Flexible Solar Power: Unlocking Solar’s Full Potential

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Abstract — **India has already embarked on an ambitious program to significantly increase the proportion of solar energy on their grid. Solar is a variable renewable energy resource (VRE) that requires additional power system flexibility to balance the grid especially under higher penetration of VRE. Solar power plants can be operated flexibly to address this operating challenge. In this paper we describe a simulation study conducted for a relatively small utility system that quantifies the value of this solar flexibility. The study finds that once solar penetration exceeds 14% of annual energy supply, the operating reserves needed to accommodate solar uncertainty necessitates increased solar curtailment to avoid oversupply during low demand periods. As the penetration continues to grow, flexible solar reduces uncertainty, enables leaner operations and provides significant economic value. At penetration levels exceeding 20%, by operating solar in a fully flexible manner solar curtailment is reduced by more than half. This creates significant additional value resulting from reduced fuel costs, operations and maintenance costs, and air emissions.**

I. INTRODUCTION

The prices for utility-scale solar have plummeted to the point where it is the least-cost new resource in many markets. Like many other countries, India is on the path to significantly increase the proportion of solar on the evolving power grid to meet the country’s growing electricity demand. This advance, however, creates a challenge for India’s evolving power grid. The grid operators have to not only manage the variability and uncertainty associated with load but also deal with the variability and uncertainty associated with increasing levels of solar generation. The conventional dispatchable generation now requires significant additional flexibility to manage this variable renewable energy (VRE) resource on the grid.

When solar is still at modest levels of penetration, there is sufficient flexibility in the system and curtailment of solar is typically not a concern. The core-value proposition for solar is to maximize the production of energy and this approach to development and utilization works well in early-stage markets with low penetration of VRE.

For other markets, like California, which have achieved moderate solar penetration, some solar curtailment occurs. The solar production depends upon the available solar irradiance and not necessarily the electricity demand. During shoulder months when the system load is low, it leads to conditions of over-supply of solar. Grid operators typically curtail utility-scale solar projects to ensure that conventional resources, that are somewhat inflexible and have extended must-run times, can remain online to meet the overall system needs. Note that this curtailment is driven by operational needs rather than reliability concerns. While the economics of solar are somewhat impacted by this moderate level of curtailment, solar is still favored over conventional thermal generation because of its low cost. The iconic California “duck curve” is a prominent example that illustrates this condition [1]. With further increase in solar penetration, real-time operational challenges will become more acute

However, by operating solar, and particularly utility-scale solar, in a flexible manner, some of the challenges associated with higher penetration can be addressed. In a recent study, it was shown that by providing essential grid services including reserves required for headroom and footroom for load and solar variability, the overall economics were improved as well as a reduction in emissions. Such operational flexibility now makes it possible for solar to go beyond being a simple energy source and creates additional value for the grid. Even if this approach leads to occasional “spilling” of solar electricity, it turns out to be a more cost-effective option to integrate the increasing share of solar in the generation mix. Through real-time dispatch, utility-scale solar can provide system flexibility and respond to dispatch instructions much more quickly than conventional generators. Dispatching solar in this manner creates value through much-needed operational flexibility, helping operators meet the needs of an evolving grid.

II. DESCRIPTION OF CASE STUDY

A. *Flexibility Solar Power Case Study*

To demonstrate the economic value of dispatching solar, unit commitment and dispatch of an actual utility system — Tampa Electric Company (TECO) — was simulated using PLEXOS Integrated Energy Model [2]. TECO has good solar resource availability and a peak demand of ~ 5 GW. TECO operates its electricity system as a Balancing Authority.

The simulation included TECO’s existing thermal generation fleet as well as 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.

B. *Variability and uncertainty in grid operations*

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. Uncertainty represents the inability to perfectly forecast future demand or other grid conditions. System operators must maintain system reliability at all times under significant variability and uncertainty of demand, as well as those introduced by solar.

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 the generator, 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. 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.

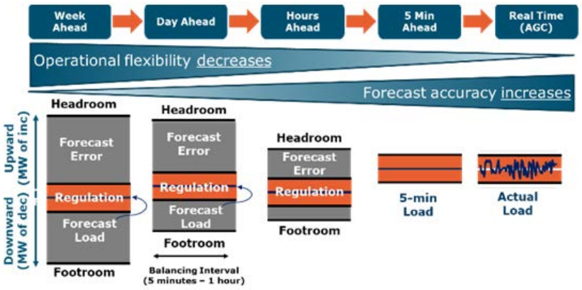


Figure 1. Commitment timeframes, forecast uncertainty, headroom and footroom

Increasing the level of solar generation on the grid increases the variability and uncertainty of electricity supply, both because of imperfect forecasts of solar output and because of fluctuations in output on a minute-to-minute basis. This 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.

Figure 2 illustrates the operation of the system without any solar at an operating time interval in the future. The thermal generation has the operating range to accommodate both headroom and footroom required to operate the system. Note that the minimum generation limit of the fleet, P_{Min}, is below the footroom level.

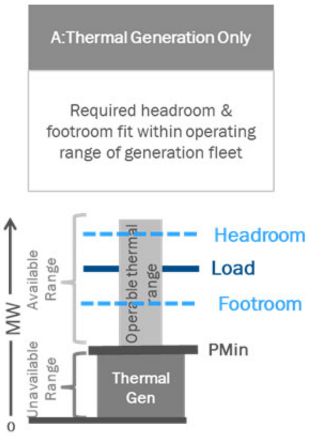


Figure 2. Generation Dispatch with Thermal Generation Only

In Figure 3, the generation dispatch for a typical spring day based on the 5 minute dispatch simulation is shown.

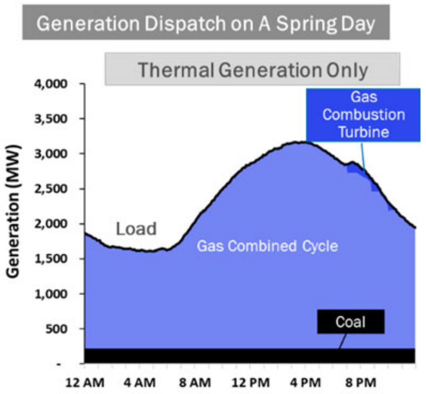


Figure 3. Typical thermal generation dispatch on a spring day

C. *Generation Dispatch with Must-Take Solar*

Figure 4 illustrates the impact of adding high penetration must-take solar. In this case, the thermal range available to operate the system between the footroom and headroom is not available. So, this is not a feasible operating condition.

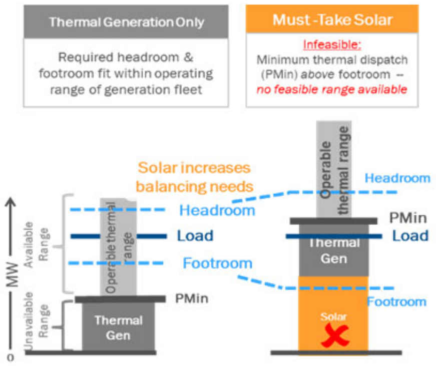


Figure 4. Increased headroom and footroom due to high penetration solar

In Figure 5, the generation dispatch for a typical spring day in presence of high penetration must-take solar is shown. Note that this is not a feasible case due to the over-generation situation.

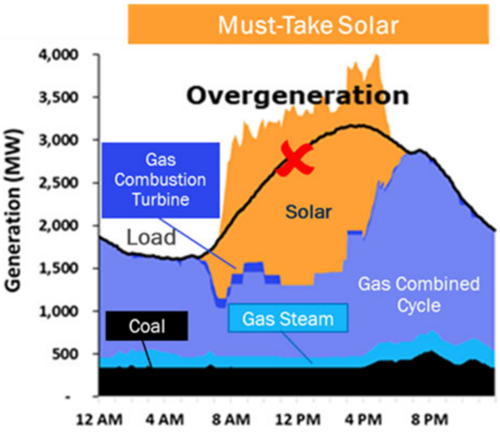


Figure 5. Typical generation dispatch on a spring day with must-take solar

D. Curtailable Solar Makes Dispatch Feasible

One way of managing the over-generation situation described earlier, is to curtail some level of solar generation as shown in Figure 6. This approach enables the operating range available from thermal generation to meet the regulation and forecast error reserve requirements. Solar operated in this mode is defined 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.

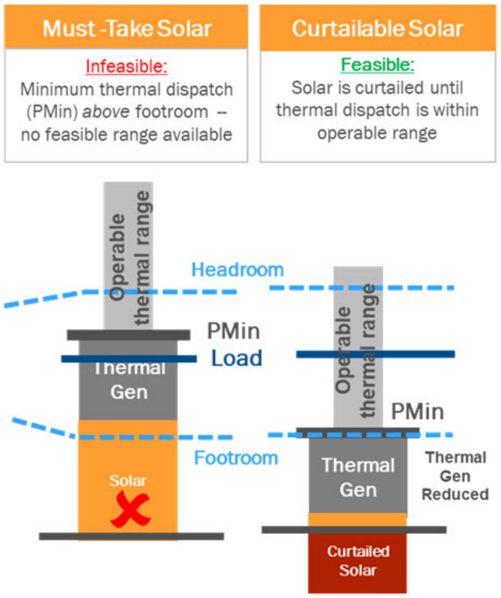


Figure 6. Making generation dispatch feasible through solar curtailment

In Figure 7, the generation dispatch for a typical spring day in presence of high penetration curtailable solar is shown. Note that a significant portion of the solar generation is curtailed in this dispatch profile.

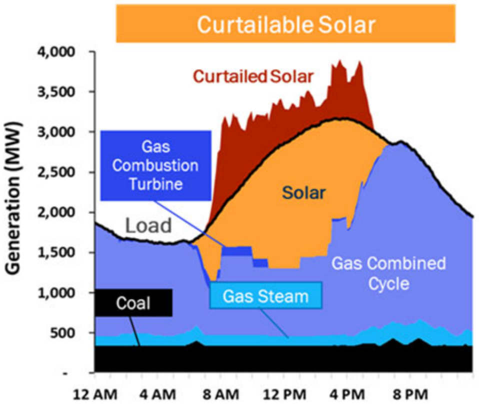


Figure 7. Typical generation dispatch on a spring day with downward dispatchable solar

E. Downward Dispatch Solar – Increases Value

The deployment of more solar capacity increases the need for “downward” flexibility, or footroom due to solar uncertainty and variability. However, solar plants can be dispatched at least downwards to contribute to balancing requirements when needed. Thus solar can provide its own downward reserves or footroom as illustrated in Figure 8. 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 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.

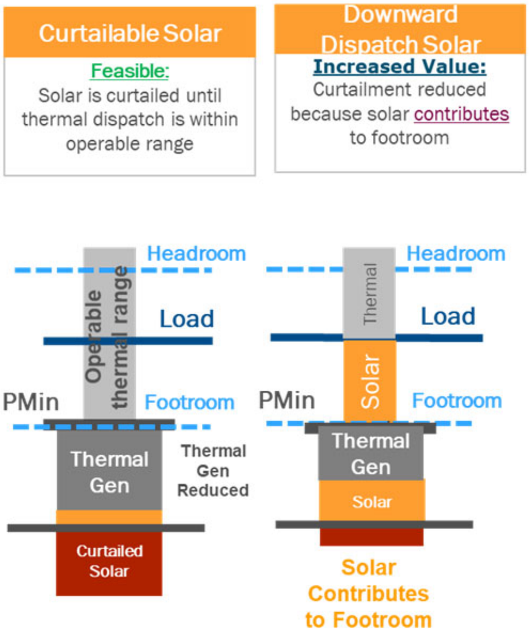


Figure 8. Dispatchable solar contributes to footroom

In Figure 9, the generation dispatch for a typical spring day in presence of downward-dispatch solar is shown. Note that in this case the curtailment of solar is reduced compared to what is illustrated in Figure 7. It also results in reduced commitment of thermal generation since more solar generation is utilized to meet the demand.

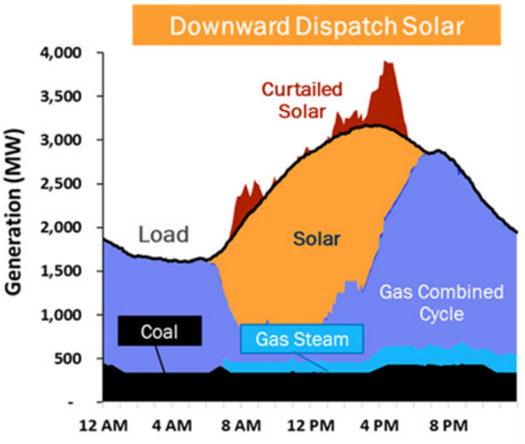


Figure 9. Typical generation dispatch on a spring day with downward dispatchable solar

F. *Full Flexibility Dispatch Solar – Optimizes Value*

In case where there is some level of solar curtailment available, it is also possible to use that curtailed solar for providing headroom as illustrated in Figure 10. This mode of operation is called full flexibility solar.

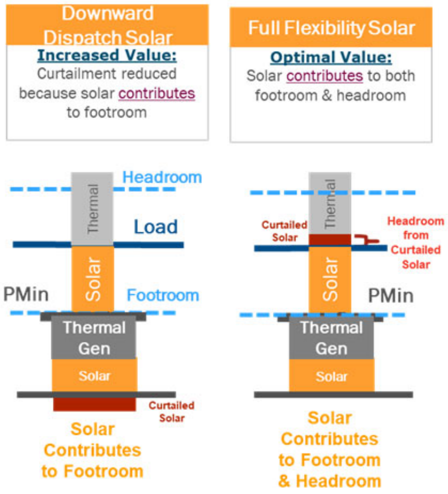


Figure 10. Fully flexible solar contributes to both footroom and headroom

In Figure 11, the generation dispatch for a typical spring day in presence of fully flexible solar is shown. Note that in this case the curtailment of solar is reduced further to what is illustrated in Figure 9.

G. *Summary of Results*

The level of annual solar curtailment with increasing penetration of solar is shown in Figure 12. The results indicate that for solar annual penetration less than 14%, the system has sufficient flexibility and curtailment of solar is very small. However, curtailment increases rapidly to 31% at high 28% solar penetration level. However, by operating solar in a fully flexible manner, the curtailment is reduced to a more modest 12% level.

The production cost savings resulting from increased use of solar are shown in Figure 13. As expected it increases linearly with solar penetration until solar curtailment starts impacting the savings.

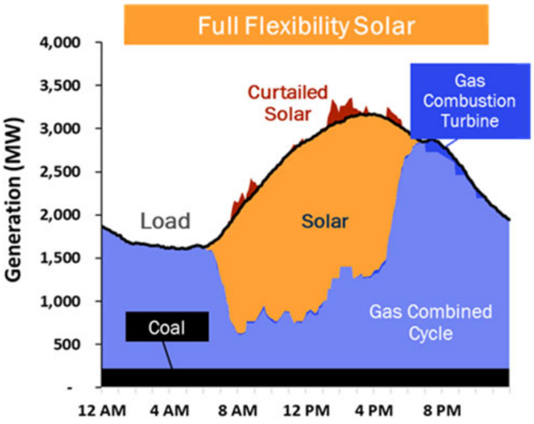


Figure 11. Typical generation dispatch on a spring day with fully flexible dispatchable solar

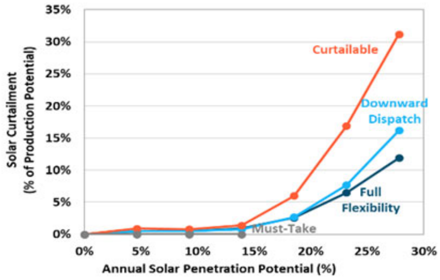


Figure 12. Level of solar curtailment with increased solar penetration for various solar operating modes

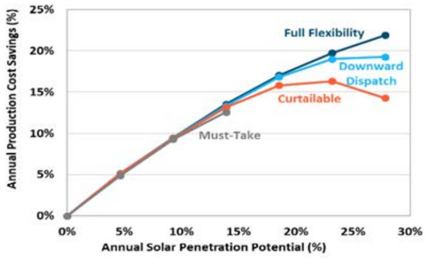


Figure 13. Production cost savings normalized to production cost without solar as a function of solar penetration for various solar operating modes

III. DISCUSSION

A. *Unleashing Solar's Flexibility*

What does it take to unleash this flexibility in solar generation? First of all in many jurisdictions, utility-scale solar plants are already required to provide conventional generation type capability that includes voltage control and regulation, voltage and frequency fault ride-through, reactive and real power control and frequency response. These requirements are based on North American Electric Reliability Corporation (NERC) recommendations that such variable generation plants must meet in order to provide their share of grid support [3]. These requirements have been implemented in solar plants with intelligent plant controls that add very little (<1%) to the plant cost [3].

This capability contributes actively to grid stability and reliability and as VRE penetration increases, its role becomes even more critical. While this capability is not yet fully mandated in India, it is a best practice for ensuring that the Indian grid continues to transform into a clean, stable and reliable grid. The revenue potential of a solar plant reduces when the grid is not stable and the plant cannot inject its power. Therefore, it is also in the interest of the plant developers and owners to have this capability. It provides benefits that far out-weigh the cost of incorporating this capability in the first place.

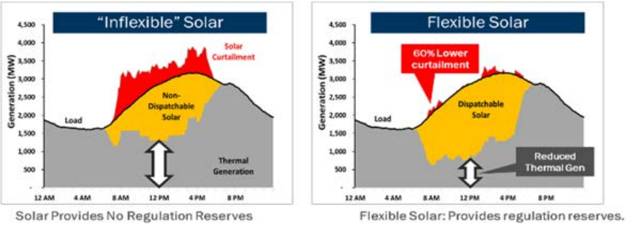
Once the plant has the technical capability to control its active power output, it has the means to be flexible (dispatchable) and contribute to regulation and balancing requirements through precise and very responsive output [4-5]. The entire suite of solar dispatch capabilities can be made available to the system operator in determining economic dispatch. The system operator can elect to use the solar resources to provide either energy or regulation reserves, or this choice may vary throughout the day depending upon the economics.

Provision of these grid services requires downward dispatch of solar, and some services require the plant operator to maintain headroom to enable upward dispatch. Since this results in lost solar energy production, 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, have the positive effect of enabling system operators to reduce fuel costs by reducing thermal generator commitments and increasing the efficiency at which they operate, as illustrated in the TECO study.

B. *Taking Advantage of Solar’s Flexibility*

Given that solar’s marginal cost of generation is nearly zero, it is in the best interest of the overall system to utilize all the energy produced by solar. However, as the solar penetration increases, the system may not have the flexibility to accommodate all the solar energy and some may need to be curtailed to ensure that the system can be operated in a stable manner.

The system flexibility can be increased through grid infrastructure, demand-side response, and electricity storage. Even market, policy, and regulatory frameworks play an important role in unlocking flexibility. Operating solar plants in a flexible manner, when needed, is yet another option to increase overall system flexibility. Figure 14 illustrates in an intuitive fashion the key result that fully dispatchable solar is utilized more effectively on the grid than inflexible solar. This results in reduced solar curtailment, reduced fuel consumption, and even reduced emissions since the thermal generation contribution is reduced.



Solar Provides No Regulation Reserves

Flexible Solar: Provides regulation reserves.

Figure 14. Flexible Solar Reduces Curtailment –
An Illustration for 28% penetration case

Such operational flexibility now makes it possible for solar to go beyond being a simple energy source and creates additional value for the grid. Even if this approach leads to occasional “spilling” of solar electricity, it turns out to be a more cost-effective option to integrate the increasing share of solar in the generation mix.

Recent cost declines in energy storage technologies enable solar to further extend its contributions to grid flexibility by providing firm dispatchable capabilities, which in turn enables even higher solar penetration. Adding storage to the grid can shift energy to when it is most needed, even if the sun has already set, combining the flexibility of solar with the firm capacity and energy-shifting capabilities of storage. However, this does require significant capital investment in storage and the economics of this option is not yet competitive to support wide spread adoption.

For an integrated utility that has a single ownership of all of the resources, performing the dispatch optimization described in this study is straightforward. However, in the context of the different market structures, there are several challenges that need to be addressed to realize the full potential of flexible solar.

How would solar’s flexibility be compensated particularly when some of the solar energy is curtailed? The Wind Solar Alliance report “Customer-focused and Clean: Power Markets for the Future” offers recommendations on market and policy reforms that will support the transition to clean and affordable electricity [7]

Most existing solar plant contracts rely on the full energy output of the plant and do not envision using the plant for grid balancing. However, as shown in the TECO study, flexible solar can add significant value to the overall system performance and cost.

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BIOGRAPHICAL INFORMATION

Dr. Mahesh Morjaria leads an R&D effort at First Solar addressing key challenges associated with integrating utility-scale solar plants into the power grid. Prior to joining First Solar in 2010, he worked at GE for over twenty years where he held various leadership positions. His academic credits include a B.Tech from IIT Bombay and a Ph.D. from Cornell University