Investigating the Economic Value of Flexible Solar Power Plant Operation

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Energy+Environmental Economics

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Abstract

Solar power is growing rapidly around the world, driven by dramatic cost reductions and increased interest in carbon-free energy sources. Solar is a variable resource, requiring grid operators to increase the available operating range on conventional generators, sometimes by committing additional units to ensure enough grid flexibility to balance the system. At very high levels of penetration, operators may not have enough flexibility on conventional generators to ensure reliable operations.

However, modern solar power plants can be operated flexibly; in fact, they can respond to dispatch instructions much more quickly than conventional generators. Flexible solar not only contributes to solving operating challenges related to solar variability but can also provide essential grid services. This study simulates operations of an actual utility system – Tampa Electric Company (TECO) – and its generation portfolio to investigate the economic value of using solar as a flexible resource. The study explores four solar operating modes: "Must-Take," "Curtailable," "Downward Dispatch," and "Full Flexibility."

The study finds that for this relatively small utility system, *Must-Take* solar becomes infeasible once solar penetration exceeds 14% of annual energy supply due to unavoidable oversupply during low demand periods, necessitating a shift to the *Curtailable* mode of solar operations. As the penetration continues to grow, the operating reserves needed to accommodate solar uncertainty become a significant cost driver, leading to more conservative thermal plant operations and increasingly large amounts of solar curtailment. Flexible solar reduces uncertainty, enabling leaner operations and providing significant economic value. At penetration levels exceeding 20% on the TECO system, solar curtailment can be reduced by more than half by moving from the *Curtailable* to the *Full Flexibility* solar operating mode. This results in significant additional value due to reduced fuel costs, operations and maintenance costs, and air emissions.

Finally, the study evaluates the impact of flexible solar in combination with energy storage. We find that flexible solar can provide some of the same grid services as energy storage, thereby reducing the value of storage on a high-solar grid.

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1 Introduction

Solar electricity is becoming an important part of the electric generation portfolio in many regions due to rapidly declining costs and policies favoring non-emitting renewable generation. The installed capacity of solar has grown exponentially over the past two decades.

Further solar growth is expected in subsequent decades. Policy targets for renewable energy installation and decarbonization of the energy system are driving solar installations around the world. Both India and China have targets to reach more than 100 GW of installed solar capacity by the early 2020s.[1] California and Hawaii have passed legislation to reach 100% renewable or zero-carbon electricity by 2045, and it is expected that solar energy will be one of the primary energy sources used meet these ambitious targets. Recent analysis on deep decarbonization pathways in California suggests that solar power could supply a large fraction of the economy-wide demand for energy by 2050.[2] Europe is also expected to increase solar energy capacity to meet decarbonization targets.

1.1 Operational challenges and opportunities

Existing or "conventional" utility-scale solar is typically designed and operated to generate and deliver the maximum amount of electricity in real-time. This approach is motivated by the desire to minimize the cost per unit of energy by amortizing the capital cost of solar across the maximum amount of energy that system could produce.

Increasing the level of solar can make it more challenging for grid operators to balance electricity supply and demand. For example, grid operators must manage rapid increases in solar generation during sunrise

[1] International Energy Agency, "IEA/IRENA Joint Policies and Measures Database: Global Renewable Energy," accessed September 2018, https://www.iea.org/policiesandmeasures/renewableenergy/.

[2] A. Mahone, Z. Subin, J. Kahn-Lang, D. Allen, V. Li, G. De Moor, N. Ryan and S. Price, "Deep Decarbonization in a High Renewables Future: Updated Results from the California PATHWAYS Model," Energy and Environmental Economics, Inc., June 2018, https://www.ethree.com/wp-content/uploads/2018/06/Deep_Decarbonization_in_a_High_Renewables_Future_CEC-500-2018-012-1.pdf.

and rapid decreases in solar production during sunset, in addition to variations in solar output caused by regional weather conditions. This often requires managing ramping events by rapidly varying the output of conventional thermal generation. At higher levels of solar penetration, operational challenges become more acute.

Many operational challenges can be addressed by making utility-scale solar available to provide flexibility for grid operations when needed. For example, ramping demands on conventional generation resources can be reduced if solar plants can control ramp rates during both morning and evening hours, thereby providing the means to flexibly operate the grid even in the presence of higher levels of solar generation. While operating solar generators in a flexible manner leads to occasional curtailment of solar output, this may still be a more economical operating mode than other options.

Recent studies have shown that utility-scale solar photovoltaic (PV) plants can provide essential grid reliability services that are typically associated with conventional generation.[3] In the most recent study, First Solar teamed with the National Renewable Energy Laboratory (NREL) and the California Independent System Operator (CAISO) to test a 300 MW utility-scale photovoltaic power plant in California. The power plant was equipped with advanced power controls by combining multiple power-electronic inverters and advanced plant-level controls. The test demonstrated that PV plants can have the technical capabilities to provide grid services such as spinning reserves, load following, voltage support, ramping, frequency response, variability smoothing, frequency regulation, and power quality improvement. Specifically, the tests included various forms of active power controls such as automatic generation control and frequency regulation, droop response, and reactive power/voltage/power factor controls. The results showed that regulation accuracy by the PV plant is significantly better than fast-ramping gas turbine technologies.

By leveraging the full suite of operational capabilities of utility-scale solar resources, solar can go beyond a simple energy source and become an important tool to help operators meet flexibility and reliability

[3] See V. Gevorgian and B. O'Neill, "Advanced Grid-Friendly Controls Demonstration Project for Utility-Scale PV Power Plants," National Renewable Energy Laboratory, January 2016, **https://www.nrel.gov/docs/fy16osti/65368.pdf**; M. Morjaria, D. Anichkov, V. Chadliev and S. Soni, "A Grid-Friendly Plant: The Role of Utility-Scale Photovoltaic Plants in Grid Stability and Reliability," IEEE Power and Energy Magazine, vol. 12, no. 3, 2014; and California ISO, National Renewable Energy Laboratory, and First Solar, "Using Renewables to Operate a Low-Carbon Grid: Demonstration of Advanced Reliability Services from a Utility-scale Solar PV Plant," 2017, **https://www.caiso.com/documents/usingrenewablestooperatelow-carbongrid.pdf**.

needs of the grid. To date, the economic value of including solar as an active participant in balancing requirements has not been widely studied. To quantify the value of flexible solar operation, our study introduces solar flexibility constraints into a detailed multi-stage production cost model. We do not explore the economic value of voltage control in this study.

Recent cost declines in energy storage technologies enable solar to further extend its capability by providing firm dispatchable capabilities, which in turn enables even higher solar penetrations. Adding storage to the grid can shift energy to when it is most needed, even if the sun has already set. Adding storage to a grid can combine the flexibility of solar with the firm capacity and energy shifting capabilities of storage, but requires significant capital investment in storage resources. The last section of this study investigates the interplay of solar flexibility and storage value.

1.2 Uncertainty and variability in grid operations

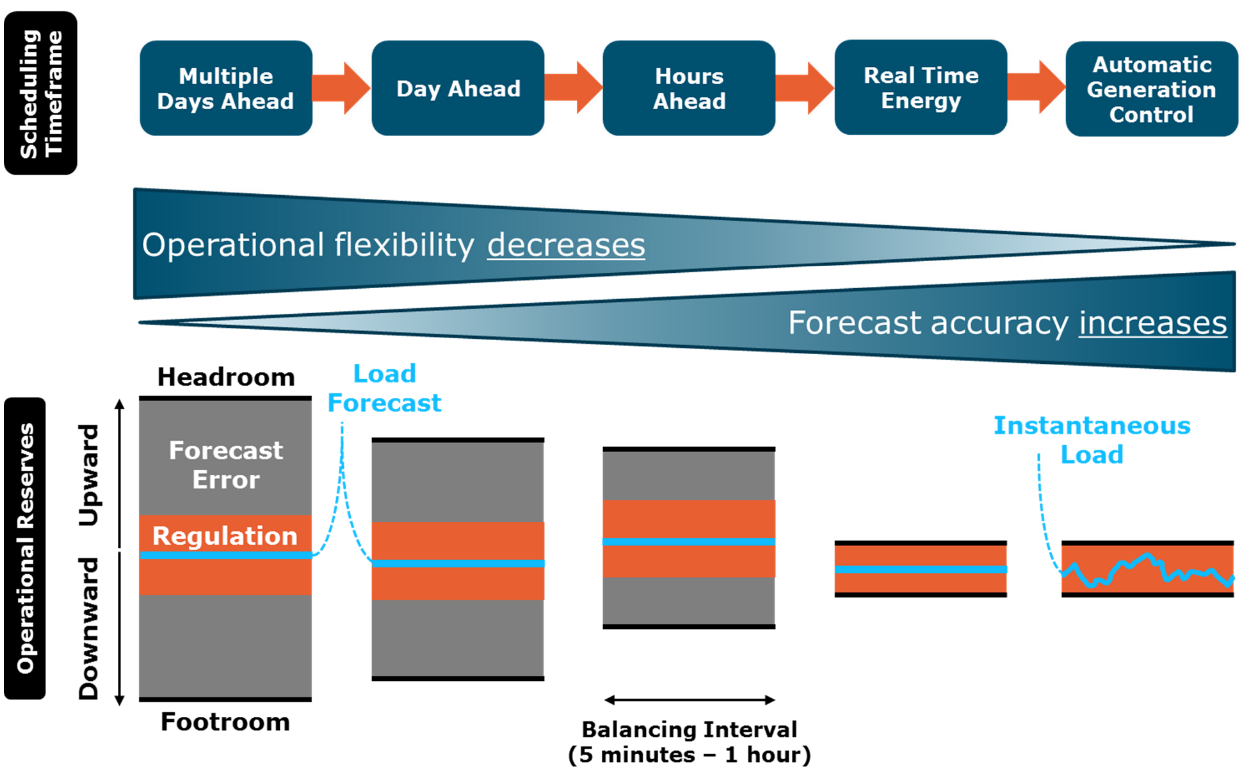
Much like musicians following the conductor in an orchestra, the system operator coordinates the dispatch of an ensemble of power plants. The system operator's goal is to meet demand at least cost while maintaining reliability.

Operational challenges are often described using the terms *variability* and *uncertainty*. Variability refers to increases and decreases in demand or resource availability that would exist even with a perfect forecast. For example, diurnal patterns in human activity are a source of demand variability because these patterns occur naturally over the course of a day. Uncertainty represents the inability to perfectly forecast future demand or other grid conditions. Even in the absence of wind and solar power plants, system operators must maintain system reliability at all times under significant variability and uncertainty of demand, as well as uncertainty with respect to generator and transmission availability.

To balance the system, operators must have information about the level of uncertainty in their forecasts as well as the capabilities of their resources to respond. Forecast accuracy increases closer to real time, but the ability to respond to unexpected events decreases because the operating range of conventional power plants is smaller over shorter time intervals. This problem is magnified by the challenges of generator scheduling ("unit commitment"), because thermal generators typically require significant lead time – hours to days, or even weeks – to be turned on or off. Once running, thermal plants must generate at minimum levels that are typically at least 20 – 50% of maximum output. For some coal-fired generation, the minimum generation level can be as high as 70%. Thus, system operators must frequently make decisions about which units will be operating and at what levels far in advance, and with imperfect information about the level of demand and renewable production.

If actual demand turns out to be much higher than forecasted, there may not be enough resources available to meet demand. To deal with this uncertainty, grid operators maintain a safety margin on top of forecasted demand ("headroom") when scheduling power plants so that a demand under-forecast does not turn into a power shortage. This is shown schematically in Figure 1. In the opposite direction, operators may also retain the ability to turn down or turn off generation ("footroom") to avoid oversupply conditions in the event of a demand over-forecast.

Figure 1: Commitment timeframes, forecast uncertainty, headroom and footroom



System operators are constantly balancing economics and reliability when making commitment and dispatch decisions. If they are conservative and commit too many power plants, generators will be forced to run at less efficient set points or cycle on and off quickly, both of which can be costly. If operators are not conservative enough, they may have to buy expensive energy from neighbors in real-time, call on expensive demand response resources, or incur penalties for violating reliability standards. The worst case is that there simply is not enough generation capacity committed to serve demand and the operator must temporarily disconnect customer loads.

In addition to the challenges of forecasting demand long before real-time, operators must also be prepared for the natural variability of demand in real-time. Common practice is to hold headroom and footroom on quick-moving units ("regulation") to ensure adequate flexibility. Organized markets – the California Independent System Operator (CAISO), the Electric Reliability Council of Texas (ERCOT), PJM Interconnection, the Midcontinent Independent System Operator (MISO), etc. – procure regulation as part of market operations, and centrally dispatched utilities typically have a similar requirement in their dispatch procedures. Operators also address variability by committing units more frequently closer to real-time operations. It is common to commit and dispatch generators on an hourly basis a day-ahead of real-time, and every five to fifteen minutes during real-time operations.

Increasing the level of solar (and wind) generation on the grid increases the variability and uncertainty of electricity supply, both because of imperfect forecasts of wind and solar output and because of fluctuations in output on a minute-to-minute basis. This frequently increases the overall forecast error and regulation requirements needed to balance supply and demand. Higher balancing requirements raise the stakes of power plant commitment decisions.

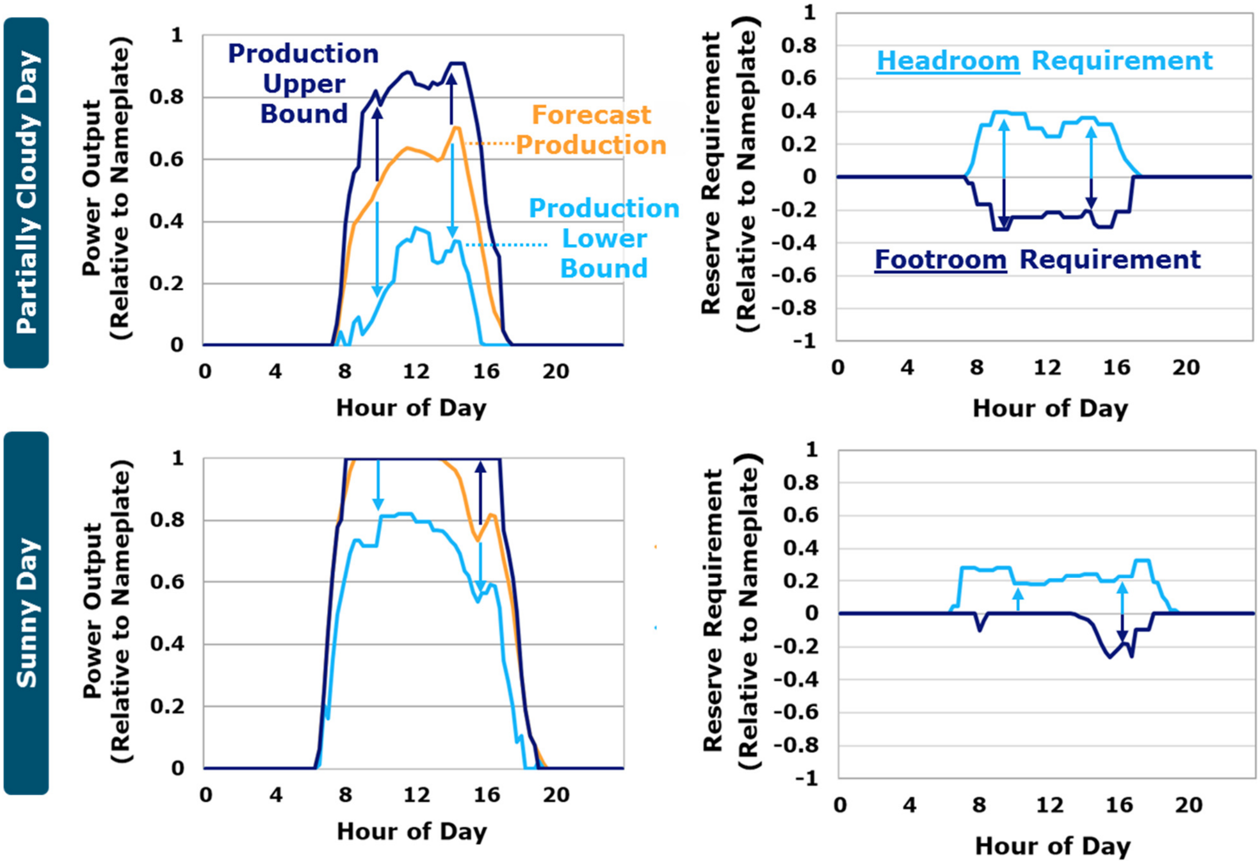
1.3 System balancing with flexible solar generators

Many modern solar power plants have the technical capabilities to contribute to regulation and balancing requirements through precise output control – this is referred to as "flexible" or "dispatchable" solar. In this operating mode, the entire suite of solar dispatch capabilities is made available to the system operator in determining economic dispatch. System operators can elect to use the solar resources to provide energy or essential grid services (e.g., regulation reserves), and this choice may vary by dispatch time interval throughout the day. Provision of these services requires downward dispatch of solar, and some services require the plant operator to maintain headroom to enable upward dispatch. While this results in lost solar production, solar plants incur no measurable variable costs from providing these services. Instead, the cost of solar providing these services is an opportunity cost that can be estimated in the context of economic dispatch. Obtaining grid services from solar plants can, in some instances, enable system operators to reduce fuel costs by reducing thermal generator commitments and increasing the efficiency at which they operate.

Sourcing essential grid services from solar requires the system operator to have an appropriate degree of confidence in the level of solar output minutes, hours, or days ahead of real-time dispatch. As shown in Figure 2, historical solar forecast errors can be used to calculate expected lower and upper bounds on solar production when making commitment decisions ahead of real-time. The lower and upper bounds are used to 1) set system-wide headroom and footroom needs for solar forecast error, and 2) if solar is represented as dispatchable, set limits on how much the solar plant could be dispatched. There are a variety of means for establishing confidence bounds, and this would be an interesting topic for future research. For the current study, we use a single standard deviation above and below the solar forecast as the upper and lower bounds when committing units ahead of real-time.

Our study focuses on the flexible operation of solar power plants in the absence of battery storage. To date, much emphasis has been placed on the role that storage can play in managing solar and wind variability and uncertainty. In this study, we focus on the operation of the solar or wind power plants themselves, and the economic benefits that may result from operating these assets in a more flexible manner. Interactions with battery storage value are explored in a sensitivity study.

Figure 2: Confidence in solar forecasts hours ahead of real-time (left) and resulting forecast error reserve levels (right) on an example partly cloudy day (top) and sunny day (bottom), normalized to solar power plant capacity. As discussed below, reserve requirements must be met by non-solar resources if solar flexibility is not integrated into system operator dispatch procedures, but can be partially met by solar power plants when solar is represented as more flexible.



1.4 Solar operating modes

In this study we explore different solar "operating modes," which represent the extent to which system operators have incorporated the inherent flexibility of many modern utility-scale solar power plants into their operational procedures. We define four solar operating modes to explore the value of solar dispatch flexibility, ordered from least to most flexible:

Solar Operating Mode	Solar can be curtailed	Solar can contribute to footroom requirements	Solar can contribute to headroom requirements
Must-Take	×	×	×
Curtailable	✓	×	×
Downward Dispatch	✓	✓	×
Full Flexibility	✓	✓	✓

In the Must-Take and Curtailable operating modes, other resources – in this study, thermal generators and batteries – are committed such that solar can produce at maximum possible output even in the case of solar under- or over-forecast. In the Downward Dispatch operating mode, solar can be dispatched downward (curtailed) to meet footroom requirements but cannot contribute to headroom requirements. In the Full Flexibility operating mode, solar can be fully dispatched to meet grid needs via economic optimization of energy production and operational reserves while accounting for physical limits imposed by solar insolation availability. When solar is scheduled to be curtailed ahead of real-time, the amount of forecast error headroom that is held on other resources is reduced.

Renewable integration studies include a range of assumptions with respect to solar (or wind) operating modes. Most studies simulate solar (or wind) in Curtailable or Downward Dispatch operating mode, though the implementation of solar operating mode in these studies depends on modeling methodology and may not map precisely onto the operating modes defined above. A smaller set of studies explores the Full Flexibility operating mode for solar, frequently as a sensitivity study. Appendix B, "Prior Research," contains citations to example renewable integration studies.

1.4.1 MUST-TAKE OPERATING MODE

Many system operators and solar integration studies treat solar power plants as "must-take." The common convention is to subtract solar production from electricity demand, which assumes there is neither the ability nor the desire to control solar output. The resulting "net load" is the amount of power that must be produced by other "dispatchable" resources.

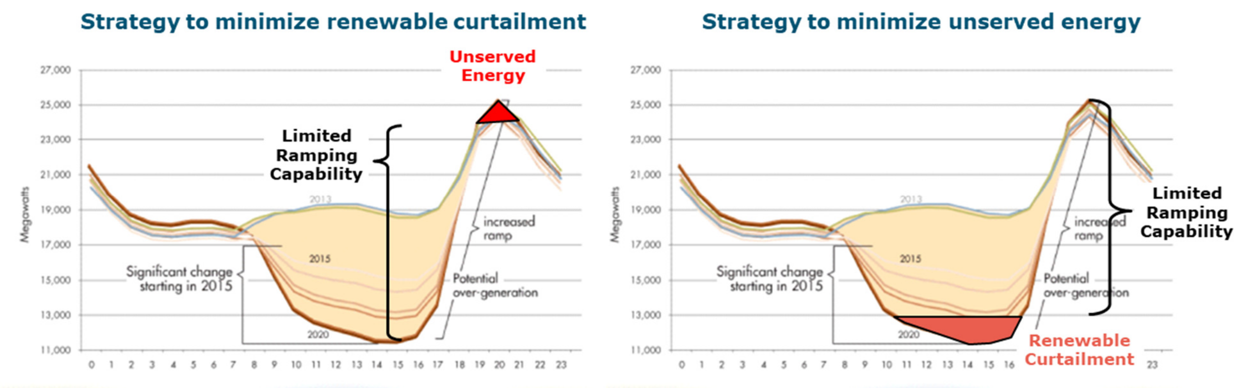
Quick thought experiments demonstrate that the concept of net load was not designed for high penetrations of solar. What if there is so much solar on the grid that there is more solar electricity production than demand? In this scenario, net load would be negative. Balancing supply and demand with negative net load would be very challenging, requiring some level of exports, flexible demand, or energy storage. In the extreme case, the system simply cannot be brought into balance without drastic action such as the temporary disconnection of generators. The term "solar overgeneration" has been used to describe the situation of solar production levels that exceed the ability of the power system to absorb all solar generation. Challenges related to overgeneration and system balancing led early analyses to conclude that power systems could accept only a small fraction of annual energy penetration from variable renewables (wind and solar) before encountering reliability challenges.

It is worthwhile to note that present-day rooftop solar installations are operated as "must-take" because they are almost never visible to or curtailable by the system operator. One of the corollaries to this study's conclusions is that reaching high rooftop solar penetrations will require some control of these resources – operator dispatch signals, pricing mechanisms, local autonomous control, or other control methods.

The CAISO's widely-circulated "duck curve" is a prominent example of operational concerns in the context of must-take solar.[4] Figure 3, based on the duck curve, demonstrates this phenomenon for a system with limited ramping capability. In the left panel, operational limitations lead to a reliability problem: unserved energy, which occurs when the system cannot ramp up fast enough to meet high demand in the evening. In the right panel, prospective curtailment of renewable generation has been used to avoid loss of load by ensuring that sufficient upward ramping capability is online and available. However, this strategy comes at the cost of lost renewable production.

[4] California ISO, "What the duck curve tells us about managing a green grid," 2016, **https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf**.

Figure 3: Prospective curtailment of renewable energy resources eliminates a reliability challenge, but introduces an economic challenge



1.4.2 CURTAILABLE OPERATING MODE

As solar penetration has increased, curtailment of solar output has become a reality during hours in which inflexibility, lack of load, or transmission constraints prevent absorption of all available solar energy. Curtailment can occur through analog means if necessary – for example, a phone call from the system operator to the plant operator requesting a reduction in output. Increasingly, solar and wind generators are providing decremental energy bids into organized markets such as CAISO, MISO and ERCOT, enabling curtailment to occur as a market outcome rather than through an emergency phone call. In many instances, power purchase agreements (PPA) between independent power producers (IPP) and utility off-takers of solar project output have evolved to accommodate some degree of curtailment flexibility to reflect this emerging reality. Many regions (e.g., Germany, Denmark, California, Hawaii, etc.) have successfully reached higher penetrations of variable renewables – as high as 42% of annual energy in the case of Denmark – by using renewable curtailment and interties with neighboring regions as important integration tools.[5]

Solar curtailment to date has been largely, if not exclusively, focused on avoiding oversupply. Even though solar output can be controlled to an extent, many renewable integration studies and grid operators continue to include solar forecast error in their calculations of headroom and footroom balancing

[5] A. Bloom, U. Helman, H. Holttinen, K. Summers, J. Bakke, G. Brinkman and A. Lopez, "It's Indisputable: Five Facts About Planning and Operating Modern Power Systems," IEEE Power and Energy Magazine, 2017.

requirements while excluding solar generators from meeting any portion of those requirements. In other words, solar can be curtailed during normal grid operations, but regulation and forecast error reserve requirements are still determined based on net load and must be met by resources other than solar generators. We refer to solar operated in this mode as "Curtailable," since curtailment is used only to avoid oversupply and the precise control of solar output is not considered in generator scheduling and economic dispatch.

1.4.3 DOWNWARD DISPATCH OPERATING MODE

The deployment of more variable renewable capacity has increased the need for "downward" flexibility, or footroom. If renewable production unexpectedly increases, other resources must ramp downward to accommodate the additional energy flowing onto the system. This is particularly a concern in real-time, after commitment decisions have been made. In this case, insufficient footroom might result in large quantities of energy flowing onto neighboring systems, violating North American Electric Reliability Corporation (NERC) control performance standards.

However, if the system operator can control output from the solar plant in real-time, it is possible to reduce solar generation to avoid overgeneration conditions. Utilizing the footroom that is available on a flexible solar resource reduces or eliminates the need to hold footroom on other resources to accommodate unexpected spikes in solar production. Stated differently, solar can provide its own downward reserves or footroom. Consequently, our simulations with the Downward Dispatch solar operating mode system operations do not require any footroom for solar uncertainty and variability.

But solar that can be dispatched downward is not limited to providing *its own* footroom – it can also provide footroom to accommodate unexpected decreases in *demand*. In other words, flexible solar can be used to provide the downward regulation service that system operators have for more than a century sourced exclusively from conventional generators. If enough solar is forecasted to be online in real-time, operators can plan to dispatch solar downwards if demand drops unexpectedly. In this study, we limit the footroom that solar can provide for meeting variability and uncertainty in demand to the lower bound of forecasted solar production potential – the distance between zero and the light blue Production Lower

Bound line in Figure 2. This limit ensures that footroom on solar will be available even if solar generation is over-forecasted.

One potential issue with relying on variable renewables for balancing services is that the operator cannot be certain that the resource will produce enough power to provide the balancing service. This concern is minimal in the case of solar footroom, because the service is needed predominantly *during the times when solar is producing too much energy*. Our production simulation results do not show any significant overgeneration events in real-time even at very high solar penetration levels, indicating that system operators can rely on solar to provide footroom when necessary. With enough flexible solar on the grid, it is unlikely that system operators will have reliability concerns related to downward flexibility in the daytime, although operators will continue to need footroom to cover load variations during nighttime hours.

1.4.4 FULL FLEXIBLITY OPERATING MODE

In this study, the Full Flexibility solar operating mode includes the most options of any operating mode for solar to contribute to essential grid services, and the highest degree of integration of solar resource characteristics into system operator dispatch procedures. The Full Flexibility operating mode includes all the footroom capability of solar from the Downward Dispatch operating mode but also allows solar to provide headroom (upward) flexibility.

Relying on solar to provide *headroom* (regulation up, spinning reserve, etc.) requires 1) plant output to be curtailed intentionally or under-scheduled (scheduled below the maximum available energy production) in order to create headroom, and 2) system operator confidence that additional solar production potential will be realized if called upon. We posit that solar can be forecasted with sufficient confidence within a lower bound as discussed above, but we recognize that system operators will naturally be conservative when relying on solar in the upward direction.

Under-scheduling solar reduces the uncertainty of solar production, and therefore the headroom that would be required for solar forecast error. For example, if at the day-ahead scheduling period it is anticipated that solar would be curtailed on the operating day due to oversupply, system operators can reduce the amount of headroom they would otherwise procure to accommodate a potential solar over-forecast. Put another way, headroom needed on other resources for solar forecast error is reduced when the operator forecasts the need to curtail solar before real-time.

In addition to reducing headroom reserves associated with solar forecast error, under-scheduled solar could be a potent provider of upward ramping service. Solar power plants can ramp up much more quickly than their conventional counterparts, suggesting that solar may be particularly well suited to provide frequency regulation or fast frequency response. This is especially true given that the supply of these fast-timescale balancing services tends to be the most limited during times of low demand and high variable renewable production.

In this study, we have allowed solar to provide upward regulation with available headroom. To ensure that the regulation headroom on solar is available in real-time, we require that additional forecast error headroom is held on other resources when scheduling solar regulation capacity before real-time. A summary of how solar provides headroom and footroom in this study is presented in Table 6 in Appendix A. We do not simulate the provision of fast frequency response in this study, nor do we simulate solar providing contingency reserve and headroom for load under-forecast events, although we believe it should be possible for solar to provide these services given enough certainty on solar production potential. This means that there may be additional value for solar headroom that is not included in this study, especially at higher solar penetration levels.

2 Description of Case Study

2.1.1 SYSTEM DESCRIPTION

To demonstrate the economic value of dispatching solar, we use the PLEXOS Integrated Energy Model to simulate unit commitment and dispatch of an actual utility system – Tampa Electric Company (TECO). TECO has good solar resource availability and a peak demand of ~ 5 GW. TECO operates its electricity system as a Balancing Authority.

TECO was an active participant in the study and provided data on its system, including real-time and forecast demand data, fuel cost projections, and detailed, unit-specific information on its thermal generation portfolio. Our study represents a snapshot of the TECO system in 2019.

TECO's thermal generation portfolio is similar to that found in many areas of the United States and other countries, making the results of this study broadly applicable. The expected 2019 portfolio consists of 60% of thermal capacity from natural gas combined cycle units, 6% from natural gas simple cycle combustion turbines, 20% from natural gas steam turbines, and 13% from coal steam and integrated gasification combined cycle units. TECO's generation portfolio does not include nuclear, wind, other renewable resources, or substantial behind-the-meter solar.

2.1.2 SOLAR DEPLOYMENT LEVELS

We simulate a range of utility-scale solar deployment levels ranging from 0% (no solar) to 28% annual energy penetration potential. The upper end of this range represents higher levels of solar energy than are currently operational in any balancing area in the United States. Annual solar energy penetration potential refers to the amount of energy available from a given capacity of solar energy facilities – the amount that would be produced in the absence of curtailment – normalized to annual balancing area electricity demand. We simulate each penetration level with four different solar operating modes: Must-Take, Curtailable, Downward Dispatch, and Full Flexibility.

This study focuses on operational cost savings of adding solar generation assets to the electricity system and does not include a full cost-benefit analysis of solar deployment. The solar penetration levels studied herein are academic in nature and are not indicative of TECO's future resource acquisition plans. TECO is currently developing 600 MW solar (~7% annual energy penetration) and a 10 MW / 27 MWh storage facility.

2.1.3 SOLAR PRODUCTION DATA

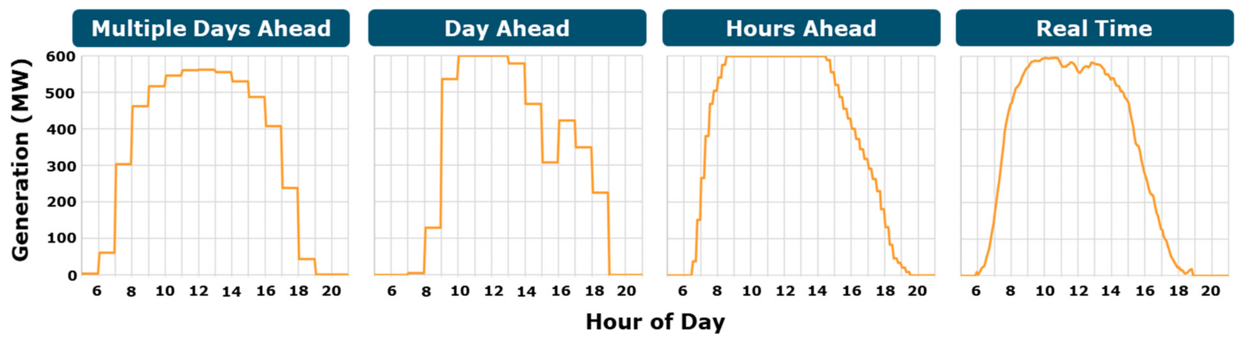
It is important to retain correlations between solar availability and weather-driven heating and cooling loads. We accomplish this by using historical data from 2017 as the basis of load and solar profiles. For demand, 2017 demand profiles are scaled to 2019 using projected 2019 annual TECO demand. For solar, TECO identified 15 sites in its service territory that are being considered for solar development. Locus Energy produced simulated 5-minute solar insolation data from 2017 for each site, and First Solar transformed the insolation data into solar plant output potential. We aggregate solar profiles for the 15 sites into a single TECO-wide solar profile and scale this profile to installed solar capacity. This approach assumes that all solar development occurs within TECO's service territory – a relatively small portion of the Florida peninsula – which therefore would not materially increase the geographic diversity of TECO's solar resources at higher levels of solar penetration. It may be possible to reduce the variability and uncertainty of solar generation by deploying solar power plants over a larger footprint.

Historical solar forecast data is not available from the Locus Energy dataset, so we synthesize solar forecasts through a day-matching algorithm utilizing a National Renewable Laboratory (NREL) solar dataset.[6] Three separate forecast error profiles from the Tampa area were averaged to generate one TECO-wide profile. The NREL dataset contains forecasts for one day ahead and four hours ahead of real-time, but TECO also uses forecasts to make commitment decisions for coal and gas steam units many days ahead of real-time. To generate multiple day-ahead solar forecasts, we simply use the month-hour

[6]National Renewable Energy Laboratory, "Solar Power Data for Integration Studies," accessed March 2018, **https://www.nrel.gov/grid/solar-power-data.html**.

average of the First Solar output profiles. Figure 4 shows how solar forecasts change ahead of real-time operations.

Figure 4: Solar profiles used for unit commitment across different timeframes from an example June day. Profiles are for 600 MW of installed solar capacity.



2.1.4 PLEXOS PRODUCTION COST MODEL

System operators have imperfect information about future grid conditions when making key operational decisions. The PLEXOS model we use in this study optimizes system unit commitment and dispatch for each day of the year in four sequential stages: multiple days-ahead, day-ahead, hours-ahead, and real-time (Table 1). The goal of each stage of the model is to represent the quality of information that TECO system operators would have at key operational decision points. To this end, load and solar production profiles are updated with better forecasts after each stage.

Table 1. PLEXOS model stages

Unit commitment stage	Dispatch and commitment decision timestep	Look-ahead length (after operating day)	Load timeseries data (provided by TECO)	Solar timeseries data
Multiple days-ahead	Hourly	Six days	Multiple days ahead forecast	Month-hour average of 5-minute real-time profiles
Day-ahead	Hourly	Eight hours	Day ahead forecast	NREL day ahead forecast
Hours-ahead	Every 15 minutes	Two hours	Average of day-of forecast and actual 5-minute demand	NREL 4-hour ahead forecast
Real-time	Every 5 minutes	None	Actual 5-minute demand profile	Simulated 5-minute profile

Based on input from TECO, each class of thermal generator is assigned a final stage beyond which commitment decisions are not allowed to be changed (Table 2). This reflects operational practice where, as real-time approaches, commitments of relatively inflexible units cannot be changed. For combined cycle gas turbines, multiple configurations (e.g., 1x1, 2x1, etc.) are modeled with the steam turbine's commitment decision preceding the associated combustion turbine commitments.

Table 2. Timing of final commitment decisions for each generator class

Generator Class	Final Commitment Decision Made in Stage:
Coal integrated gasification combined cycle	Not economically dispatched (must-run)
Simple cycle coal steam turbine	Multiple days-ahead
Simple cycle gas steam turbine	Multiple days-ahead
Steam turbine of gas combined cycle	Day-ahead (or must-run, depending on unit)
Combustion turbine of gas combined cycle	Hours-ahead
Market transactions	Hours-ahead
Simple cycle gas combustion turbine	Real-time

Thermal generators are represented using standard unit commitment and dispatch constraints, including ramping limitations, minimum uptime and minimum downtime constraints, and co-optimized energy and reserve provision. Reserve calculations and requirements are described in Appendix A. Generator economics are reflected via heat rate curves, variable operations and maintenance costs, fuel offtake at startup, and startup costs. TECO also provided unit-specific maintenance and outage schedules. Consistent with current TECO dispatch practices, a price on CO_2 emissions was not included.

For simplicity of case construction and interpretation, market transactions with external entities are restricted to hours in which the TECO system does not have enough generation available to serve load. Market transactions are limited by hourly transmission availability data provided by TECO. Exports from the TECO system to external entities were not considered. In reality, TECO would have additional opportunities to deliver solar energy to external entities and reduce operating cost beyond what is simulated here.

3 Flexible Solar Production Simulation Results

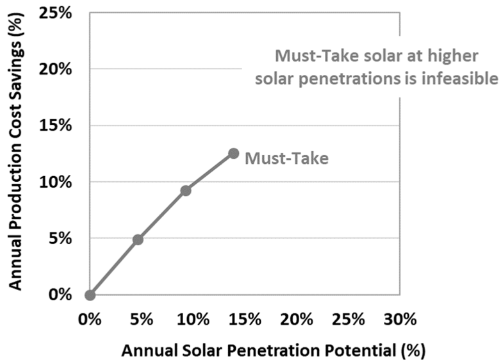
3.1 "Must-Take" operating mode: Limited by overgeneration

We first explore the limits of the Must-Take solar operating mode. We find that Must-Take solar can be absorbed by the TECO system up to about 14% of annual energy penetration potential. At solar penetrations above this level, we begin to observe overgeneration conditions, indicating that the system does not have enough flexibility to balance supply and demand while also accepting every MWh of solar generation. An example dispatch day demonstrating overgeneration conditions is shown in the middle panel of Figure 5. Solar penetrations above 14% on the TECO system are infeasible in Must-Take operating mode.

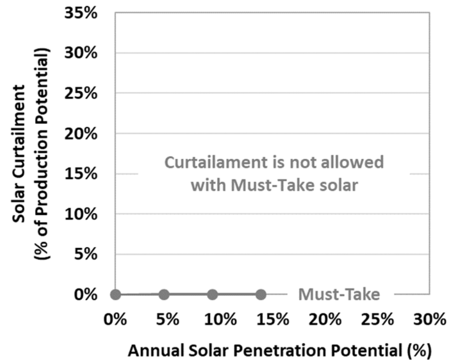
The appearance of overgeneration indicates that solar curtailment is a necessary tool to balance the system above a threshold level of solar penetration. This result is generalizable to any system, though the annual energy penetration threshold will depend on the characteristics of each individual system, including the load shape and the flexibility of its generation fleet. Shown schematically in the bottom panel of Figure 5, Must-Take solar at high solar generation levels can cause conflicting requirements to 1) accept all solar generation and 2) maintain headroom and footroom on thermal generation. Most thermal generators have minimum power (PMin) requirements; if turned on, a typical thermal generator must generate at a minimum of 20 – 50% of its rated capacity (PMax). The commitment decision for many generators must be made hours to days ahead of real-time, when the actual real-time solar output is not known with great certainty. Committing enough generation capacity to create the headroom and footroom required to plan for many possible levels of solar generation (cloudy to sunny) exhausts the operational range (PMin to PMax) of the thermal fleet. Our results demonstrate that planning to absorb all solar generation is untenable at higher solar penetration levels.

Figure 5: Summary: "Must-Take" Operating Mode

Production Cost Savings, normalized to system production cost without solar generation



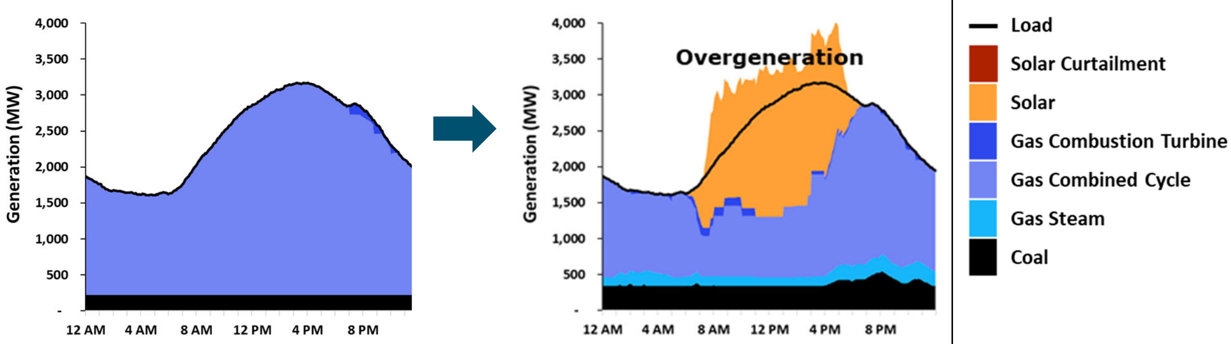
Solar Curtailment



Generation Dispatch on an example spring day

No Solar

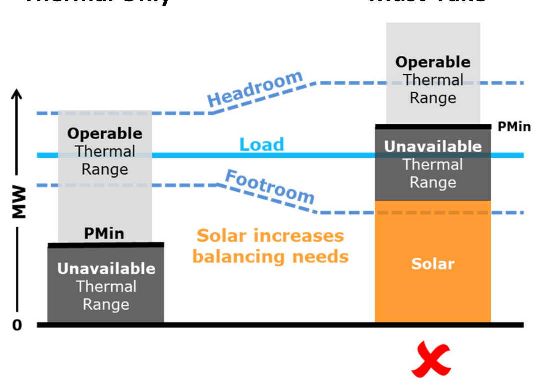
Must-Take with 28% annual solar energy penetration potential



Schematic of balancing requirements, thermal operational range, and solar generation

Thermal Only

Must-Take



Summary

With Must-Take solar at higher penetration levels, no footroom is available and overgeneration is observed when the minimum thermal dispatch (PMin) is above load.

3.2 "Curtailable" operating mode: Feasible dispatch

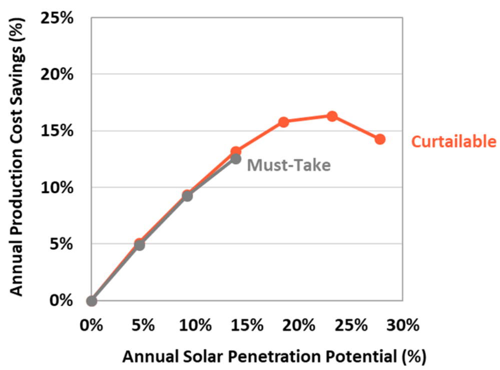
A key indicator of inadequate operational flexibility is the curtailment of variable renewable generation. As shown in the top right panel of Figure 6, solar can contribute up to 14% of energy with very low levels of curtailment, indicating that the thermal generation fleet has adequate flexibility to integrate up to this level of solar generation with minimal challenges. Since very little solar curtailment is necessary at this level of solar penetration, increasing the flexibility of solar generation provides limited additional value.

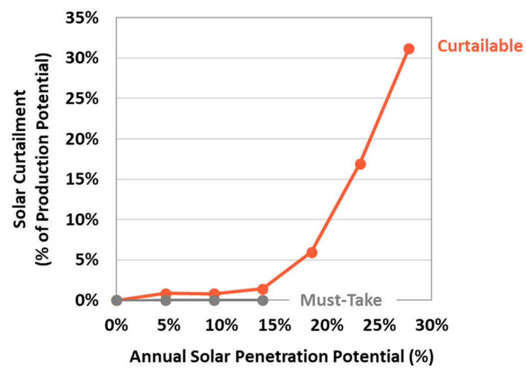
At intermediate levels of solar penetration on the TECO system (~15 – 25% solar energy penetration), curtailing solar generation allows what would otherwise be an inoperable system with Must-Take solar to become operable. Curtailing solar enables more thermal generators to be committed, thereby creating enough space within the dispatch stack to maintain adequate headroom and footroom on thermal units (Figure 6, bottom panel). Even though the system is operable, curtailment levels resulting from this operational strategy become very high as more solar is added to the system. Adding more solar causes additional thermal units to be committed to meet increased operational reserve requirements. Committing these units causes more fuel to be burned in conventional generators, which in turn reduces the energy value of solar generation.

The energy value (Figure 6, top panel) on the TECO system of additional solar energy in Curtailable operating mode decays rapidly above about 14% solar energy penetration. The energy value (or, equivalently, the production cost savings) is calculated as the change in annual production costs as solar penetration increases, excluding the capital cost of additional solar resources. Solar provides very little marginal energy value at penetration levels above 19%. In the extreme – above 23% solar energy production potential – solar has a *negative* marginal energy value. This occurs because the increase in headroom and footroom required to balance solar forecast error is so large, and the fuel penalty for providing these reserves on thermal units so significant, that adding solar actually increases fuel consumption. The relatively small footprint of TECO's balancing area and solar resources contribute to the steep drop-off in energy value in Curtailable operating mode. The solar penetration level at which Curtailable operating mode becomes ineffective will be system-specific, but we expect that other systems will show similar dynamics as the level of solar generation is increased. Given the economic inefficiencies that result from Curtailable operating mode at higher levels of solar penetration, our results suggest that as more solar is deployed, system operators should adapt dispatch procedures to include more flexible solar plant operation.

Figure 6: Summary: "Curtailable" Operating Mode

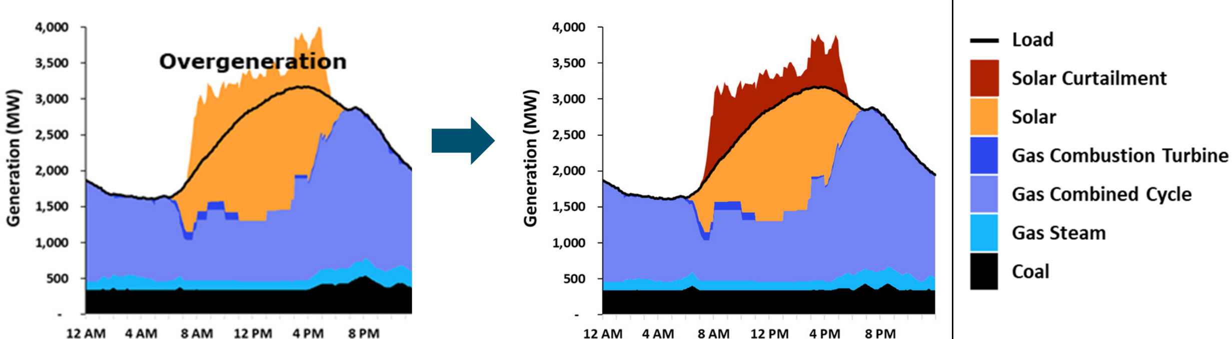
Production Cost Savings, normalized to system production cost without solar generation	Solar Curtailment





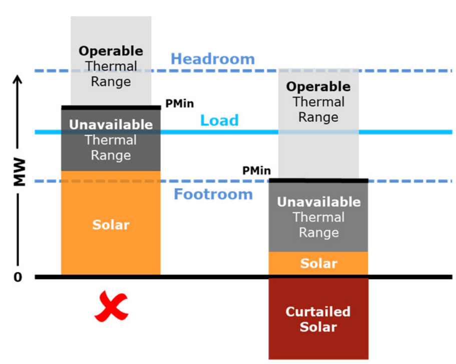
Generation Dispatch on an example spring day at 28% annual solar energy penetration potential

Must-Take **Curtailable**



Schematic of balancing requirements, thermal operational range, and solar generation

Must-Take **Curtailable**



Summary

Dispatch is feasible with Curtailable solar because solar generation can be reduced until thermal dispatch is within the operable range.

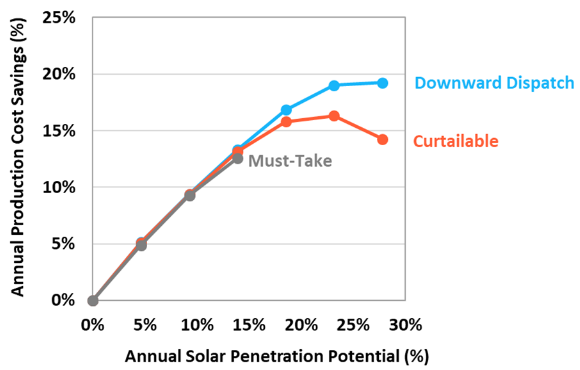
3.3 "Downward Dispatch" operating mode: Reduced curtailment and thermal commitment, and increased value

Compared to Curtailable operating mode, Downward Dispatch operating mode allows solar to retain value at higher levels of solar generation (Figure 7, top panel). Downward Dispatch improves on Curtailable by allowing the system operator to plan to turn down solar generation if solar is over-forecasted ahead of real-time operations. Downward Dispatch also allows regulation footroom requirements to be provided by solar generators. The middle and bottom panels of Figure 7 demonstrate that, during hours of very high solar output, downward dispatch of solar enables the operator to commit fewer thermal power plants, which reduces the minimum output requirement for thermal generation and increases the quantity of solar delivered to the grid. It may seem paradoxical, but in our simulations, solar in Downward Dispatch operating mode has *more opportunities* to be curtailed, but *less actual curtailment* is observed.[7] At 28% solar penetration potential, Downward Dispatch would reduce expected curtailment by half – from 31%, in Curtailable operating mode, to 16% – enabling solar to provide positive incremental value at higher solar penetration levels. Our simulation results show that, with the right economic dispatch rules, solar curtailment can be minimized by allowing solar to provide the most constrained grid services at key times.

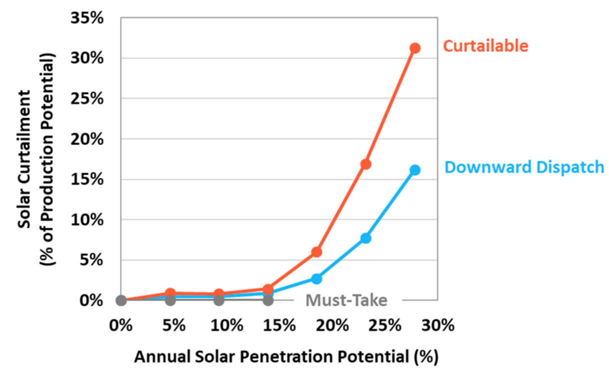
[7] We do not estimate the amount of regulation that would be dispatched by AGC below the 5-minute timescale, and the resultant differences in energy production from AGC dispatch. In the Downward Dispatch and the Full Flexibility operating modes, we develop rules by which the system operator can rely on solar to provide downward regulation, but we do not assess whether it would be most economical to turn down solar or other resources in response to an AGC signal. In some instances, it may be more economical to turn thermal generation down instead of solar, thereby avoiding fuel costs.

Figure 7: Summary: "Downward Dispatch" Operating Mode

Production Cost Savings, normalized to system production cost without solar generation

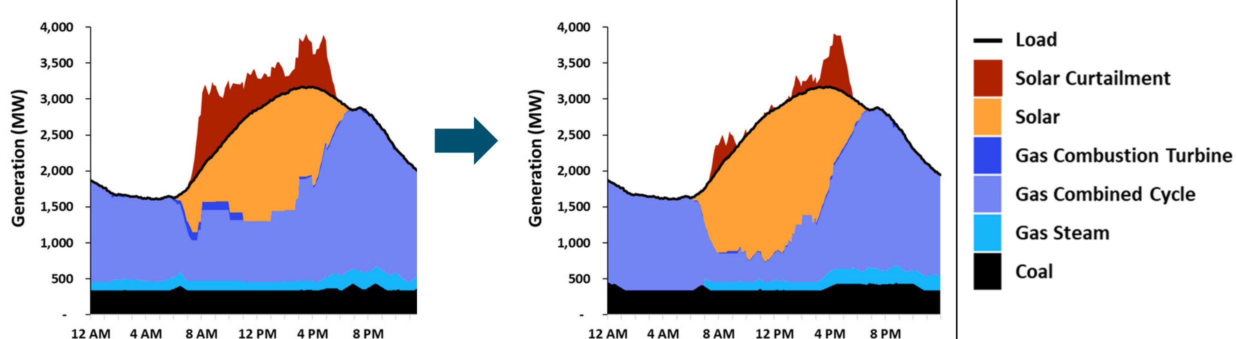


Solar Curtailment



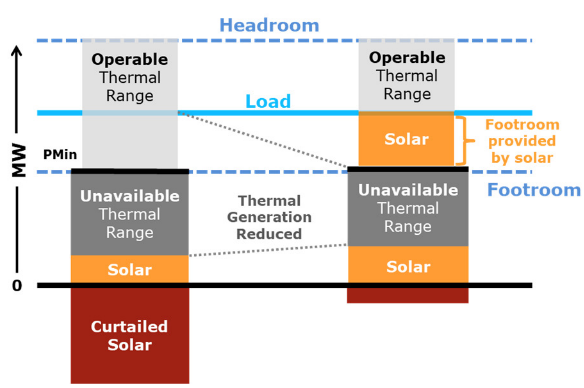
Generation Dispatch on an example spring day at 28% annual solar energy penetration potential

Curtailable **Downward Dispatch**



Schematic of balancing requirements, thermal operational range, and solar generation

Curtailable **Downward Dispatch**



Summary

With Downward Dispatch, curtailment and thermal generation is reduced because solar provides footroom. Solar headroom is not used.

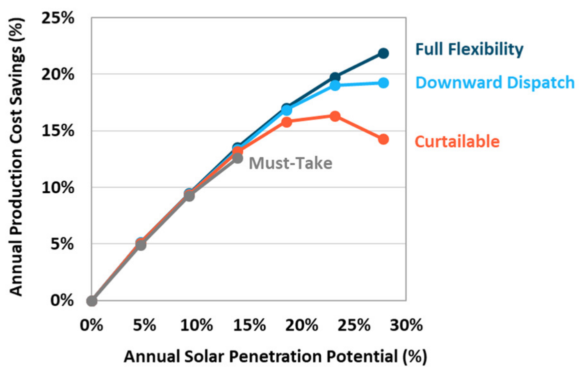
3.4 "Full Flexibility" operating mode: Additional value at higher solar penetrations

Sharing balancing requirements between thermal and solar generators becomes increasingly valuable as more solar capacity is added to the grid. Provision of balancing services from solar plants allows thermal generators to operate more efficiently by reducing the need for cycling and load following services, resulting in less fuel consumption. This also avoids commitment of inefficient thermal generation, reducing curtailment of solar during times of overgeneration.

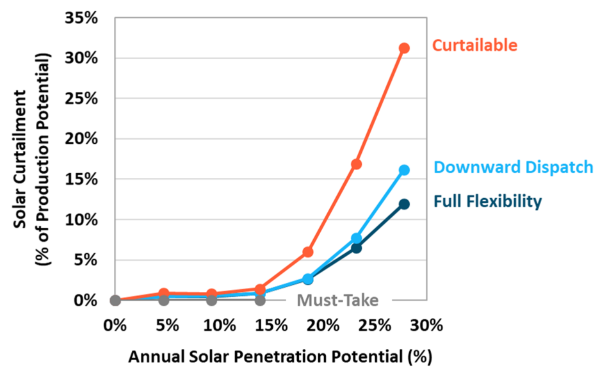
Figure 8 shows that these savings can be substantial for the TECO system. The curtailment observed in Downward Dispatch operating mode on an example spring day (Figure 8, middle panel) suggests that at higher solar penetration levels, it could be particularly challenging to ramp TECO's thermal generation fleet down at sunrise and up at sunset. Operating solar in Full Flexibility operating mode would allow system operators to reduce forecast error headroom requirements and use any available solar headroom to meet regulation headroom requirements. On this example day, integrating these capabilities into operational procedures makes thermal generator ramping at sunrise and sunset more manageable.

Figure 8: Summary: "Full Flexibility" Operating Mode

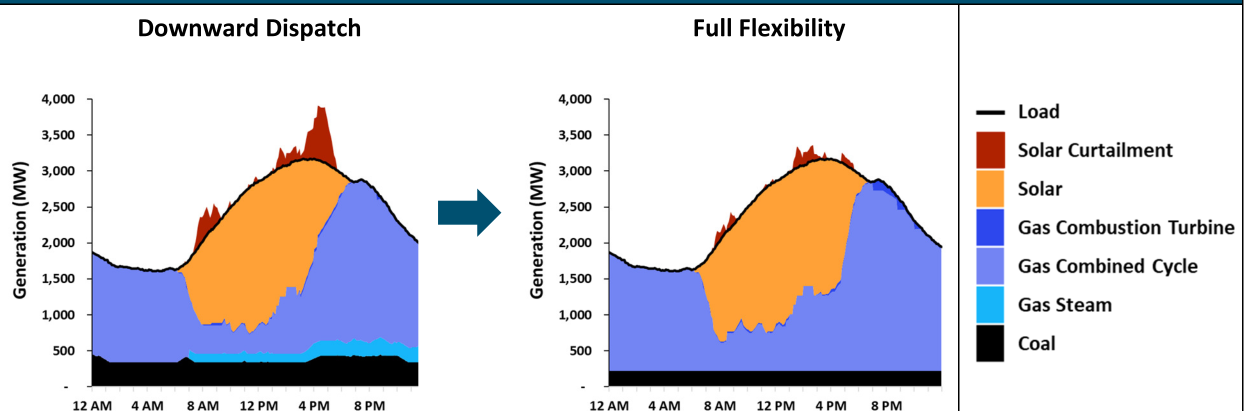
Production Cost Savings, normalized to system production cost without solar generation



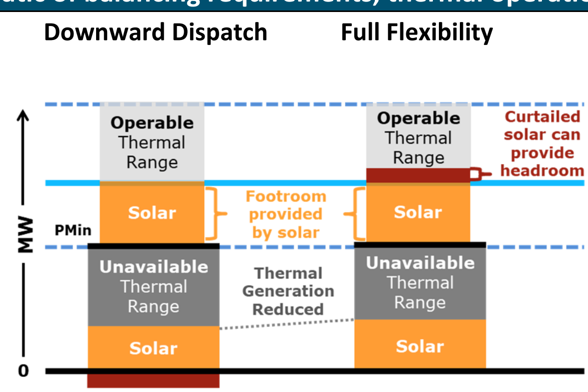
Solar Curtailment



Generation Dispatch on an example spring day at 28% annual solar energy penetration potential



Schematic of balancing requirements, thermal operational range, and solar generation



Summary

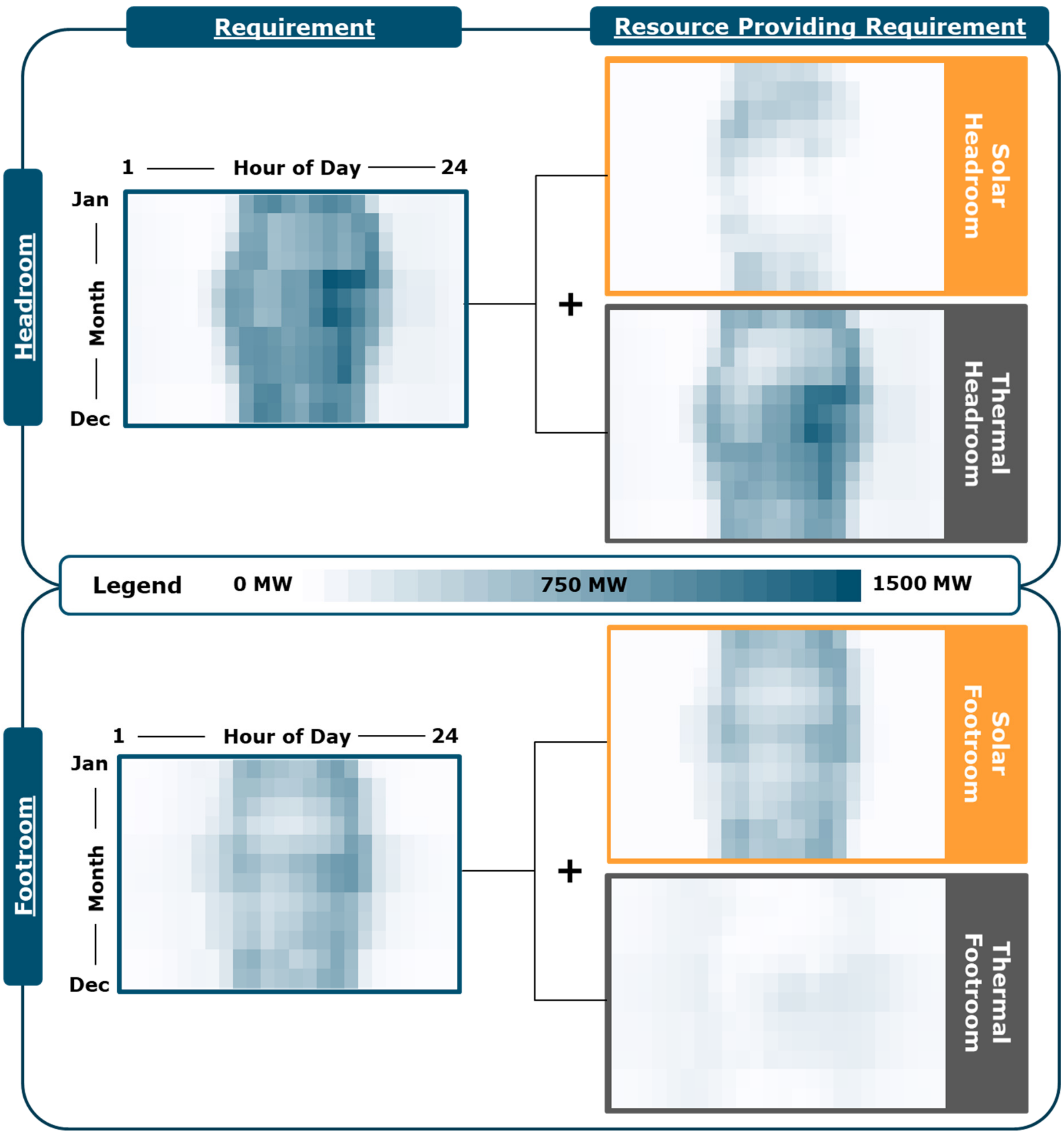
With Full Flexibiltiy, curtailment and thermal generation are minimized because solar contributes to footroom and headroom.

Figure 9 shows the distribution of headroom requirements between thermal and solar resources for the hours-ahead unit commitment stage. Footroom requirements during the daytime are met predominantly by solar.[8] Solar provides headroom to mitigate forecast uncertainties via committing to curtail and by committing to provide regulation. For example, solar is curtailed frequently in spring morning and early afternoon hours, thereby creating headroom that could be used productively to meet operational requirements. During summer late afternoon and early evening hours, solar does not typically reduce headroom requirements by committing to curtail because load is high enough in these hours to absorb (not curtail) most solar generation, and the TECO generation fleet has enough headroom flexibility to absorb all solar generation. Our results confirm that headroom on solar is most likely to be available during periods of low load and high solar output, but that solar generators are unlikely to be curtailed for the purpose of creating headroom during higher-load hours.

The scope of this study is limited to the operation of resources within TECO balancing area, and consequently transactions with external entities are not represented in detail. Energy market transactions with neighboring regions may become more valuable and/or frequent at higher solar penetrations. These transactions would allow TECO to access the capabilities of a larger pool of thermal resources, thereby making it easier to meet headroom, footroom, and ramping requirements. Forecast error headroom requirements may be particularly impacted by increased regional coordination, because the aggregate forecast error of a larger footprint of solar resources will be reduced relative to the same capacity of solar resources deployed over a smaller footprint. Increasing the level of regional coordination would reduce flexibility challenges related to adding solar resources into TECO's generation portfolio, thereby allowing solar energy to retain value at higher solar penetration levels. We expect that for a given level of solar generation, increased regional coordination would decrease the value of operating solar power plants in a more flexible manner. However, higher value for solar energy may hasten the pace of solar development across the region, thereby increasing solar penetration and consequently the value of solar flexibility.

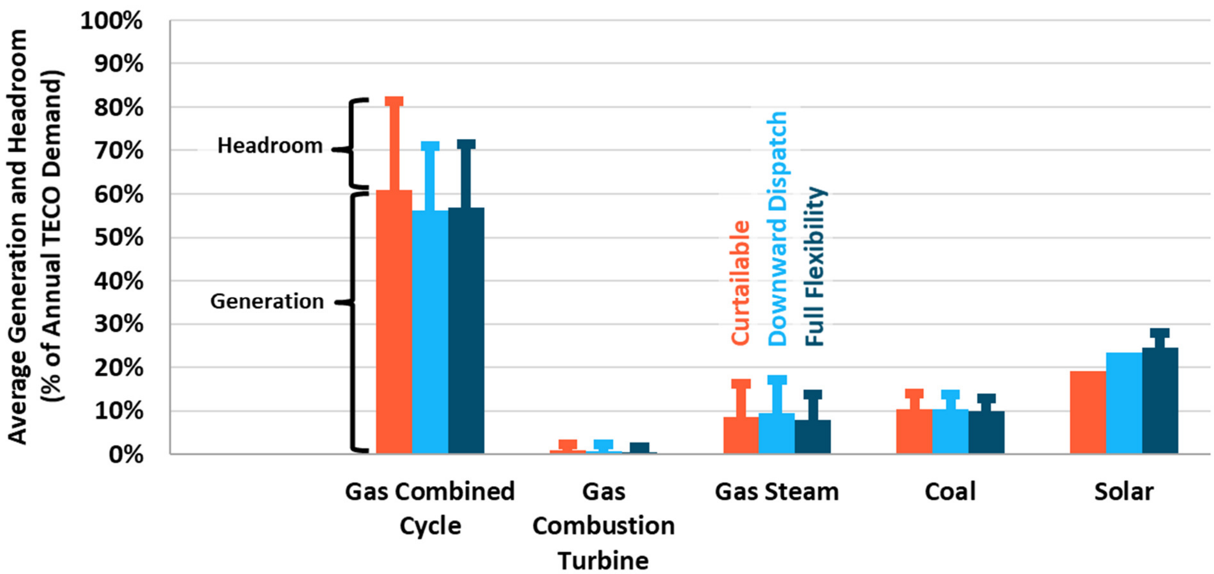
[8] When simulating the Downward Dispatch and Full Flexibility operating modes in PLEXOS, footroom requirements resulting from solar variability and uncertainty are not explicitly modeled because it is assumed that solar can provide these requirements if necessary. Simulation results do not show significant overgeneration events in real-time, confirming that footroom on solar for forecast error and within-hour variability is an effective balancing strategy. Our modeling does not simulate the dispatch of solar footroom held on AGC for balancing below the 5-minute timescale, but we expect solar to be effective on this timescale as well given the demonstrated capabilities of flexible solar plants.

Figure 9: Headroom and footroom requirements (left) and the portion of each requirement provided by solar and thermal resources (right) for the hours-ahead unit commitment stage at 28% annual solar energy production potential (2400 MW nameplate solar capacity) in the Full Flexibility operating mode. Values are month-hour averages.



Comparing thermal headroom and generation between the Curtailable and Full Flexibility operating modes (Figure 10, orange vs. dark blue bars) demonstrates that increasing solar flexibility reduces both thermal commitments and generation. The Curtailable, Downward Dispatch, and Full Flexibility simulations in Figure 10 have identical generator capacities and operational characteristics, except for their levels of solar flexibility. Note that no additional large capital investments would be necessary to reduce thermal capacity factors and commitment levels; increasing solar flexibility simply uses existing assets more efficiently, resulting in lower production costs.

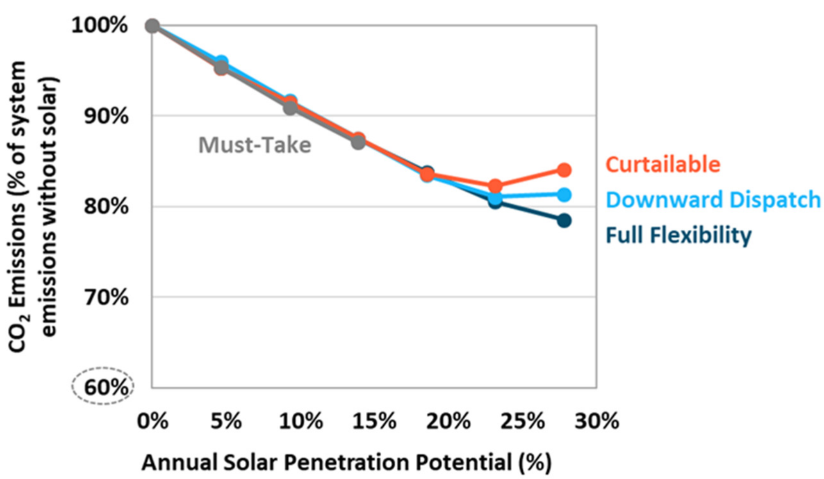
Figure 10: Annual average generation and headroom at 28% annual solar energy production potential, expressed as a fraction of annual TECO demand. Headroom is calculated as the difference between generation setpoint and committed capacity (or available production for solar) in real-time. Headroom on solar is only shown for the Full Flexibility operating mode.



3.5 CO_2 emissions results

Operating solar power plants in a more flexible manner enhances the ability of solar to reduce CO_2 emissions from electricity generation. As solar capacity increases, CO_2 emissions are reduced in all cases when solar is operated in Full Flexibility operating mode (Figure 11). At higher solar penetrations, Curtailable and Downward Dispatch operating modes result in more curtailment and higher levels of CO_2 emissions relative to Full Flexibility. At lower levels of solar penetration (less than ~19% annual solar penetration potential), we observe small differences in CO_2 emissions among the solar operating modes but do not believe them to be material.

Figure 11: CO_2 emissions as a function of solar deployment and solar operating mode



Flexibly scheduling and controlling solar plants can provide significant reliability, financial, and environmental value. Solar dispatch flexibility an important tool that grid operators can use to address challenges associated with higher solar penetrations and to integrate increasing amounts of solar cost-effectively. Dispatching solar power plants to the needs of the grid will reduce CO_2 emissions at higher solar penetrations and may reduce criteria pollutant emissions (such as NO_x), which can be significantly higher for power plants that frequently ramp up and down.

3.6 Summary tables

The numeric values in Table 3 and Table 4 indicate that increasing solar flexibility increases the value of solar energy and decreases solar curtailment. These values are for one specific system configuration, and depend on resource capabilities and capacity, fuel cost projections, and other many factors. Consequently, the values should not be applied to other jurisdictions or other TECO system conditions.

Table 3. Average and marginal energy value of solar, in $/MWh of solar production potential. The energy value of solar represents only production cost savings and does not include other value streams such as avoided peak capacity. The marginal energy value of solar is calculated as the change in production cost resulting from the addition of an incremental 400 MW of solar capacity.

Available Solar Generation			Average Energy Value of Solar ($/MWh)				**Marginal Energy Value of Solar ($/MWh)**			
Nameplate MW	Annual GWh	% of 2019 TECO Demand	Must-Take	Curtailable	Downward Dispatch	Full Flexibility	Must-Take	Curtailable	Downward Dispatch	Full Flexibility
400	958	4.6%	$28.7	$29.9	$30.1	$30.1	$28.7	$29.9	$30.1	$30.1
800	1,916	9.3%	$27.2	$27.5	$27.6	$27.8	$25.8	$25.1	$25.1	$25.5
1,200	2,874	13.9%	$24.6	$25.8	$26.1	$26.5	$19.5	$22.3	$23.2	$24.0
1,600	3,832	18.5%	N/A	$23.2	$24.7	$25.0	N/A	$15.5	$20.6	$20.5
2,000	4,790	23.2%	N/A	$19.2	$22.3	$23.2	N/A	$3.1	$12.8	$15.9
2,400	5,747	27.8%	N/A	$14.0	$18.9	$21.4	N/A	$ (12.1)	$1.4	$12.7

Table 4. Solar resource availability and solar curtailment results for each solar penetration level and operating mode.

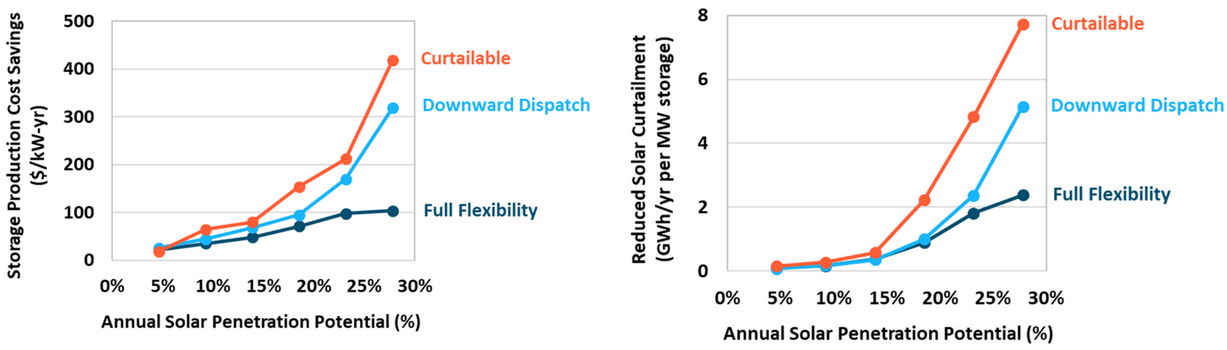
Available Solar Generation			Solar Curtailment (GWh)				Solar Curtailment (% of available solar energy)				Solar Penetration Achieved (% of 2019 TECO demand)			
Nameplate MW	Annual GWh	% of 2019 TECO Demand	Must-Take	Curtailable	Downward Dispatch	Full Flexibility	Must-Take	Curtailable	Downward Dispatch	Full Flexibility	Must-Take	Curtailable	Downward Dispatch	Full Flexibility
400	958	4.6%	0	8	5	5	0%	0.9%	0.5%	0.5%	4.6%	4.6%	4.6%	4.6%
800	1,916	9.3%	0	16	10	10	0%	0.8%	0.5%	0.5%	9.3%	9.2%	9.2%	9.2%
1,200	2,874	13.9%	0	41	24	26	0%	1.4%	0.8%	0.9%	13.9%	13.7%	13.8%	13.8%
1,600	3,832	18.5%	N/A	230	105	101	N/A	6.0%	2.7%	2.6%	N/A	17.4%	18.0%	18.0%
2,000	4,790	23.2%	N/A	811	370	311	N/A	16.9%	7.7%	6.5%	N/A	19.2%	21.4%	21.7%
2,400	5,747	27.8%	N/A	1,795	929	686	N/A	31.2%	16.2%	11.9%	N/A	19.1%	23.3%	24.5%

3.7 Sensitivity study: Incremental value of storage

Energy storage, particularly from fast-responding batteries such as lithium-ion, can quickly ramp from charging to discharge, providing an operating range that is double the nameplate capacity. Moreover, batteries can reduce fuel costs and avoid solar curtailment by charging during times of curtailment and discharging during times when thermal generation is on the margin.

For our final set of simulations, we add a small battery (50 MW, equivalent to ~1% of peak demand) with four hours of energy duration (200 MWh) to the TECO system at various levels of solar penetration to explore the value of storage in the context different solar operating modes. We find similar results to other storage production cost studies: storage provides production cost savings across all solar penetrations, with larger savings occurring at higher solar penetrations. Storage is used for a mix of regulation, forecast error reserves, and within-day energy shifting. Storage also reduces the magnitude of ramps during sunrise and sundown, which is more valuable at higher solar penetrations. The value of shifting energy increases significantly in the presence of solar curtailment (Figure 12). This study focuses on operational cost savings of storage, and therefore does not consider storage capital costs or a full cost-benefit analysis of storage.

Figure 12: Increasing solar operational flexibility can reduce the operational value of storage at a given solar penetration.



The opportunity for storage to add value is reduced when the system operator increases reliance on solar power plant flexibility, because flexible operation of solar can provide some of the same grid services as storage, especially footroom flexibility. Storage resources can be held in reserve ahead of real-time to address forecast errors in solar generation. The value of storage resources will be reduced if system operators can reduce forecast error footroom and headroom held on thermal generators by including solar curtailment in forecast error requirement calculations. In many renewable integration and storage valuation studies, a significant fraction of storage value comes from providing regulation. Solar resources could provide the same service during some portions of the day, potentially allowing the storage device to perform other functions. Also, solar curtailment decreases as solar operational flexibility is increased, thereby reducing the value of storage (see Figure 12) because fewer opportunities exist for energy shifting at a given solar penetration level. Renewable integration studies at higher renewable penetrations do not typically simulate wind or solar in the Full Flexibility operating mode, and therefore may overstate the value of storage. However, we recognize that if an electricity system already has a significant amount of storage or other flexible resources, the incremental value of increasing solar flexibility would be reduced relative to a system with less flexibility.

While our results suggest that increasing solar flexibility may reduce the need for storage (and/or other flexible resources) at intermediate solar penetrations, there is still a significant role for storage to play at high solar penetrations. As more and more solar is deployed in a grid, the operational value of adding energy storage will increase due to increased balancing requirements and increased solar curtailment. Storage can also provide significant system capacity value, whereas the marginal capacity contribution of solar resources tends to drop relatively quickly with increasing solar penetration.

4 Areas for Future Research

This study lays out some of the technical considerations that must be implemented to tap the full potential of flexible solar in grid operations. Further work is necessary on many fronts to fully realize the potential of flexible solar:

- Solar forecasts are key to unlocking the potential of flexible solar. Without some certainty on the possible bounds of power production, it is impossible to rely on a variable resource for balancing services, especially for services that require headroom. A method is needed to develop a confidence interval for flexible solar that is conservative enough to be workable in a control room while still providing a reasonable solar dispatch range. Providing footroom with solar requires significantly less forecast accuracy than is required to provide headroom.

- Disincentives for flexible solar exist in markets where Renewable Energy Certificates (RECs) are a primary revenue source, because RECs are only generated when the generator produces a MWh of renewable energy. A renewable power plant would not want to forgo REC revenue by offering to be dispatched unless doing so provided the generator with positive net revenue. Further research can shed light on the value of solar dispatch in a market with RECs.

- Many existing renewable power plants have contracts that do not envision using the plant for grid balancing, so contracts would need to be clarified or renegotiated to enable dispatchability from existing facilities.

- In organized electricity markets, it remains to be seen how variable renewables would bid their flexibility into energy and ancillary service markets. Existing methods of calculating opportunity cost for ancillary services are largely based on thermal opportunity cost of producing less energy and dispatching at less efficient setpoints. Compared to thermal generators, variable renewables have more uncertainty surrounding day-ahead or hour-ahead maximum production levels. Also, variable renewables may have no marginal cost of providing ancillary services if they are already curtailed due to system-wide conditions.

- Some organized markets do not separately procure upward (headroom) and downward (footroom) services. However, our study indicates that the cost for solar to provide headroom and footroom is highly asymmetric. Flexible solar is likely to have significantly higher value in markets, like the California ISO, with distinct upward and downward reserve products. Other market operators in areas with high wind and solar penetration should consider establishing separate downward and upward reserve products.

5 Conclusions

When envisioning a power system with large amounts of variable renewable energy, system planners must include information on the least-cost manner of reliably operating that system, in both the present and future. If system operators can control the power output of variable renewable resources, these resources can be viewed as assets that help to maintain reliability rather than liabilities that create operational challenges. Bringing the operational value of dispatching variable renewables into utility resource plans may change the investments made in resources going forward. The flexibility brought by dispatching variable renewable generators could reduce the need for investments in other types of flexible resources. But dispatching renewables helps to retain their value at higher penetrations, which may induce further renewable deployment and, in turn, increase the need for other flexible resources. In either scenario, reducing operational costs and CO_2 emissions from the power system is easier when solar power is treated as an active participant in grid balancing rather than an invisible part of the "net load."

6 Appendix A: Reserve Calculations and Requirements

Many renewable integration studies calculate headroom and footroom requirements such that unit commitment and dispatch decisions include enough flexibility to successfully navigate variability and uncertainty from load and variable renewable resources. Calculating reserve requirements is an active area of research, but at present most studies follow a similar calculation methodology.[9] In our study, we calculate reserve requirements largely using standard methods but make modifications necessitated by the multi-stage structure of our PLEXOS model and solar flexibility constraints.

We enforce three separate categories of reserve requirements in PLEXOS: forecast error (Section 6.1), regulation (Section 6.2), and contingency (Section 6.3). Section 6.4 describes how different classes of resources provide each category of reserves.

To calculate forecast error and regulation reserve requirements, we rely on year-long timeseries data for load and solar production. Both load and solar datasets include forecasted and real-time (5-minute actual) data. Solar timeseries data is described in Section 2.1.3. TECO provided a year-long timeseries of forecast and actual (5-minute) load data.

6.1 Forecast error reserves

Forecast error reserves ensure that enough capacity is committed before real-time such that load and solar forecast error do not cause reliability concerns. Both upward and downward requirements (headroom and footroom, respectively) are enforced in every model stage before real-time. Our

[9] E. Ibanez, I. Krad and E. Ela, "A Systematic Comparison of Operating Reserve Methodologies," National Renewable Energy Laboratory, 2014, **https://www.nrel.gov/docs/fy14osti/61016.pdf**; I. Krad, E. Ibanez and W. Gao, "A Comprehensive Comparison of Current Operating Reserve Methodologies," IEEE/PES Transmission and Distribution Conference and Exposition (T&D), 2016.

treatment of forecast error reserves is similar to “load following” or “flexibility” reserves in other renewable integration studies, with the exception that the within-hour variability traditionally associated with “load following” calculations is included as part of the regulation requirement in this study.

6.1.1 FORECAST ERROR REQUIREMENT CALCULATION

For each of the three model stages before real-time (i.e., multiple days-ahead, day-ahead, and hours-ahead), the difference between forecast and average actual output is calculated, resulting in a library of positive and negative MW forecast error values. The calculation is performed *individually* on demand and solar profiles. To capture correlations between demand and variable renewable resources, many studies in the literature subtract variable renewable output from demand to create a library of *net load* forecast error values. We do not employ this method because quantifying the level of solar forecast error is key to representing solar flexibility in the production simulation. At higher levels of solar penetration, we observe that solar forecast error is much larger than demand forecast error, which minimizes the difference between individual and net load forecast error calculation methodologies. In future analyses, it may be possible to retain correlations between solar and demand forecast errors when modeling solar flexibility.

To reflect different levels of forecast error at different times of the day, the library of forecast errors is divided into bins by hour of day. Because TECO experiences different weather conditions during different times of year, the hourly bins for solar forecast error are subdivided by season. Finally, to reflect differences in forecast accuracy resulting from cloud cover, the season-hour bins are divided into two separate bins: “cloudy” and “clear sky.” Solar forecasts are placed into the “cloudy” bin if the forecasted solar output is less than 80% of an estimate of the clear sky output.

System operators make conservative decisions when committing generation units, but it is not common practice to commit units to prepare the system for *every* possible future level of load or solar production. In the case of extreme forecast error, operators can perform a set of emergency actions that fall outside of the scope of production cost modeling, such as making an emergency phone call to a neighboring balancing area, dispatching contingency reserves, or allowing a small imbalance in supply and demand (thereby causing area control error) for a short period of time. Consequently, an appropriate threshold for forecast error reserves must be defined beyond which the system operator does not need to hold headroom or footroom for forecast error. This threshold can be the product of a detailed analysis that compares the value of a more reliable system with the incremental cost of holding more reserves. In many studies, a detailed cost/benefit analysis is not within scope so reserve requirement levels are selected by choosing a percentage of forecast errors based on prior studies of similar systems. Commonly used thresholds are either ~68 – 70% (roughly one standard deviation, 1σ, for a normally distributed set of forecast errors) or 95% (2σ), meaning that the unit commitment simulation will ensure that all but ~28 – 30% or 5% (respectively) of all possible forecast errors can be met by available resources.

To calculate forecast error reserves for solar in our study, we truncate the library of forecast errors to include 70% (~1σ) of all forecast errors when committing units ahead of real-time (i.e., the multiple days-ahead, day-ahead, and hours-ahead unit commitment stages). Doing so results in forecast error reserve requirements in both the upward (headroom) and downward (footroom) directions because both under- and over-forecast events are included in the timeseries datasets. We follow the same procedure for load forecast error, except that we expand the range of forecast errors that we included in the hours-ahead stage to include 95% (2σ) of all forecast errors. We truncate the library of forecast errors separately for load and solar, and then add the result to obtain the final reserve requirement.

The final step of the forecast error reserve calculation ensures that solar forecast error reserve levels remain within the bounds of possible solar production. Because solar production cannot go below zero, the forecast error headroom requirement is adjusted if the forecasted solar production minus the headroom requirement is less than zero. Because solar production cannot go above the level at which the power plant would produce under clear sky conditions, the forecast error footroom requirement is adjusted if the forecasted solar production plus the footroom requirement is greater than an estimate of the clear sky production potential for a given timestep.

Studies in the literature demonstrate that forecast error for a geographically diverse set of variable renewable resources is typically lower than forecast error for the same capacity of resources installed on a smaller footprint. For this study we assume that all solar deployment will occur within the TECO service territory, which is a relativity small portion of the Florida peninsula. Consequently, we do not reduce the marginal forecast error contribution of additional solar resources as more solar is added to the TECO system. If solar resources were to be deployed on a larger geographic footprint, forecast error requirements would be reduced and consequently the benefits of flexible solar operation would be lower at a given solar penetration. Similarly, improved solar forecasting would decrease the cost of solar integration, which would raise the value of solar facilities at any solar penetration and decrease the value of flexible solar operation at a given solar penetration.

6.2 Regulation reserves

Regulation reserves are held for short-timescale variation – less than 1 hour – of load and variable renewable output. In our study regulation reserves represent the amount of within-timestep variability that the system operator must manage if average load and solar production are perfectly forecasted at an hourly timestep for the multiple days and day-ahead unit commitment stages, a 15-minute timestep in the hours-ahead unit commitment stage, or a 5-minute timestep in the real-time unit commitment stage.

6.2.1 REGULATION RESERVE REQUIREMENT CALCULATION

We calculate regulation requirements on two different timescales (hourly to 5-minute and 5-minute to automatic generation control (AGC)) and add the result to obtain the final reserve requirement. Only the 5-minute to AGC component of the regulation requirement is held in real-time dispatch, because the real-time stage economically commits and dispatches on 5-minute intervals, thereby removing the need to hold additional headroom and footroom for variability between hourly and 5-minute commitment intervals. Regulation requirements for solar are calculated from a real-time 5-minute production profile that is the average of many individual production profiles from across the TECO region.

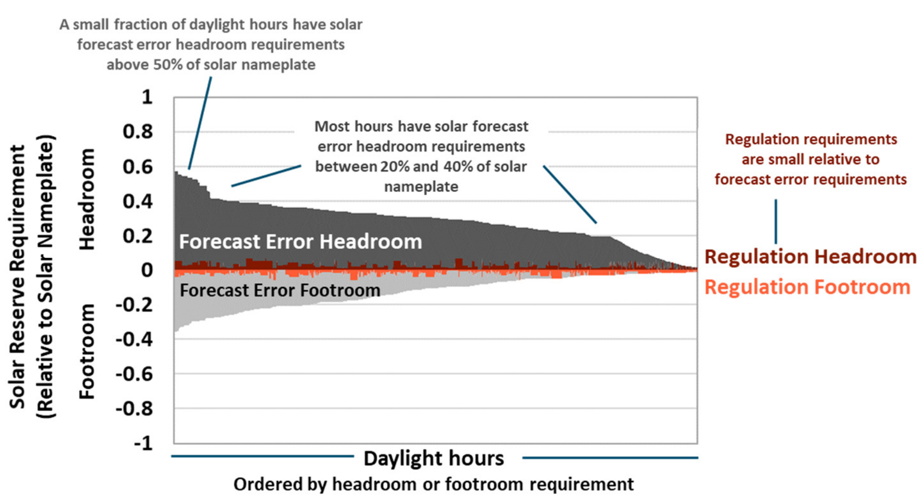
<u>Hourly to 5-minute timescale:</u> Real-time 5-minute load or solar production profiles are subtracted from a linear interpolation between hourly (multiple days-ahead and day-ahead) or 15-minute (hours-ahead) averages of the same real time profile. As with the forecast error calculation, this results in a library of positive and negative error values. Errors are divided into bins by hour of day for load, and by hour of day, season, and a cloudy/clear sky binary for solar. We calculate the hourly to 5-minute regulation requirement by truncating the library of errors within each bin to include 95% of errors.

5-minute to AGC timescale: To calculate the solar component of the AGC requirement, we estimate the short-term variation in plant output on a 5-minute timescale. We compare a cloud cover persistence forecast based on solar output in one 5-minute timestep to actual solar output in the next 5-minute timestep. Similar to other calculations, we bin the result by hour of day and season, and then apply a 95% error cutoff.

We calculate the 5-minute to AGC requirement for demand as 1% of demand, a value frequently used in other production simulations.

Figure 13 shows the combined regulation and forecast error headroom and footroom requirements for solar uncertainty and variability for the hours-ahead unit commitment stage. Only daylight hours are depicted in Figure 13. Forecast error requirements are typically much larger than regulation requirements. The relatively large magnitude of the forecast error headroom requirements is in part due to the small geographic scope of the TECO balancing area.

Figure 13: Solar reserve requirement duration curve for the hours-ahead unit commitment stage.



6.3 Contingency reserves

Contingency reserves are held for infrequent but extreme events, typically the loss of a large generation unit or transmission line. In our simulations, contingency reserves are held in all model stages, including real-time, because system operators must always be prepared for contingency events. Consistent with current operational practice, contingency reserves are only enforced in the upward (headroom) direction.

6.3.1 CONTINGENCY REQUIREMENT CALCULATION

Contingency reserve requirements for the TECO system were implemented with input from TECO staff. The magnitude of reserve need is calculated endogenously in PLEXOS for every time step as the maximum of:

- TECO’s largest generation contingency
- TECO’s share of the Florida reserve sharing obligation
- A minimum contingency reserve level of 315 MW

6.4 How resources provided reserves

Table 5. How different classes of resources provide headroom and footroom capacity to each reserve type.

Resource	Forecast error	Regulation	Contingency
Online thermal	Headroom and footroom*	Headroom and footroom, subject to ramp rate limits	Headroom, subject to ramp rate limits
Offline thermal	Nameplate capacity of generators that could start within the required timeframe, but combustion turbines in a combined cycle can only contribute if the steam turbine was committed	Could not contribute	Nameplate capacity of simple cycle combustion turbines that can start within the required timeframe
Batteries	Available headroom and footroom	Available headroom and footroom	Available headroom
Demand response	Does not contribute	Does not contribute	Available capacity
Solar	See Table 6 below		

*Online generators that can shut down with sufficient speed contribute capacity equal to their minimum production (PMin) to forecast error reserve footroom, in addition to available footroom between their setpoint and PMin.

Table 6. Schematic representing how solar generators provide reserves in this study.

Total Headroom

Headroom (MW)

Forecast Load

Footroom (MW)

Total Footroom

Reserve Type	Source of need	How does solar provide?	
Contingency	Largest contingency	Headroom on solar for contingency reserves is not modeled in this study, but would be possible with enough production potential certainty	
Forecast Error + Regulation <u>Headroom</u>	<u>Solar</u> variability and uncertainty	Forecast error up from solar is reduced when solar is curtailed	When solar provides regulation headroom, more forecast error reserve is held in case of solar over-forecast
	<u>Load</u> variability and uncertainty	Headroom on solar for load under-forecast is not modeled in this study, but would be possible with enough production potential certainty	
Forecast Error + Regulation <u>Footroom</u>	<u>Load</u> variability and uncertainty	Solar provides footroom for load over-forecast, limited by the amount of solar generation below the lower bound on solar production	
	<u>Solar</u> variability and uncertainty	Reserve need is not modeled because solar can be curtailed in real time if energy cannot be absorbed	

7 Appendix B: Prior Research

Prior research that simulates solar (or wind) in Curtailable or Downward Dispatch operating mode includes the following:

- GE Energy, "Western Wind and Solar Integration Study," National Renewable Energy Laboratory, May 2010, https://www.nrel.gov/docs/fy10osti/47434.pdf.
- Mills, A., A. Botterud, J. Wu, Z. Zhou, B.-M. Hodge and M. Heaney, "Integrating Solar PV in Utility System Operations," Argonne National Laboratory, 2013, http://eta-publications.lbl.gov/sites/default/files/lbnl-6525e.pdf.
- Eber, K. and D. Corbus, "Hawaii Solar Integration Study: Executive Summary," National Renewable Energy Laboratory, June 2013, https://www.nrel.gov/docs/fy13osti/57215.pdf.
- Energy and Environmental Economics, "Investigating a higher renewables portfolio standard in California," 2014, https://www.ethree.com/documents/E3_Final_RPS_Report_2014_01_06_with_appendices.pdf.
- California ISO, "Phase 1.A. Direct testimony of Dr. Shucheng Liu on behalf of the California Independent System Operator," 13 August 2014, http://www.caiso.com/Documents/Aug13_2014_InitialTestimony_ShuchengLiu_Phase1A_LTPP_R13-12-010.pdf.
- Energy and Environmental Economics, Inc. and National Renewable Energy Laboratory, "Western Interconnection Flexibility Assessment," Western Electricity Coordinating Council and Western Interstate Energy Board, 2015, https://www.ethree.com/wp-content/uploads/2017/02/WECC_Flexibility_Assessment_Report_2016-01-11.pdf.
- Brinkman, G., J. Jorgenson, A. Ehlen and J. Caldwell, "Low Carbon Grid Study: Analysis of a 50% Emission Reduction in California," National Renewable Energy Laboratory, January 2016, https://www.nrel.gov/docs/fy16osti/64884.pdf.
- Seel, J., A. Mills, R. Wiser, S. Deb, A. Asokkumar, M. Hassanzadeh and A. Aarabali, "Impacts of High Variable Renewable Energy Futures on Wholesale Electricity Prices, and on Electric-Sector Decision Making," Lawrence Berkeley National Laboratory, May 2018, http://eta-publications.lbl.gov/sites/default/files/report_pdf_0.pdf.

Prior research that simulates solar (or wind) in Full Flexibility operating mode – frequently as a sensitivity – includes the following:

- Van Hulle, F., I. Pineda and P. Wilczek, "Economic grid support services by wind and solar PV: A review of system needs, technology options, economic benefits and suitable market mechanisms," REserviceS project, September 2014, http://www.reservices-project.eu/wp-content/uploads/REserviceS-full-publication-EN.pdf.
- Nelson, J. and L. Wisland, "Achieving 50 Percent Renewable Electricity in California," Union of Concerned Scientists, August 2015, https://www.ucsusa.org/sites/default/files/attach/2015/08/Achieving-50-Percent-Renewable-Electricity-In-California.pdf.
- Tabone, M. D., C. Goebel and D. S. Callaway, "The effect of PV siting on power system flexibility needs," Solar Energy, vol. 139, pp. 776-786, 2016.
- Denholm, P., J. Novacheck, J. Jorgenson and M. O'Connell, "Impact of Flexibility Options on Grid Economic Carrying Capacity of Solar and Wind: Three Case Studies," National Renewable Energy Laboratory, December 2016, https://www.nrel.gov/docs/fy17osti/66854.pdf.
- Hale, E. T., B. Stoll and J. Novacheck, "Integrating solar into Florida's power system: Potential roles for flexibility," Solar Energy, vol. 170, pp. 741-751, 2018.