Title: **Economic Value of Flexible Solar Power Plant Operation**

Questions from Webinar Audiences and Responses.

ESIG webinar (1/23/2019) and First Solar webinar (12/7/2018)

- Grid inertia. In a scenario of 100% renewables, in particular with a high solar penetration, what will be the effects on grid inertia, if any?

  With increasing use of inverter-based technology the grid inertia will typically decrease as conventional generation that provides traditional inertia is decommitted. The question of what grid impacts will result from lowered inertia is a much more involved topic. See "Ignoring Electrical Frequency in an All Converter Power System" (https://www.esig.energy/author/deepak-ramasubramanian-epri/) for more details.

  There have been many mitigating measures proposed to inject power or remove demand on the timescales necessary to replace traditional inertia from spinning mass with other non-spinning resources, including very fast demand response, battery storage, and running conventional turbines as synchronous condensers. Solar, if already curtailed, could ramp up very quickly, meeting some of the need for inertia-like grid services (see http://www.caiso.com/Documents/TestsShowRenewablePlantsCanBalanceLow-CarbonGrid.pdf).

  In the future, production simulations and grid operations should include constraints and/or ancillary service products to ensure proper post-contingency response from a combination of traditional and non-traditional resources. If inertia requirements become significant in some hours, solar could be pre-curtailed to provide this service.

- NERC Acceptance. Is there any difficulty in gaining acceptance of solar as "spinning reserves" from NERC?

  This has not been addressed with NERC to date. From a technical perspective to provide spinning reserves, solar will need to be operated in a way that makes sure that the committed headroom will be available when the grid operator needs it. Operators will need to understand how solar forecasting and uncertainty relate to reliability committing solar headroom. In the long run it will make sense update terminology away from "spinning" and "non-spinning" when a significant fraction of the flexible resources on the system aren't based on conventional turbine technologies.

- Down to the bolts of it, how is full solar flexibility obtained? Is that an additional controller or set of breakers connected to a string of inverters? Or do inverters have that capability? Could you please discuss how the solar curtailment is done? Do we have a ballpark estimate for the cost to enable a solar power plant to provide real time A/S such as is being proposed here?

  A key component of a grid-friendly PV power plant is a plant-level controller that is designed to regulate real and reactive power output from the PV plant, such that it behaves as a single large generator. While the plant is composed of individual inverters, the plant controller coordinates the power output of the whole plant. See "M. Morjaria, D. Anichkov, V. Chadliev, and S. Soni. "A Grid-Friendly Plant." IEEE Power and Energy Magazine May/June (2014)". An important point to stress is that solar plants through the use of power electronics can be easily curtailed continuously from its maximum production down to zero production in a very short time and without needing any special breakers and without impacting O&M of the plants. The cost of the plant controller is very small compared to the overall cost of the complete plant, and in most cases it is already required.

- It wasn't clear what the first steps would be by a utility interested in this area. Adding equipment to new or existing solar facilities? Grid-connected storage, co-located with renewables or not?

Solar PV plants that have ability to control active power can provide the described capability. It does not require storage facility as such. See the previous response on how the solar flexibility is obtained. It is largely up to the system operator to include the capabilities of these plants in their unit commitment and dispatch procedures. Xcel in Colorado has found value in doing this for wind. Also, incentives to provide flexibility must be aligned with system value – a solar plant won't voluntarily turn down if it doesn't have an economic incentive to do so.

- What is the most likely first investment by a utility with quickly rising solar penetration? A bit of grid-connected storage or something else? And where is that storage? Co-located with the solar generation?

  In general, the key investment by a utility facing rising solar (or more generally variable renewable energy -VRE) is to increase power system flexibility. While storage helps provide increased system flexibility it is not necessarily the least cost alternative. Some of the most effective ways to increase flexibility at lower investment costs include creating larger balancing area, shorter dispatch intervals, demand response, flexible generation etc. The results of this study demonstrate that exploiting flexibility of solar could provide a significant amount of operational benefit at a very low incremental cost. One of the biggest potential value streams for storage is to reduce solar curtailment, but most power systems can accommodate about 10-20% of variable renewable energy without significant curtailment. With much higher penetration, storage or other means will indeed be necessary to deploy more solar cost-effectively.

- In full flexible mode, would the output of the solar plants and signals to curtail the inverters need to be connected to an entity's AGC in its EMS? *Similar question:* What is the mechanism for curtailing solar?

  In general the solar plant needs to be connected to the grid operator's system in the same manner as conventional generation plants are. For example, in CAISO area most plants have a RIG that is electronically connected to provide two way communications to CAISO. For 4 second dispatch, AGC capability is implemented through that interface. For five minute dispatch (which is more typical) ADS (Automated Dispatch System) is utilized. Note that part of the value of full flexibility is ahead of real time when the system operator is making unit commitment decisions. Adjusting an operator's unit commitment decisions doesn't require the solar plant to be on AGC, but does require the operator to be confident that the plant can control its output in real time.

- What is holding back utilities from running in the "Full Flexibility" mode for solar?

  Previous questions address technical details of operating solar in Full Flexibility mode. Some utility-scale solar plants already have these technical capabilities, but some do not. Going forward, we expect more and more new plants to be technically capable of operating in Full Flexibility mode.

  The "Solar Flexibility Guidebook" slide towards the end of the presentation (Slide 34) outlines a path forward to make incremental steps towards full flexibility. Many of the recommendations we outline would need to be implemented in the utility or system operator control room. One example is modification of unit commitment and dispatch algorithms in order to allow solar to provide headroom towards grid services when curtailed. Perhaps the most important conceptual step is to represent solar generation as a supply resource capable of producing energy and grid reliability services rather than subtracting solar from demand and balancing the rest of the grid using "net load."

- Are you aware of any markets where solar / wind are allowed to participate in the frequency regulation market? I'm aware that PJM (New England) has a regulation market payment mechanism but, to my knowledge, wind / solar don't currently participate. *Similar question:* can renewable energy (solar) can provide reserves in any organized market?

  We do not know of any organized market in the United States in which wind or solar currently provide regulation – please let us know if we have missed something. In Xcel's Colorado service territory (not an organized market), wind plants can provide regulation by following the system operator's automatic generation control signal.

In most organized markets it is possible to dispatch wind and solar resources down via real-time energy markets.

- At what scale these services from solar start being helpful. Some of Jimmy's slides suggested only after 10% or 15% or more solar penetration, but I actually didn't know if that was share of kWh or share of peak nameplate. Also, has anyone connected this to RVoS calculations?

  The results shared in this study refer to the annual share of kWh. In this study it was found that under high penetration scenarios (i.e., annual penetration exceeding 14% on the TECO system), the solar curtailment starts increasing. It was found that the services become more valuable at that point and increase in value as the penetration increases to 28%. The point at which flexible solar operation adds significant value will be system-specific, with higher levels of solar curtailment indicating more potential value for solar dispatch. Systems that experience challenges with downward ("Dec") flexibility during the daytime will tend to show more value for solar dispatch. An example of this in organized markets is high regulation down prices during the day.

- Quick terminology question: "Curtailment" usually means that the energy is lost. You seem to imply but not always state that this "curtailment" is diverting the energy to storage. Is that right?

  By curtailment we mean that the plant is commanded to produce less power than it is capable of at any instant. We did not make the assumption that the un-utilized power (or integrated in time—the potential lost energy) is diverted to an energy storage device. If an energy storage is present it certainly can utilize that excess energy assuming that it is economical to do so.

- Is the KIUC (Kauai) 17 MW 52 MWh 4 hr Tesla battery an example of Utility Scale Dispatchable "future" (or future+) segment noted on slide #19?

  Most simulations in this study do not include any energy storage. We defined solar operating modes to focus on how to operate the solar asset, with or without an energy storage device. Slide 33 shows a sensitivity study in which we investigate the role of storage.

- Can roof solar be controlled/curtailed remotely, the same way the HVAC at our home is controlled by the some utility companies? Could this add value to the ISO? *Similar question:* Have you encountered situations where flexible solar has been dispatched on distribution systems (either larger scale commercial or aggregated behind the meter systems)?

  Technically it is possible to curtail roof top solar remotely. The technology to perform these control actions exists in inverters. However, it would require that appropriate features are activated in the inverter to control its active power and communication means are established. The overall complexity may be cost prohibitive, and hence, even if the roof top solar can add value to the ISO, it is not apparent whether it will be cost-effective compared to other means. Hawaii, which is one of the first places in the world that is addressing rooftop solar flexibility, has recently studied how it could turn down rooftop solar if necessary. A logical next step would be to investigate how to use the curtailed rooftop solar as headroom in system operations, but this would require more control than operators currently have over rooftop solar generation. ISOs may be able to reduce costs at higher solar penetrations if rooftop solar could be controlled/curtailed, though it may be more straightforward to focus on control of utility-scale solar plants if the ISO footprint has both rooftop and utility scale solar.

Also, an ESIG webinar participant notes: "I believe the smart inverter tariff (the replacement for NEM) in ComEd territory allows for the use of inverter-based grid services like frequency regulation from DG solar. Not the best example for these purposes but a start."

- How is downward dispatch mode different from curtailment mode?

  In Curtailable mode, solar can be curtailed in the production simulation both ahead of real time and in real time but thermal generators have to hold all headroom and footroom requirements for both forecast error and real time regulation. Downward dispatch assumes that solar can be turned down to meet forecast error footroom requirements (example: when the forecast is cloudy but there is a chance that the forecast is wrong and it will actually be sunny in real time). Downward dispatch also allows solar to be curtailed in real time to provide regulation in response to an Automatic Generation Control signal (AGC), but only in the downward/footroom/Dec direction.

- Is the primary difference between Downward Dispatch and Full Flexibility the timeframe i.e. Day Ahead vs Real-Time control? *Similar question:* Please provide more detail on full flexibility operating mode.

  When solar is forecasted to be curtailed ahead of real time (for example Day Ahead), the full flexibility mode reduces impact of solar forecast error, or equivalently solar provides part of the net load forecast error requirement in the headroom direction. Full flexibility also allows regulation headroom (real-time balancing on AGC) to be provided when solar is curtailed.

- Slides 27-29 seem to imply that production cost models had been using inappropriate logic to optimize the system under a curtailment scenario--not recognizing that curtailment could be reversed in near real time to provide head room. Is this what's happening?

  Correct, other production cost models commit reserve capacity in a way that doesn't allow solar to be un-curtailed to provide headroom (Up/Inc) reserves. Curtailment used to be thought of as an edge case, so it was sufficient to calculate reserves and balancing requirements using "net load" (load minus wind and solar production). Doing so makes it challenging to reduce balancing requirements when solar is curtailed because it is hard to determine the portion of the uncertainty and variability attributable to solar. The extreme example is if the operator curtails every last MWh of solar (we're <u>not</u> saying that they should do this, but it's a useful bookend example), the variability and uncertainty from solar is ZERO. If the balancing requirements aren't adjusted to reflect the curtailment, other resources would be balancing non-existent solar variability and uncertainty. The middle ground is to calculate balancing requirements on the basis of net load, but also let solar "supply" some of the requirements, within the bounds of possible levels of solar output.

- From an energy hedge perspective, is the price received in DA for regulation down A/S the same as the DA energy hedge?

  The goal is to align economics of providing flexibility with providing energy, similar to the way that thermal generators bid an opportunity cost of holding back production when making ancillary service bids. In California where producing a MWh of renewable energy has value due to the Renewables Portfolio Standard, this may involve including the expected level of curtailment (and resultant loss of REC value) in ancillary service bids made by renewable generators. Solar generators currently don't bid into regulation markets in most or all ISO markets, so how this works remains to be seen.

- Would requiring full flexible solar from a developer conflict with any PURPA rights the developer may have? In a dispatched curtailment how would the tariff work? I.e is an IPP assumed to be paid the same for the energy produced as the energy that was curtailed? Would this only work with a PPA between an IPP and Utility, as it would seems challenging in a merchant market where IPPs are generating with Old or Newer facilities, with and without storage. *Similar question:* Please provide more details on financial impacts of the flexible solar product.

One of the challenges with unlocking the value of solar flexibility, not only for PURPA projects but also for regions with a Renewables Portfolio Standard, is that generation of MWh is frequently the only thing that is valued in operations. To turn down flexibly, solar needs to be compensated to do so. More work will be needed to understand how to best compensate solar for flexible operation under different ownership structures and system operators. An integrated utility that owns and operates their solar plants can operate them efficiently because they can dispatch to minimize production costs, whether or not that involves generating the maximum MWh from each solar project.

- I agree that solar without storage, can be more flexible, and own plants that behave this way. The plants have the technology, BUT, the financing that values MWh. What financial tools are there to value flexibility, or quantify the benefits of building a larger but curtailed plant?

  In ISO markets, solar could bid into ancillary service markets and receive compensation when selected to provide the ancillary service. Solar is well positioned to provide regulation down during the day, so this should be perhaps the first place to extract value from solar flexibility. ISOs are currently working on how to address Day Ahead or Hour Ahead uncertainty (which grows significantly with higher levels of wind and solar), and are contemplating adding market products for this type of "forecast error" or "flexibility" reserve. Solar should bid into this type of market too. Some of the value of flexible solar results from the system operator reducing curtailment via dispatch procedures that fully integrate the ability to curtail the resource in real time. This part of the solar flexibility value stack would appear in the form of increased production. Vertically integrated utilities that own and dispatch the plant may be willing to oversize the plant to provide flexibility if their resource planning studies show value for doing so.

- Can you explain cost savings to whom? How can individual developers with solar curtailed share the cost savings of the overall because of lower fuel use? *Similar question:* Have you all calculated the economic benefit of solar flexibility options? *Similar question:* You looked at the price decrease in operating the grid as a whole. But in terms of the amount of revenue the same size solar system makes over the 4 possible schemes, is operating in the flexible mode reducing revenue?

  For a vertically integrated utility like Tampa Electric (TECO), if they own and operate the solar plants then they can save fuel and other operations costs by leveraging solar flexibility at higher solar penetrations. By owning the solar asset they have the flexibility to use it in the way that results in the lowest production cost across their fleet of generators.

  In organized markets, the production cost savings would translate into a lower cost of serving the region-wide load. Solar plants may be able to capture additional revenue by being dispatched in energy and ancillary service markets, but would need to bid in a way that did not decrease their expected revenues.

  In general, solar plants that are solely compensated based on the amount of energy they produce have a financially disincentive to offer flexibility because doing so can reduce their energy production and by extension revenues. Compensation based on the solar production *potential* allows for more dispatch flexibility.

- We are a flywheel energy storage supplier from Germany and participating in some modelling projects at a university for similar flexible solar resources coupled with short duration energy storage. Have you modelled storage coupled solar?

  The study includes a sensitivity section towards the end on the interaction between solar flexibility and storage.

- Are you willing to speculate how far above 28% solar Tampa Electric could go, cost-effectively?

  TECO has committed to build 600 MW of solar (~7% of annual energy). The higher solar penetration levels (up to 28%) that we studied were academic in nature and were focused on answering the question of how to operate the system most efficiently at various solar penetrations. However, since we did not perform an analysis at even higher penetration levels, we prefer not to speculate.

- What would be the maximum penetration of Solar PV paired with batteries?

  The question of how much solar, battery, or other resource capacity to deploy is largely a resource planning question about the most cost-effective way to meet energy supply needs and policy goals. While it may be technically possible to meet 100% of energy demand with solar and batteries, economic factors can limit deployment. As the cost of solar and batteries continue to decline, and as system operators become more comfortable operating a system with larger shares of these resources, the economically justified level of deployment would increase.

- When you calculate cost savings, do you compare the value of curtailable solar vs. cost of adding batteries and electronic equipment to create downward dispatchability? *Similar question*: Have you computed the cost difference in using solar dispatch vs. a battery to produce the same system results? *Similar question*: What is the extra cost for future installments to make them fully flexible? (Presumably much lower than costs of storage) *Similar question:* What is the economic benefit of energy storage? *Similar question*: Have you done any analysis comparing the more flexible solar with adding storage? The constraint on solar output to enable higher solar flexibility may cost more than storage inefficiency.

  Increasing the dispatch flexibility of solar plants that are already equipped with modern control technology comes at minimal incremental cost and does not require any large capital investments. We performed sensitivity runs to investigate how the operational savings that result from adding a battery to the grid change in response to different levels of solar flexibility (Slide 33). Adding storage to the grid can provide benefits in addition to production cost savings (distribution deferral, peak capacity reduction, etc.), and we did not do a full cost-benefit analysis of storage in this study.

- Can you comment on how a system with significant nuclear resources might perform?

  Nuclear resources typically act as baseload, must-run generation, and usually do not participate in system balancing requirements. Reaching higher solar penetrations in systems with significant nuclear (or other less flexible generation) is more challenging than in systems that can reduce output during times of high solar generation. Solar flexibility will typically provide more value in a less flexible system, so at a given solar penetration (as a % of annual load), solar flexibility will be more valuable in a system with nuclear.

- Would like to know more about dynamics of mixed solar and onshore and/or offshore wind. *Similar question:* The system studied is basically thermal. Have you tried to study solar flexibility in a system in which wind is also high? Do you think there would be some changes in the results?"

  At a given solar penetration, adding more wind to the system will tend to cause system flexibility demands to increase, thereby increasing the “market size”/demand for operational flexibility. However, modern wind power plants can perform many of the same balancing services as modern solar plants, so there may be additional supply of operational flexibility from wind. Studying a system with both significant penetration of wind and solar resources would be an interesting follow-up.

- Providing 4 s AGC from solar plants is very similar to work with wind farms from the Wind Energy Institute of Canada. Any reports / studies that you know of which examine the net effect of AGC from wind + solar?

Not that we know of, but this would be an interesting area of investigation.

- I would like to know more as to how the solar scenarios were modeled in each case. How did the model see that solar could be dispatched like thermal during the day?

  We designed rules in the PLEXOS production cost model that use information about solar forecast error to limit the solar resource's contribution to balancing requirements. If operators are certain enough about how much solar they are going to have during real time operations, they can count on solar output in ways that are similar to how thermal capacity is currently treated. Appendix A, especially Table 6 (p.53) of the report discusses how solar provides reserve requirements in the PLEXOS model. Section 1.4 of the report describes the different operating modes (p.15-21). The report can be found here: https://www.ethree.com/wp-content/uploads/2018/10/Investigating-the-Economic-Value-of-Flexible-Solar-Power-Plant-Operation.pdf

- What is the accuracy percentage of solar forecasting in your study?
  We did not calculate this value directly. Figure 13 of the report (p.50) shows the headroom and footroom requirements for solar forecast error hours ahead of real-time. The report can be found here: https://www.ethree.com/wp-content/uploads/2018/10/Investigating-the-Economic-Value-of-Flexible-Solar-Power-Plant-Operation.pdf

- How did you capture impacts of forecast uncertainty and value of improved forecasting?

  The Appendix of the report (starting at p.46) describes our forecast error calculations and how forecast error reserves are implemented in PLEXOS (see especially Table 6 on p.52 for implementation details). The report can be found here: https://www.ethree.com/wp-content/uploads/2018/10/Investigating-the-Economic-Value-of-Flexible-Solar-Power-Plant-Operation.pdf

  We did not investigate the value of improved forecasting, but qualitatively, improved forecasting would 1) make it easier to count on solar to provide flexibility, thereby increasing the value of solar flexibility, and 2) would make it easier to position the thermal fleet ahead of real time to absorb as much solar as possible, thereby decreasing the value of solar flexibility. The net effect of 1) and 2) is unknown.

- The AGC plot from Mahesh's slides, was that a simulation or real data?

  Real data.