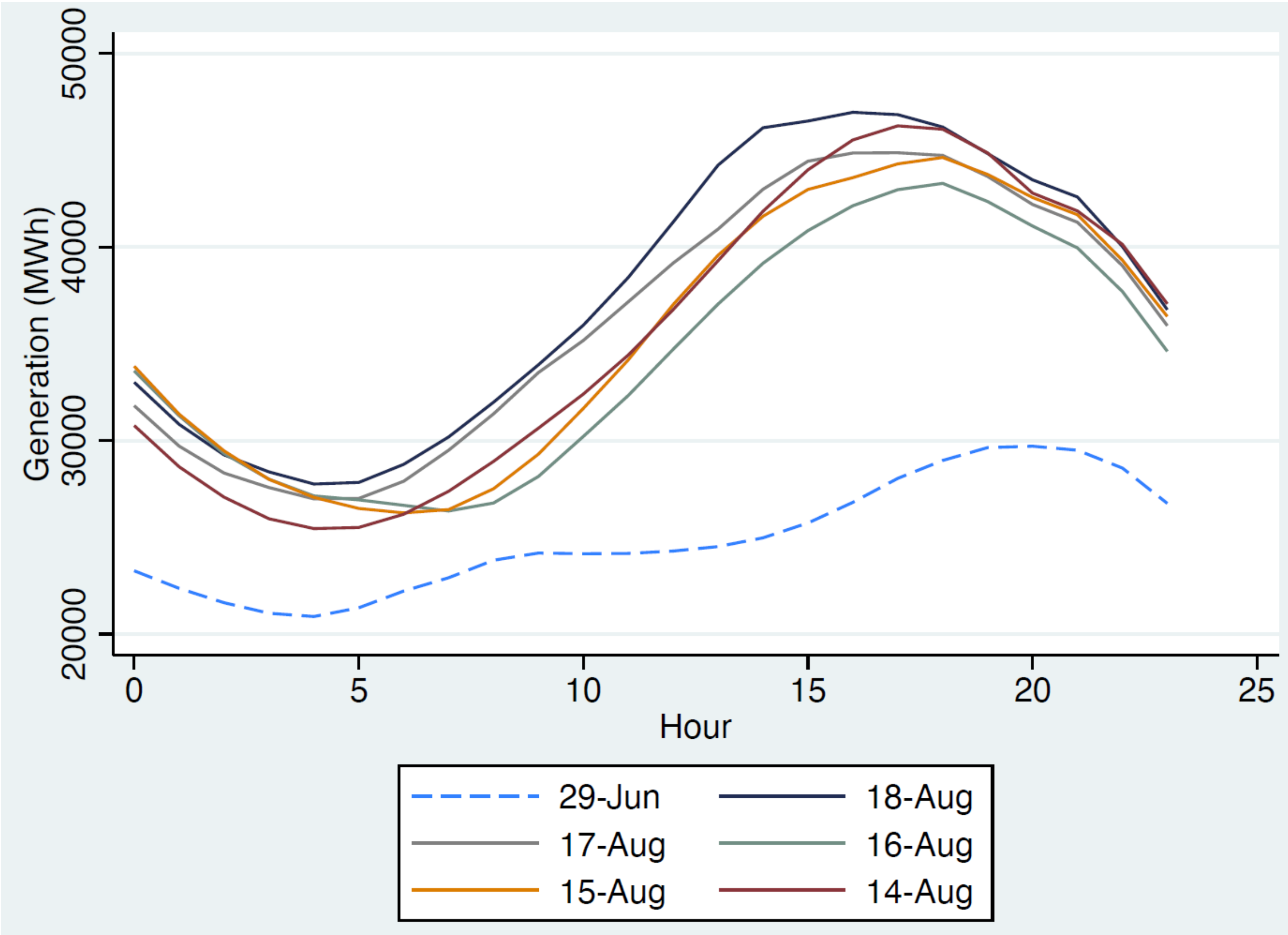
~18 GW of Solar PV in 2023

California's Retail Market Policies

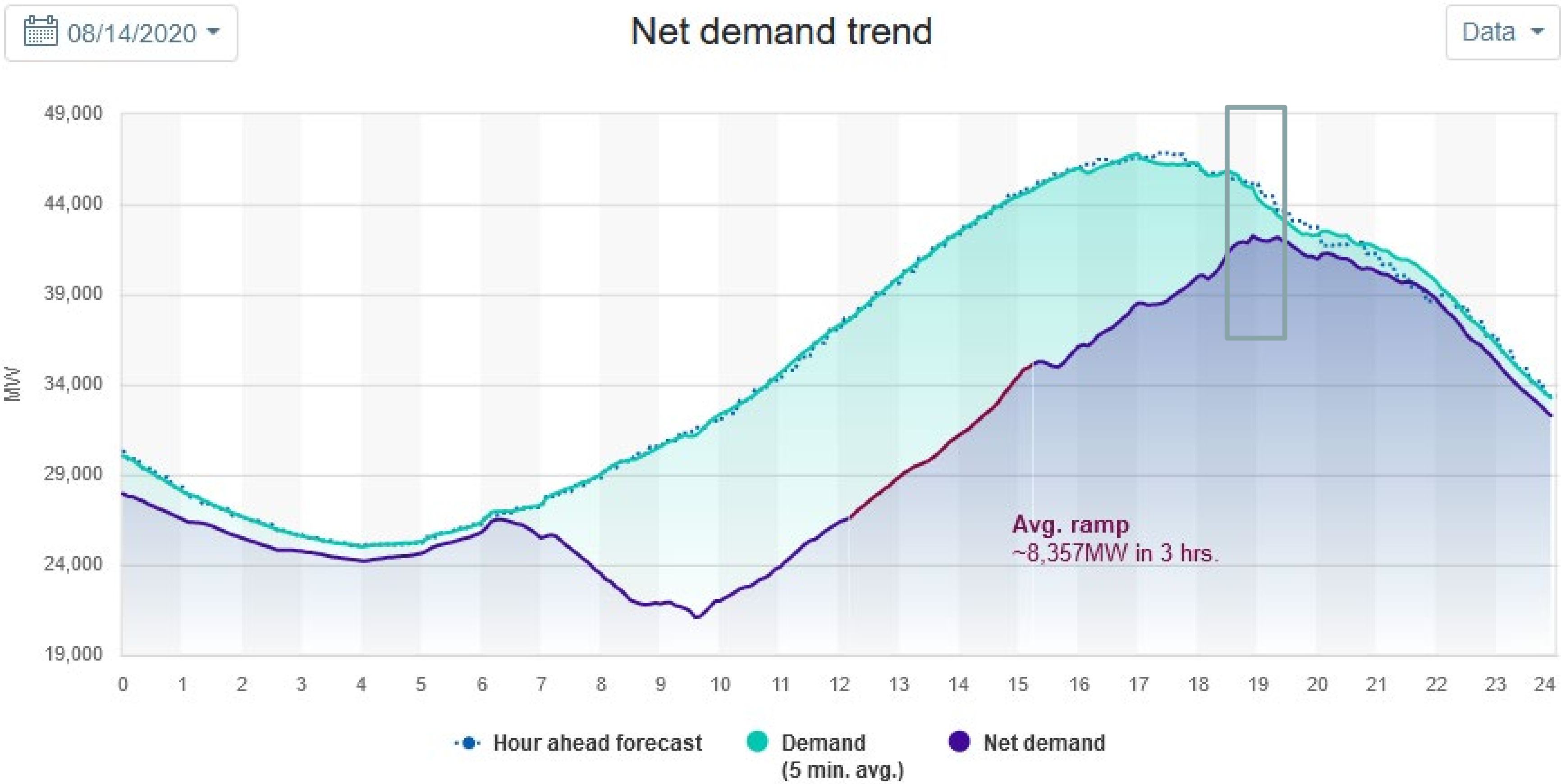
- All customers of three large investor-owned utilities—Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electricity—have interval meters
  - Meter records customer's consumption on a 15-minute basis
- No dynamic retail pricing plans offered for residential customers
  - Dynamic prices vary with real-time system conditions in wholesale market
  - Time-of-use prices are NOT dynamic prices because customer is charged same price during *peak* and *off-peak* periods of day, regardless of real-time price of wholesale electricity
- In regions with increasing share of intermittent renewables, demand must shift across of the day maintain real-time supply and demand balance
  - Andersen, Hansen, Jensen, and Wolak (2019) "Can Incentives to Increase Electricity Use Reduce the Cost of Integrating Renewable Resources?" (on web-site)

How Does California Keep the Lights On: Lessons from Blackouts of August 14-15, 2020

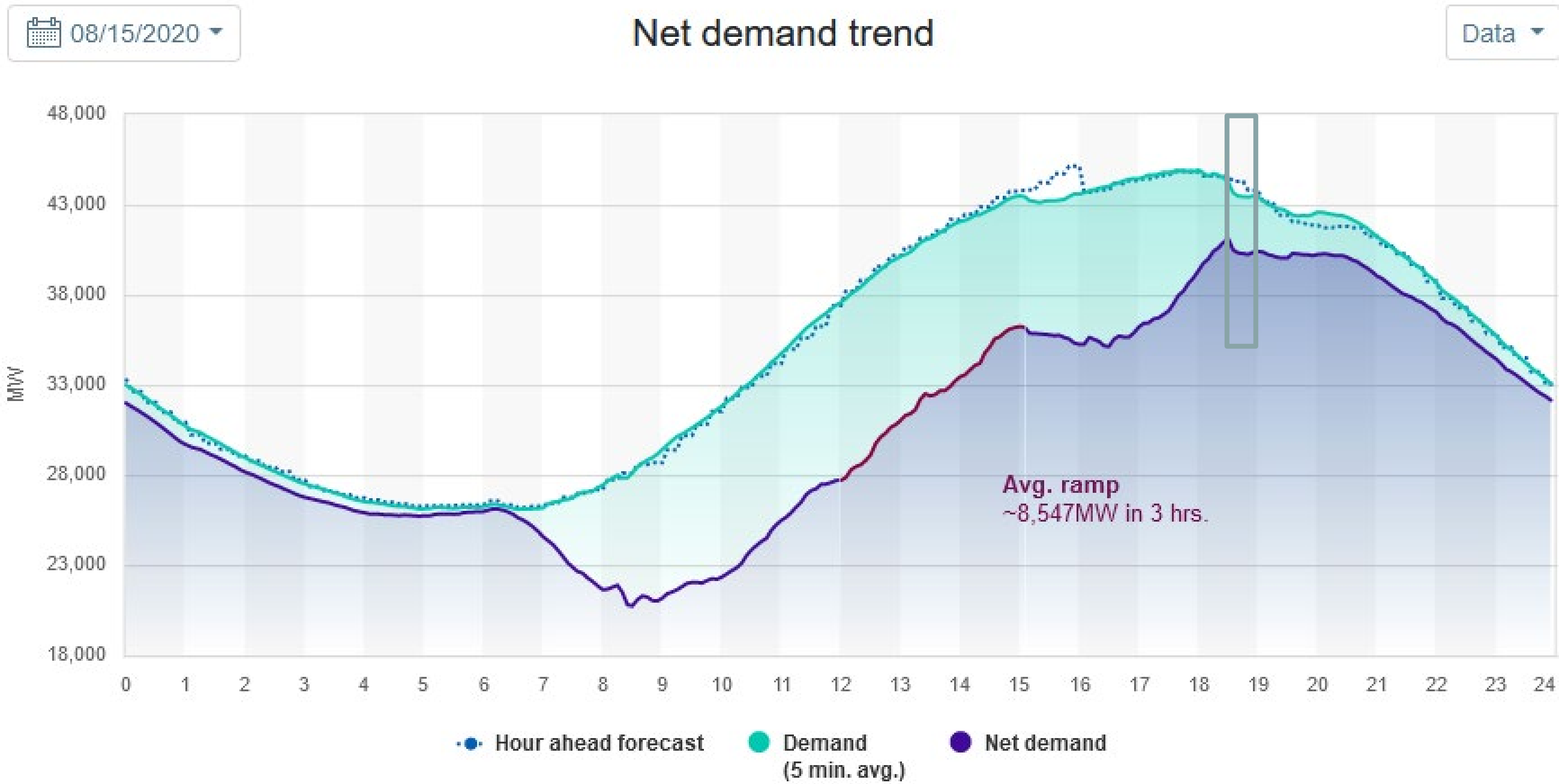
The Rolling Blackouts of 8/14/20-8/15/20 (Hourly Demand in MWh)



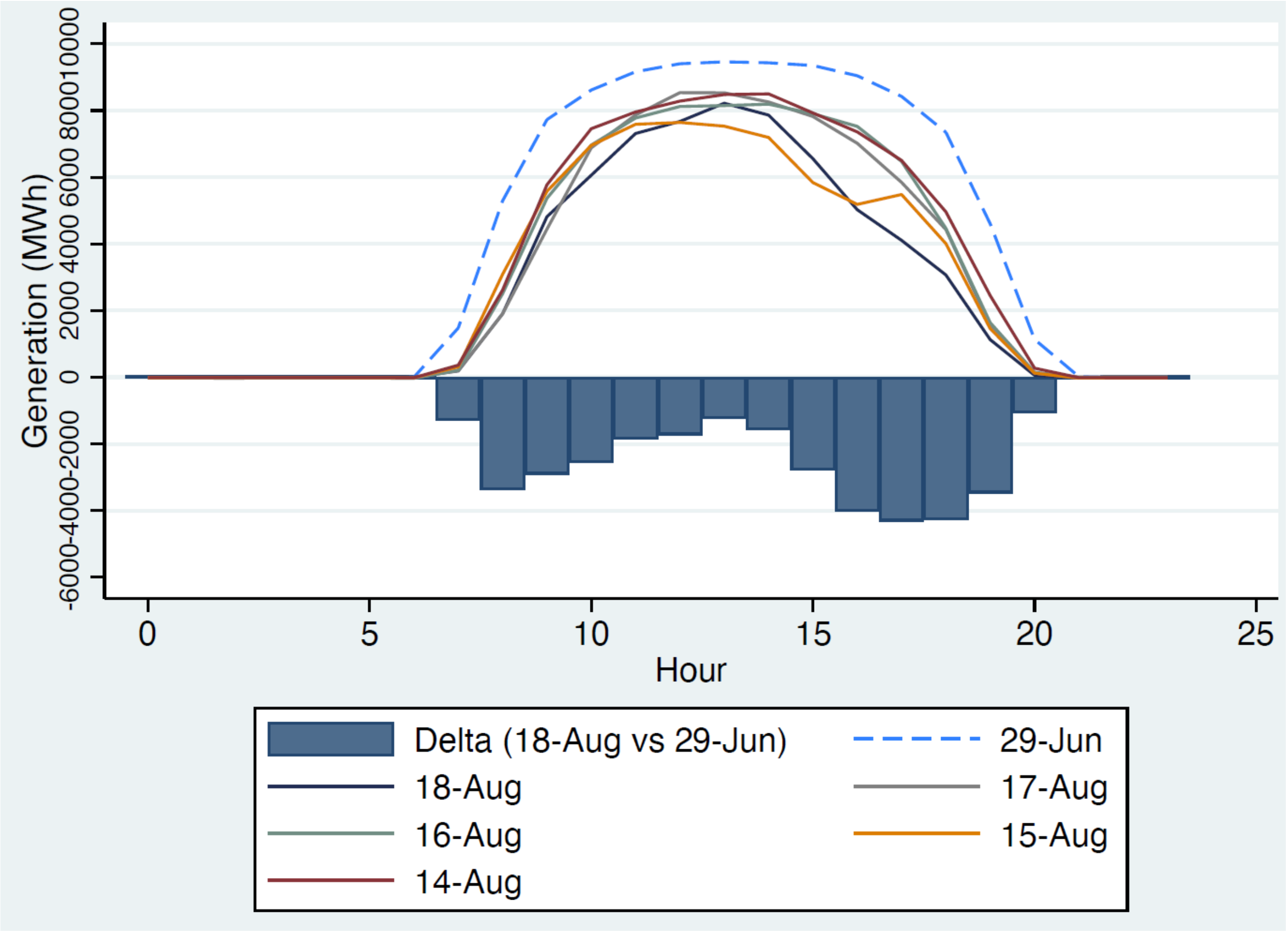
The Rolling Blackouts of 8/14/20-8/15/20



The Rolling Blackouts of 8/14/20-8/15/20



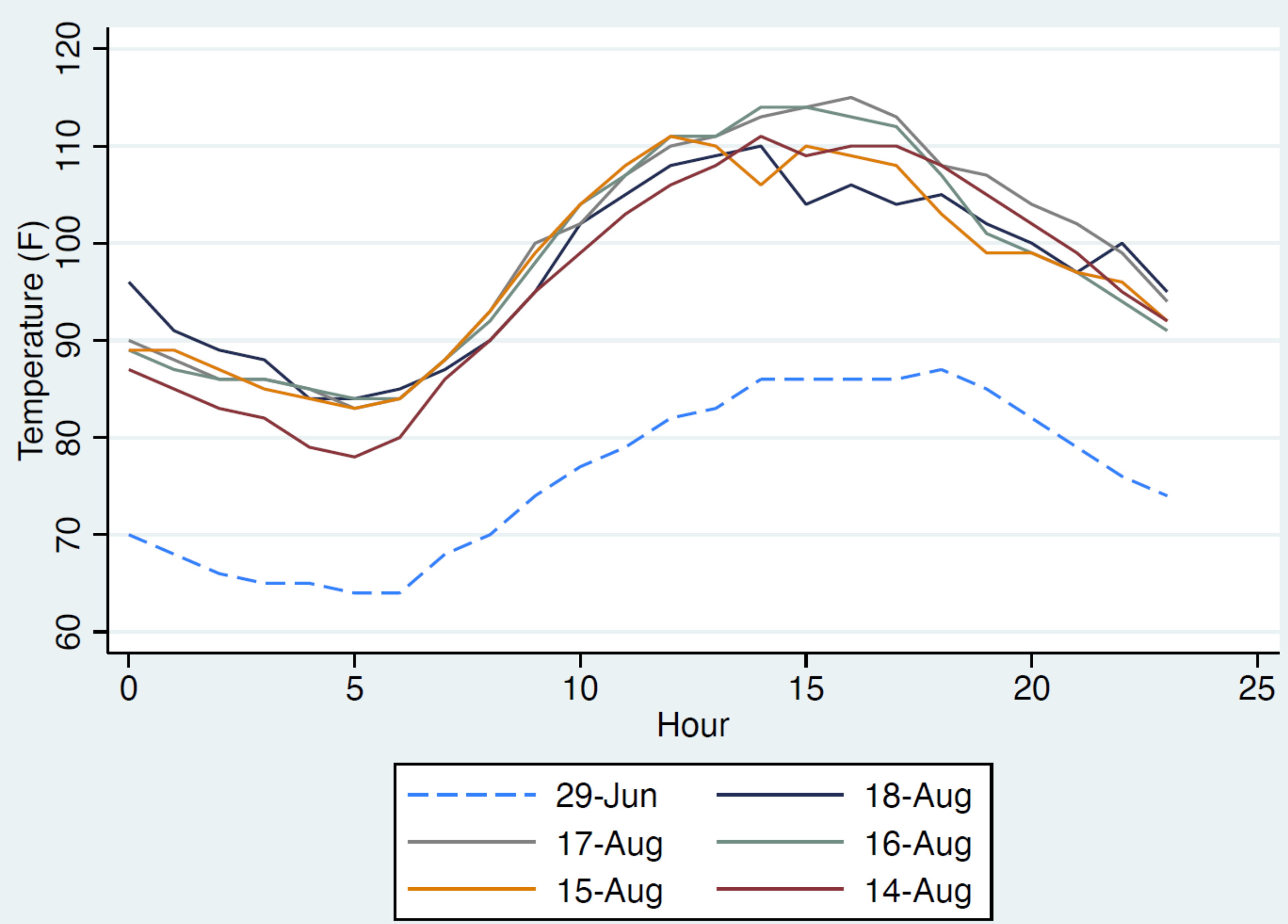
The Rolling Blackouts of 8/14/20-8/15/20 (Hourly Production of Grid-Scale Solar Energy)



Solar Production in California

- June 29, 2020 is an ideal day for solar production in California
  - Panels have maximum efficiency for converting light into electricity at a temperature of 77^{o} F
- Hot days with significant particulate matter in the air are not ideal for solar production
- What explains almost 20% reduction in solar production relative to ideal conditions on August 14 to 18, 2020?

The Rolling Blackouts of 8/14/20-8/15/20
(Hourly Temperature in Barstow, CA)



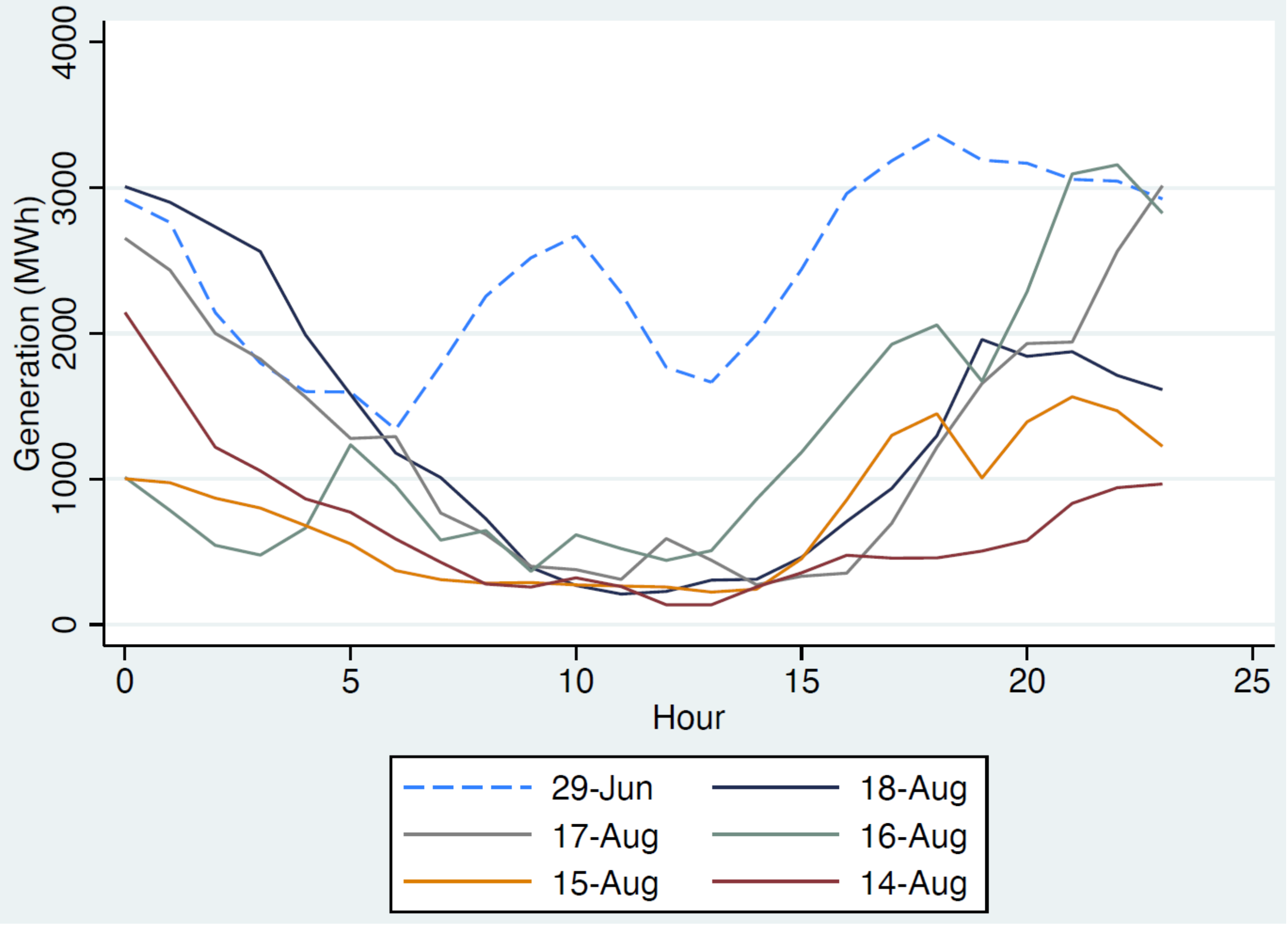
Solar Panels and Temperature

- PV panels are rated at 77^o F temperature
  - Convert light into electricity
- Efficiency of panels declines linearly with every degree of temperature above 77^o F
- On-site electricity consumption on high temperature days likely to be greater than on lower temperature days
  - Air conditioning load
- Both factors lead to lower net injections to grid from solar PV units
  - Explains less net production from solar units on August 14-18 versus June 29

Wind Production and Temperature

- Wind production on extremely hot days unlikely to be very high
  - Wind occurs because of temperature differentials between locations
  - If it is hot everywhere, there is likely to be very little wind
  - Higher wind production on lower temperature days
- Wind production likely to be greatest at beginning and end of the daylight hours

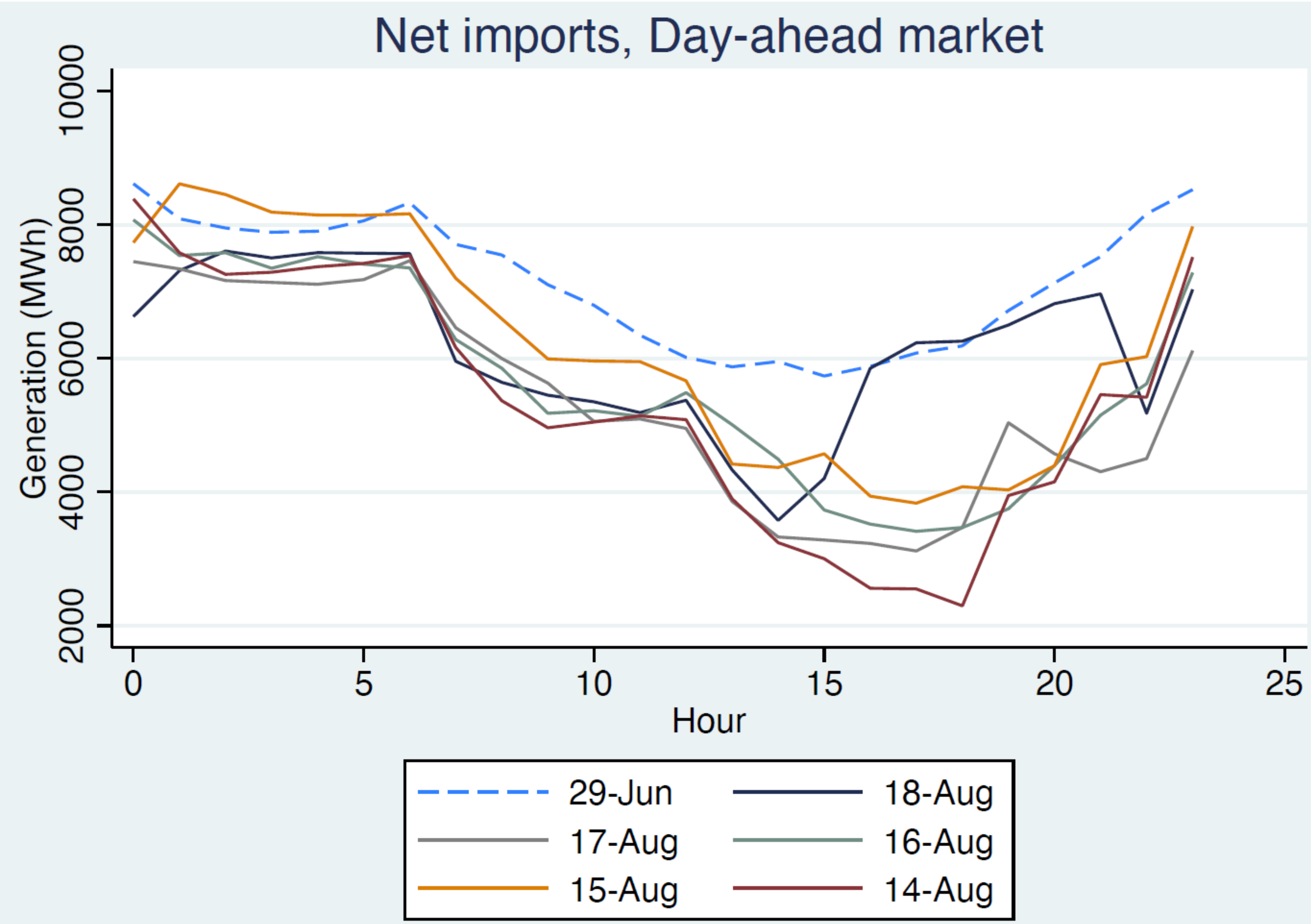
Wind Production and Temperature (Hourly Wind Output)



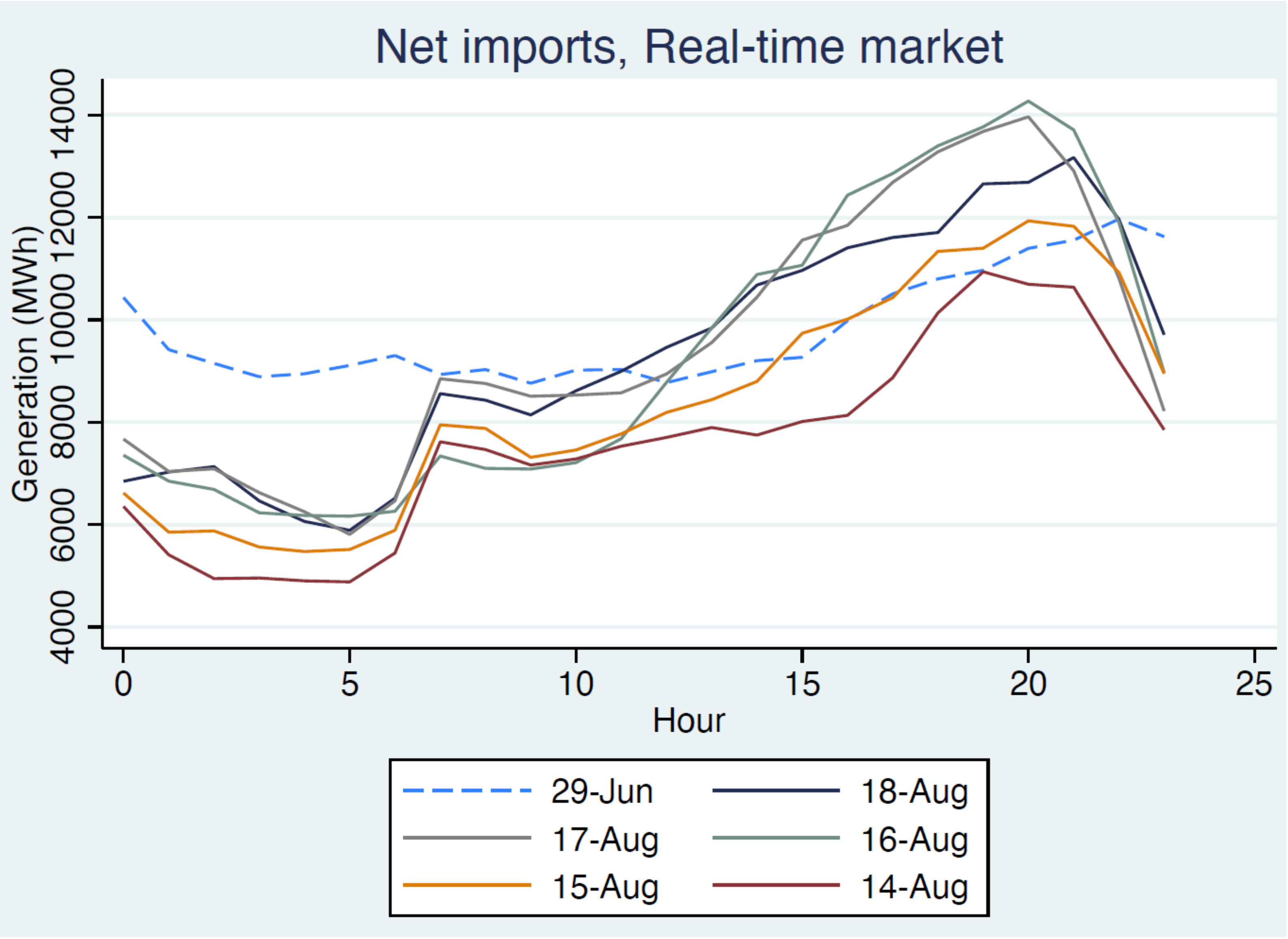
Imports and Temperature in the WECC

- Recall that neighboring control areas have priority for output of generation units in their state
- California load-serving entities can purchase this energy in advance in a fixed-price forward contract to ensure that it is supplied to California
- California can also purchase energy in real-time market
  - Only if price California is willing to pay is higher than price other control areas are willing to pay
  - Prices outside of California were higher than offer cap on California ISO's real-time market on August 14 and 15
- Important lesson—Offer caps on California market can reduce real-time supply to state during stressed system conditions

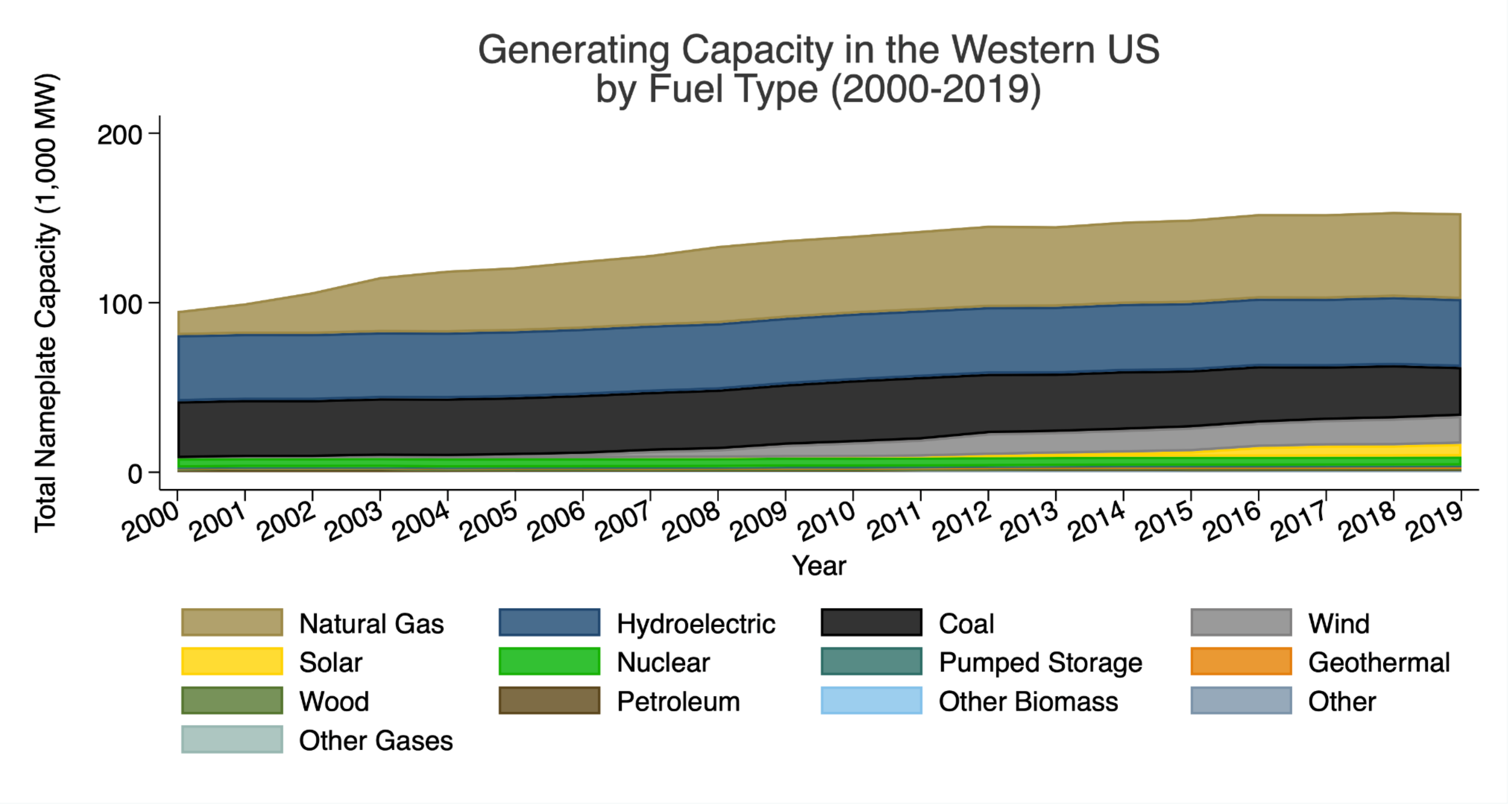
Imports and Temperature



Imports and Temperature



Fuel Mix of Imports



Imports and Temperature

- Difference between August 14 and 15 and August 16 to 18 is that California was able to obtain more imports in real-time market
- A substantial amount of generation capacity exists in the WECC
  - Owners of these units need a financial incentive to turn units on and sell energy to California
  - Events of August 14 and 15 demonstrated California was willing to pay high price for needed energy
- September 5 and 6 heat wave in WECC led to real-time prices during late evening close to $1,000/MWh
  - Annual average wholesale price in 2020 was slightly less than $45/MWh

Imports and Carbon Emissions

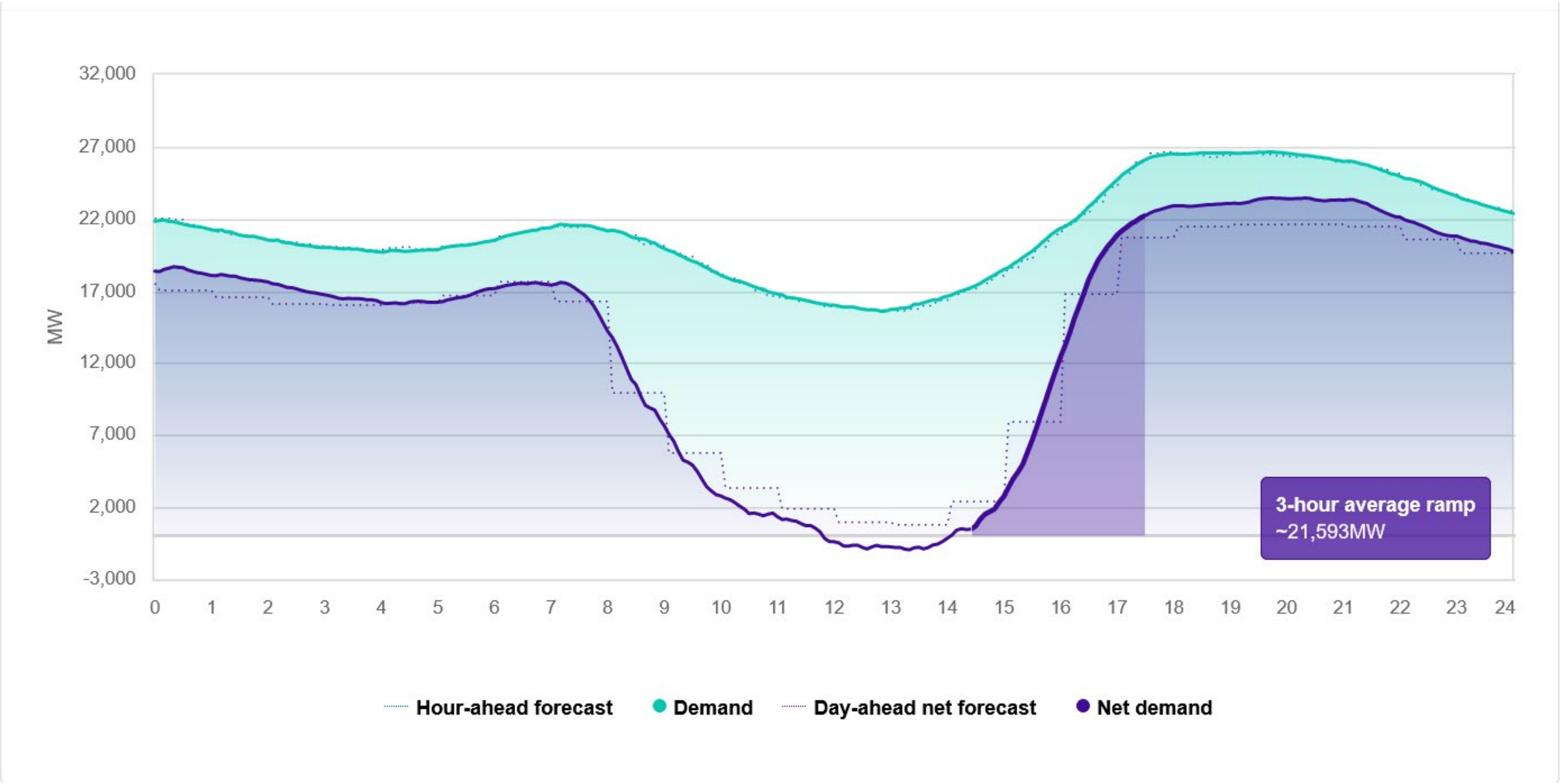
- Imports are at least as carbon intensive as natural gas-fired generation in California
  - Coal or natural gas is input fuel for marginal imports
- California can continue to rely on imports when renewables inside California disappear
  - More global carbon intensive solution to meeting renewables shortfalls in California
- Do California policymakers want to reduce GHG emissions from energy produced in California or global GHG emissions?
  - Maintaining natural gas units in California accomplishes second goal and reduces probability of events like August 14 and 15, 2020

California's Future Options for a Greener Grid

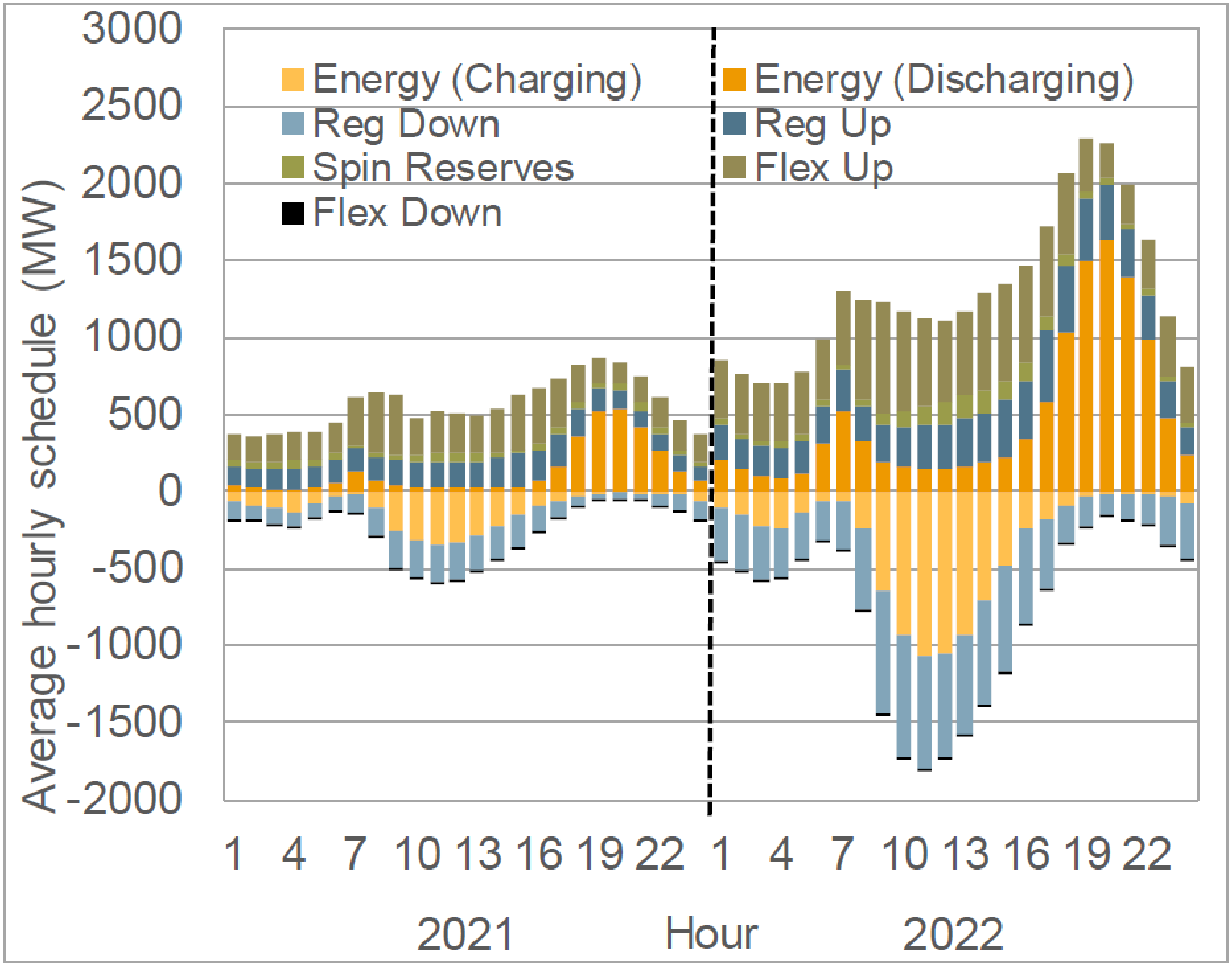
Net Demand in California

- More grid scale solar PV capacity in California implies a larger 3-hour ramp when solar energy disappears at end of the day
  - Steepest 3-hour average ramp 21,000 MWh on January 7, 2024
- Peak system demand typically occurs later in the day as more distributed solar is installed
  - 52,061 MW at 5 pm September 6, 2022
- Batteries can help meet 3-hour average ramp
  - Currently ~7,000 MW of batteries in California
  - Batteries do not produce energy
    - Withdraw and discharge energy
    - Charge at low price and then discharge higher price
  - Most battery capacity currently used to provide operating reserves rather than energy arbitrage

Net Demand in California (1/7/2024)



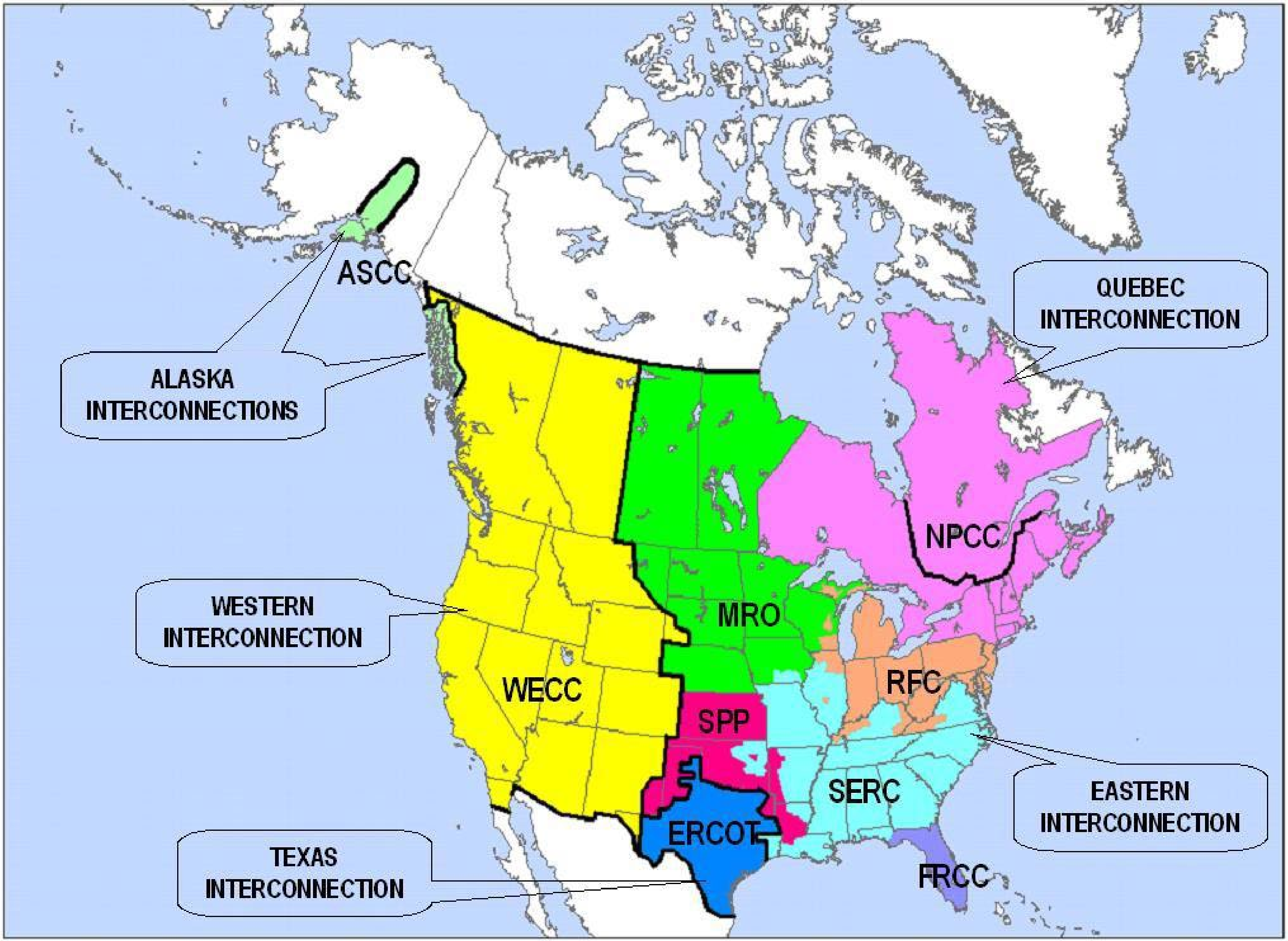
Average hourly real-time battery schedules



Conclusions

- Replacing dispatchable generation capacity with intermittent generation capacity is challenging particularly in a wholesale market regime
- California currently has two options to meet real-time demand with less solar and wind energy without instate natural gas units
  – Increase imports, which can be difficult if entire WECC region is hot and California has a finite offer cap on short-term market
  – Reduce real-time demand, which is difficult because of no customers pay according to dynamic prices
- Most promising approach to greening California's grid
  – Expand footprint of California market to rest of Western Interconnection (WECC)
    - Enhanced Day-Ahead Market (EDAM)
    - Energy Imbalance Market (EIM)

North America's Interconnections



Questions/Comments

For more information

http://www.stanford.edu/~wolak