Least-Cost Firm PV Power Generation:
Dynamic Curtailment vs. Inverter-Limited Curtailment:

Marc Perez[1], Richard Perez[2] and Thomas E. Hoff[1]

[1] Clean Power Research, Napa, California, 94558, USA
[2] Atmospheric Sciences Research Center, SUNY, Albany, New York, 12203, USA

Abstract—**Overbuilding and dynamic curtailment are increasingly acknowledged as central to cost-optimally transforming intermittent PV and wind resources into firm power resources. While this strategy is not currently monetizable, firm power generation will be a prerequisite at ultra-high renewable penetration when demand will have to be met 24/365 without reliance on underlying dispatchable generation.**

A distinct overbuilding/curtailment strategy is increasingly implemented today: inverter-limited curtailment. This strategy can take advantage of some existing remuneration systems.

In this article, we compare the effectiveness of the two strategies to deliver firm power generation at least cost. We consider the extreme case of PV meeting demand with 100% certainty using two MISO's load balancing areas (#4 and #10) as experimental support. We show that, while both strategies can achieve firm power generation at a lower cost than curtailment avoidance would, dynamic curtailment is far more cost-effective than inverter-limited curtailment. Importantly, we also show that optimally combining both strategies can further reduce firm power generation cost.

Index Terms — firm power, ultra-high grid penetration, PV modeling, grid integration, storage, solar resource.

I. CURTAILMENT & FIRM POWER GENERATION

A new IEA activity on firm renewable power generation [1] states that grid-connected PV, either dispersed or centralized, has grown at the margin of a core of dispatchable and baseload conventional generation. This is a direct result of the resource's intermittency. The challenge ahead for PV is to grow beyond this margin. As for wind, the transformation from intermittent to firm, effectively dispatchable PV generation is a prerequisite to displacing the underlying conventional generation core and to acquiring a grid-dominant position.

A growing body of research demonstrates that cost-optimal intermittent-to-firm transformation entails overbuilding and dynamically curtailing PV to keep long-term storage costs acceptably low [2-6]. We introduced the term *implicit storage* to describe this overbuilding/dynamic curtailment strategy because it enables actual energy storage to do what it is designed to do -- firmly supplying power when the intermittent resource is not available -- but doing so using considerably less storage, hence at a considerably lower cost.

Because grid-connected PV is still considered a marginal resource today, firm PV power is not yet monetizable. Therefore, dynamic curtailment strategies are not implemented operationally. Current monetization systems such as power purchase agreements (PPAs) seek to maximize production, hence, to avoid curtailment. Interestingly, remote, islanded power plants have operated optimally with built-in curtailment for many years [7] since meeting load is an unavoidable requirement. Identifying the least cost solutions that allow the energy system to meet this requirement will become imperative for grid-connected systems as penetration increases and PV becomes grid-dominant. As a preview of this approaching reality, we note the reactive curtailments increasingly imposed by grid-operators when renewable supplies exceed what the grid can accept, but that result in increasing economic losses for plants designed and financed to operate on full production premises.

A. *Two curtailment strategies:*

Dynamic Curtailment: An optimally designed firm power PV plant will size PV, storage, and overbuild/curtailment to meet load at least cost. The optimum implicit storage solution depends on the relative capital and operational costs of PV and storage as well as well as on the characteristics of the load and the solar resource. Figure 1 (from [3]) illustrates how the least-cost "sweet spot" occurs at a point where the cost of PV overbuild starts exceeding the savings from storage reduction. Operationally, curtailment occurs dynamically as a function of demand, resource availability and storage state of charge.

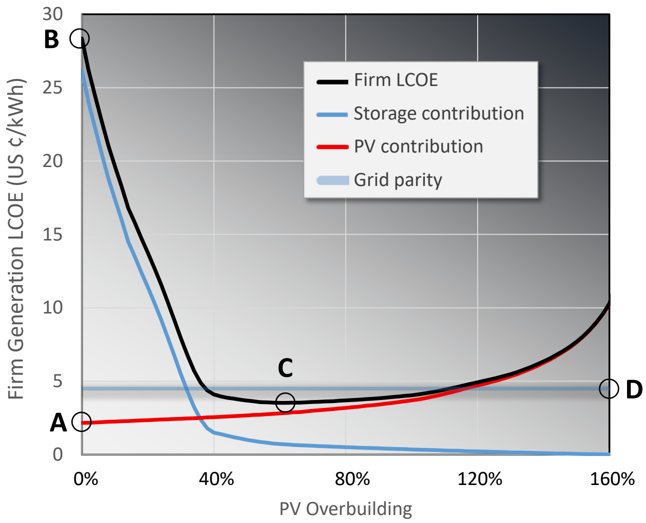

Fig. 1. Influence of PV overbuilding on firm power generation LCOE. While unconstrained PV (A) is inexpensive (apparently below grid parity), firming PV to meet demand 24/365 with storage alone (B) is unrealistically expensive. Overbuilding of PV fleets reduces storage requirements to the point (C) where firm PV power generation can achieve true grid parity (D). Source: Reference [3]

Inverter-limited curtailment: Inverter-limited curtailment is a distinct, non-dynamic overbuilding/curtailment strategy that is increasingly applied today [8]. Inverter-limited curtailment is different than dynamic curtailment. Curtailment occurs as the DC PV capacity exceeds inverter rating by design. This strategy flattens the daily production curve of PV plants and can take advantages some existing regulatory practices and remuneration structures such as time-of-day pricing, intraday peak shaving, or ancillary services procurement [9].

While both dynamic and inverter-limited curtailment strategies can lead to reduced storage requirements and a reduced cost of firm power generation compared to entirely avoiding curtailment, there is fundamental difference between the two. Inverter-limited curtailment occurs across the board above a given fraction of PV capacity; dynamic curtailment as described by [2] occurs when two conditions occur simultaneously: storage is full, and PV production exceeds demand.

Figure 2 compares the output of uncurtailed, dynamically curtailed, and inverted-limited PV fleets. The two curtailed fleets are optimally overbuilt to deliver the same quantity of electrical energy after curtailment as the uncurtailed PV fleet on an annual basis (i.e., to meet the same annual load). Two periods are illustrated: (1) a predominantly sunny high solar yield period (top); and (2) a lower yield period (bottom). The low-yield period shows that while the inverter-limited system is capped at the same maximum production, the dynamically curtailed system can deliver full output when needed to meet load and recharge electricity storage that can be depleted during low solar yield periods. This capability to supply a larger fraction of power during low yield periods allows for smaller (i.e., cheaper) storage systems than required by the inverter-curtailed fleet, leading to lower LCOEs as will be shown and discussed below.

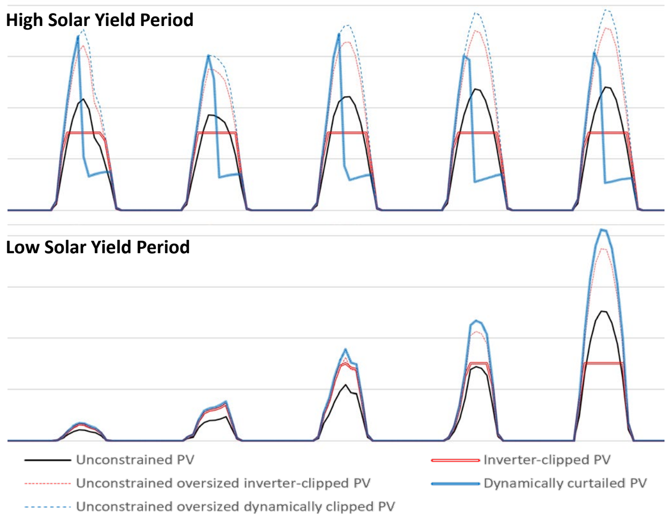

Fig. 2. Comparing unconstrained, oversized inverter-clipped and oversized dynamically curtailed regionally distributed PV production. The high solar yield period (top) shows dynamic curtailment occurring every day after storage spent at night is fully recharged and daytime demand is fully met by the uncurtailed portion. In the low yield period, dynamically curtailed PV production can be maximized as needed to recharge storage spent during long cloudy periods, but the inverter-clipped system remains maxed-out at its clipping ratio. Note that the annual energy production of each of the three considered PV fleets integrates to the same annual value equal to annual load.

II. METHODS & DATA

We evaluate and compare the cost-effectiveness of the two curtailment strategies using a representative experimental case study. We consider the extreme case where PV must meet demand with 100% certainty, i.e., without demand or supply side flexibility (e.g., from natural gas) and without blending with other renewable resources such as wind or hydropower that have been shown to further lower firm power generation costs [4].

As experimental support for our analysis, we consider the case of homogenously distributed latitude-tilt PV generation within the Midcontinent Independent System Operator (MISO) Regions #4 and #10 (Figure 3) for the year 2016. We apply high-resolution satellite-derived SolarAnywhere® simulations [10] to estimate hourly time/site-specific PV generation coincident with the region's hourly load data. Figure 4 contrasts normalized annual unconstrained PV generation and load shape for each region. Both PV and load curves consist of 30-day running means to better visualize multi-day and seasonal supply/demand mismatches that are costliest to resolve. The PV resource is sized so that annually integrated PV output equals annually integrated demand. Note the substantial PV surplus in summer and the large deficit in winter in MISO balancing area #4. The seasonal mismatch is also apparent, but substantially reduced in lower latitude balancing area #10.

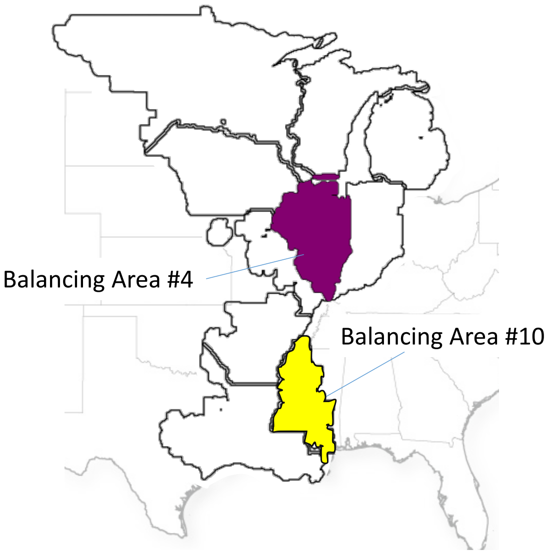

Fig. 3. Map of MISO transmission system operator highlighting balancing areas #4 and #10 used for the present investigation.

III. RESULTS & DISCUSSION

We calculated the firm power production LCOE of all considered PV configurations assuming future (2050) utility-scale high-technological development storage and PV technology capital and operational costs (capex and opex) per NREL's annual technology baseline [11], namely:

- Storage (electrochemical) energy capex: $41/kWh
- Storage (electrochemical) capacity capex: $133/kW
- Storage (electrochemical) opex: 0.25%/yr.
- PV capex: $356/kW
- PV opex: $4/kW/yr.
- Wind capex: $813/kW
- Wind opex: $24/kW/yr.

Note that for the inverter-limited configuration, the PV capex is slightly lower, commensurately with the clipping ratio, i.e., the relative size of the inverter. For the considered time horizon, inverter should account for approximatively 10% of the turnkey PV capex [12].

An average cost of capital of 3% (representative of the utility industry) was applied to levelized life-cycle cash flows.

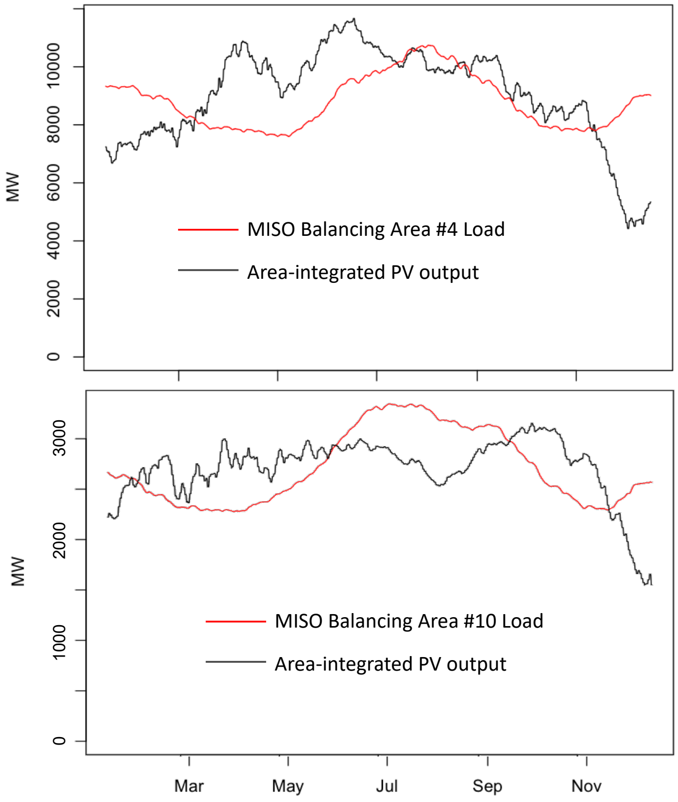

Fig. 4. Annual Load and PV Resources Profiles in MISO Balancing Area #4 (top) and #10 (bottom)

Figure 5 illustrates the firm generation LCOEs for MISO balancing area # 4 as a function of energy curtailment fraction for both strategies. It is manifest that, while both dynamic and inverter limited curtailment can achieve lower LCOEs than curtailment avoidance, the dynamic curtailment strategy is considerably more cost-effective than the inverter-limited strategy. In this mid-latitude electrical region, the former achieves a 77% LCOE reduction compared to unconstrained, uncurtailed PV generation, while inverter-limited curtailment can only achieve an 18% reduction. The optimum amount of energy curtailed is also higher for the inverter-limited strategy: 62% vs. 54% for the dynamic strategy -- note that 62% energy curtailment correspond to an inverter clipping ratio of 83% (see figure 6).

The main reason for this performance difference between the two strategies is traceable to winter production where the solar resource is lower than demand. Inverter-limited curtailment discards large amounts of potentially available solar supply regardless of season/conditions, while dynamic curtailment effectively utilizes all available production for charging when needed during low-yield periods (see figure 2), hence minimizing storage size. As a result, the firm power generation cost difference between the two approaches is considerable.

Interestingly, combining both strategies – dynamically curtailing optimally inverter clipped PV – can lead to further firm generation cost reduction with an LCOE of 5.8 ¢/kWh (dotted line in figure 5). This optimum combined 'sweet spot' entails a total energy curtailment of 55% (equivalent to the dynamically curtailed strategy) with an inverter clipping ratio of 47% (considerably less than the cost-optimal inverter-curtailed-only strategy).

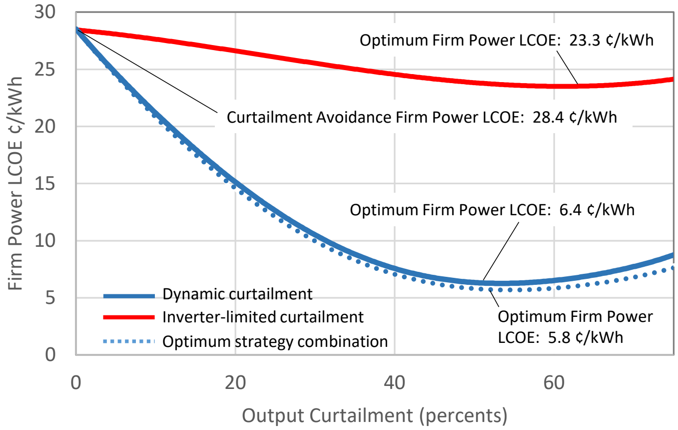

Fig. 5. Comparing firm power generation LCOE in balancing area #4 as a function of overbuilt PV resource curtailment for both curtailment strategies and for an optimal combination of both.

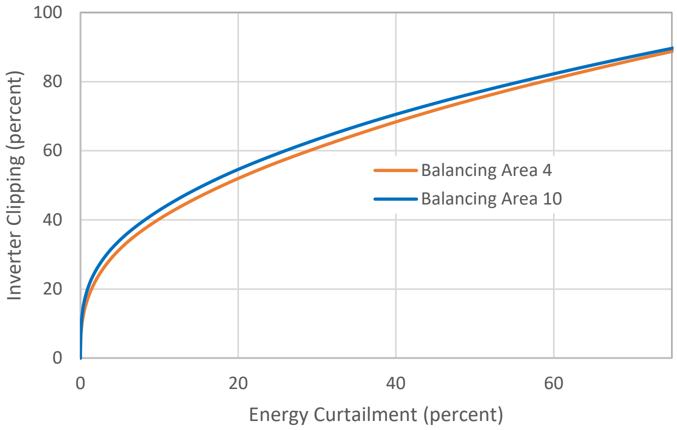

Fig. 6. Relationship between curtailed energy output and inverter clipping ratio for an inverted-limited PV latitude-tilt PV system in balancing areas #4 and #10. Note that the smaller seasonality in area #10 (lower latitude) results in slightly higher potential energy losses for a given inverter clipping ratio than it does for area #4 (higher latitude).

Figure 7 illustrates the LCOE trends observed for balancing area #10. In this lower-latitude electrical region with less seasonality, the LCOE of the uncurtailed PV is significantly lower than in area #4. The difference between the two curtailment strategies, while still significant (14.6 cents per kWh vs. 5.7 cents per kWh) is less pronounced than in area #4.

The reduced seasonality also leads to reduced optimum amount amounts of curtailment for both strategies – respectively 44% and 31% for the dynamic and inverter clipping strategies. For the latter, the optimum energy curtailment corresponds to an inverter clipping ratio of 64% (see figure 6).

In region 10 as well, combining both strategies – dynamically curtailing optimally inverter clipped PV – can lead to further firm generation cost reduction with an LCOE of 5.4 ¢/kWh (dotted line in figure 7). This optimum combined 'sweet spot' entails a total energy curtailment of 44% (equivalent to the dynamically curtailed strategy) with an inverter clipping ratio of 50%.

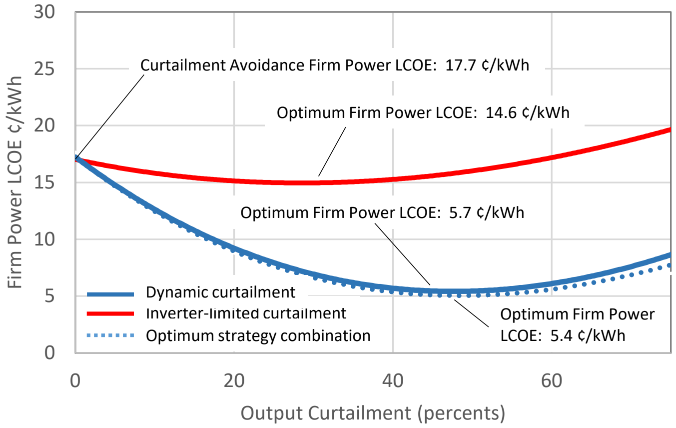

Fig. 7. Comparing firm power generation LCOE in balancing area #10 as a function of overbuilt PV resource curtailment for both curtailment strategies and for an optimal combination of both.

III. CONCLUSION

This investigation clearly suggests that, while inverter-limited curtailment may be an attractive option today to optimally price PV plants and take advantage of existing regulations and remuneration arrangements, it must be combined with dynamic curtailment, in terms of cost reduction per amount of energy curtailed, to achieve least-cost firm power generation. Importantly, the analysis showed that combining both strategy with a lesser level of inverter clipping could lead to lowest cost firm power solutions. This result is important because it signifies that plants that are deployed today with a moderate amount of inverter clipping could easily be adapted to optimally exploit firm power generation remuneration systems should future regulations make these available to the industry.

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