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Too much of a good thing? Global trends in the curtailment of solar PV

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ABSTRACT

Solar photovoltaic (PV) systems generate electricity with no marginal costs or emissions. As a result, PV output is almost always prioritized over other fuel sources and delivered to the electric grid. However, PV curtailment is increasing as PV composes greater shares of grid capacity. In this paper, we present a novel synthesis of curtailment in four key countries: Chile, China, Germany, and the United States. We find that about 6.5 million MWh of PV output was curtailed in these countries in 2018. We find that: Policy and grid planning practices influence where, when, and how much PV is curtailed; Some PV curtailment is attributable to limited transmission capacity connecting remote solar resources to load centers; PV curtailment peaks in the spring and fall, when PV output is relatively high but electricity demand is relatively low. We discuss available measures to reduce PV curtailment as well as increasing PV curtailment in the contexts of evolving grids and energy technologies.

1. Introduction

Global solar photovoltaic (PV) capacity is projected to more than double over the next decade from about 500 GW in 2018 to 1290 GW by 2030 (International Energy Agency (IEA), 2018; Masson et al., 2019). As a result of its zero marginal cost characteristics, PV output is almost always prioritized in electricity grid dispatches and delivered to the grid. However, as PV composes increasing shares of grid capacity, it will become increasingly common that some available PV output will be unused for technical or economic reasons. Unlike fuel-based generators whose unused output represents fuel that can be burned to generate output at a later time, unused PV output represents available electricity that is lost forever (Sterling et al., 2017). The term "curtailment" has emerged as an industry term of art for the practice of foregoing and thus losing available renewable energy output, including PV.

Most PV curtailment stems from some system constraint that impedes the grid from absorbing more PV output.[1] To build some intuition around how system constraints can drive curtailment, Fig. 1 depicts an actual PV curtailment event in California in May 2018. As PV came online at 6 am, some flexible generators—mostly imports and natural gas—went offline, conceptually "making room" for the PV output. However, at least some non-variable generation on the grid cannot be significantly ramped up or down, at least in the near term, because the generation provides essential grid reliability services or because of mechanical limitations. After the system had scaled back flexible generation, the sum of variable generation (including other renewables) and the inflexible generation began to exceed load, a phenomenon we will refer to as *oversupply*. In order to maintain supply/demand balance, the system curtailed about 12,000 MWh of PV output on this particular day, represented by the red area on the top of the chart.

Oversupply and curtailment are largely driven by two mismatches between PV output (supply) and load (demand). First, there is often a temporal mismatch between when PV output is available (midday) and when that output can be absorbed by the grid. Temporal mismatch is clearly evident in Fig. 1. On that day, the PV output peak occurred in the midday when demand was too low to absorb the output. The temporal mismatch is exacerbated by the fact that behind-the-meter PV systems reduce grid net load throughout the day, leaving less load to absorb available utility-scale PV. Second, there may be a geographic mismatch between where PV output is available (sunny, dry areas) and where that output can be absorbed (load centers). Land use and land cost considerations may also play a role in PV siting, particularly when fixed feed-in tariffs or other incentives are location agnostic (Krauter, 2018). Geographic mismatches occur when solar-rich regions are located far

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[1] Other forms of curtailment include foregone output during system maintenance and clipping that occurs when PV output exceeds inverter capacity. These other forms of curtailment are outside the scope of this paper.

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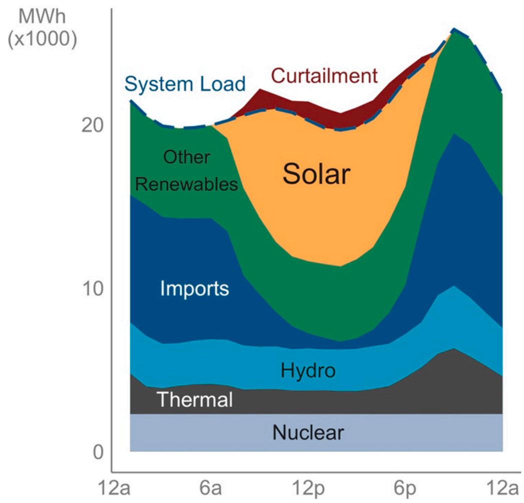

Fig. 1. PV curtailment event on May 13, 2018, in California. Based on data from CAISO (2019a).

from load centers and when there is limited transmission capacity connecting the two regions.

Oversupply risk generally increases as more PV is integrated onto the grid (Denholm et al., 2016; Nelson et al., 2018). Each marginal unit of PV output pushes down the midday net load, making it more likely that PV output will exceed the grid's ability to absorb that output during the solar peak. As a result, PV curtailment is projected to increase as PV composes greater shares of grid capacity (Denholm et al., 2015). An illustrative example is California, where PV curtailment doubled from 2018 to 2019 alone (CAISO, 2019a).

PV curtailment is often framed as a loss given that effectively free and clean electricity goes unused (Bird et al., 2016; Henriot, 2015). Curtailment may also undermine PV project economics and could hinder future PV deployment (Golden and Paulos, 2015). As a result, various grid and market practices discourage curtailment. For instance, some grid policies require utilities to compensate generators for curtailed output, and some interconnection policies prohibit systems from interconnecting if those systems will result in curtailment.

In this paper, we describe the extent of PV curtailment through a novel synthesis of data from four key PV markets where curtailment is occurring: Chile, China, Germany, and the United States. We present the data and key trends in Section 2 and review the literature on measures to reduce curtailment in Section 3. Finally, in Section 4 we explore how evolving grid and technological contexts may force a reexamination of grid and market practices that discourage curtailment. We restrict the scope of our article to PV curtailment. It should be noted that similar trends prevail in the curtailment of wind power. Wind power systems have—historically—been curtailed at higher rates than PV systems, primarily because more wind capacity has been deployed. See Bird et al. (2016) for a review of trends in wind curtailment.

2. PV curtailment in key markets

All data presented in this section represent estimates of PV curtailment in 2018. Where available, we mention more recent estimates based on 2019 data. Data sources and methodologies are described in each sub-section. The curtailment data compiled in this section generally represent curtailment of utility-scale PV. Distributed behind-the-meter PV are generally not controlled by grid operators and thus generally not subject to curtailment. The exception is Germany, where the German Renewable Energy Act requires distributed PV to be installed with inverters that allow grid operators to curtail those systems as needed. Curtailment estimates are presented in terms of absolute curtailment (MWh) and as a percentage of potential PV output, i.e., the percentage of PV output that *could have* been curtailed that actually was curtailed:

$$Curtailment\ \% = \frac{Curtailed\ \ Output}{Delivered\ \ Output + Curtailed\ \ Output}$$

PV curtailment generally only occurs on grids with relatively high levels of PV penetration. Significant levels of PV curtailment (>1% of potential output) have been recorded in Chile, China, Germany, and certain markets in the United States. Table 1 summarizes the curtailment trends in these areas. In this section, we explore the current state of curtailment on each of these grids.

Through the end of 2018, PV curtailment in other markets has been minimal. In Australia, some utility-scale PV was potentially curtailed in 2018 as part of a broader set of variable renewable energy curtailments (primarily wind) to maintain system reliability. However, the rapid expansion of utility-scale PV across Australia in 2018 and 2019 (about 3000 MW of increased capacity) has led to increased curtailment in 2019, due to both PV-specific system reliability issues and negative daytime market prices (AEMO, 2020). Outside of Germany, PV curtailment in Europe has been limited (Bird et al., 2016; Yasuda et al., 2015), though increasing PV penetration may drive future PV curtailment, particularly in Portugal and Spain (Bossman et al., 2018). In Japan, PV curtailment was reported for the first time on the Japanese mainland in 2018, though some PV curtailment may have occurred previously on remote islands (Tsukimori, 2018). Future PV curtailment levels are projected to reach as high as 10% of available output in Japan at higher PV penetration levels (Yasuda et al., 2015).

2.1. Chile

The Atacama and Antofagasta regions of northern Chile have some of the strongest solar resources in the world. The region has attracted increasing investment in large-scale PV capacity, with more than 1600 MW online by the end of 2018 (Energía Abierta, 2019). However, the

Table 1
2018 PV curtailment statistics in key PV markets.*

Location	PV Penetration (% of Generation)	Curtailed PV Output in 2018 (MWh)	% of Potential PV Output Curtailed	Curtailment Drivers / Primary Mitigation Measure
Chile	6%	150,000	6%	Geographic mismatch between solar resource and load / Transmission expansion
China	2%	5,490,000	3.0%	Geographic mismatch between solar resource and load / Transmission expansion
Germany	7%	116,470	0.3%	Grid congestion / Compensation requirements
United States				
California	13%	432,000	1.5%	Systemwide oversupply / Balancing market expansion
Texas	1%	270,000	8.4%	Geographic mismatch between solar resource and load / Transmission expansion
Arizona	4%	17,100	2.9%	Oversupply in regional market / Energy storage
Hawaii	2%	4,100	2.7%	Local oversupply / Energy storage

* Data sources and estimation methods are defined in each sub-section.

strong solar resource is far from the nation's primary load center in Santiago (Fig. 2). There is currently no transmission capacity linking Antofagasta to the rest of the country, leaving more than 800 MW of PV capacity isolated from the large load centers to the south (CEN, 2017). Further, there are currently only three 220 kV transmission lines linking Atacama to the rest of the system (CEN, 2017). Limited transmission capacity between the northern regions and Santiago is expected to drive increasing PV curtailment in Chile (CNE, 2018). There are also local transmission constraints around Santiago that contribute to curtailment (Matus et al., 2016). Curtailment of all renewables—including wind—increased from about 2% of potential output in 2016 (Matus et al., 2016) to about 6% of output in 2018 (Valgesta Energía, 2019).[2]

Ongoing transmission system expansions may alleviate PV curtailment in Chile (CNE, 2018). The country is building more than 600 km of high-voltage transmission lines linking Antofagasta and Atacama to load centers in Santiago (CEN, 2017). The National Electricity Coordinator estimates that a recent transmission upgrade will reduce renewable curtailment by as much as 80% (CEN, 2018).

2.2. China

Installed PV capacity reached 174,450 MW by the end of 2018, with 123,840 MW of utility-scale PV, making China the world leader in deployed PV capacity (National Energy Administration (NEA), 2019b). Utility-scale PV capacity is concentrated in the solar-rich northwestern provinces of Shaanxi, Gansu and Qinghai, and the autonomous regions of Xinjiang and Ningxia (Fig. 3, left). In 2018, about 27% of PV output in China came from the northwest (Northwest China Energy Regulatory Bureau (NWCERB), 2019). However, the country's load centers are concentrated in the south and eastern parts of the country, creating a geographical mismatch between PV output and demand similar to the situation in Chile. Due in part to this geographical mismatch, about 12.6% of PV output was curtailed in China in 2015 (National Energy Administration (NEA), 2016), though curtailment has since fallen to about 3.0% of PV output in 2018 (National Energy Administration (NEA), 2019b). Curtailment has been and remains relatively high in the northwest: about 16% and 10% of PV output was curtailed in 2018 the Xinjiang and Gansu provinces, respectively (Fig. 3, right).

As of the Q3 2019, the total cumulative installed PV has reached 190,190 MW, of which 131,490 MW is utility-scale PV. Meanwhile, 1.9% (3250 GWh) of solar output has been curtailed, with 81.5% of curtailment occurring in northwest China. Regionally, curtailment in the Xinjiang, Qinghai, and Gansu provinces reached 8.9%, 5.8%, and 4.8% of solar output, respectively (National Energy Administration (NEA), 2019a).

PV curtailment in China stems primarily from system inflexibility, oversupply, and insufficient transmission capacity ((BNEF), 2017). The Chinese government is considering transmission system expansions that would connect solar and wind resources in the northwest to the southeastern load centers. In 2016, there were 3 ultra-high-voltage transmission lines that connected non-hydro renewable resources in the northwest to southeastern load centers (China Power, 2016; National Energy Administration (NEA), 2017). By the end of 2018, at least 20 ultra-high-voltage lines were in operation with at least 5 lines transmitting non-hydro renewable generation. These transmission system upgrades are part of a broader set of Chinese policies aiming to reduce PV curtailment (National Development and Reform Commission (NDRC), 2018).

Curtailment trends in China also illustrate how policy can drive trends in PV curtailment. In 2011, China implemented a nationwide feed-in tariff that offered the same value for PV output anywhere in the country. The fixed feed-in tariff provided an incentive to develop systems in the solar-rich northwest, where PV developers could maximize their revenue despite the relatively low value of marginal generation in the region. Ongoing investments in the northwest, supported by the feed-in tariff, resulted in local oversupply and PV curtailment. In part to address this issue, in 2013 China instead regionalized the feed-in tariff (Ye et al., 2017). The regional tariff provides higher compensation rates to PV systems sited in the populous south and eastern provinces and lower compensation rates to PV sited in the northwest. China is expected to transition towards a subsidy-free market by 2021.

2.3. Germany

By the end of 2018, Germany had about 46,000 MW of installed PV capacity – and reached about 49,170 MW at the end of 2019 – making Germany the leader among European countries in terms of installed PV capacity (Deign, 2019; ISE, 2020). Between 2009 and 2014, PV curtailment steadily increased from 0.01% of potential output in 2009 to about 0.74% of potential output in 2014, before falling back to just 0.3% of potential output in 2018 (BMWi, 2018, 2019; ISE, 2019). Renewable curtailment in Germany is primarily driven by grid congestion. In 2018, 74% of curtailment took place in the distribution network, with the remainder occurring in the transmission network (Bun-desnet-za-gen-tur, 2018).

PV curtailment in Germany is relatively low compared to U.S. states with similar levels of PV penetration. This relatively low PV curtailment in Germany may reflect unique deployment trends and policies that discourage curtailment. The vast majority of German PV capacity is distributed, in contrast to other comparably-sized markets such as California where more than half of PV capacity is utility scale. Since 2012, small-scale (<10 kW) PV systems are required to be equipped with remote controls allowing system operators to curtail the system (system owners can alternatively choose to limit power exported to the grid to 70% of the system's rated capacity) (McLaren, 2015). As a result, system operators can remotely control and curtail distributed PV, which accounts for the majority of PV curtailment in Germany, whereas in California only utility-scale PV is typically curtailed. Additionally, Germany requires grid operators to compensate PV system owners for 95% of their revenue losses due to curtailment up to 1% of curtailed PV output, and for 100% of revenue losses for any losses above 1% curtailment. This compensation rule effectively penalizes curtailment at the feed-in tariff rate, making curtailment relatively costly in Germany. In contrast, the cost of curtailment in California is equal to a compensation rate that is defined in the purchase contract. Further, since 2012, German law requires all PV systems to be equipped with advanced inverters that either reduce system output or shut systems down during high frequency events (McLaren, 2015). These high-frequency events may result in brief periods of curtailment. However, by making distributed PV systems more responsive to grid conditions, the advanced inverter requirements may contribute to the relatively low curtailment levels observed in Germany. The relationship between distributed advanced inverters and PV curtailment levels is a potential area for future research.

2.4. United States

The U.S. electric grid is a patchwork of regional and local markets and balancing areas that are reasonably proxied by state borders. For simplicity, we describe curtailment data and trends in four states: California, Texas, Arizona, and Hawaii.

2.4.1. California

At the end of 2018, about 23,200 MW of PV capacity was online in California, by far the most of any U.S. state (Perea et al., 2019). About 13,500 MW of that capacity is utility-scale and thus subject to PV curtailment. PV curtailment in CAISO is primarily implemented through

[2] The estimate of 6% curtailment includes both PV and wind. The authors confirmed that this level is a reasonable estimate of PV-specific curtailment through personal conversations with representatives from the Chilean Ministry of Energy and the National Electricity Coordinator (10/23/2019).

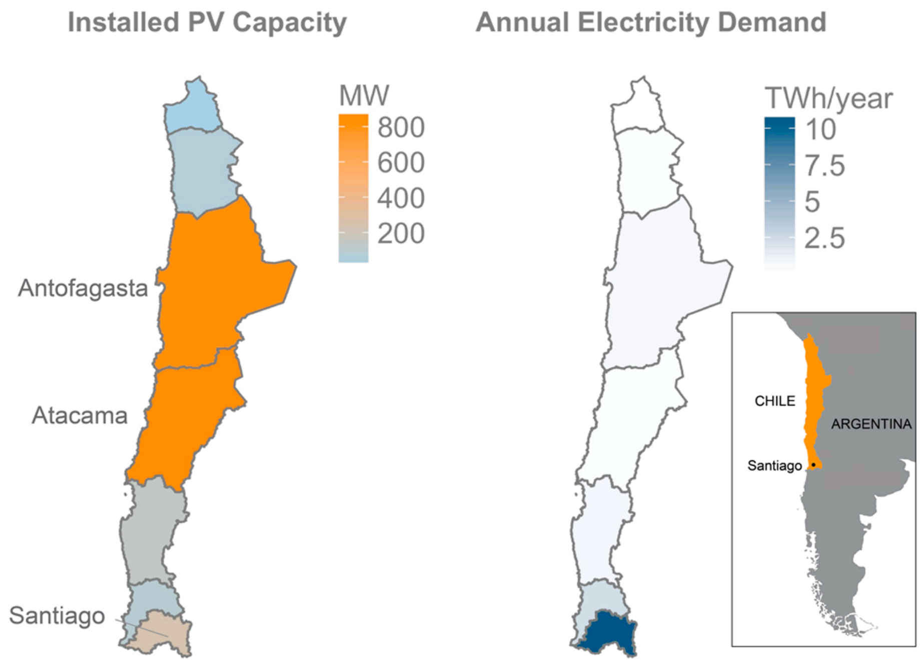

Fig. 2. Region-level installed PV capacity (left) and electricity demand (right) in Chile. Figure based on data from Energía Abierta (2019).

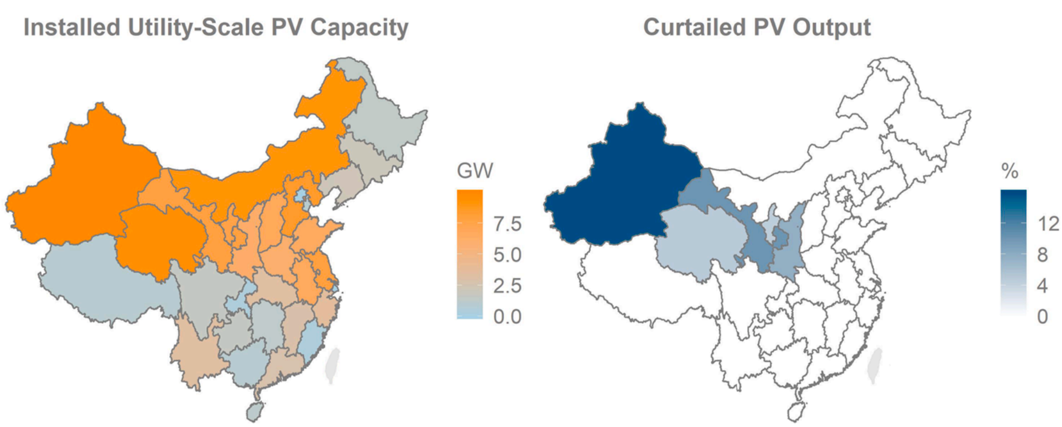

Fig. 3. Province-level installed PV capacity (left) and curtailment (right) in China, based on 2018 data.

negative pricing in the California Independent System Operator (CAISO) wholesale market. CAISO may also accept offers from generators to curtail at some level of compensation, known as decremental bids. These economic measures resolve the issue in the majority of cases (Hildebrandt et al., 2019). In rare events, CAISO manually curtails PV output when market signals do not resolve the system constraint (Hildebrandt et al., 2019).

California PV curtailment data were obtained from CAISO (2019a). The data are publicly available. According to these data, about 432,000 MWh of PV was curtailed in 2018, representing about 1.5% of potential PV output. PV curtailment in CAISO follows a seasonal pattern with peaks in the spring and fall (Fig. 4). Recently-published 2019 estimates suggest that PV curtailment significantly increased in 2019, to about 922,000 MWh or 3% of potential output (CAISO, 2019a). This increase is likely due to continued increases in PV capacity and generation coupled with increased hydroelectric generation from a wetter / snowier winter as compared with previous years (Maloney, 2019; Roselund, 2019).

The seasonal curtailment cycle illustrated in Fig. 4 is the result of a slight temporal mismatch between annual PV output and electricity demand cycles. PV output peaks in the early summer around the summer solstice. However, system load tends to peak in the late summer when high temperatures increase demand for energy-intensive air

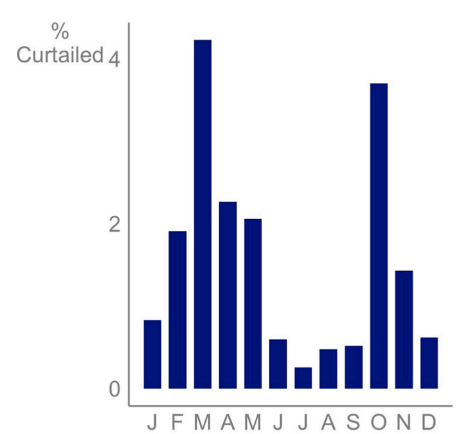

Fig. 4. Percentage of potential PV output curtailed by month in California in 2018.

conditioning. This temporal mismatch creates the conditions for PV oversupply events in the late spring when PV output is approaching its peak but load remains relatively modest. These oversupply events can result in negative pricing and curtailment. The potential oversupply situation is exacerbated by the fact that the state's hydroelectric capacity peaks from February to June (Hildebrandt et al., 2019). A similar situation occurs in the fall when cooler temperatures reduce demand for air conditioning, but PV output remains relatively high. By late summer, electricity demand is generally sufficient to absorb high levels of PV output, resulting in relatively low curtailment. In the winter, PV output is low enough that the system can generally absorb PV output even if electricity demand is relatively low.

CAISO wholesale market prices reflect the intersection of supply and demand over most of California and several neighboring states. As a result, PV curtailment events tend to be systemwide rather than localized, and curtailment is not limited to transmission-constrained portions of the balancing area. In 2018, at least some PV was curtailed on 152 grid nodes in California (Fig. 5). More PV was curtailed on nodes with higher PV capacity: about 61% of PV curtailment occurred on 10 nodes with relatively high PV penetration. In terms of percentage of potential output, curtailment was relatively evenly distributed across the nodes: curtailment was between 0.1% and 5% of potential output on 66% of the nodes. However, local curtailment was high relative to the statewide average on some nodes, exceeding 5% of potential output on about 8% of nodes and 10% of potential output on 4% of nodes.

Relative to other high-PV penetration U.S. markets like Hawaii and Texas, PV curtailment remains relatively low in California. This lower PV curtailment in California is attributable, in part, to the large size of the CAISO balancing area. Furthermore, in 2014, CAISO extended the range of its balancing area through the creation of a regional energy imbalance market (EIM). The EIM allows balancing areas outside of CAISO to voluntarily trade in the CAISO real-time market. Curtailment reduction was one of the key objectives and outcomes of the EIM (Hildebrandt et al., 2019). Fig. 6 illustrates how CAISO effectively uses the EIM to accommodate high PV output levels. Imported generation increases in the morning to meet electricity demand during the morning peak. The imported generation profile is then roughly the inverse of the PV output profile for much of the day. Conceptually, CAISO is using imports as a source of flexible generation, though all of the dispatch is achieved through market pricing. The ability to scale imports back to make room for PV output allows CAISO to reduce PV curtailment. CAISO estimates that the EIM has avoided more than 900,000 MWh of renewable energy curtailment since its inception (CAISO, 2019b).

2.4.2. Texas

Texas has seen a boom in utility-scale PV in recent years. Cumulative installed utility-scale PV capacity in Texas increased from about 410 MW in 2015 to 2,400 MW installed by the end of 2018, with 863 MW installed in 2018 alone (Perea et al., 2019). This PV deployment has concentrated in the southwestern portion of the state, where a strong solar resource and growing electricity needs from industrial development are driving PV investments (Electric Reliability Council of Texas (ERCOT), 2018). Significant wind capacity also exists in this portion of the state. The clustering of these PV and wind projects along with insufficient transmission capacity connecting the region to load centers has depressed locational marginal prices in the area and, in some cases, caused negative pricing and PV curtailment (Fig. 7).

We derived PV curtailment estimates from publicly-available security constrained economic dispatch data from the Electric Reliability Council of Texas (ERCOT), the state's wholesale market operator (Electric Reliability Council of Texas (ERCOT), 2019). For each 15-minute interval and for each system we calculated the difference between what the PV generator could have generated based on the high-sustained limit and what the PV generator actually generated based on telemetered net output. In some cases, the calculated differences were trivial and likely due to noise in the reported data. To identify true curtailment, we identified cases where the difference between possible and actual output was greater than 10% and the possible output was greater than 10% of the PV generator's capacity.[3]

We estimate that about 8.4% of potential PV output was curtailed in Texas in 2018. Similar to California, PV curtailment peaks in the spring, with an estimated 17% of potential output curtailed in May. These data suggest that PV curtailment in Texas follows similar patterns as observed elsewhere, with curtailment peaking on days with strong PV output but relatively modest load. Unlike California, there is no pronounced curtailment peak in the fall.

2.4.3. Arizona

At the end of 2018 about 2,000 MW of utility-scale PV was online in Arizona (Perea et al., 2019). Representatives from three Arizona utilities interviewed for this study stated that local PV systems have not caused local constraints that merit curtailment. All current PV curtailment in Arizona, to our knowledge, is the result of economic responses to negative pricing in the CAISO EIM. Arizona Public Service (APS), the largest electric utility in Arizona, participates in the EIM. APS tends to be a net importer on the EIM in the first half of the year and a net exporter in the second half (Fig. 8). In the first half of the year, particularly in the spring, APS tends to import during the midday when plenty of low-cost California PV is on the system. If midday EIM prices are negative, APS curtails its own PV systems, resulting in economic savings for the utility's customers. In other words, system constraints in CAISO are currently the sole driver of curtailment in Arizona. In the second half of the year, APS exports to CAISO in the midday and evening when wholesale market prices are relatively high in California, but net exports from APS to CAISO fall to near zero in the midday when PV generation depresses wholesale market prices.

In 2018, APS curtailed about 17,100 MWh of PV, or about 2.9% of potential PV output. Curtailment in APS follows roughly the same seasonal patterns as APS's EIM imports as well as curtailment in CAISO, with a pronounced peak in March and April and a lesser peak in October.

2.4.4. Hawaii

Hawaii presents a unique context for PV operation, curtailment, and grid balancing challenges. Each island is a separate grid with no interconnection to the other islands. System flexibility thus cannot be maintained through inter-regional transfers, as can be done on mainland grids. Hawaii also has the highest per-capita levels of distributed PV in the United States. Most of these distributed PV systems are fully behind the meter and thus beyond the control of Hawaiian utilities. As a result, Hawaiian utilities must frequently curtail utility-scale PV in response to local oversupply or other system constraints. Curtailment for oversupply generally follows a last-in first-out protocol, whereby the newest generators are curtailed first, and the oldest generators are curtailed last. Curtailment order when curtailment is needed to address system constraints depends on grid needs.

Curtailment data were obtained from public filings by the Hawaiian Electric Company's (HECO) Reliability Standards Working Group ((HECO), 2019b). The Working Group reports most PV curtailment in terms of event duration in hours rather than output (MWh). We therefore augmented the Working Group data by obtaining additional island-level renewable energy output and curtailment data from HECO quarterly reports ((HECO), 2019a) as well as renewable portfolio standard filings by HECO and the Kauai Island Electric Cooperative (HECO and KIUC, 2019). For Oahu, we estimated curtailment by dividing the reported curtailed MWh for all renewable sources by the ratios of solar-to-wind capacity and total curtailed dispatch times for each resource from the Working Group reports. The island of Hawaii reports MW outputs

[3] The validity of this methodology and the results were corroborated through personal conversations with representatives from the Electric Reliability Council of Texas.

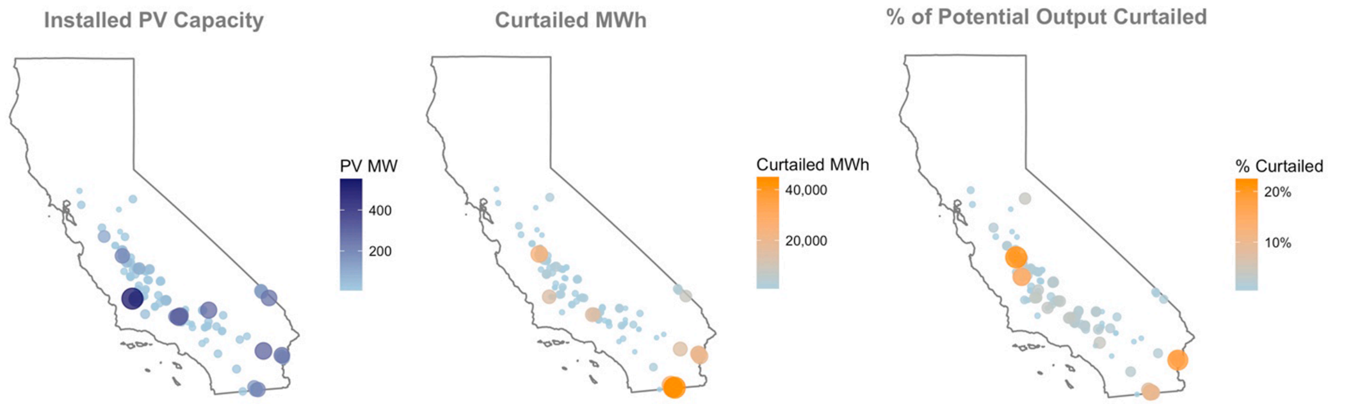

Fig. 5. PV capacity (left), curtailed MWh (center), and estimated curtailment as a percentage of potential output (right), by node in California in 2018. Nodal-level PV capacity and curtailed MWh are based on data provided by CAISO. Curtailment as a percentage of potential output is calculated using assumed PV generation levels based on nodal-level insolation profiles from the National Renewable Energy Laboratory (NREL) National Solar Radiation Data Base.

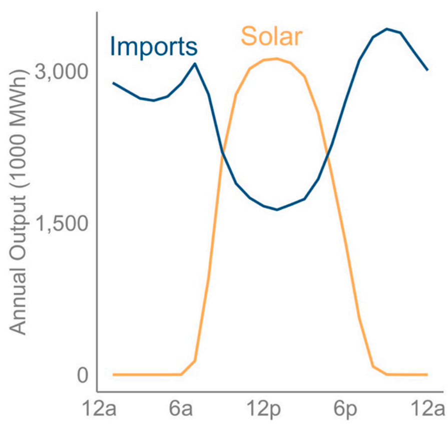

Fig. 6. Daily generation profiles in CAISO for PV and other generation resources.

before and after curtailment, from which curtailed MWh estimates can be made based on curtailed dispatch times. For Maui, though the Maui Electric Company generally reports curtailed MWh for each curtailment event, these estimates were missing for two of the months. The missing values were estimated using the curtailed dispatch time for the month and a curtailed energy per hour value averaged from the other months. Finally, for Lanai, the Maui Electric Company reports PV curtailment directly for the single utility-scale PV array on the island.

The resulting island-level curtailment estimates are shown in Table 2. We estimate that about 2.7% of potential Hawaiian PV output was curtailed in 2018. The state-level curtailment estimate is largely driven by the relatively low curtailment level on Oahu, the state's most populous island. However, significantly more PV is curtailed on the smaller islands of Lanai and Maui. Estimated curtailment is particularly high on Maui, an island roughly the size of Oahu but with a significantly smaller population.

Hawaiian PV curtailment follows roughly the same seasonal patterns as in California. On both Lanai and Maui—the islands with the highest PV curtailment—curtailment is lowest in the third quarter (July through August) when electricity demand is relatively high, and highest in in the second and fourth quarters, comparable to the seasonal patterns evident

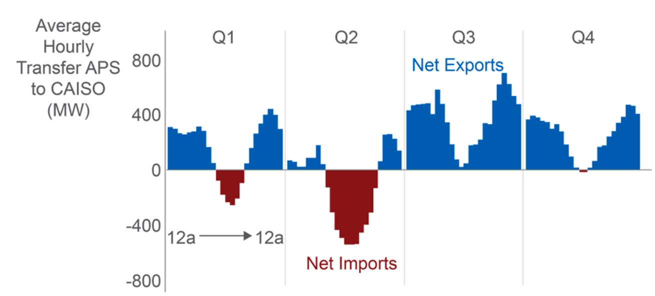

Fig. 8. Average hourly transfer from APS to CAISO in the EIM by quarter in 2018. Figure adapted by Hildebrandt et al. (2019).

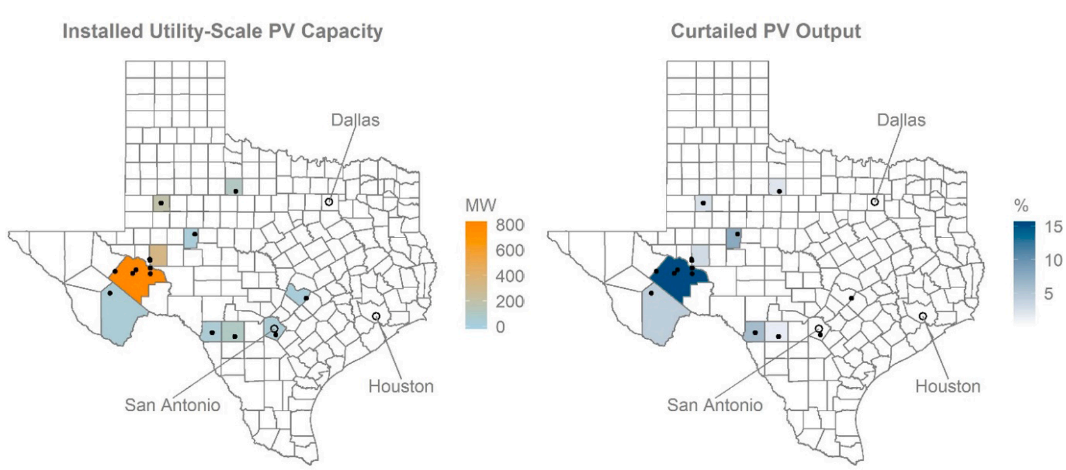

Fig. 7. Installed PV capacity (left) and curtailment (right) by county in Texas in 2018.

Table 2
Hawaiian PV curtailment estimates by Island.

Island	Utility PV Output (MWh)	Curtailed PV (MWh)	% Curtailed
Hawaii	3,924	22	<1%
Kauai	*	*	*
Lanai	1,344	136	9%
Maui	11,515	1,818	14%
Molokai	*	*	*
Oahu	132,366	2,094	2%
State Total	149,149[‡]	**4,071**	**2.7%**

[*] Data not available.
[‡] Percentage estimate excludes Kauai and Molokai, where curtailment data were not available.

in California and Texas.

2.5. Summary of key market curtailment trends

Three trends emerge from the curtailment data that are shared across multiple regions:

- *Policy and grid planning practices influence where, when, and how much PV is curtailed.* In China, the initial structure of the feed-in tariff contributed to increasing curtailment in the northwest provinces. In Germany, compensation requirements for curtailed output likely keep curtailment lower in Germany than it would otherwise be without those compensation requirements. In California, the EIM has reduced curtailment in California by, in part, shifting some PV curtailment into Arizona.
- *Geographical mismatches and limited transmission capacity can drive near-term PV curtailment.* Geographical mismatches are at least partially responsible for relatively high curtailment in Chile, China, and Texas. In each case, grid planners are pursuing measures to increase transmission capacity and reduce the curtailment caused by the geographical mismatches.
- *PV curtailment follows seasonal patterns*. PV curtailment tends to peak in the spring and fall, when PV output is relatively high but load is relatively low. High electricity demand for energy-intensive air conditioning is generally sufficient to absorb PV output and limit curtailment during the summer.

3. Available measures to address increasing curtailment

The literature suggests that at least four measures are effective at reducing PV curtailment: increasing grid flexibility; energy storage; load flexibility; and regional coordination (Table 3).

Flexibility refers to the ability of a grid to respond to changes in the supply and demand of electricity (Cochran et al., 2014). All else equal, a more flexible grid is able to accommodate more PV without resorting to curtailment than a less flexible grid. Increasing grid flexibility is therefore a way to effectively manage curtailment. Flexible generators such as natural gas and hydropower can be quickly and efficiently ramped up and down to respond to supply/demand changes due to variable generation (Cochran et al., 2014). Cole et al. (2016) find that increased natural gas capacity could reduce renewable energy curtailment by 25% relative to a reference scenario of 22% renewable energy penetration. Nelson and Wisland (2015) find that increasing the flexibility of natural gas plants—such as through decreasing their minimum power level—could reduce curtailment by about 37% relative to a reference scenario with 50% penetration in California. Finally, (Perez et al., 2019) find that the minimal use of natural gas (5% of generation) to provide load flexibility in Minnesota could reduce PV oversizing / curtailment and achieve cost reductions below current market price. However, it should be noted that the use of natural gas to reduce PV curtailment may be incompatible with clean energy mandates or objectives. Hence, even if natural gas-based flexibility could reduce PV curtailment, achieving

Table 3
Grid-level curtailment management measures.

Measure	Description	Pros (+) / Cons (−)
Grid flexibility	Investments in flexible assets that allow the grid to respond more effectively to changes in PV supply.	+ Can leverage existing grid assets; PV systems can provide their own flexibility − Some flexible assets (e.g., natural gas generators) may be incompatible with clean energy mandates or objectives
Energy storage	Energy storage devices can store and shift PV output according to grid needs.	+ Energy storage, particularly batteries, can provide a variety of grid services. − Batteries currently entail high up-front costs.
Load flexibility	Flexible loads could be planned or shifted to absorb excess PV output.	+ Could be a cost-effective use of low-cost PV electricity. − Load flexibility relies on voluntary enrollment and actions of disparate grid actors.
Regional coordination	Larger coordinated systems can manage PV output to reduce curtailment.	+ Regional coordination has already proven effective for reducing curtailment (e.g., CAISO) − Limited by transmission constraints and challenges associated with building new transmission

high renewable energy targets may require accepting higher levels of curtailment or relying on other grid flexibility measures (Jenkins et al., 2018).

Increasing grid energy storage capacity could reduce oversupply risk and increase grid flexibility, thus reducing the need for PV curtailment (Lian et al., 2019; Nelson and Wisland, 2015; Solomon et al., 2019). During potential oversupply events the otherwise curtailed PV output can be stored and re-dispatched later in the day, obviating the need for curtailment.[4] Denholm et al. (2016) show that adding 4000 MW of storage to the Florida grid could avoid more than 3 million MWh/year of PV curtailment at PV penetration levels above 25%. Similarly, Hledik et al. (2018) estimate that adding 1000 MW of storage capacity to the Nevada grid could reduce renewable energy curtailment by 50%. Besides pairing with stationary batteries, variable electricity generation can also be stored in renewable methane and reused for electricity generation through a "power to gas" approach (Vandewalle et al., 2015). However, the avoided costs of curtailment must be weighed against the capital costs of battery storage investments (Putnam and Perez, 2018).

Load flexibility is another tool for increasing grid flexibility and managing curtailment. Demand response—a common form of load flexibility—has historically been deployed to reduce loads during critical peak demand periods. However, demand response could also be deployed to *increase* loads during oversupply events to mitigate PV curtailment (Golden and Paulos, 2015). For instance, demand response programs could control electric water heaters to use otherwise curtailed PV output to heat water. Electric vehicle chargers could similarly be leveraged to charge electric vehicles during potential curtailment events. Smart thermostats are another common demand response resource. However, smart thermostats are less likely to be effective in managing PV curtailment given that curtailment tends to peak on days when air conditioning loads are relatively low. Load flexibility could also be leveraged on an industrial scale. For instance, otherwise curtailed PV output could provide a low- or no-cost input for intermittent industrial processes such as hydrogen fuel production and desalination.

[4] At least some PV output is lost, generally on the order of 20%, when PV is stored and re-dispatched. From a grid perspective, the round-trip efficiency losses associated with storage represent curtailed PV output. Thus storage of PV output cannot fully eliminate curtailment.

Capitalizing on low- or no-cost PV for industrial processes is a suggested area for future research.

Finally, regional coordination can reduce the need for PV curtailment because, all else equal, larger systems are more reliable and more flexible (Golden and Paulos, 2015). In some cases, regional coordination is not possible, such as on remote islands. But in other cases, regional coordination can be enhanced through increased regional transmission capacity (e.g., Chile, China) or simply through market measures (e.g., California EIM).

4. PV curtailment in evolving grid and technological contexts

Curtailment has generally been defined as any situation in which a variable generator (e.g., PV) generates less than its potential output (Bird et al., 2016). Further, PV curtailment has often been framed as a loss, given that effectively free electricity goes unused (Henriot, 2015). PV curtailment often represents foregone opportunities to reduce the emissions intensity of the grid. Curtailment reduces PV project economics and could hinder future PV deployment by reducing the ability of developers to finance their projects (Golden and Paulos, 2015). As a result of these perceived negative impacts, curtailment is frequently discouraged, such as through rules that require compensation for curtailed output (e.g., German Renewable Energy Act) or through interconnection rules that effectively prohibit systems that would result in curtailment.

However, changing grid and technological contexts require a reexamination of the definition of curtailment and its stigma (Table 1). In the grid context, it is increasingly clear that curtailment prevention is not a viable or cost-effective option on grids with high PV penetration (Baltensperger et al., 2017; Nelson et al., 2018; Nelson and Wisland, 2015; Sterling et al., 2017). Beyond some critical PV penetration it becomes more efficient to seek an optimal rather than a minimal level of curtailment (Henriot, 2015; Klinge Jacobsen and Schröder, 2012; Olson et al., 2014; Putnam and Perez, 2018; Schermeyer et al., 2018; Solomon et al., 2019). In the technological context, emerging technologies such as advanced inverters and low-cost battery storage are making PV systems more flexible and capable of providing non-generation services (Ghosh et al., 2017; Loutan et al., 2017; Luthander et al., 2017; Nelson et al., 2018; Sterling et al., 2017), and various national policies increasingly require these advanced capabilities (e.g., FERC Orders 827 and 828 in the United States). Grid and market customs that aim to prevent PV curtailment may undercut the ability of grid operators to use PV to provide non-generation services.

As PV curtailment becomes an increasingly common and perhaps *valuable* component of PV deployment, grid operators and planners may need to shift from a stance of curtailment prevention toward curtailment management. (Tabone et al., 2016) find that PV can provide additional reserves (up and down) by curtailing less than 5% generation in California grid system. Nelson et al. (2018) provide a modeling case study of how actively managed curtailment can increase the value of PV to the grid, increase the amount of PV on the grid, and (paradoxically) reduce the share of PV that is curtailed.

Looking forward, PV curtailment is likely to increase in the near and long term. Indeed, about 8% of potential PV output was curtailed in California in the first five months of 2020—though this significant increase is at least partially due to depressed demand associated with the coronavirus pandemic (St. John, 2020)—and PV curtailment has recently emerged in new markets such as Australia and Japan. Further, an increasing number of countries and states are committing to high levels of renewable energy, with targets often exceeding 80% of generation derived from renewables. PV—given its increasingly attractive economics—is likely to play a crucial role in meeting these targets. PV curtailment will likely increase as PV deployment outpaces deployment of measures to curb curtailment—such as battery storage and industrial uses (e.g., hydrogen fuel production). Even with expansions of curtailment management measures, curtailment will likely become increasingly commonplace on future grids with high levels of renewable energy penetration (Jenkins et al., 2018). There are numerous open questions on the future trajectory of PV curtailment. Future researchers could study the geographic, technological, and temporal factors that will determine future PV curtailment trends.

5. Conclusion

In 2018, more than 1% of potential PV output was curtailed in Chile, China, and several U.S. markets (Arizona, California, Hawaii, Texas). PV curtailment is likely to increase in these and other markets as PV penetration increases. At the same time, increasing grid flexibility and technological advances such as low-cost battery storage could obviate some future PV curtailment.

Differences in regional PV curtailment levels primarily reflect differences in policy and grid planning practices, geographical constraints, and seasonal cycles. Policy and grid planning practices can influence where, when, and how much PV is curtailed. For example, the California EIM resulted in some shifting of PV curtailment from California into Arizona. In terms of geographical constraints, limited transmission capacity between solar-heavy regions and load centers is a key driver of PV curtailment in regions such as Chile, China, and Texas. In each case, grid planners have responded with initiatives to increase transmission capacity connecting the solar resources to load centers. Finally, seasonal cycles explain curtailment patterns to varying degrees in different markets. Curtailment tends to peak in the spring and fall when PV output is relatively high but electricity demand is relatively low.

Curtailment is generally framed as a loss, and various grid and market customs discourage PV curtailment. However, changing grid and technological contexts are forcing a re-examination of PV curtailment and its stigma. In the grid context, as grids reach higher levels of PV penetration it becomes more efficient to emphasize an optimal rather than a minimal PV curtailment level. In the technological context, emerging technologies such as advanced inverters may allow grid operators to withhold PV output to provide a variety of grid services such as capacity reserves and frequency regulation. Grid and market customs that discourage curtailment could undercut the ability of grid operators to utilize PV to provide these ancillary services. A shift in thinking toward curtailment *management* rather than prevention could increase the value of delivered and curtailed PV output to the grid. Various grid flexibility measures—including flexible generation, storage, load flexibility, and regional coordination—could be key components of a curtailment management scheme.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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