As Grids Reach 100% Renewable at Peak, Growing Curtailment of 8 Gigawatts Looms as a Challenge to Decarbonization

ANDREW A. CHIEN, Computer Science, The University of Chicago and Argonne National Laboratory, USA
LIUZIXUAN LIN, Computer Science, The University of Chicago, USA

In April 2022, the California Independent System Operator (CAISO) power grid reached momentary peaks of 100% renewable energy for the first time. After a year, momentary 100% supply from renewables isn't a news any more, and CAISO reported record wind and solar renewable curtailment of 606 GWh (March 2023) and 686 GWh (April 2023). In addition, peak renewable coincided with curtailment rates of 8 GW in April 2023. Our prior studies documented monthly-peak renewable curtailment growth of 40% annually (23 GWh in March 2015 growing to 82 GWh in March 2017). Updating for 2018-2023 shows that 40% annual growth has continued through April 2023 and with it, CAISO has reached an average sunlight hours curtailment rate of 2 GW. If this 9-year trend continues unchecked for the next 5 years, monthly curtailment is projected to reach 3.3 TWh in both March and April of 2028, an average sunlight curtailment rate of nearly 11 GW.

We analyze causes of increased curtailment, and discuss its likely future trajectory (growth). We also discuss the challenges its growth represents for grid decarbonization. Finally we outline the difficulties in reducing curtailment growth and highlight several new opportunities for power grids and computing systems.

CCS Concepts: • **Hardware → Renewable energy**; • **Social and professional topics → Sustainability**.

Additional Key Words and Phrases: Curtailment, Power grid, Decarbonization

Availability of Data and Material:
No additional material provided.

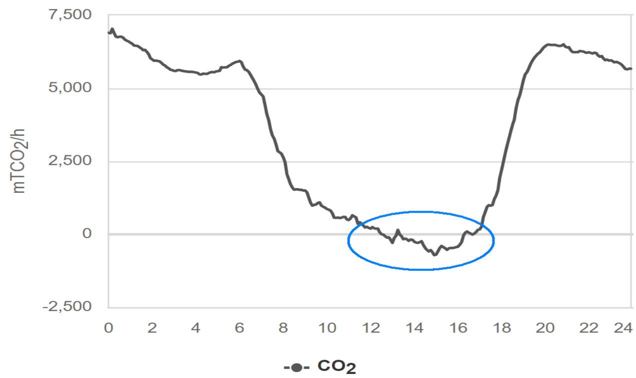


Fig. 1. CAISO Carbon Emissions on April 30, 2022 [19]. As renewables met 100% of demand in the afternoon, CAISO's carbon-emissions for power reached zero and even became negative.

1 INTRODUCTION

At 2:50pm on April 30, 2022, the California Independent System Operator (CAISO) reached 100% renewable generation as the combination of solar, wind, hydro, and geothermal generation satisfied its entire load for a few minutes [24]. This was an important milestone on the way to a fully decarbonized power grid, and occurred as CAISO on annual basis is operating below 40% renewable portfolio standard (RPS) (2020 reports for the major utilities are 34–39% annual RPS).

In April 2023, CAISO achieved 100% renewable power generation again [18], and is now regularly achieving zero carbon emissions[1], achieving this for a few minutes to hours on nineteen (19) distinct days in the first half of 2023 (Jan 1 to June 30). With increased renewable generation, CAISO is also setting records for wind and solar renewable curtailment, hitting 606 GWh in March and 686 GWh in April. In a single day (April 1, 2023), peak renewable generation coincided with 8 GW wind and solar curtailment rates. This concurrence is no accident. Rather it is the result of grid dynamics that present important challenges for deep decarbonization of power grids around the world [36]. At higher RPS, adding variable generation provides decreasing grid capacity credit, the lost capacity becomes curtailment [34]. Analysis of CAISO data reveals this phenomenon: for the month of March in years 2021, 2022, and 2023 grid load and absorbed renewable generation is similar. But, renewable curtailment increased 120 GWh (35%) and 140 GWh (31%) year-to-year respectively. Increased renewable generation was curtailed; the CAISO grid has reached its capacity to absorb renewable generation in the spring—March, April and May.

Our prior studies [6] showed that peak monthly-curtailed renewable generation grew at 40% annually from March 2015 to March 2017, increasing from 23 to 82 GWh. Updated analysis for 2018-2023 shows the 40% CAGR (compound annual growth rate) has continued through April 2023, producing a 740% increase over the six-year period. If this trend continues, 2028 may bring a peak monthly curtailment of 3.3 TWh and 18.4 TWh total curtailment for the year.

Growth in CAISO's renewable curtailment has been widely observed, and varied strategies to slow its growth have been proposed and employed. Continued curtailment growth shows that these strategies have not stopped, or even slowed curtailment growth. In this paper, we summarize recent years' curtailment growth and analyze the intrinsic causes of renewable curtailment in CAISO (Section 2, 3), and project future growth of curtailment. Key insights include:

- Despite longstanding predictions of excess solar and growing daytime curtailments [6, 9], the California ISO has been unable to slow the rapid growth of curtailment (40% annual growth).

[1] In fact, CAISO regularly reports negative carbon emissions, which occur when CAISO exports excess renewable generation and thus reduces neighboring grids' carbon emissions.

Authors' addresses: Andrew A. Chien, aachien@uchicago.edu, Computer Science, The University of Chicago and Argonne National Laboratory, 5730 South Ellis Avenue, Chicago, Illinois, USA, 60637; Liuzixuan Lin, lzixuan@uchicago.edu, Computer Science, The University of Chicago, 5730 South Ellis Avenue, Chicago, Illinois, USA, 60637.

- Growth trends for solar generation (behind the meter and industrial scale) suggest continued rapid growth of renewable curtailment that may exceed 18 TWh in 2028.
- Growing curtailment calls for large and growing amounts of flexible load, available during daytime hours. Computing is one such possible load. Others include electric vehicle charging and hydrogen production.
- There is a large and growing economic incentive to shift power consumption to daylight hours (8am to 6pm). For example, the excess power curtailed in March 2023 has wholesale value of approximately $58M, and in March 2028, would be worth $310M.

We close with a discussion of the classical solutions to balance generation and load, and hence reduce curtailment, that continue to fail in CAISO. We also describe the new opportunities that growing curtailment presents (Section 4) in both grid management and novel use.

2 OPPORTUNITY POWER (CURTAILMENT+NEGATIVE PRICING)

Renewable energy curtailment not only reflects an imbalance in supply and load, but through the marginal-pricing market mechanism it impacts grid economics. A 2018 study, using proprietary CAISO market and dispatch data found that curtailment could be linked to the occurrence of negative pricing in power markets—day-ahead, real-time, etc [6]. This negative-priced power represents a market imbalance for power. This study data from 2015-2017 produced three models for estimating the quantity of power transacted at negative prices (Figure 2).

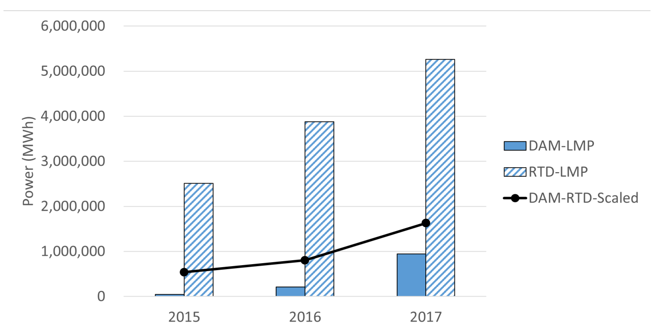


Fig. 2. Three Models of Negative-priced Power (MWh) in CAISO (2015–2017) from [6].

DAM-LMP captures the quantity of power transacted at a negative price in the day-ahead market. RTD-LMP captures the quanity of power transacted at a negative price in the real-time dispatch market. Unfortunately, this market data is not generally publicly available. Because the day-ahead and real-time dispatch markets are progressive, RTD-LMP overestimates negative pricing. The DAM-RTD-Scaled (DAM-LMP + scaled fraction of RTD-LMP) combines them to avoid double-counting. DAM-RTD-Scaled analysis shows that annual negative-priced power grew from 539 GWh to 1,627 GWh (>945 GWh in DAM) in 2017, in [6]. This negative-priced power combined with curtailment is called *opportunity power* (also "Stranded Power" in [7, 27]. This opportunity power includes curtailment, but is much larger. Further, in the CAISO grid, as in most grids, curtailed power is not transacted in the market, as it is not available for use to service loads. In fact, it is generally not even counted in generation, or renewable generation mixes.

3 RENEWABLE CURTAILMENT AND OPPORTUNITY POWER, 2015–2022

3.1 Growing Curtailment and Opportunity Power

To put recent events in a long-term perspective, we update our prior opportunity power study (including curtailment) using public data from CAISO for 2015–2023 (Figure 3). Because proprietary pricing data is not available for 2018–2023, we estimate negative-priced power using the DAM-RTD-Scaled/Curtailed ratio of 4:1 computed in the prior study as the most accurate approach [6].

The wind and solar curtailment peak, typically in March or April, shows an average 40% compound annual growth over the seven years' period, reaching 606 GWh in March 2023. Figure 3 shows strong seasonal fluctuations, typical of the load, generation, and imports dynamics of CAISO, as well as annual fluctuations which could be attributed to variation in hydro generation, COVID load changes, etc. The estimated monthly opportunity (stranded) power grows in similar fashion and is estimated at 3.1 TWh (March 2023).

Overall, this data shows that growth trends of renewable curtailment and negative pricing observed in 2018 [6] have continued through 2023, and over 1,000% growth since 2015! The ongoing growth of excess power represents both significant challenge and opportunity for both the power market and grid.

3.2 Daily Grid Dynamics

In Figure 4 and 5, we illustrate the daily dynamics of curtailment and its progression from 2019 to 2023. Each graph from CAISO's "daily wind and renewable curtailment report" for a Spring day shows the timing of curtailment is primarily during solar peak hours. It demonstrates that the excess renewable power is largely solar generation. The progression of graphs show the steady growth of curtailment in recent years (the trend goes back much further, but CAISO has only reported detailed daily curtailment for the past five years).

In finer detail, the graphs color-code different sources of curtailment, i.e., "Economic-Local" (green) and "Economic-System" (blue), account for most of the curtailment. The larger, "Economic-System" (blue) reflects system-wide oversupply (market imbalance between supply and load). Such oversupply can already be the dominant source of curtailment and continues to grow, reaching a peak of 8 GW.

Significant curtailment is also due to lack of sufficient transmission capacity (green). However, that curtailment while once dominant, is now a decreasing share, illustrating the limits of additional transmission in solving the curtailment challenge.

3.3 Drivers: Renewable Generation Growth 2015-2022

To assess the persistence of curtailment growth, we analyze the drivers behind it. Solar generation capacity in CAISO has grown

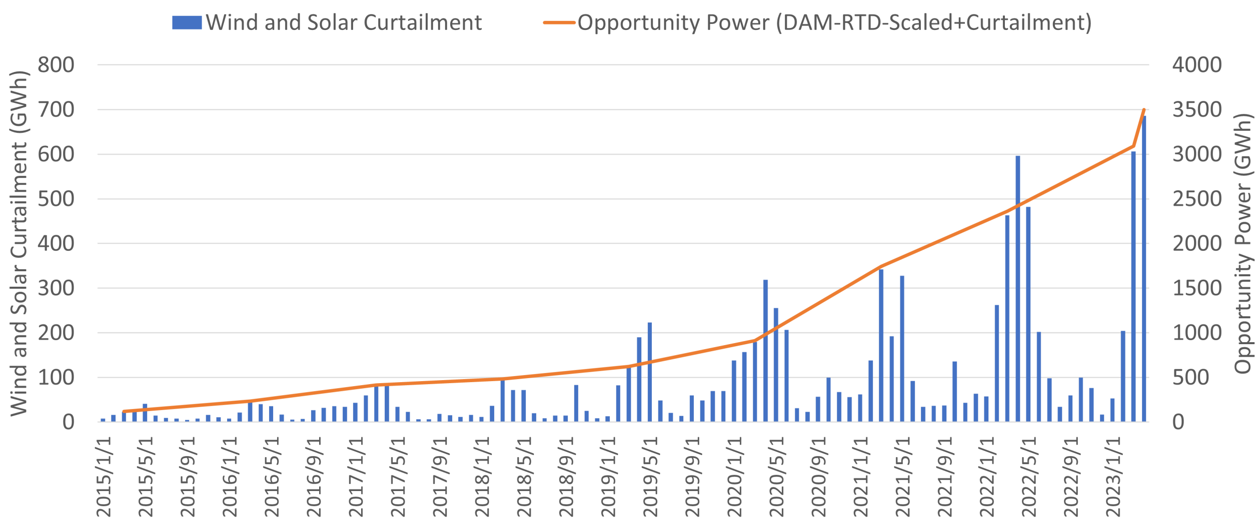


Fig. 3. The Growth of Monthly Renewable Curtailment (686 GWh, April 2023) [22] and Growth of Estimated Monthly Opportunity Power to 3.5 TWh.

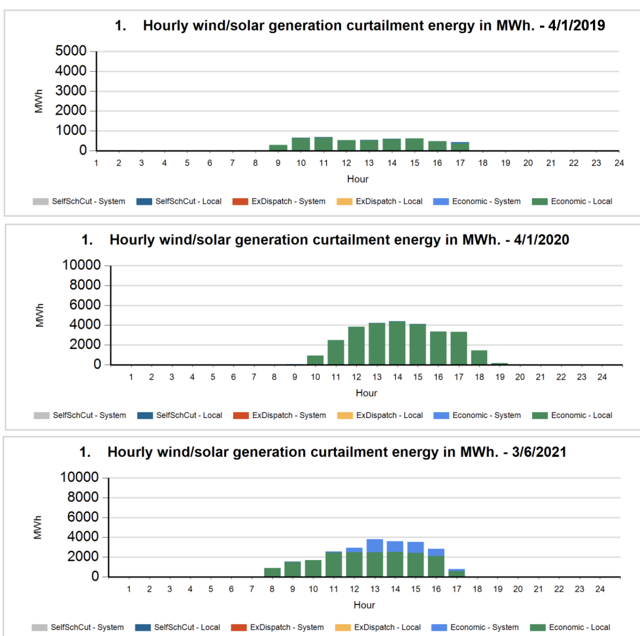


Fig. 4. Selected Daily Curtailment Graphs for April 1, 2019, 2020, March 6, 2021 (Courtesy of CAISO). These graphs show a growing solar-driven peak during peak sunlight hours (1000 to 1800). Note scale changes.

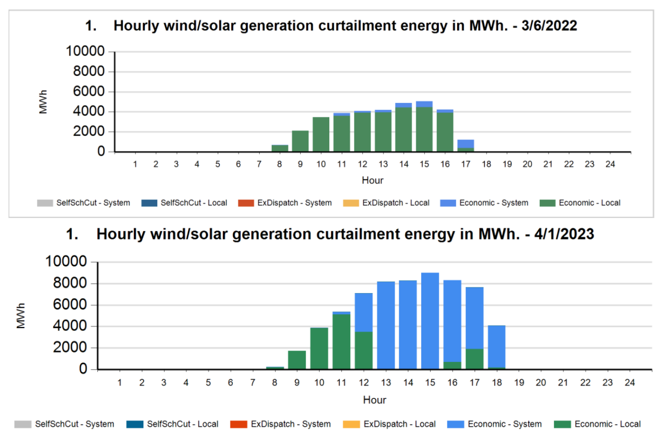


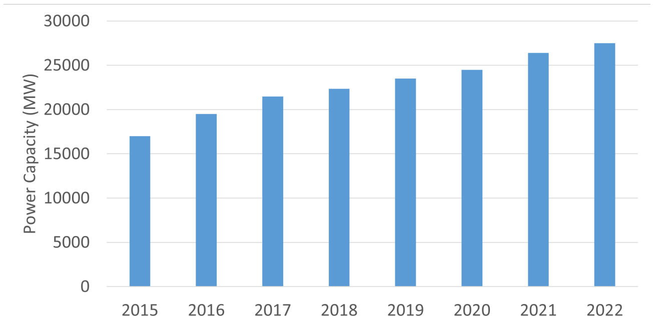
Fig. 5. Selected Daily Curtailment Graphs for March 6, 2022 and April 1, 2023 (Courtesy of CAISO). These graphs show a growing solar-driven peak during peak sunlight hours (1000 to 1800). The curtailment peak grows less than 1 to 8 GW from 2019 to 2023. Daily charts for March and April 2023 have many examples where curtailment exceeds 2 GW [21].

slowly, experiencing a 40% total increase for the 7-year period from 2015 to 2022. The corresponding growth in total renewable generation was 60%. These increases are documented in Figure 6, and they allowed utilities to meet the mandated California Public Utilities Commission (CPUC) renewable portfolio standards [1].

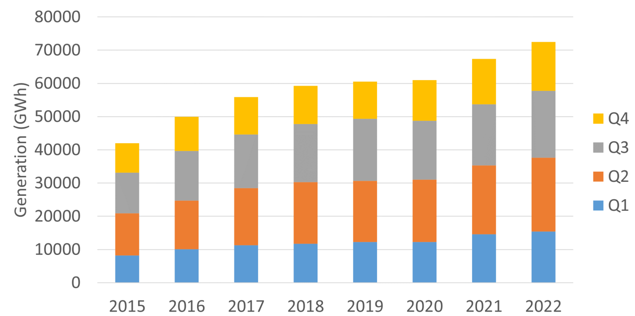
CAISO grid has significant "behind the meter" (Net Energy Metering or NEM) renewable generation growth, mostly solar. This generation is not included in CAISO renewable capacity shown in Figure 6, but reduces grid load. This NEM generation has grown faster, exceeding 400% over the 7-year period, a 9 GW capacity increase. NEM has added 1.3 GW capacity annually, which is nearly all renewable energy[2], but not counted in the CPUC's renewable energy goals for utilities (e.g. 60% RPS by 2030) [1].

While the percentage growth rates differ, grid solar and NEM have averaged 1.5 GW capacity increase each annually; for overall growth of 3 GW/year.

[2] One conservative estimate is 5 hrs x 12 GW capacity = 60 GWh/day, and 22 TWh/year.



(a) Renewable Capacity



(b) Renewable Generation

Fig. 6. CAISO Renewable Capacity (MW) and Quarterly Metered Generation (GWh), 2015–2022.

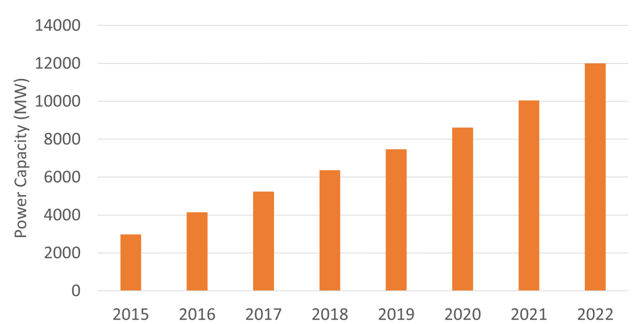
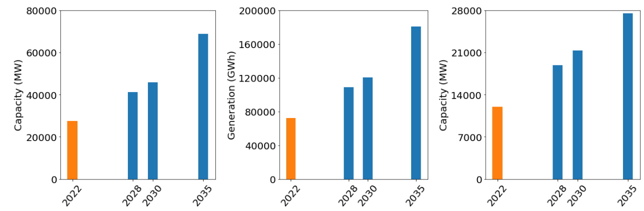


Fig. 7. California's Net Energy Metering (NEM) Solar PV Capacity (MW).

3.4 Projecting Continued Renewable Generation Growth

The drivers of growing renewable curtailment in CAISO are projected to continue, driven by renewable purchasing to meet California RPS goals—60% by 2030 and 90% by 2035. Projections for renewable capacity, generation, and NEM solar capacity to meet these goals are shown in Figure 8. California's 36% renewable fraction in 2022 and essentially stable load, mean that achieving 2030 and 2035 RPS goals requires 1.7x (46 GW/120 TWh) and 2.5x (69 GW/181 TWh) renewable capacity/generation respectively.

In California, behind the meter solar (NEM solar) is not counted as part of the RPS requirement, and independently NEM solar capacity is projected to increase 1.8x (21 GW) by 2030 and 2.3x (27.5 GW) by 2035 based on historic growth rates (since 2015). This continued solar growth is the foundation for curtailment growth. For example, today's CAISO already sees 8 GW system curtailment, with potential additional 24 GW grid solar capacity.[3]

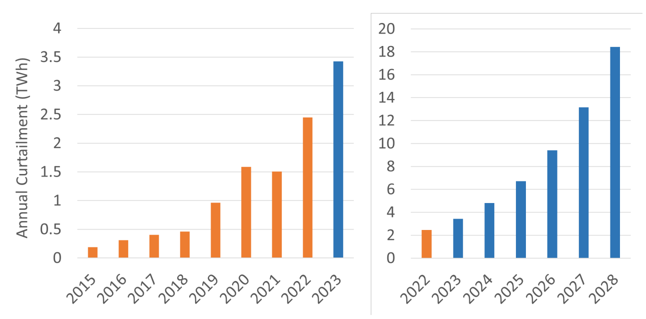


(a) Capacity (b) Metered Generation (c) NEM Solar Capacity

Fig. 8. CAISO Renewable Capacity, Annual Generation, and NEM Solar Capacity Projections According to 2030 (60%) and 2035 (90%) RPS Goals.

3.5 Projecting Curtailment 2023-2028

Looking across 2015–2022, CAISO averaged 40% annual growth in annual renewable curtailment (see Figure 9). If this trend continues, gigawatt and terawatt-hour curtailment will spread from spring weekends to spring weekdays and to other seasons. It is already spreading from subsections (interconnect curtailment) to the entire grid (economic curtailment). By 2028, annual renewable curtailment in the CAISO market would reach 18.4 TWh, with a peak monthly curtailment of 3.3 TWh. The projections of additional 7.7 GW grid solar and 6.3 GW NEM solar capacity seem unlikely to be realized as they could drive peak curtailment in Spring 8 GW in March 2023 to over 22 GW, due to radical changes to net-metering and growing adoption of hybrid generators [23]. Perhaps a reasonable projection might be 15GW peak, a number which is 50% of CAISO's average load [16].



(a) 2015–2023 (b) 2022–2028

Fig. 9. CAISO Annual Renewable Curtailment (2015–2022, orange) and Projection (2023–2028, blue). The y-axes are scaled differently to highlight the growth.

Is such growth in renewable curtailment realistic? Current policy structure suggests the answer is yes. As is discussed in Section 3.4, to

[3] Assuming the same share of capacity as 2022 and 15 GW NEM solar capacity in 2035, the peak curtailment rate could be 47 GW!

reach 2030's 60% RPS goal, the major utilities must rapidly increase renewable purchases, increasing grid renewable generation from 72 TWh to 109 TWh by 2028. If the NEM program growth continues it will add 7 GW capacity, producing an additional 12.8 TWh of renewable power. Assuming the overall 50 TWh increase is mostly solar, an 16 TWh increase in curtailment by 2028 is plausible.

Projecting opportunity power with the methodology in Section 2, from 17.5 TWh in 2023, annual opportunity power is projected to grow to 94 TWh in 2028. If realized, this is nearly 90% of the 109 TWh of grid renewable generation in 2028, which is more than today's grid renewable generation.

3.6 Discussion

We expect to see continued curtailment growth despite the fact that curtailment was recognized as a potential challenge by CPUC and CAISO planning and operations as early as 2014 [9]. By 2018, CAISO initiated a range of programs to mitigate curtailment, including advanced load management, energy storage, and more (see CAISO "Managing Oversupply" [17]). Our analysis shows that these programs have not stopped the rapid growth of curtailed renewable generation.

Established public policies of NEM, mandated solar on new homes or buildings, and grid RPS goals continue to drive growth in solar generation. Solar generation benefits from decreasing levelized-cost-of-energy (LCOE) (est. \$24–\$96/MWh in 2023[4] [26]), well below alternatives. Renewable generation is likely to match grid load with increasing frequency, spreading curtailment to weekdays, and other seasons. Studies suggest increasing price differences across the "duck curve" may drive addition of a few hours storage, but not enough to slow the growing imbalance [3]. Directly, it appears likely that curtailment will continue to grow rapidly.

The growing curtailment can be translated to potential cost savings for the grid customers. For example, the daily curtailment on April 1, 2023 shown in Figure 5 is 63.8 GWh, approximately \$3.6M value at 2021 CAISO average power price (\$56/MWh) [15] or \$6.1M at 2022 price (\$95/MWh) [16]. March 2023's monthly curtailment is 606 GWh with approximately \$58M value at 2022 price, which can grow to 3260 GWh with \$310M value in 2028. These monetary benefits present economic incentive for grid customers to change their behaviors and are opportunities to improve social welfare.

4 CHALLENGES AND OPPORTUNITIES

4.1 What Has NOT Worked

The growth of renewable curtailment is not unique to CAISO, but rather a common phenomenon in grids with rising renewable generation fractions [4, 13, 14, 34]. In the past 10 years, many structures expected to solve the curtailment problem have not worked. Here we briefly summarize them and why.

(1) **Market Self-correction.** Many attribute to free markets a rich power of self-correction, matching pricing and supply efficiently between buyers and sellers. Power is a difficult market as both perishable and a localized commodity, producing markets with properties radically different from Economics 101 intuition [30]. The demand of buyers has not grown to match sellers of renewable power. More remarkably, grid power markets exhibit anomalies such as zero or even negative prices lower than -\$100/MWh, and increasing volatility. Here due to externalities, the renewable generators produce power, and bid it at zero or even negative prices [7], producing oversupply and curtailment. Renewable generators fail to reduce zero-incremental cost production, supported by feed-in tariffs of production tax credits.

(2) **Transmission and Broader Dispatch.** Proposals to broaden CAISO's dispatch area (promotion of the WEIM [20] to a single dispatch area, and corollary increase of transmission across a wide geographic area) are a commonly proposed solution to both renewable curtailment and decarbonized grid reliability. These efforts have not evidently slowed curtailment, for complicated political and procedural reasons. There appears no evidence these obstacles are likely to ease, much less disappear as there are significant economic and political interests at stake.

(3) **Energy Storage.** The dream of solving mismatch between renewable generation and load with energy storage is simple and intuitive. Unfortunately, low-cost storage (pumped-storage hydro, etc.) is in scarce supply in many power grids, and scalable storage (e.g. batteries) remains too expensive to be used for time-shifting very low-cost power. Solar combined with energy storage is still 2-fold (\$46-102/MWh) that of solar generation alone [26], and it is projected to remain so beyond 2028 [3].

While many traditional grid and economics theorists might expect these mechanisms to slow curtailment growth, their net impact has not reduced the 40% compound annual growth rate of curtailment.

4.2 Potential Solutions

(1) **New Market Product for DownScalable Loads**, allowing traditional downward load flexibility to be coordinated with utilizing curtailment. The existing demand response programs in CAISO [22] shed non-critical loads only at peak times for grid reliability. The use case is rare (emergencies vs. curtailment as a regular phenomenon). New initiatives to express load that can be downscaled as needed [32] have the potential to create new kinds of flexible demand. These could reduce curtailment by safely allowing increased consumption.

(2) **New Market Products for UpScalable Loads**, enabling the grid to increase load, priced appropriately [2, 5, 31], for long running low-cost energy enabled processes such as green hydrogen and fertilizer manufacture. Compared with traditional grid connection that assumes on-demand, reliable grid power, the key pattern of these loads is that they can tolerate frequent outages and can ramp up production fast when the cheap, excess power is available.

[4]The average slightly increased in 2023 due to inflation and supply chain challenges.

(3) **New Load-Grid Coupling Paradigms** and frameworks that negotiate binding load changes. Advanced load management involving datacenters [25, 28, 29, 35, 37], factories [12], electric vehicles [8], etc. has been proposed. [11] is a comprehensive study that assesses the potential load flexibility ("Shape, Shift, Shed, and Shimmy") and cost in CAISO. Routine, gigawatt shifts are needed (e.g. daily, seasonal, with weather fronts, etc.). While many load types are being studied, one of particular interest to us are AI training datacenters. Cloud datacenters exceeding 100MW and experiencing rapid growth are good candidates. Northern Virginia's grid operator documents rapid load growth (12 GW increase in 2030 peak load projection in just the past 4 years [10]). Furthermore, the recent AI boom is widely viewed as accelerating this growth and expanding it around the world [33].

(4) **New Foundations for Grid Markets and Dispatch** based on statistical, portfolios, not sets of single power bids. With growing curtailment and negative pricing, markets may be ineffective. Marginal prices may fluctuate violently ±$1000/MWh as the grid swings from overgeneration to use of expensive peaker or other fossil fuel generation. With frequent overgeneration, can markets incentivize a balanced portfolio of generation? Can it integrate variation to create reliable supply?

5 SUMMARY

Curtailment of renewable generation is a well-known phenomenon, but historically studied long-term as an inefficiency concern. Despite the longstanding predictions of excess solar and growing daytime curtailments, the grid and power markets of CAISO have been unable to slow the 40% CAGR growth, which has now accumulated to 1966% and average rates of 2GW in peak months. If it continues unchecked, unthinkable rates exceeding 10GW are projected. While more difficult to estimate, the quantities of negative-priced power are likely much larger.

As a daily temporal and spatial issue critical to balancing in the California power grid now, curtailment is a basic challenge of grid decarbonization, and it's also an economic challenge with the wasted power's potential value now exceeding $232M/year. It is perhaps simplest in the CAISO market because of its narrow geographic latitude, and well-developed because of California's aggressive RPS goals. However, the reality that it's unsolved for 10 years suggests that new ideas and innovation are required.

We propose several promising alternatives, but all require significant change: new market products for flexibility in load, new paradigms for binding load changes and advanced load management, and fundamental new grid market structures. We call for more inspiring solutions from computing and power grid researchers.

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