Solar PV Curtailment in Changing Grid and Technological Contexts

Preprint

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SUMMARY

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. At increasing levels of PV penetration situations arise where PV is curtailed, either because of local supply/demand imbalances or to maintain system flexibility. In this paper, we present a novel synthesis of recent 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 PV curtailment peaks in the spring and fall, when PV output is relatively high but electricity demand is relatively low. Similar to the case of wind, some PV curtailment is attributable to limited transmission capacity connecting sparsely populated solar-heavy regions to load centers.

Grid policies generally seek to minimize curtailment because it is viewed as an economic and environmental loss. However, changing grid and technological contexts warrant new thinking on PV curtailment. In the grid context, as grids integrate more PV and other renewable energy generation, seeking an optimal level of accepted curtailment becomes more efficient than preventing it. In the technological context, emerging technologies such as advanced inverters and low-cost battery storage are making PV systems more flexible. With flexible PV, grid operators can use withheld PV output to provide various non-generation grid services. This withheld PV output is a form of curtailment under prevailing definitions of the term. Hence, policies that aim to minimize curtailment may undercut the ability of grid operators to fully use the emerging capabilities of flexible PV systems. As a result, we propose a more exclusive definition of curtailment as unused PV output rather than the more expansive conventional definition as any reduction in system output from its technical potential. The terminological distinction is more than a question of semantics. Facilitating grid services by withholding PV output may increase the potential value of flexible PV systems to the grid.

This shift in thinking may allow grid operators and policymakers to think in terms of PV curtailment management rather than minimization. Effective curtailment management may include policies that increase PV system dispatchability, alternative PV compensation schemes that decouple generator revenue from system output, and policies to increase grid flexibility.

KEYWORDS

solar photovoltaics, curtailment, flexibility, dispatch, system constraints, grid policy

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1. Introduction

Solar photovoltaic (PV) systems generate electricity with no marginal costs or emissions. As a result, PV output is almost always prioritized over electricity from other forms of generation and delivered to the grid. At increasing levels of PV penetration, there arise situations where the grid cannot handle additional PV output for technical or economic reasons. These situations may result in unused or "curtailed" PV output. Curtailment is generally defined as situations where a variable renewable energy generator, such as a PV plant, generates less electricity than its technical potential [1]. Curtailment is an industry term of art used to distinguish unused variable renewable energy output from unused potential output from a dispatchable generator such as a natural gas plant. The key difference is that when variable output is unused the potential electricity is lost forever, whereas unused output from a dispatchable generator represents unused fuel that can be burned to generate electricity at a later time [2]. PV curtailment is becoming increasingly common as more PV capacity comes online. We estimate that in key markets such as Chile and China as well as certain parts of the United States (Arizona, California, Hawaii, and Texas), more than 1% of potential PV output was curtailed in 2018.[1]

PV curtailment is often framed as a loss given that effectively free and clean electricity goes unused [1, 3]. Curtailment may also undermine PV project economics and could hinder future PV deployment [1, 4]. As a result of these negative effects, grid policies generally aim to prevent PV curtailment. However, changing grid and technological contexts warrant a re-examination of the existing curtailment-prevention framework (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 levels of PV penetration [2, 5-7]. Beyond some critical level of PV penetration it becomes more efficient to seek an optimal rather than a minimal level of curtailment [3, 8-12]. 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 [2, 6, 13-15], and various national policies increasingly require these advanced capabilities (e.g., FERC Orders 827 and 828 in the United States). Policies that aim to prevent PV curtailment may undercut the ability of grid operators to use PV to provide non-generation services.

Table 1. Old and New Grid and Technological Contexts and Implications for PV Curtailment

	OLD CONTEXT	NEW CONTEXT
GRID	Low PV penetration	High PV penetration
	Curtailment is an avoidable loss	Curtailment is inevitable and, in some cases, desirable
TECHNOLOGICAL	PV output is variable	PV output is flexible
	PV systems only provide generation grid services	PV provides a suite of generation and non-generation grid services

In this paper, we explore PV curtailment in these changing grid and technological contexts. We begin in Section 2 with a background on the primary drivers of PV curtailment. In Section 3, we provide the first presentation PV curtailment estimates from four PV markets in the United States and key international PV markets. Based on the data and extant literature, in Section 4 we explore options to improve the management of PV curtailment. We conclude our paper in Section 5.

[1] Though the focus of this study is on PV, much of the discussion on the drivers, implications, and management of curtailment is also applicable to wind energy. For further discussion on wind curtailment, see Bird et al. (2016).

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2. Background

Most modern grids operate under some form of constrained economic dispatch, maintaining system reliability and flexibility at the lowest possible cost. PV and other forms of renewable energy have two characteristics that determine their roles in constrained economic dispatches. First, PV is effectively a zero-marginal-cost generator. Second, conventional PV is mostly variable and cannot be dispatched to the same extent as a conventional generator such as a natural gas plant. In a constrained economic dispatch, variable PV output is either accepted or curtailed. Because of its zero-cost attributes, PV output is almost always accepted in a constrained economic dispatch and only curtailed when additional PV output could compromise system reliability.

To build some intuition around PV curtailment in a constrained economic dispatch, Figure 1 depicts an actual PV curtailment event in California in May 2018. As PV begins to come online at 6am, the logic of the constrained economic dispatch forces other higher-marginal-cost generators to scale back generation to maintain system reliability, particularly imports. On this particular day, about 87,000 MWh of PV output was delivered, but about 12,000 MWh was curtailed. Importantly, the figure shows that some PV output was curtailed even as the system continued to dispatch less flexible baseload generators such as nuclear and thermal plants (e.g., coal).

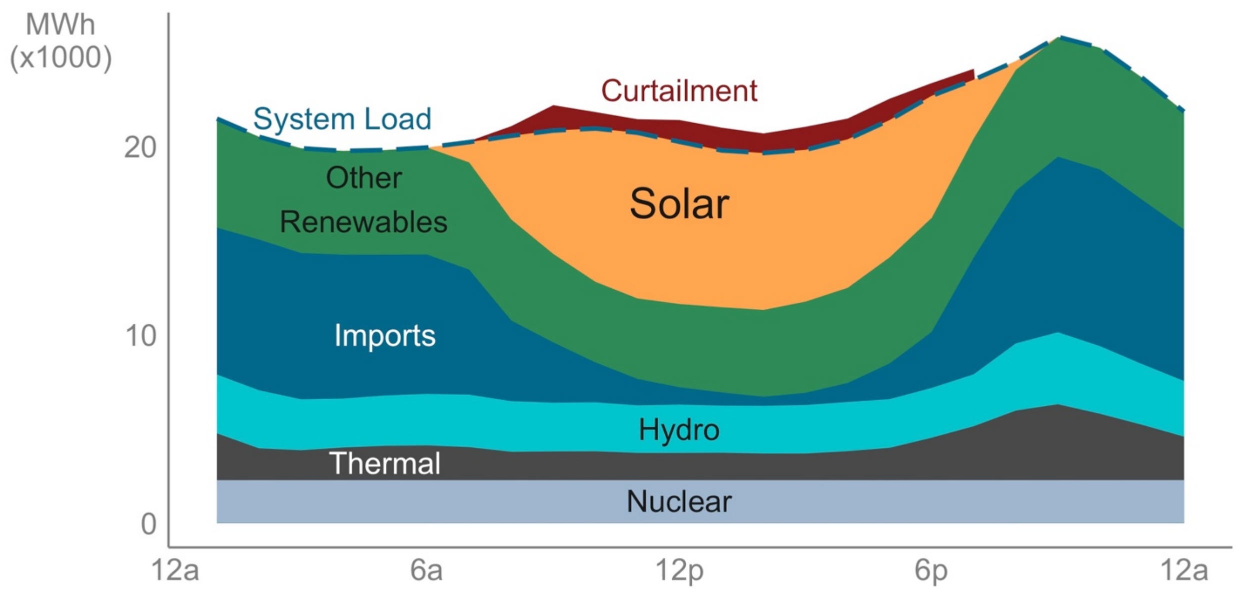

Figure 1. PV curtailment event on May 13, 2018 in California. Based on data from CAISO [16].

All PV curtailment ultimately stems from the need to maintain system reliability and flexibility. The curtailment literature generally breaks the drivers of PV curtailment events into two broad categories: 1) curtailment to resolve oversupply; and 2) curtailment to maintain grid flexibility.

Oversupply occurs when the sum of must-run baseload and variable electricity generation exceed demand on some node of the grid. In some cases, oversupply may be addressed by scaling back or increasing exchanges of electricity between nodes via transmission lines. This solution is clearly depicted in Figure 1, where the system nearly eliminates imports in order to accommodate increasing PV output. However, if the supply/demand imbalance exceeds transmission line capacity, the risk of oversupply will force the grid to shed some generation. Under the logic of a constrained economic dispatch, the grid will shed higher-marginal-cost generators first, either through direct commands by the utility or through wholesale market price signals. This is illustrated in Figure 1, where output from thermal plants drops from about 1,850 MWh at 6am to about 1,460 MWh by 1pm. If the oversupply is deep enough, the system will scale back

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all of its flexible generation and begin curtailing variable generators such as PV. Some baseload generation (e.g., nuclear, coal) typically remains online either because these generators face high ramping costs or they provide essentially system reliability services. Figure 1 shows how about 3,800 MWh of nuclear and thermal generation was delivered at 9am even as about 1,350 MWh of PV was curtailed.

All else equal, the risks of oversupply increase as more PV is integrated onto the grid [6, 17]. As PV is integrated onto some node of the grid, PV begins to meet more and more of the midday load, reducing the remaining "net" load left to be served by baseload generation at that node. As more PV is integrated onto the node, the risks of oversupply increase at that node, increasing the risks of PV curtailment. PV curtailment due to local oversupply is therefore generally only observed on grids with relatively high levels of PV penetration.

A grid's flexibility determines the grid's ability to accommodate increasing levels of PV capacity [5, 17, 18]. All else equal, a more flexible grid can technically and economically integrate more PV. Existing grids were not necessarily designed with enough flexibility to accommodate high levels of variable renewable energy output. At high levels of PV penetration, existing grid flexibility measures may be insufficient to respond to fluctuations in variable PV output [5, 17]. In these cases, grid operators may resort to PV curtailment to maintain system flexibility.

Curtailment has generally been defined as any situation where a variable generator (e.g., PV) generates less than its potential output [1]. We argue that the changing grid and technological contexts warrant a re-examination of this definition. Advanced inverters and battery storage can allow PV systems to provide non-generation grid services [2, 6, 13-15]. Under the prevailing definition of curtailment, PV output reserved for non-generation services would be considered curtailed. We argue that the term curtailment should not apply in cases where withheld PV output is used to provide grid services. In such cases, withheld PV output is not unused in the same sense as curtailed output in response to oversupply or system flexibility constraints. Rather, the withheld PV output provides value to the grid the same way as the withheld capacity of a conventional generator provides value. Applying the term curtailment in these cases may stymy the evolution of PV system operation toward the provision of a broader set of grid services. For these reasons, we propose a more exclusive definition of curtailment as available PV output that is rejected or unused due to system constraints. We argue that available PV output that is purposefully withheld to provide non-generation services should be described using the same terminology of *dispatch* used to describe the non-generation services of any other generator.

3. PV Curtailment in Key Markets

For the reasons outlined in Section 2, PV curtailment generally only occurs on grids with relatively high levels of PV penetration. In the United States, such grids exist in California, Hawaii, and Texas. Curtailment also occurs in Arizona, though this curtailment is attributable to grid constraints in California. Internationally, significant levels of PV curtailment have also been recorded in Chile, China, and Germany, and to a lesser extent in Australia and Japan. Table 2 summarizes the curtailment trends in these areas. In this section, we explore the current state of curtailment on each of these grids.

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Table 2. PV Curtailment Statistics in Key PV Markets

Location	Installed Curtailable PV Capacity (MW)	Curtailed PV Output in 2018 (MWh)[b]	% of Potential PV Output that is Curtailed	Curtailment Drivers
United States				
California	13,500[a]	432,000	1.5%	System-wide oversupply
Texas	2,400[a]	270,000	8.4%	Oversupply due to clustering of PV projects
Arizona	2,000[a]	17,100	2.9%	Negative pricing in regional market
Hawaii	140	4,100	2.7%	Oversupply
Other Countries				
Chile	2,340[b]	150,000*	6%*	Regional transmission constraints
China	123,840[c]	5,490,000	3.8%	Regional transmission constraints
Germany	46,000[d]	116,470	0.3%	Grid congestion

[a] [19]; [b] [20]; [c] [21]; [d] [22] [e] Data sources are defined in each sub-section; * Based on 2016 estimated PV output from the International Renewable Energy Agency [23], estimate of 6% curtailment of all renewables—including wind [24].

3.1 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 therefore describe curtailment data and trends in four states: California, Texas, Arizona, and Hawaii.

3.1.1 California

As of the end of 2018, about 23,200 MW of PV capacity is online in California, by far the most of any state [19]. About 13,500 MW of that capacity is utility-scale and therefore, in theory, subject to PV curtailment. The constrained economic dispatch in California is implemented by a wholesale market administered by the California Independent System Operator (CAISO). PV curtailment in CAISO is primarily implemented through negative pricing. 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 [25]. In rare events, CAISO manually curtails PV output when market signals do not resolve the system constraint [25].

California PV curtailment data were obtained from CAISO [16]. 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. The left pane of Figure 2 depicts delivered and curtailed PV output by month in CAISO in 2018. The figure shows the intuitive annual pattern of total PV output with a peak in the summer months. The right pane of the figure depicts the percentage of potential PV output that is curtailed in each month. PV curtailment in CAISO peaks in the spring and fall and is relatively lower in the summer and winter.

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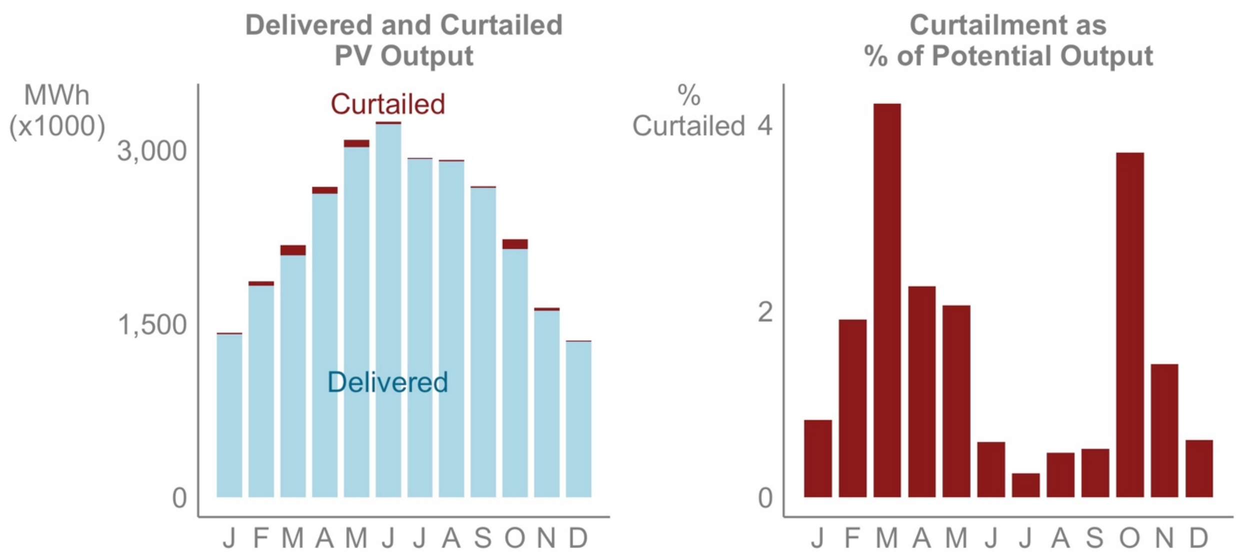

Figure 2. Delivered and curtailed PV output (left pane) and PV curtailment as a percentage of potential output (right pane) by month in California in 2018

The seasonal curtailment cycle illustrated in Figure 2 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 conditioning. As a result, the annual PV output and load cycles are slightly mismatched. 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 [25]. A similar situation occurs in the fall when cooler temperatures reduce demand for air conditioning, but PV output remains relatively high. In the late summer, high levels of electricity demand are generally sufficient to absorb high levels of PV output, resulting in relatively low levels of curtailment. In the winter, PV output is low enough that the system can generally integrate PV output even if electricity demand is relatively low. This seasonal pattern is evident in the other three states discussed in this section.

CAISO wholesale market prices reflect the intersection of supply and demand over most of California and several neighboring states through an energy imbalance market (EIM), discussed further below. 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 (Figure 3). 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.

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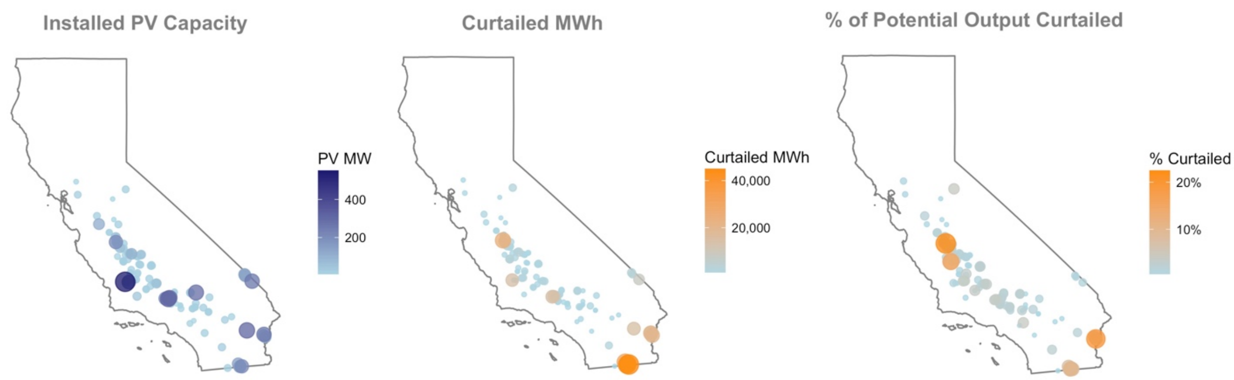

Figure 3. PV capacity (left pane), curtailed MWh (center pane), and estimated curtailment as a percentage of potential output (right pane), by node in California in 2018
Nodal-level PV capacity and curtailed MWh are based on data provided by CAISO. Curtailment as a percentage of potential output is calculated using assumed PV generation levels based on nodal-level insolation profiles from the National Renewable Energy Laboratory (NREL) National Solar Radiation Data Base.

Although CAISO PV curtailment is largely a system-level phenomenon, there is some geographic variation in curtailment due to the geographic locations of different PV systems. For instance, PV curtailment tends to begin and end slightly earlier in the east than in the west. Figure 4 illustrates this concept by splitting California into four geographic zones from east to west. In the early hours of the day, nearly all curtailment occurs in the far eastern portion of the state, where PV systems begin generating earlier than systems in the west. Curtailment generally becomes more balanced from east to west in the middle part of the day, with a subtle shift from curtailment in the east to curtailment in the west throughout the course of the day. Finally, in the early evening, there is a clear shift toward more curtailment in the western regions of the state as systems in the east come offline before systems in the west.

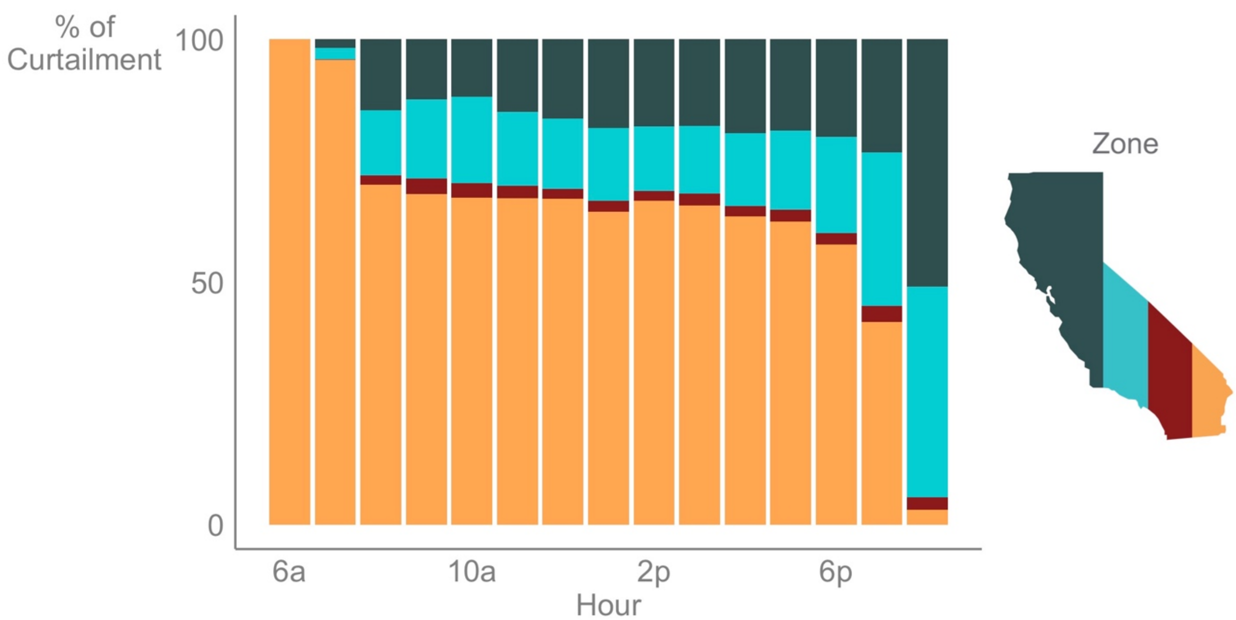

Figure 4. Percentage of curtailment occurring in different zones (east to west) of California by hour in 2018

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Relative to other high-PV penetration markets like Hawaii and Texas, PV curtailment remains relatively low in California. The relatively low levels of PV curtailment in California are attributable, in part, to the large size of the CAISO balancing area. Further, 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. Reduction of PV curtailment was one of the key objectives and outcomes of the EIM [25]. Figure 5 illustrates how CAISO effectively uses the EIM to accommodate high levels of PV output. 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 800,000 MWh of renewable energy curtailment since its inception.

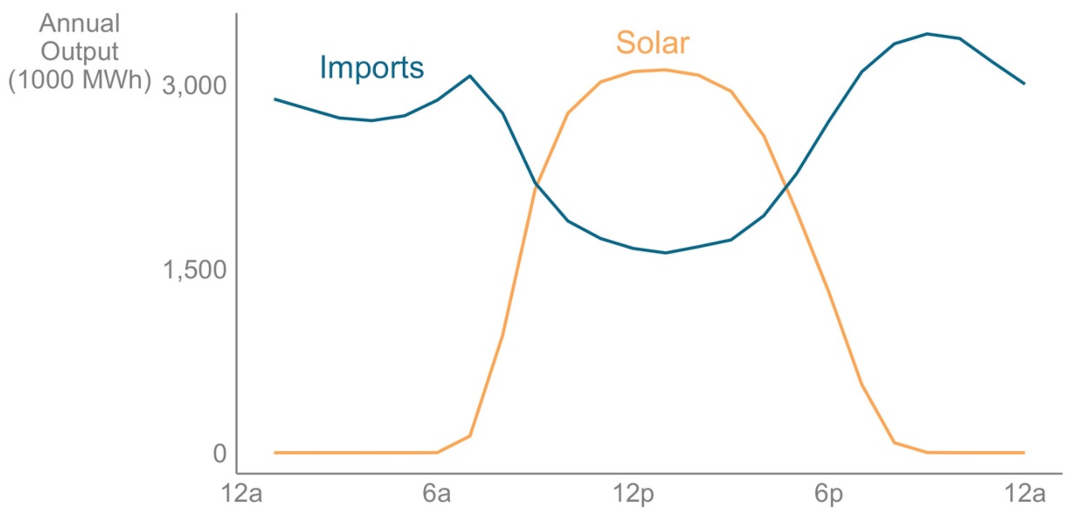

Figure 5. Daily generation profiles in CAISO for PV and other generation resources

3.1.2 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 [19]. This PV deployment has concentrated in the southwestern portion of the state, where a strong solar resource coupled with growing electricity needs from industrial development in the area are driving PV investments. The clustering of projects and limited transmission capacity connecting the region to load centers such as Dallas, Houston, and San Antonio has depressed locational marginal prices in the area and, in some cases, caused negative pricing and PV curtailment (Figure 6).

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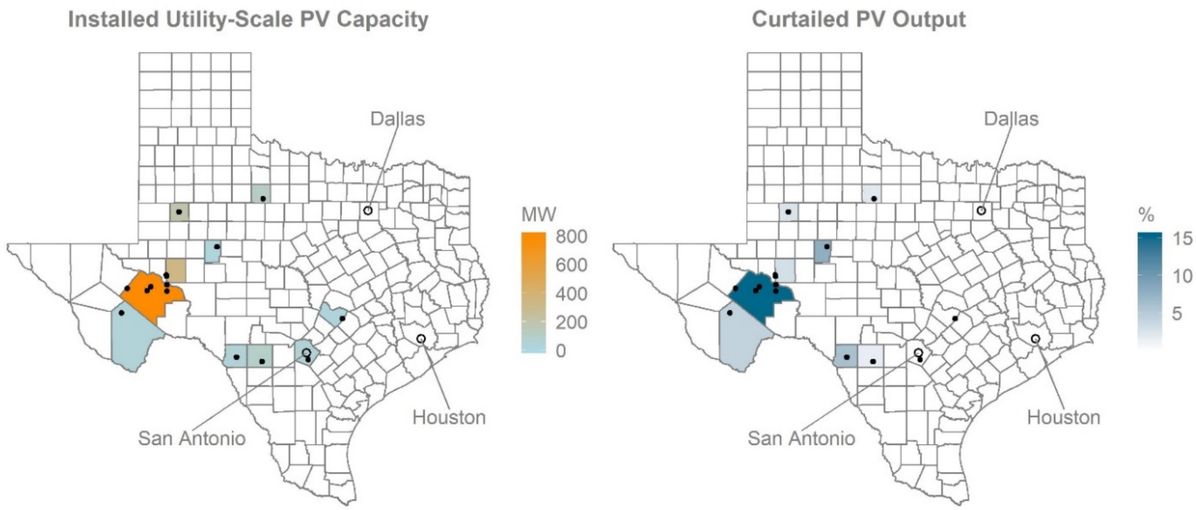

Figure 6. Installed PV capacity (left pane) and curtailment (right pane) by county in Texas in 2018

We derived PV curtailment estimates from publicly-available security constrained economic dispatch data from the Electric Reliability Council of Texas, the state's wholesale market operator. For each 15-minute interval 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.

Figure 7 illustrates curtailed and delivered PV output in Texas by month. Similar to California, PV curtailment peaks in the spring, with an estimated 17% of potential PV output curtailed in May. These data suggest that PV curtailment in Texas follows similar patterns as observed elsewhere, with PV curtailment peaking on days with strong PV output but relatively modest load. Unlike California, there is no pronounced curtailment peak in the fall.

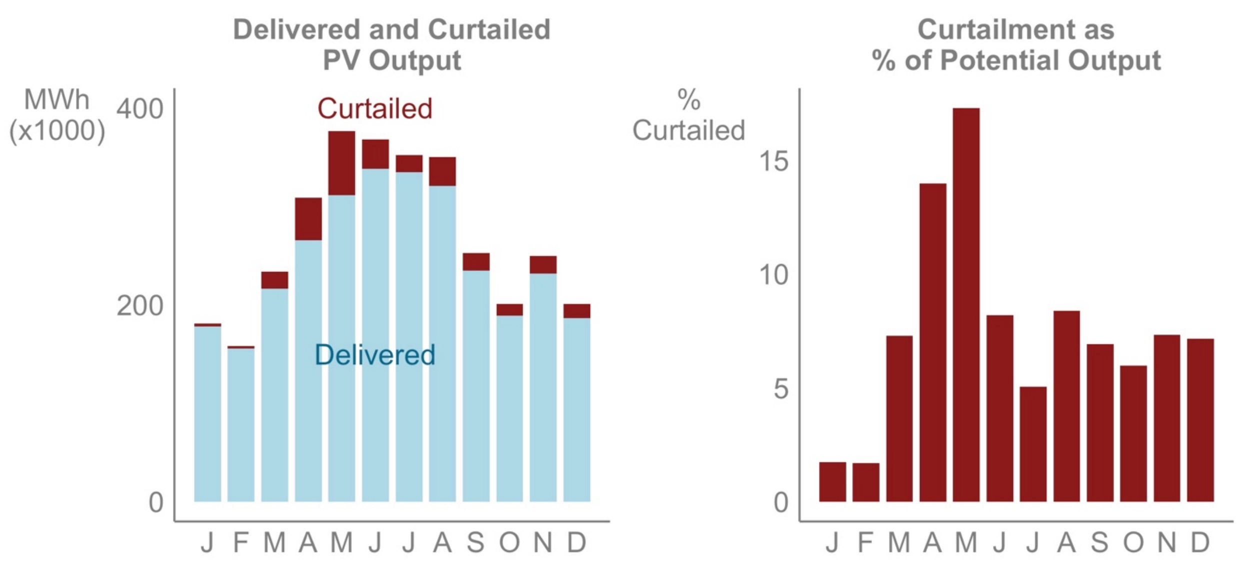

Figure 7. Delivered and curtailed PV output (left pane) and PV curtailment as a percentage of potential output (right pane) by month in Texas in 2018

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3.1.3 Arizona

As of the end of 2018 about 2,000 MW of utility-scale PV were online in Arizona [19]. Representatives from three Arizona utilities interviewed for this study stated that current levels of local PV penetration have not caused local constraints that merit PV 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 (Figure 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.

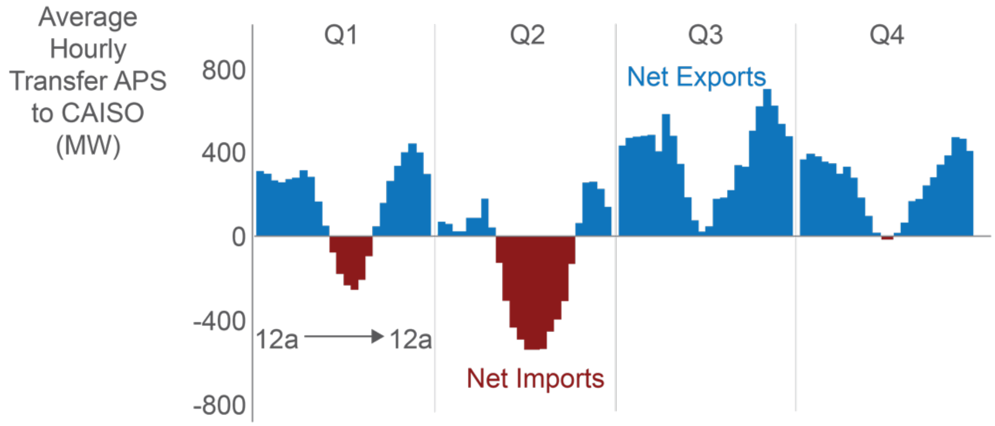

Figure 8. Average hourly transfer from APS to CAISO in the EIM by quarter in 2018

Figure adapted by Hildebrandt et al. [25].

In 2018, APS curtailed about 17,100 MWh of PV, or about 2.9% of potential PV output (Figure 9). 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. Figure 10 illustrates the direct relationship between PV curtailment in CAISO and in APS.

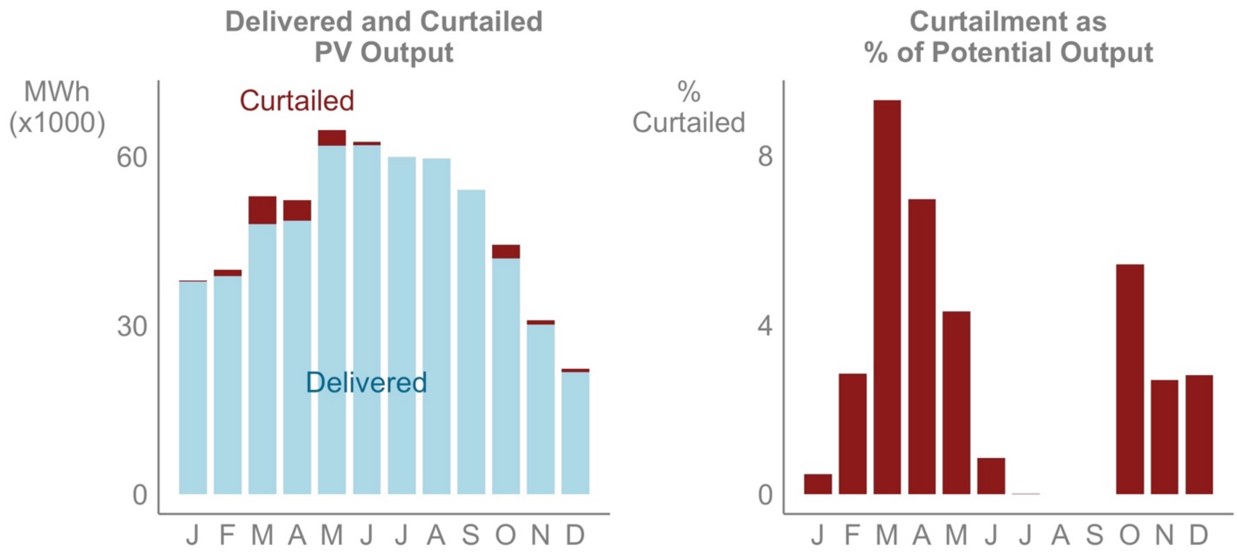

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Figure 9. Delivered and curtailed PV output (left pane) and PV curtailment as a percentage of potential output (right pane) by month in the APS service territory, 2018

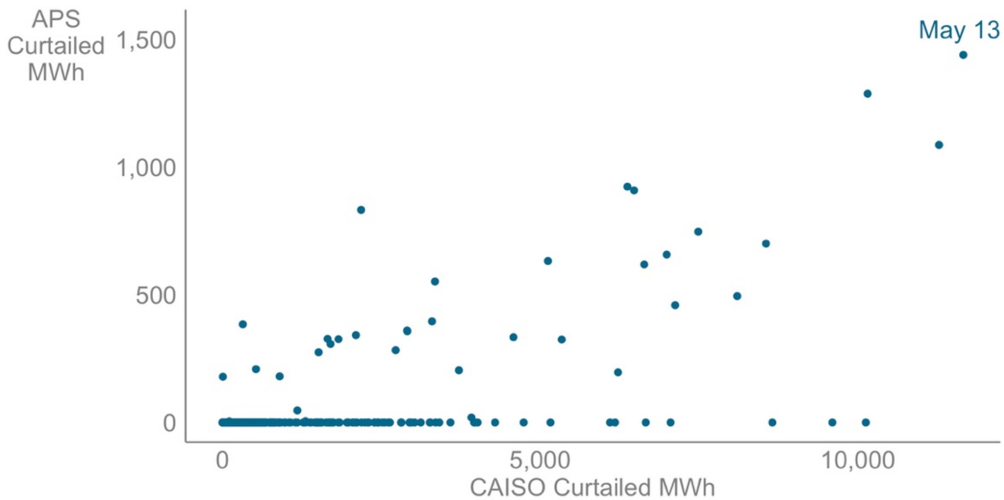

Figure 10. Relationship between CAISO and APS PV curtailment (MWh) for each day in 2018

3.1.4 Hawaii

Hawaii presents a unique context for PV operation, curtailment, and grid balancing challenges. Each island represents 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 country. Most of these distributed PV systems are fully behind the meter and thus beyond the control of Hawaiian utilities. As a result of these unique characteristics, 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.[2] The Working Group reports 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 quarterly reports compiled by the Hawaiian Electric Company (HECO), as well as renewable portfolio standard filings by HECO and the Kauai Island Electric Cooperative. For Oahu, PV curtailment estimates were derived 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 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 curtailed MWh and percentage values are shown in Table 3. We estimate that about 2.7% of potential Hawaiian PV output was curtailed in 2018. The state-level curtailment estimate is largely driven

[2] KIUC does not file these reports and thus solar curtailment data is not publicly available.

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by the relatively low curtailment level on Oahu, the state's most populous island. However, significantly higher levels of PV are curtailed in 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.

Table 3. 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.

Hawaiian PV curtailment appears to follow 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 in California and Texas (Figure 11).

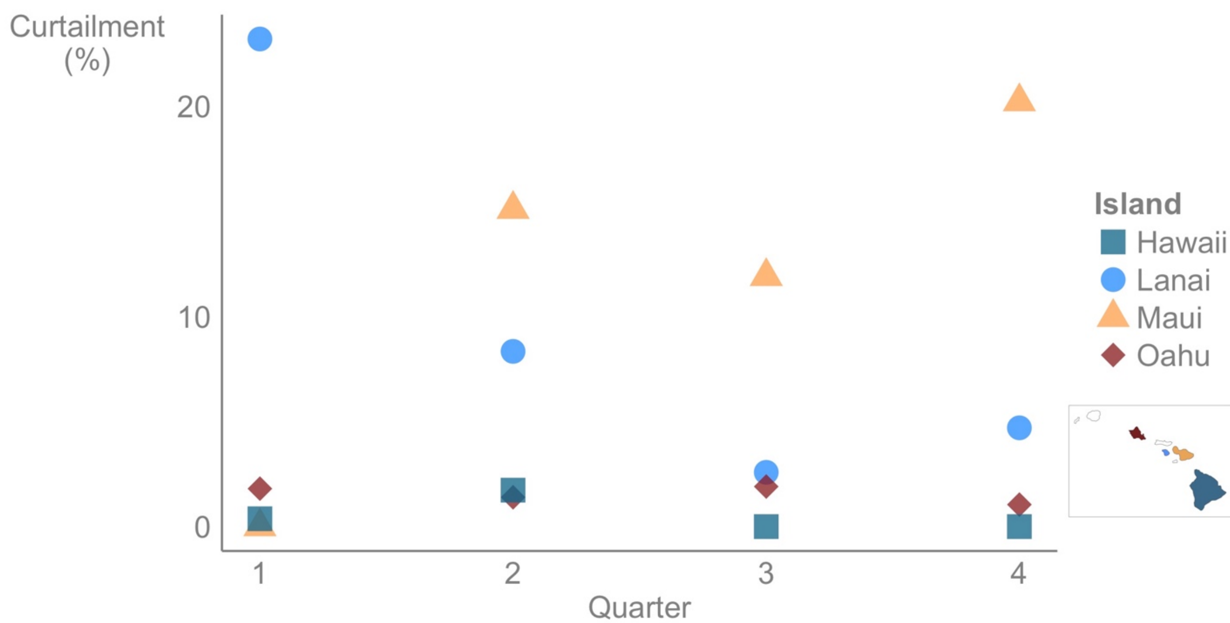

Figure 11. PV curtailment (% of potential output) by quarter by island in Hawaii

The island of Lanai offers a unique case study that may illustrate the future of PV curtailment on the Hawaiian Islands and mainland grids. Lanai is a small and completely independent grid serving a population of just over 3,000 people. Peak load on the island was about 5.4 MW in 2018, primarily met by around 10 MW of firm generation capacity. A 1.2 MW PV array came online in late 2008. However, the grid interconnection study for the project indicated that ramp rate control issues would affect grid reliability if the system operated at full capacity. As a result, the Maui Electric Company, the island's

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utility, limited the array's output to 600 kW until a suitable battery system could be developed—effectively curtailing around 20% to 40% of the system's potential output on an annual basis (Figure 12). In 2011, a 1.1 MW / 15-minute duration system was installed to support the PV array. The battery allows the PV array to operate at full capacity, however, as illustrated in Figure 12, curtailment levels remain relatively high on Lanai.

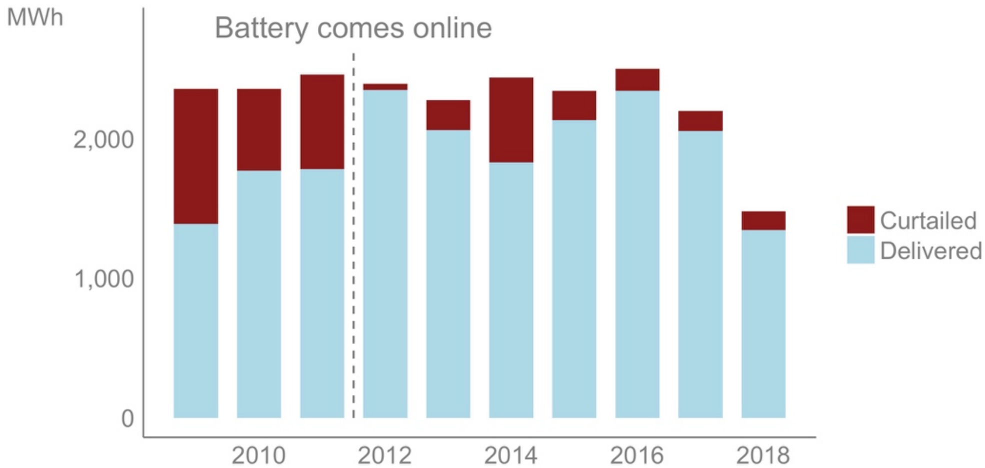

Figure 12. Estimated PV curtailment by year on the island of Lanai, Hawaii

Battery storage is frequently cited as a means to mitigate PV curtailment. Nonetheless, the Lanai case study illustrates that battery storage does not necessarily eliminate or even necessarily reduce curtailment: curtailed output in 2014 was about the same as curtailed output in 2010. In this case, Lanai deployed a relatively short-duration battery not necessarily designed to reduce curtailment. Nonetheless, the persistence of PV curtailment on Lanai illustrates that some degree of curtailment is inevitable on grids with high levels of PV penetration.

3.2 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 1,600 MW online by the end of 2018 [20]. However, the strong solar resource is far from the nation's primary load center in Santiago (Figure 13). There is currently no transmission capacity linking Antofastaga to the rest of the country, leaving more than 800 MW of PV capacity isolated from the large load centers to the south [26]. Further, there are currently only three 220 kV transmission lines linking Atacama to the rest of the system [26]. Limited transmission capacity between the northern regions and Santiago is expected to drive increasing levels of PV curtailment in Chile [27]. There are also local transmission constraints around Santiago that contribute to PV curtailment [28]. Curtailment of all renewables—including wind—increased from about 2% of potential output in 2016 [28] to about 6% of output in 2018 [24].

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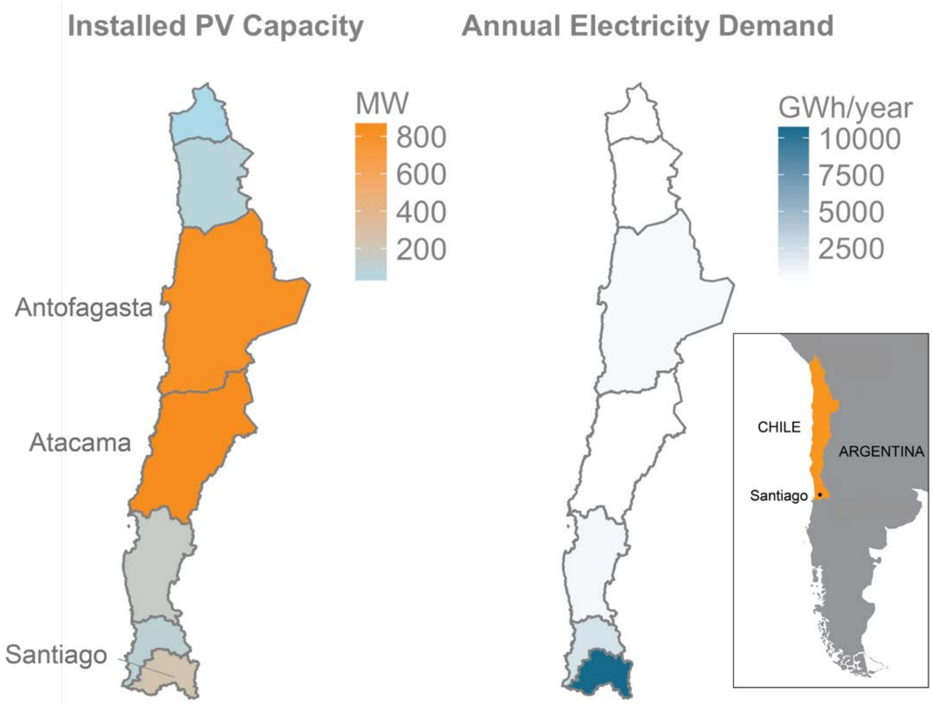

Figure 13. Region-level installed PV capacity (left pane) and electricity demand (right pane) in Chile. Figure based on data from Energía Abierta [20].

Ongoing transmission system expansions may alleviate PV curtailment in Chile [27]. The country is building more than 600 kilometers of high-voltage transmission lines linking Antofagasta and Atacama to load centers in Santiago [26]. The National Electricity Coordinator estimates that a recent transmission upgrade will reduce renewable curtailment by as much as 80% [29].

3.3 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 [21]. 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 (Figure 14, left pane). In 2018, about 27% of PV output in China came from the northwest [30]. 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% of PV output was curtailed in China in 2015 [31], though curtailment has since fallen to about 3.8% of PV output in 2018 [21]. 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 (Figure 14, right pane).

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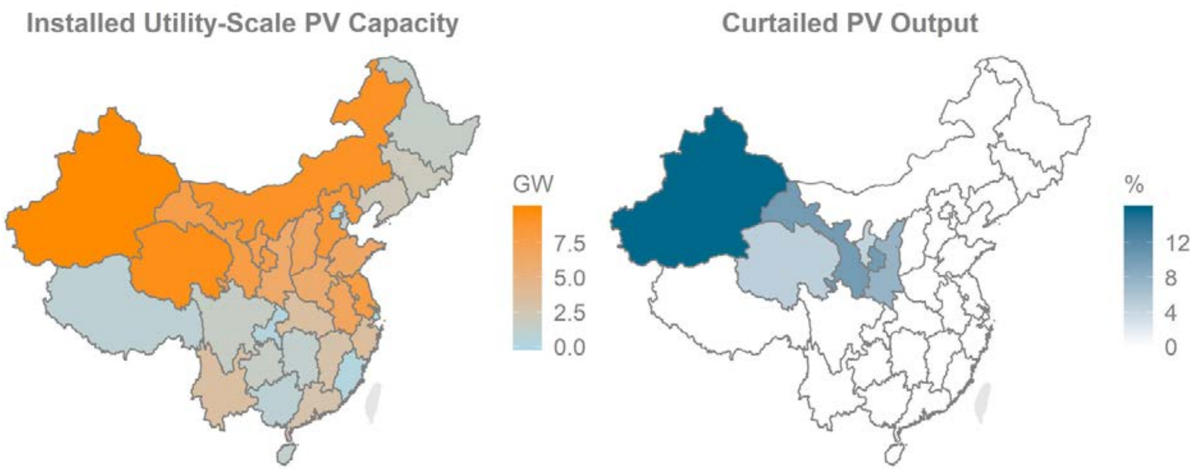

Figure 14. Province-level installed PV capacity (left pane) and curtailment (right pane) in China, based on 2018 data

PV curtailment in China stems primarily from system inflexibility, oversupply, and insufficient transmission capacity [32]. 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, three ultra-high-voltage transmission lines connected non-hydro renewable resources in the northwest to southeastern load centers [33, 34]. By the end of 2018, over 20 ultra-high-voltage lines were in operation with at least 5 lines transmitting non-hydro renewable generation. Transmissions system upgrades are part of a broader set of Chinese policies aiming to reduce PV curtailment [35].

Similar to other regions, trends in China illustrate how policy can drive trends in PV curtailment. In 2011, China implemented a nationwide feed-in tariff. The fixed value of the feed-in tariff resulted in a disconnect between PV compensation rates and the value of PV output. As a result, the nationwide feed-in tariff drove a boom in investment 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 regionalized the feed-in tariff [36]. 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.

3.4 Germany

By the end of 2018, Germany had about 46,000 MW of installed PV capacity, making Germany the leader among European countries in terms of installed PV capacity [22]. From 2009 to 2014, PV curtailment steadily increased from 0.01% of potential output in 2009 to 0.74% of potential output in 2014, before falling to just 0.3% of potential output in 2018 [37-39].

PV curtailment in Germany is relatively low compared to U.S. states with similar levels of PV penetration,[3] and far lower than in states like Arizona and Texas. 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

[3] For example, PV and other solar resources account for about 9% of electricity use in California, comparable to the 7% share of PV in Germany (Wirth 2018), yet curtailment in 2018 was about three times higher on a percentage basis in California than in Germany.

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California where more than half of PV capacity is utility scale [19]. The German Renewable Energy Act requires that distributed systems larger than 10 kW be equipped with technologies allowing grid operators to remotely curtail the PV systems. As a result, distributed PV accounts for the majority of PV curtailment in Germany, in contrast to California where only utility-scale PV is curtailed. In Germany, grid operators are required 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% of curtailed PV output. The cost of curtailment in Germany is therefore equal to the value of relatively generous feed-in tariffs that determine the revenue losses from curtailed output. In contrast, the cost of curtailment in California is equal to a compensation rate defined in a purchase contract. This policy creates a relatively strong penalty that discourages curtailment in Germany.

4. Options to Effectively Manage PV Curtailment

The data summarized in Section 3 may be indicative of future levels of curtailment as PV reaches higher levels of penetration on more grids. All else equal, PV curtailment should generally increase, both because PV penetration will continue to increase in the markets described in Section 3 and because PV penetration levels will increase in other emerging PV markets. How will grid operators and policymakers respond to these increasing levels of PV penetration and PV curtailment? To date, grid policies have largely been designed to minimize PV curtailment due to its zero-cost and zero-emissions benefits. However, as we have noted, the evolving grid and technological contexts are changing how stakeholders think about PV curtailment. We argue that these changing contexts merit a shift in focus from curtailment prevention to curtailment *management*. In this section, we explore three options to more effectively manage PV curtailment: increase PV dispatchability; develop and implement alternative contract structures; and increase grid flexibility.[4]

4.1 Dispatchable PV

The increasing prevalence of advanced inverters and lower-cost batteries may allow grid operators to treat PV as a dispatchable resource [15]. Further, grid policies increasingly require that new PV systems include advanced capabilities. For instance, FERC Order 828 in the United States requires that all small inverter-based generators (<20 MW) be equipped with inverters capable of riding through abnormal frequency and voltage events. Modern PV systems could be controlled by intentionally withholding some PV from the grid, also known as downward dispatch. All else equal, downward dispatches reduce the amount of PV output delivered to the grid. However, effectively implemented downward dispatch can reduce overall levels of PV curtailment and facilitate PV integration [2, 4-8]. See Nelson et al. [6] for a modeling study of how dispatchable PV can reduce curtailment. In that study, the authors find that curtailment on a high-PV penetration grid could be reduced from about 30% of potential output curtailed to about 15% of potential output curtailed through actively implemented downward dispatches.

4.2 Alternative Contract Structures

Traditional PV contractual structures such as power purchase agreements (PPAs) generally base PV system revenue on *delivered* output. PPAs, in some cases, compensate generators for curtailed output though often at a lower rate. Generators must therefore bid PPA rates while accounting for some level of expected future curtailment. Under PPAs with discounted compensation for curtailed output, generators always bear some financial risk from the possibility that actual curtailment levels exceed expected

[4] We are grateful for the time and insights provided by representatives from the following organizations that contributed to the discussion in this section: Arizona Public Service; AES; CAISO; the Electric Reliability Council of Texas; First Solar; HECO; NextEra; Salt River Project; the Smart Electric Power Alliance; Tampa Electric Company; and Tucson Electric Power.

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curtailment [2, 40]. Curtailment risk reduces revenue certainty, which could ultimately increase the costs of financing PV projects and undermine future PV deployment [1, 4]. Further, traditional PPA structures were not designed for dispatchable PV systems. As a result, industry stakeholders have begun to develop and implement new contract structures that decouple PV system revenue from delivered output and assign value to withheld output.

These alternative contract structures at least partially decouple PV revenue from delivered PV output. Sterling et al. [2] propose two such structures: capacity and energy PPAs and time-of-delivery (TOD) PPAs. In a capacity and energy PPA, the generator and offtaker agree to separate compensation rates for capacity ($/MW/month) and output ($/MWh). The capacity portion ensures that at least some of the generator's revenue is decoupled from output, insulating the generator from the financially detrimental effects of curtailment (Figure 15). The output portion may or may not include a tiered rate for delivered and curtailed output. At an extreme, all of the contract's payments can be capacity-based, in which case the generator bears no curtailment risk. A capacity-only model would allow the offtaker to proactively curtail the PV array without affecting the PV generator's revenue stream. Under a TOD PPA, the generator's compensation rate varies based on when PV output is delivered to the grid. TOD structures can reduce generator curtailment risk because curtailment is more likely to occur in off-peak periods when TOD compensation rates tend to be relatively low. Put another way, TOD structures tend to reduce the financial penalties associated with curtailed output.

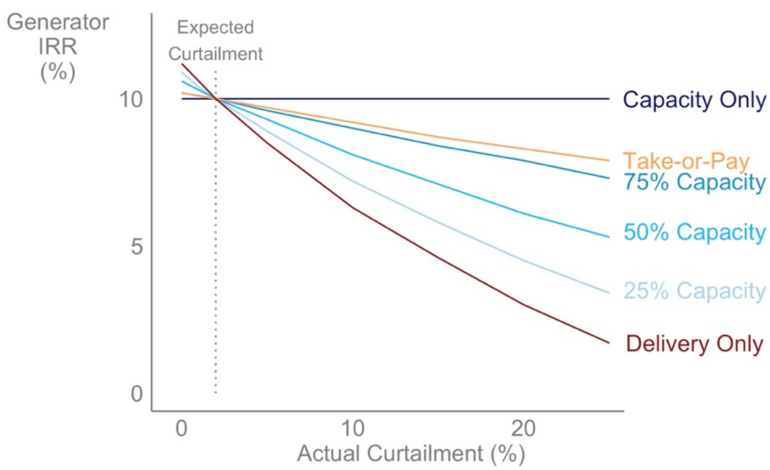

Figure 15. Modeled generator internal rate of return (IRR) under conventional delivery-only and take-or-pay contract structures compared with IRR under alternative capacity-based structures

Figure notes: Results based on modeled results for a 30-MW system located in Phoenix, AZ using the U.S. National Renewable Energy Laboratory's System Advisor Model. Delivery-only represents a contract where all payments are volumetric and curtailment is uncompensated. Take-or-pay represents a volumetric contract where curtailment is compensated at 50% of delivered-output rate. The slopes of the lines represent the generator's curtailment risk: the steeper the lines, the more risk borne by the generator.

These alternative contract structures could fundamentally change the incentives of grid operators and PV developers and increase the potential value of PV systems to the grid. By decoupling generator revenue from *delivered* output, these alternative contract structures could facilitate the use of advanced inverters and battery storage to provide non-generation services. These alternative contract structures may result in more curtailed output, at least under the prevailing definition of curtailment, but that curtailed output would provide grid services and revenue would still accrue to the generator.

4.3 Grid Flexibility

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All else equal, a more flexible grid is able to accommodate more PV output 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 changes in grid supply and demand [18]. That flexibility can also be used to quickly respond to changes in variable renewable energy generation. For instance, Cole et al. [41] find that increased natural gas capacity could reduce renewable energy curtailment by 25% relative to a reference scenario. Nelson and Wisland [5] find that increasing the flexibility of natural gas plants—such as through decreasing their minimum power level—could reduce renewable energy curtailment by about 37% relative to a reference scenario with 50% renewable energy penetration in California.

Increasing grid energy storage capacity could reduce risks of oversupply and increase grid flexibility, thus reducing the need for PV curtailment [5, 12]. In terms of oversupply, during potential oversupply events the otherwise curtailed PV output can be stored and re-dispatched later in the day, obviating the need for curtailment.[5] Denholm et al. [17] show that adding 4,000 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. [42] estimate that adding 1,000 MW of storage capacity to the Nevada grid could reduce renewable energy curtailment by 50%. However, the capital costs of battery storage investments must be weighed against the avoided costs of curtailment [10].

Demand response is another tool for increasing grid flexibility and managing curtailment. Demand response is generally deployed to reduce loads during critical peak demand periods. However, demand response could also be deployed to *increase* loads during PV oversupply events to mitigate PV curtailment [4]. 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 PV 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 demand for air conditioning is relatively low.

Finally, regional coordination is an additional grid flexibility measure that facilitates power trading over broad geographic areas. Regional coordination can reduce the need for PV curtailment because, all else equal, larger systems are more reliable and more flexible [4]. 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., in Chile and China, see Sections 3.2 and 3.3) or simply through market measures (e.g., the California EIM, see Section 3.1.1).

5. Conclusion

In 2018, about 2% of potential PV output was curtailed in Arizona, California, Hawaii, and Texas. Internationally, meaningful levels of PV curtailment have been observed in Chile, China, and Germany, and to a lesser extent in Australia and Japan. 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 system constraints and grid policies. In terms of system 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, policymakers and grid planners have responded with initiatives to increase transmission capacity

[5] 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.

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connecting the solar resources to load centers. In terms of policy, PV curtailment is discouraged to different degrees by different regional policies. For instance, load-serving entities in California face relatively stricter renewable energy requirements than load-serving entities in Arizona. As a result, PV curtailment tends to be exported from California to Arizona. Similarly, low levels of PV curtailment in Germany can be explained by policies that make PV curtailment relatively costly.

Changing grid and technological contexts are forcing a re-examination of PV curtailment policies. In the grid context, as grids reach higher levels of PV penetration it becomes more efficient to emphasize an optimal rather than a minimal level of PV curtailment. In the technological context, emerging technologies such as advanced inverters are creating new use cases for withheld PV output. These emerging technologies may allow grid operators to withhold PV output to provide a variety of grid services such as capacity reserves and frequency regulation. We argue that PV output that is intentionally withheld in order to provide grid services is fundamentally different from PV that is curtailed in response to grid constraints. We have therefore offered a more exclusive definition of curtailment as unused PV output rather than simply any reduction from in PV output from its technical potential. The terminological distinction is not only a question of semantics. By viewing grid services as a use case for withheld PV output grid operators and policymakers may increase the potential value of flexible PV systems. This shift in thinking may allow grid operators and policymakers to think in terms of PV curtailment *management* rather than minimization. Effective curtailment management may include policies that increase the dispatchability of PV systems, alternative PV compensation schemes that decouple generator revenue from system output, and policies to increase grid flexibility in order to increase grid PV carrying capacity.

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