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The Power Markets Project (www.powermarkets.org) studies and promotes market policies that align with clean energy goals. It is a project of PaulosAnalysis, with financial support from the Heinrich Böll Foundation, the Cynthia and George Mitchell Foundation, and the Rockefeller Brothers Fund.

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Curtailment of Renewable Energy in California and Beyond

California is blazing a path to a low-carbon future through greater use of renewable electricity. But as wind and solar rapidly grow, grid operators are raising concerns about periods of over-generation and the specter of large amounts of curtailment. Curtailment is an easy response, but it is wasteful and undermines the investor confidence needed to transition the California power system. A host of supply-side and demand-side measures can keep curtailment to minimal levels, but policy reforms also are needed to make curtailment a viable tool.

Rachel Golden and Bentham Paulos

I. Introduction

As a result of the passage of AB327, the California Public Utilities Commission is authorized to increase the renewable portfolio standard (RPS) beyond the current goal of 33 percent by 2020. SB350, pending in the California legislature, would set a goal of 50 percent by 2030. Along with the multiple benefits of renewables, higher penetration of variable renewable energy also brings several challenges. This article examines some of these challenges, particularly over-generation and curtailment of renewables in California and other states. The article addresses the use of low levels of

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curtailment to balance the grid, along with a summary of the policy options that may help to alleviate over-generation and constraints on renewable energy generation. The article also considers analysis that current projections for curtailment may be overstated.

The topic is important: strategies to prevent or reduce curtailment can improve overall system flexibility and resiliency, help the state meet clean energy and climate goals, and pave the way for optimal integration of electric vehicles, distributed resources, and other technologies beyond the RPS.

This primer addresses the following fundamental questions:

1) What are the potential positive and negative impacts of curtailment? How is curtailment a resource at low levels and a problem at higher levels?

2) What are the unintended consequences of curtailment and how can they be prevented?

3) To what extent will renewables be curtailed with a higher (40-50 percent) RPS?

4) How have other states utilized curtailment? What was their experience and what policy tools were utilized?

5) What are the main causes of renewable curtailment in California?

6) What systems or policies does California already have in place to mitigate curtailment of renewables?

7) What other systems, policies, or strategies have other states or countries used to mitigate curtailment of renewables that may be advisable for California?

II. The Basics: What, Why, How?

There are many different definitions of curtailment and there is no standardized way to measure it.[1] For the purposes of this article, we define curtailment as a reduction in the output of a wind or solar generator from what it could otherwise produce given available resources like wind or sunlight. We consider this distinct from running a dispatchable power plant at less than full capacity, which is common. There are several causes for curtailment of renewable energy. Curtailment can be the result of excess generation during low load periods (i.e. over-generation), transmission congestion, lack of transmission access, and voltage and interconnection issues.

Over-generation can happen when ''must-run generation—wind and solar, combined-heat-and-power (CHP), nuclear generation, run-of-river hydro, and minimum levels of thermal generation needed for grid stability—is greater than load plus exports,'' according to E3.

Wind and solar do not have to supply 100 percent of demand for over-generation to occur. Inflexibility can occur for technical reasons, as with a nuclear plant that has limited ability to run at partial load, or for grid reliability reasons, as when dispatchable power plants have reliability must run (RMR) designations, or for financial reasons, when an incumbent utility prefers its own resource over those of contracted generators.

Curtailment of renewables typically occurs when an operator or utility directs a generator to reduce output. The common metric to measure curtailment is as a percent of what a generator could have produced. As shown in **Figure 1**, curtailment levels in

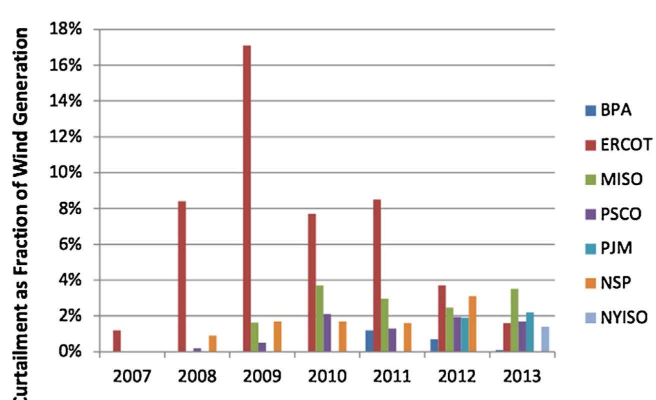

Figure 1: Curtailment Levels by Region
Source: Bird et al., NREL.

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the U.S. have generally been around 4 percent or less, with the notable exception of ERCOT, where curtailment levels reached 17 percent in one year, primarily because wind generation came online ahead of new transmission capacity. These levels have since receded to less than 2 percent.[2] Many utilities in the western states report negligible levels of curtailment.

In California, CAISO reports only four instances of curtailment from the spring of 2014, and none in 2015 to date. However, they expect curtailment to increase with higher penetration of renewables, particularly solar.

III. Curtailment: A Problem or a Resource?

There is a debate on whether curtailment of renewables is a problem or a resource.

On the one hand, curtailment can be problematic because it decreases the capacity factor of renewable energy projects, and can thereby reduce project revenues and contract values, weaken investor confidence in renewable energy revenues, and, possibly make it more difficult to meet greenhouse gas (GHG) emissions targets.[3] Since wind and solar generators have large capital costs, no fuel costs, and low operating expenses (i.e. low marginal costs), their ability to recover capital expenses hinges on maximizing energy output.[4] Depending on the terms in their power purchase agreements (PPAs), renewable developers can lose revenue when resources are curtailed, both by selling less generation and losing the value of production tax credits.[5] Moreover, as curtailment increases beyond a certain threshold[6]—some analysis says around 5 percent—owners of renewable projects face a significant risk of not being able to pay off loans for existing projects or secure financing for new projects.[7] If current or forecast curtailment levels are too high, banks may assume higher risk levels and therefore increase the cost of financing.[8] Lastly, a recent report by E3 concluded that under a 50 percent RPS with very large amounts of solar PV development, an ''exponential'' increase in curtailment could also lead to a significant rate increase as there would need to be a major overbuild of renewable resources to meet the higher RPS target.''[9] Clearly, large curtailment of renewables without adequate compensation to renewable generators could be a roadblock in achieving clean energy and GHG-reduction goals.

Due to the speed in which renewables can be ramped up or down, curtailing renewables can help to relieve over-generation and potentially provide ancillary services.

On the other hand, curtailment can be a valuable resource, helping stabilize the grid and improve system flexibility. Due to the speed in which renewables can be ramped up or down, curtailing renewables can help to relieve over-generation and potentially provide ancillary services.[10] A recent report by NREL describes that ''curtailment [of wind] can provide more time for other plants on the system to ramp down if there is a sudden imbalance of high supply and low demand. Curtailment can also be used to require a renewable energy generator to generate at reduced levels so that it can ramp up quickly to balance a system.''[11] Low levels of curtailment (less than ~3 percent) may be a cost-effective source of flexibility.[12] Additionally, allowing some small level of curtailment may be beneficial from a cost-benefit approach as it avoids an overinvestment in grid infrastructure.[13] For example, investing in expensive transmission upgrades in order to prevent a few hours of curtailment a year may not be a prudent use of resources.

Based on a literature review and interviews with analysts at NREL, LBNL, and CAISO, it is clear that curtailment of renewables up to a certain threshold[14] is an acceptable component of a strategy to

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provide supply-side flexibility to help balance the grid. However, above this threshold, renewable energy curtailments expose the inflexibility of the grid and indicate that larger changes are needed to maintain an economic and efficient electric power system. Andrew Mills at LBNL thinks of this threshold as a ''valley of reasonable curtailment,'' where if you try to absorb more renewables on one side the costs become very steep, and on the other side, if there is too much curtailment then it becomes too costly to build renewable resources. In the middle is a sweet spot that is cost-effective and reasonable from a ratepayer and a cost-benefit perspective.[15]

IV. Curtailment Experiences in the U.S.

Most curtailment in this U.S. is a result of local oversupply or transmission constraints. These are not necessarily optimal uses of curtailment, as other system upgrades (i.e. transmission upgrades and expansion, automated dispatch, negative pricing, etc.) may better address the fundamental problem.

Curtailment is one of many tools to prevent over-generation of electricity and enhance grid flexibility. Although curtailment literally means using *less* renewables than is possible, it is feasible, with the right systems and policies in place, for operators to use curtailment to actually *increase* the overall net utilization of renewables. That is, the capacity factor of a handful of renewable projects may decrease while overall renewable capacity and generation will increase. This strategic use of curtailment requires a modern grid infrastructure and supportive regulatory and compensation policies.

Very few grid operators or utilities in the U.S. are equipped to use curtailment efficiently as a resource. The Public Service Company of Colorado (PSCO), which has had periods of over 60 percent wind power on their system, controls wind generators to provide both up and down regulation reserves. Since wind turbines can quickly respond to signals, they have found wind to be a reliable and valuable resource for flexibility.[16] Using curtailed wind for positive reserves enables PSCO to avoid curtailment of other available wind resources. PSCO is able to use wind as an ancillary service for frequency control by installing automatic generation control (AGC) technology on wind turbines.

Renewable resources in California do not currently provide ancillary services, and there are many issues to sort out for this to be possible.

Unlike Colorado, California does not have any wind or solar resources on automatic generation control (AGC), so this is not a current possibility. Renewable resources in California do not currently provide ancillary services and there are many issues to sort out for this to be possible. For instance, renewable resources will need to install AGC, the Public Utilities Commission will need to determine if these generators will get full RPS credit if they provide ancillary services, and generators will need to handle forecast error.[17]

According to Steven Greenlee of CAISO, only four incidents of curtailment have occurred so far, all in early 2014.[18] Curtailment is most likely to happen in the spring, due to low power demand combined with mountain runoff driving hydroelectric systems and strong wind power output. However, Greenlee said that CAISO does not track the reason for over-generation, just that it does occur. He also points out that over-generation is not caused just by wind and solar, but by all generation on the system at the time.

He said that CAISO has its own ''loading order'' of responses to over-generation. Their first preference is for the market to respond. They put out a request for bids for generators to

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voluntarily curtail, earning the value of the negative price at the time. According to Greenlee, this almost always cures the problem. If not, their next step is to ask neighboring balance areas to take excess supply, such as public power systems in California and utilities in neighboring states. The energy imbalance market (EIM) formalizes this process.

The last resort is curtailment, ordering plants to turn down to zero and disconnect from the grid. According to federal reliability rules, they have a maximum of 30 minutes to cure the problem.

V. Compensation for Curtailment

If curtailment is forecast either to grow or to be used as flexible capacity, then contracts and market incentives may need to be revisited to prevent unintentionally creating both an untenable environment for renewable energy investors and developers *and* high costs for ratepayers.

Compensation and contract terms between utilities and developers are currently evolving as curtailment becomes a more common practice. Compensation to generators for revenue loss from curtailed resources varies greatly across the U.S. and Europe and typically depends on the cause for curtailment.[19]

Currently in California, RPS *pro forma* contracts for the three large IOUs include economic curtailment rights whereby some number of hours of economic curtailment is allowed without compensation, and curtailment beyond this level is compensated by the IOU at the PPA price.[20] The number of hours of uncompensated curtailment varies among contracts, as there is no hard and fast rule. These curtailment rights allow the IOUs to respond to negative price signals and purchase less generation.

One yet-unaddressed concern is that some owners of dispatchable power plants have contracts that limit their response to grid needs for flexibility, such as during periods of over-generation.

Generators still get investment tax credits (ITC) and resource adequacy payments, which are not based on generation. Some IOUs reimburse generators for loss of production tax credits (PTC), but this is not required by the Commission and varies among utilities. In cases where there are a certain number of allowable curtailment hours without compensation, generators may try to back into the contract higher prices to cover some or all of the potential curtailment and revenue loss.[21] There is a tension in California between the IOUs who favor unlimited and uncompensated curtailment and the renewable energy industry, which fears unlimited curtailment would significantly hurt the industry in California.

One concern that is yet unaddressed in state policy is that some owners of dispatchable power plants have contracts that limit their response to grid needs for flexibility, such as during periods of over-generation. While CAISO is not privy to what is in private bilateral contracts, Steven Greenlee of CAISO does suspect that many power purchase agreements include ‘‘use limitations’’ that restrict the amount of stops, starts, and ramps that a generator is required to perform. In other words, while generators may be technically able to respond, their contract allows them to ignore calls for flexibility. As a result, one way to manage oversupply conditions is to get contracting parties to modify their use limitation provisions.

VI. When and Why Renewable Curtailment Occurs in California

In California, curtailment predominantly occurs due to oversupply and ramping constraints, transmission limitations, and line congestion.[22] Curtailment can be ordered by operators like CAISO or by utilities themselves. IOUs typically decide to curtail renewables in response to instances of negative prices for

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electricity. CAISO will order curtailments due to congestion, ramping constraints, or over-generation that is not resolved economically.

Curtailment typically occurs on spring days when demand is low and there is snow melt runoff and hydropower must operate.[23] In these instances, CAISO may have to curtail more than the regular dispatchable resources.

In early 2014, CAISO curtailment was low, totaling 19.39 GWh from 13 renewable resources. There seemed to be four primary incidents of curtailment, the largest being the morning of April 27, when 485 MW of wind and 657 MW of solar were curtailed.[24] ''Of the total year-to-date curtailment, 17.2 GWh was accomplished through the CAISO real-time market optimization through curtailment of self-schedules and economic bids based on reliability need,'' wrote Dr. Karl Meeusen in testimony on behalf of CAISO. ''The CAISO market optimization engine will only curtail self-schedules when all other economic bids to reduce output are exhausted.''[25] There have been no incidents of curtailment in the first half of 2015.

VII. How Much Curtailment is Expected in California

The question of how much renewable energy is expected to be curtailed in California is a highly contested and difficult question to answer. Forecast curtailment levels depend largely on assumptions about the energy portfolio, what complementary policies are employed that help to prevent or minimize over-generation, the size and responsiveness of load, and other model inputs.

Nonetheless, curtailment is widely expected to increase as more variable renewables come online.

- The National Renewable Energy Lab (NREL) predicts that curtailment will increase as about 11 GW of new solar and wind come online by 2020.[26] NREL is currently modeling curtailment in the WECC under a scenario of 55 percent renewable penetration. The model predicts curtailment levels of 0–10 percent depending on the level of imports and exports across balancing areas and the use of other complementary policies.[27]
- CAISO has modeled curtailment at 33 percent and 40 percent renewables in 2024 first with the assumption that there is an unlimited ability to economically curtail renewables,[28] and second with an assumption that curtailment was not allowed, ''to provide a bookend analysis of system reliability.''[29] The unlimited curtailment analysis predicts exponential curtailment from current levels. In the Expanded Preferred Resources scenario, which models a 40 percent RPS with additional rooftop solar, combined heat and power and expanded energy efficiency, annual curtailment is predicted to be 6.5 percent. Renewable curtailment was observed in all 12 months of the year in this scenario, with up to 20.1 percent curtailment in April.[30] In the more recent analysis with no curtailment allowed, CAISO found over-generation (what they call ''dump energy'') adding up to 1,363 GWh over a year, which is lower than the 2,825 GWh of total renewable curtailment in the original 40 percent RPS in 2024 scenario. This occurs ''because making renewable generation non-curtailable forces re-dispatch of generation resources that are more expensive (including startup and variable operation costs) than curtailing renewable generation at the −\$300/MWh price.''
- E3 also predicts significant increases in curtailment if California moves from a 33

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percent to a 50 percent RPS. Curtailment in this case is largely a result of over-generation. E3 ran five scenarios: a 40 percent RPS, and four different scenarios to meet a 50 percent RPS (a large solar, small solar, rooftop solar, and a diverse resources scenario). At the high end, under the large solar scenario, the study predicts curtailment of 9 percent of renewable output and significantly higher costs to achieve the 50 percent RPS target.[31]

- Two studies critiqued the E3 study, both faulting it for not seeking out a least-cost mix of renewables and relying too much on solar.[32] Dariush Shirmohammadi, former director of regional transmission at CAISO, writing for the California Wind Energy Association (CalWEA), complained that the integration options were only applied to the ''large solar'' scenario. Applying them to the ''diverse'' 50 percent renewable scenario would reduce overall rate impacts from 9 percent to only 3.9 percent, and shifting the mix to more wind and less solar would further reduce costs to a 2.2 percent increase. Another review, by Crossborder Energy for CalWEA and The Alliance for Solar Choice, echoed the critique, pointing out that most scenarios relied on solar for 80 percent of the incremental generation. The current California RPS requires that utilities choose a ''least-cost, best-fit'' mix of resources, where higher cost resources sometimes prevail because they fit better in the overall portfolio. The E3 scenarios ''do not represent reasonable or likely portfolios of resources to achieve a 50 percent RPS goal, because they add solar far beyond the point where it ceases to be economic,'' Crossborder argues.
- NREL is working with GE Consulting and others on the Low

Carbon Grid Study, modeling various scenarios for getting to a low-carbon power supply in California.[33] To reduce carbon emissions and curtailment levels, they rely less on natural gas power plants for load-following, and more on dispatchable hydro, imports and exports, demand response, and energy storage—known as ''zero-emission load balancing.'' Final results are expected in the summer of 2015.
- A study using the SWITCH model of UC Berkeley found that California could power a system of 59 GW of peak demand with 80 percent wind and solar, provided it included 186 GWh/22 GW of storage, curtailment of 15 percent of the wind and solar generation, and total renewable capacity of 115 GW. Without any storage, such a system would have 40 percent total loss and close to 170 GW renewable capacity.[34]

Although the exact levels of over-generation and curtailment are disputed, it is widely agreed that (1) as California adds more variable renewable resources, especially solar power, over-generation is expected to become more frequent and (2) ways to improve the flexibility of the grid will become ever more important.

VIII. Systems in Place (or Planned) in California that Help to Mitigate Curtailment of Renewables

California already has employed several strategies that reduce over-generation and curtailment. Before considering *new* strategies to mitigate curtailment, it is important to understand the *existing* mechanisms as it may be possible to build upon these.

A. Automatic generation control

Automatic generation control (AGC) is a system employed by CAISO to automatically adjust power output both upwards and downwards at certain power plants in response to real-time

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changes in load.[35] AGC allows CAISO to deal with the second-by-second variability of load within 5-minute intervals and maintain a desired frequency level on the grid.

AGC is considered superior to older systems employed by other states and balancing areas[36] where grid operators manually adjust one generating unit, which is designated as the regulating unit, in order to maintain the desired system frequency. With AGC, many units in a system can be adjusted upward or downward, which helps to reduce wear on a single unit's controls and improves overall system efficiency and stability. This automatic system is known to more effectively address changes in variable generation and load. By dispatching the system in shorter increments, sudden changes to conventional generators needed to balance the system can be reduced. AGC thereby enables the system to run more economically, minimize reserve requirements, and reduce curtailment.[37]

If renewable generators in California install AGC then operators could potentially use renewables, like Colorado does with wind, to balance load and reduce overall curtailment levels. Manual processes, on the other hand, can extend instances of curtailment ''because of the time needed for implementation and hesitancy [of operators] to release units from curtailment orders.''[38]

B. Negative pricing

Negative pricing is one market-based technique CAISO uses to address over-generation. A negative price for electricity sends a signal to generators to curtail their resource or pay to generate at times when the system does not need power. Negative prices essentially dissuade generators

from bidding in too much power when the system cannot handle it. Due to federal production tax credits, CAISO's bid floor of −$30/MWh was not sufficient (i.e. low enough) to discourage wind from bidding into the system. In May 2014, CAISO reduced its bid floor to −$150/MWh to account for the PTC and to dissuade bids when power is not needed. If needed, CAISO may drop the floor further to −$300/MWh.[39]

C. Energy imbalance market

CAISO and PacifiCorp have launched an Energy Imbalance Market (EIM) that allows participating balancing areas to share reserves and more cost effectively balance energy *within* the hour. It offers to extend CAISO's real-time market to other balancing authorities in the West.[40] NV Energy also plans to join later in 2015, while Puget Sound Energy and Arizona Public Service have expressed interest in joining. PacifiCorp is also considering become a full member of CAISO.[41]

The EIM is expected to help participating utilities better manage higher penetration of variable renewable generation and is predicted to result in fewer instances of curtailment and lower renewable integration costs.[42] In the first two months of operation, the EIM saved about $6 million.[43] Broadening the supply of resources available to balance renewable generation, more efficiently managing transmission resources to minimize congestion, and better managing wind ramps through an automated (rather than manual) process are reducing the need for curtailment in PacifiCorp and CAISO territory.

In Dr. Shucheng Liu's testimony on California's Long Term Procurement Plan (LTPP), he explains that the EIM ''is a positive step because it helps facilitate neighboring balancing authority areas to absorb over-generation based on the real-time imbalance and pricing conditions. However, the EIM still has limited capability to address over-generation because it cannot

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decommit long start resources that have already been committed through neighboring balancing areas day-ahead operational planning process.''[44] Although the EIM is a good step forward, more is needed to optimize relations with neighboring balancing areas.

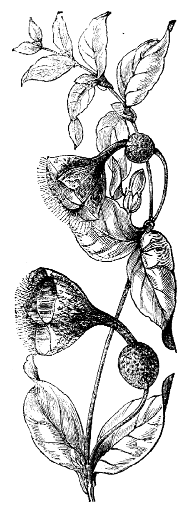
D. Storage

California's 1.3 GW energy storage mandate is expected to help avoid unnecessary curtailment of renewable energy by absorbing surplus energy and reducing instances of over-generation. Storage, such as pumped hydro, batteries, flywheels, and compressed air, can contribute to system flexibility, load shifting and smoothing, reduce transmission congestion (when strategically placed), and reduce the need for spinning reserves.[45]

IX. Main Strategies and Solutions to Reduce Curtailment

Most states in the U.S. and countries in Europe have been able to manage curtailment levels by installing or upgrading transmission, importing and exporting power with neighbors, and modernizing the grid (i.e. moving toward a market-based and automated system). Although California can learn from some of these examples, given California's specific geography and ambitious RPS goals, the State once again finds itself in a leadership position without a tested model or a regulatory regime to emulate.

The literature suggests many strategies to reduce curtailment and over-generation; it highlights the fact that there is no silver bullet solution and that a myriad of approaches from the



demand, supply, and operations sides must be employed. Below we outline four main strategies to reduce curtailment and over-generation, but also to enhance the overall flexibility and resiliency of the grid. The scope and timing of this article does not permit adequate analysis of the costs, feasibility, or progress of each strategy.

A. Diversify the renewable resource portfolio

Having a diverse portfolio of renewables is widely recognized as an important strategy to reduce over-generation, curtailment, and costs. E3 included a ''diverse'' scenario for a 50 percent RPS based on a mix of large utility-scale resources including small and large scale solar PV, solar thermal with storage, in-state wind, out-of-state wind, geothermal, biomass, and biogas resources. This kind of portfolio was found to reduce daytime over-generation to 4 percent of total renewable energy (compared to 9 percent in the large solar scenario).[46] NREL's Low Carbon Grid Study has taken this concept further, and found 50 percent carbon reduction scenarios that reduce curtailment to as low as 1 percent. In Phase 1 of the study, they found a worst-case scenario with curtailment as high as 11.9 percent.[47] But deploying a variety of mitigation options, most notably regional trade across the Western U.S., curtailment was dramatically reduced.

Establishing policies to ensure a diverse resource portfolio is an important step. As the CPUC reforms the least-cost/best-fit, renewable auction mechanism, and other tools in RPS rulemaking, it will be important to examine if the procurement policy will lead to a ''diverse and balanced'' portfolio or if modifications are needed. The RPS calculator may also be an important tool to identify plausible portfolios of renewable resources. The challenge is to home in on how much resource diversity is needed, and at what cost to ratepayers. Additionally, there may be political pressures

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on the CPUC supporting some renewable industries over others.

The legislature has shown a willingness to tweak the RPS to encourage more diversity. SB1122, approved in 2012, adds a 250 MW set-aside for bioenergy projects to the state RPS. SB1139, which would have created a 500 MW geothermal mandate by 2024, passed the full state Senate and three Assembly committees in 2014 before the session ended.[48]

B. Enhance regional coordination

A common theme throughout the literature is that achieving higher renewable penetration is more practical with larger interconnected systems.[49] A larger geographic balancing area can have several advantages, including:

- reduced vulnerability of system to weather events[50];
- lower aggregate forecasting errors[51];
- substantially lower variability and uncertainty in both load and RE generation[52];
- availability of more resources to provide reserves and flexible generation, which can accommodate the variability of wind and solar[53];
- lower rates of curtailment[54];
- reduced system reserve requirements[55]; and,
- lower power prices and integration costs.[56]

E3 predicts that increased regional coordination will lead to reduced over-generation and lower curtailment levels in California. Based on an assessment of current transmission operating capabilities, the E3 study assumes that California can become a net-exporter of up to 1,500 MW of energy during every hour of the year by 2030. Under this scenario, total over-generation is reduced

from 9 percent (in the 50 percent RPS Large Solar scenario) to 3 percent of the total renewable energy.[57]

However, the feasibility of California becoming a net exporter of electricity is both uncertain and a longer-term goal. California is currently a net importer of electricity.[58] A study is needed to determine the appetite for exports of surplus power from California and the ability of the western grid to accommodate such exports.[59] Although it may be technically feasible[60] to export large amounts of electricity, there are several political and institutional barriers to overcome. Given that California dominates electricity demand in the West, and its dense population makes renewable power development more difficult, it is more likely to remain an energy importer.

CAISO's Shucheng Liu explains that, ''ideally there should be a west-wide jointly cleared market with both day-ahead and real-time scheduling processes. That could produce a coordinated resource plan recognizing forecasted renewable supply. Such a west-wide coordinated approach would greatly improve the capability to address over-generation and potentially mitigate renewable generation curtailment issues.''[61] A regional day-ahead market could have a big impact on reducing curtailment. Given sufficient lead time of high renewable generation, then there is an option to turn off or down larger thermal units. Gregory Binkman, an energy analysis engineer at NREL, asserts that even if all states in WECC build and generate more renewables, a regional day-ahead market is still advantageous and important as it allows more units to be scheduled ahead of time.[62]

California's coordination with neighboring balancing areas in WECC is considered the best way to mitigate over-generation and curtailment.[63] The growing acceptance of and positive early experience with the EIM, combined with continuing rapid growth of wind and solar across the West, is starting to make

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greater regional coordination look inevitable.

C. Increase flexibility of load

The ability to shift load to different periods of the day to absorb excess renewable generation can play a significant role in reducing over-generation and curtailment. While advanced demand response is often used to reduce demand during peak times, it can also create flexible loads that *increase* energy demand to absorb excess renewable generation when needed. Advanced demand response programs can include using time-of-use (TOU) pricing or other rate design options to shift load, controlled charging of electric vehicles, thermal energy storage (preheating or precooling), and other technologies and mechanisms. E3 found that advanced demand response can provide ''both the ramping contributions of conventional demand response and the downward flexibility benefits of the Enhanced Regional Coordination case,'' reducing over-generation (under a 50 percent RPS) to only 4 percent of total renewable energy.[64]

Yet California has lagged behind other regions in implementing demand response. While programs have been evolving away from emergency-based direct load control and interruptible rates, it remains a utility-controlled resource, with many free riders, not geographically focused, dispatched rarely, and not bid into the CAISO market, according to GTM Research. A docket has been open since 2013 to modernize demand response, and parties proposed a settlement in July 2014. Working groups are currently investigating program changes.[65]

The growth of electric vehicles is offering additional opportunities for load flexibility. The California Energy Commission expects EVs on the road in 2025 will have a battery capacity of about 7.5 GW. ''Vehicles have three main characteristics that make them an attractive grid resource: operational flexibility, embedded communications and actuation technology, and low capacity utilization,'' according to the CPUC.[66] They point out that the typical vehicle is driven only 4 percent of the time, making it available for grid services day and night.

They identify three categories of grid services that electric vehicles would be able to offer:

Wholesale Market Services
- Frequency Regulation
- Spinning, Non-Spinning, and Supplemental Reserve
- Load Following/Ramping Support for Renewables

Distribution Infrastructure Services
- Distribution Upgrade Deferral
- Voltage Support

Customer-Facing Services
- Power Quality
- Power Reliability
- Retail Energy Time-Shift
- Demand Charge Mitigation

However, the appropriate policies, market structure, and incentives need to be developed to tap these services.

Lastly, California's impressive and sizable energy efficiency programs can be deployed to change the shape of demand, such as by targeting the early evening peak that occurs when solar output falls, the so-called ''head of the duck.'' Efficiency programs targeted at air conditioning load, lighting, and other contributors to early evening demand may be especially valuable at reducing ramp size and rate. Sierra Martinez and Dylan Sullivan of the Natural Resources Defense Council demonstrated in a recent paper that energy efficiency programs, particularly at the residential level, can help California dramatically reduce the evening ramp and thereby provide flexible resource needs to integrate high levels of

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renewables into the grid.[67] CAISO's roadmap for efficiency and demand response refers to this as the ''load-reshaping path.''[68]

D. Increase flexibility of supply-side resources

A common theme in the literature is the need for energy resources to be flexible and able to ramp up or down quickly in order to prevent over-generation and curtailment.

The Commission can adopt policies that increase incentives for flexible resources. CAISO's Karl Meeusen testified before the LTPP proceeding at the CPUC that ''flexible capacity should not simply be a measure of whether or not the CAISO can follow load. The need for flexible capacity should also consider the portion of a resource available for dispatch and the amount a resource's minimum operating levels may increase the probability of over-generation at certain times and under certain circumstances.''[69]

There are several ways to incentivize flexible resources on the supply side.

- *Create markets for additional services:* New markets or capacity markets can reward generators with fast ramping, ramp rate control, and quick-start capabilities. This may incentivize generators to build-in sufficient flexibility needed by the system.[70]
- *Build flexibility criteria into contracts:* Utilities can place a larger weight on flexibility of generation when evaluating bids for new generation resources. This would ensure that generation added to the system would be as flexible as possible and enable the system to more easily accommodate higher penetrations of variable renewables.[71]
- *Provide direct financial incentives:* Germany has developed a fund to encourage new fossil-fired power plants to use the most flexible technology available in order to maximize their ability to ramp to meet the system's balancing needs.[72] In California, this could help to ensure that any new gas plants that are built are able to operate at lower thermal levels.

- *Bulk energy storage:* Utility-scale storage is considered one of the more straightforward strategies to optimize the use of renewable energy and minimize over-generation and curtailment. The challenge is the cost of the storage capacity and if it is cost-effective compared with curtailment. Andrew Mills of LBNL suggests that it could be cost-effective if curtailment levels are high, but may not be as economical at low levels of over-generation.[73]
- *Use combined heat and power (CHP) to balance load:* In Denmark, CHP plants, representing more than 55 percent of all electricity production, are a major resource for flexibility. CHP plants are required to participate in the spot power market, and around one-third of small CHP plants are active in the Regulating Power Market. When wind is high, CHP plants rely on their thermal storage to continue to provide district heating, without needing to generate electricity and compete with wind generation. When electricity prices are very low or negative, it is cost effective to use cheap (wind) electricity to produce the low-temperature steam needed for district heating.[74]

X. Conclusion

California is clearly headed for an electricity system with greater amounts of renewable energy with substantially lower carbon emissions and hazardous air pollution. In order for the former to help achieve the latter, it will be critical to adjust policies, incentives, and operations to accommodate higher levels of variable energy generation from wind and solar power and reduce generation from natural gas.

In order to integrate large levels of renewable energy

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and avoid over-generation and curtailment, California should prioritize policies that diversify the types of renewable resources, expand regional coordination (i.e. Energy Imbalance Market and regional day-ahead wholesale energy market), increase use of demand-side flexible resources (i.e. demand response, EVs, storage), and develop and deploy supply-side flexible resources. The above energy reforms will not only enable a cleaner grid, but it will strengthen the resilience and efficient operations of the grid, making it more modern, dynamic, and reliable.

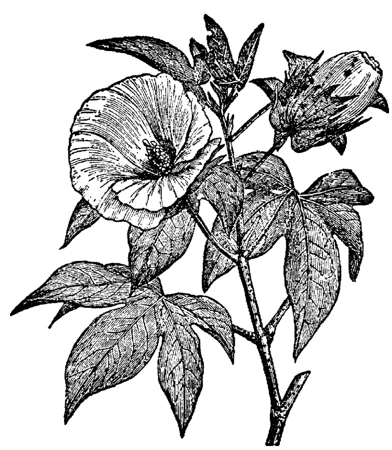
As these larger policy necessary changes are considered, it is important that regulators address near-term fixes to ensure that renewables curtailment—real or perceived—does not erode the renewables market. At low levels and in the near term – as larger policy changes take hold – curtailment may remain a viable and low-cost option to be deployed. To make curtailment work, however, policymakers must address the financial and contractual issues that make curtailment disruptive to the market and to a low-carbon future.■

Endnotes:

1. For instance, what some operators like ERCOT and MISO consider system-wide ''downward dispatch,'' others consider and count as curtailment.

2. Lori Bird, Jaquelin Cochran, and Xi Wang, ''Wind and Solar Energy Curtailment: Experience and Practices in the United States,'' National Renewable Energy Lab, March 2014, http://www.nrel.gov/docs/fy14osti/60983.pdf

3. Jaquelin Cochran, Mackay Miller, Owen Zinaman, Michael Milligan, Doug Arent, Bryan Palmintier, Mark O'Malley, Simon Mueller, Eamonn Lannoye, Aidan Tuohy, Ben Kujala, Morten Sommer, Hannele Holttinen, Juha Kiviluoma, S.K. Soonee, ''Flexibility in 21st Century Power Systems,'' 21st Century Power Partnership (NREL, University



College Dublin, IEA, EPRI, Northwest Power and Conservation Council, Energinet.dk, VTT Technical Research Centre of Finland, Power System Operation Corporation), May 2014, http://www.nrel.gov/docs/fy14osti/61721.pdf

4. Bird et al., ''Wind and Solar Energy Curtailment: Experience and Practices in the United States.''

5. Ibid.

6. More research is needed to determine the threshold for curtailment in California below which the renewables industry will not be hurt. There is no reliable national average for how much curtailment is acceptable. Rather, the threshold differs depending on state and federal policies. For example, if generators are fully compensated for curtailment (including lost PTC revenue) and if there is investor confidence that the contract and policy environment is reliable and stable, then the threshold for curtailment is likely much higher than in a territory where generators are not compensated for curtailment.

7. Jonathan Cheszes, ''Impact of Curtailment on Wind Economics,'' Renewable Energy World.Com, March 20, 2012, http://www.renewableenergyworld.com/rea/news/article/2012/03/impact-of-curtailment-on-wind-economics

8. Cochran et al., ''Flexibility in 21st Century Power Systems.''

9. Energy+Environmental Economics, ''Investigating a Higher Renewables Portfolio Standard in California,'' Jan. 2014. https://ethree.com/documents/E3_Final_RPS_Report_2014_01_06_with_appendices.pdf

10. Bird et al., ''Wind and Solar Energy Curtailment: Experience and Practices in the United States.''

11. Jaquelin Cochran, Lori Bird, Jenny Heeter, and Douglas J. Arent, ''Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience,'' National Renewable Energy Lab, April 2012, http://www.nrel.gov/docs/fy12osti/53732.pdf

12. Cochran et al., ''Flexibility in 21st Century Power Systems.''

13. Jacobsen, H.K., Schroder, S.T. Curtailment of renewable generation: economic optimality and incentives. Energy Policy 49, 663–675, Postprint 2012, DTU Management Engineering, Technical University of Denmark.

14. The specific threshold-level is system-specific and depends on the system flexibility supply curve. There is no rule-of-thumb number that applies to energy markets across the U.S.

15. Interview with Andrew Mills, Lawrence Berkeley National Laboratory, Aug. 11, 2014.

16. GE Energy, ''Western Wind and Solar: Integration Study,'' Prepared for the National Renewable Energy Lab, May 2010, http://www.nrel.gov/docs/fy10osti/47781.pdf

17. Interview with Heather Sanders, Deane Lyon, and Karl Meeusen, CAISO, Aug. 11, 2014.

  http://dx.doi.org/10.1016/j.tej.2015.06.008

18. Steven Greenlee, CAISO, personal communication with the authors, June 5, 2015.

19. Bird et al., ''Wind and Solar Energy Curtailment: Experience and Practices in the United States.''

20. CPUC, D.11-04-030 Approves IOUs' procurement plans for 2011 RPS solicitations and integrated resource plan supplements.

21. Conversation with Cheryl Lee, CPUC, June 23, 2014.

22. Bird et al., ''Wind and Solar Energy Curtailment: Experience and Practices in the United States.''

23. Federal limits on dissolved gasses and fish habitat protection requirements mean that hydro operators cannot use spillways (the only alternative to generation) to lower high river water levels.

24. Greenlee, personal communication.

25. Dr. Karl Meeusen, Direct Testimony on behalf of the CAISO, Order Instituting Rulemaking to Integrate and Refine Procurement Policies and Consider Long-Term Procurement Plans, CPUC R.13-12-010, Submitted Aug. 13, 2014.

26. Bird et al., ''Wind and Solar Energy Curtailment: Experience and Practices in the United States.''

27. Interview with Greg Brinkman, NREL, Aug. 14, 2014.

28. The assumption of unlimited economic renewable curtailment is not necessarily a practical assumption. Dr. Karl Meeusen (CAISO) is ''not aware of any contracts with renewable capacity that allows for unlimited curtailment provisions of the renewable resources. . .Further, these contracts may not provide for any economic curtailment. Renewable resources without curtailment provisions are offered into the CAISO as self-schedules. This means that the CAISO can only curtail the output of these resources based on reliability concerns.'' Source: Dr. Karl Meeusen Direct Testimony to CPUC, Aug. 13, 2014.

29. ''California Independent System Operator Corporation Deterministic Studies,'' rulemaking 13-12-010, May 8, 2015. http://www.caiso.com/Documents/May8_2015_DeterministicStudies_nocurtailment_ExistingTrajectory_40percentRPS_R13-12-010.pdf

30. Dr. Karl Meeusen, Direct Testimony to CPUC, Aug. 13, 2014.

31. Energy+Environmental Economics, ''Investigating a Higher

Renewables Portfolio Standard in California.''

32. Bentham Paulos, ''California Plans for Even More Renewable Power in Its Future,'' POWER Magazine, 12/17/2014. http://www.powermag.com/california-plans-for-even-more-renewable-power-in-its-future/?pagenum=1

33. California 2030 Low Carbon Grid Study, Phase 1 Results, Sept. 2014. http://www.lowcarbongrid2030.org

34. Solomon, A.A., Kammen, D.M., Callaway, D., 2014. The role of large-scale energy storage design and dispatch in the power grid: a study of very high grid penetration of variable renewable resources. Appl. Energy 134, 75–89.

35. Official definition from CAISO: ''Generation equipment that automatically responds to signals from the CAISO's energy management system control in real-time to control the power output of generating units within a prescribed area in response to a change in system frequency, tie-line loading, or the relation frequency and the established interchange with other Balancing Authority Areas within the predetermined limits.''

36. Manual curtailment is used by APS, Salt River Project, Tucson Electric, ISO-NE, PacifiCorp, SPP, and MISO (NREL, March 2014).

37. Cochran et al., ''Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience.''

38. Bird et al., ''Wind and Solar Energy Curtailment: Experience and Practices in the United States.''

39. Ibid.

40. Regulatory Assistance Project, ''Meeting Renewable Energy Targets in the West at Least Cost: the Integration Challenge,'' Western Governors Association, June 10, 2012, http://www.raponline.org/featured-work/meeting-renewable-energy-targets-in-the-west-at-least-cost-the-integration

41. ''How the West's new Energy Imbalance Market is building a smarter energy system,'' Utility Dive, Feb. 19, 2015.

42. Various studies of a larger EIM in the Western Interconnection could result in benefits ranging from $50 million to several hundred millions of dollars per year under current RPS targets, with much of the benefit resulting from reduced renewable integration costs. Source: Energy + Environmental Economics, ''Investigating a Higher Renewables Portfolio Standard in California,'' Jan. 2014. https://ethree.com/documents/E3_Final_RPS_Report_2014_01_06_with_appendices.pdf

43. Utility Dive, Feb. 19, 2015.

44. Dr. Shucheng Liu, Direct Testimony on behalf of the CAISO, Order Instituting Rulemaking to Integrate and Refine Procurement Policies and Consider Long-Term

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Procurement Plans, CPUC R.13-12-010, Submitted Aug. 13, 2014.

45. Cochran et al., ''Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience.''

46. Energy+Environmental Economics, ''Investigating a Higher Renewables Portfolio Standard in California.''

47. Greg Brinkman, Jennie Jorgenson, and Marissa Hummon, NREL, *California Low Carbon Grid Study: Phase 1*, http://www.lowcarbongrid2030.org/wp-content/uploads/2014/10/LCGS_PhaseI_NRELslides.pdf

48. California Legislative Information, http://leginfo.legislature.ca.gov/

49. One of the integration solutions E3 modeled analyzes the impact of increased coordination between California and other regions in reducing integration costs. Under this scenario, California exports up to 6,500 MW of power.

50. Cochran et al., ''Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience.''

51. North American Electric Reliability Corporation, ''IVGTF Task 2.4 Report: Operating Practices, Procedures, and Tools,'' March 2011, http://www.nerc.com/docs/pc/ivgtf/IVGTF2-4CleanBK(11.22).pdf

52. GE Energy, ''Western Wind and Solar: Integration Study.''

53. Cochran et al., ''Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience.''

54. Holttinen, H., et al., 2009. Design and Operation of Power Systems with Large Amounts of Wind Power. Final report, IEA WIND Task 25, Phase One 2006–2008. VTT, Vuorimiehentie, Finland. http://www.vtt.fi/inf/pdf/tiedotteet/2009/T2493.pdf

55. Ibid.

56. Cochran et al., ''Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience.''

57. Energy+Environmental Economics, ''Investigating a Higher Renewables Portfolio Standard in California.''

58. These imports consist of ''baseload'' power scheduled from coal and nuclear resources owned by or contracted to California utilities, surplus hydroelectric generation from the Northwest, and economic imports of natural gas power from the

Northwest and Southwest. During some hours, California imports as much as 12,400 MW of power over its interties with the rest of the Western Interconnection. California also currently exports a small amount of power to the Pacific Northwest during some hours in the wintertime; however, these exports are more than offset by imports from the Southwest, such that California is never a net exporter of power'' (Source: E3).

59. Ibid.

60. ''Indeed, while the West-of-River transmission path connecting California to the Desert Southwest has an East-to-West rating of 10,600 MW, it does not have a formal West-to-East rating. It is therefore unknown at this time what level of exports from California the western grid can support. Nevertheless, an analysis of load growth projections, resource retirements, and RPS policies in neighboring states suggested that by 2030, it may be possible to export up to 6,500 MW of power to the rest of the West'' (Source: E3).

61. Ibid.

62. Interview with Greg Brinkman, NREL, Aug. 14, 2014.

63. Ibid.

64. Energy+Environmental Economics, ''Investigating a Higher Renewables Portfolio Standard in California.''

65. GTM Research, *Regulating The Utility Of The Future: Implications for the Grid Edge*, Jan. 2015.

66. Adam Langton and Noel Crisostomo, Energy Division, California Public Utilities Commission, *Vehicle-Grid Integration: A Vision for Zero-Emission Transportation Interconnected throughout California's Electricity System*, http://www.cpuc.ca.gov/PUC/energy/altvehicles/ (March 2014).

67. Sierra Martinez and Dylan Sullivan, ''Using Energy Efficiency To Meet Flexible Resource Needs and Integrate High Levels of Renewables Into The Grid,'' Natural Resources Defense Council, 2014, http://aceee.org/files/proceedings/2014/data/papers/5-1012.pdf

68. California ISO Demand Response and Energy Efficiency Roadmap: Maximizing Preferred Resources, Dec. 2013, http://www.caiso.com/documents/dr-eeroadmap.pdf

69. Dr. Karl Meeusen, Direct Testimony to CPUC, Aug. 13, 2014.

70. Cochran et al., ''Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience.''

71. Ibid.

72. Ibid.

73. Interview with Andrew Mills, LBNL, Aug. 11, 2014.

74. Cochran et al., ''Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience.''

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