Maximizing DPV Hosting Capacity with Regional Firm VRE Power

Marc Perez[*]
Richard Perez[*+]
Upama Nakarmi
Thomas E. Hoff[*]
Jeffrey Freedman[+]
Elizabeth McCabe[+]
Marco Pierro[&]
Jan Remund[#]

[*]Clean Power Research, Napa, CA
+Atmospheric Sciences Research Center, SUNY, Albany, NY
[&]EURAC, Bolzano, Italy
[#]Meteotest, Bern, Switzerland

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Abstract

A growing body of work demonstrates that Variable Renewable Energy resources (VREs) such as weather-driven wind and solar could firmly and economically meet current and future regional electric demand 24/365 nearly anywhere on the planet if effective regulations and market rules enabling their transformation from intermittent to firm are implemented. The question we pose in this paper is whether Distributed PV (DPV) hosting capacities could be enhanced if DPV systems actively participated in the larger [transmission] grid's firm VRE power generation objective. We show that this is indeed the case with the possibility of multifold DPV hosting capacity increases.

Keywords: grid integration, high renewable penetration, distribution system utilities (DSO), distributed PV, saturation, load growth

Introduction

The International Energy Agency (IEA) defines firm power generation as the capability for a generating resource or an ensemble of resources to meet electrical demand 24x365 (Perez et al., 2023). PV and wind are weather/season-driven Variable Renewable Energy (VRE) resources that inherently do not meet the firm power criterion. Their intermittency does not pose issues at low grid penetration, operating at the margin of conventional baseload and dispatchable generation.

However, as penetration increases, load-management issues gradually arise (steeper ramps, deeper duck curves, etc.) until deployment reaches the limits of what power grids can absorb, leading to a host of issues such as reactive curtailments, negative market prices, and a growing opposition to further renewable deployments, particularly at the distribution level. The left side of Figure 1 illustrates the intensifying VRE supply/demand imbalance as penetration increases for a hypothetical 50%/50% wind/PV blend on the New York City power grid that has been traditionally supplied with baseload and dispatchable resources.

The IEA work (Perez et al., 2023) shows that it is possible to economically transform VREs from intermittent to firm so their output can match a given load shape, removing imbalances and enabling a seamless gradual displacement of underlying conventional resources. The right side of Figure 1 illustrates the penetration of VREs, transformed from weather-driven to firmly matching the load shape of dispatchable generation.

The transformation requires an optimum blend of technologies and strategies that include energy storage, coupling solar and wind, supply or demand-side flexibility, and most importantly, overbuilding VREs and proactively curtailing (i.e., apparently wasting) a portion of their generation. The overbuilding/curtailment (implicit storage) strategy reduces real energy storage requirements and allows for realistic firm power generation costs.

A number of studies undertaken as part of IEA Task 16 suggest that, by 2040 or before, these enabled VREs could firmly supply nearly 100% of electric demand in most regions of the world at generation costs equal or below that of current conventional generation (Perez, 2020; Remund et al., 2022; Rey-Costa et al., 2023). However, the overbuilding/implicit storage strategy that is essential to achieving this objective cannot be implemented today. This is because remuneration pathways for VREs are guided by energy-market rules that inherently penalize curtailment. As a result, VREs continue to deploy unconstrained at the margin (left side of Figure 1). Such unconstrained deployments are self-limiting beyond a small margin because of the grid imbalances they engender. A recent article by the IEA team of experts argues that firm VRE deployments could be fostered with capacity-based market rules applied to VREs in parallel to and independently of conventional energy markets (Remund et al., 2023). This article also makes the case that flexibility

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provided on the supply side with a small amount (<5%) of 100% renewable e-fuel-powered dispatchable generation is very effective at minimizing firm power electricity costs, despite the cost of e-fuels (Viscardi et al., 2021) that can be 4-5 times higher than conventional [fossil] fuels. This small amount of clean dispatchable generation also constitutes a fail-safe insurance in case of extreme VRE droughts (more extreme than what could be captured in the 20 years analyzed).

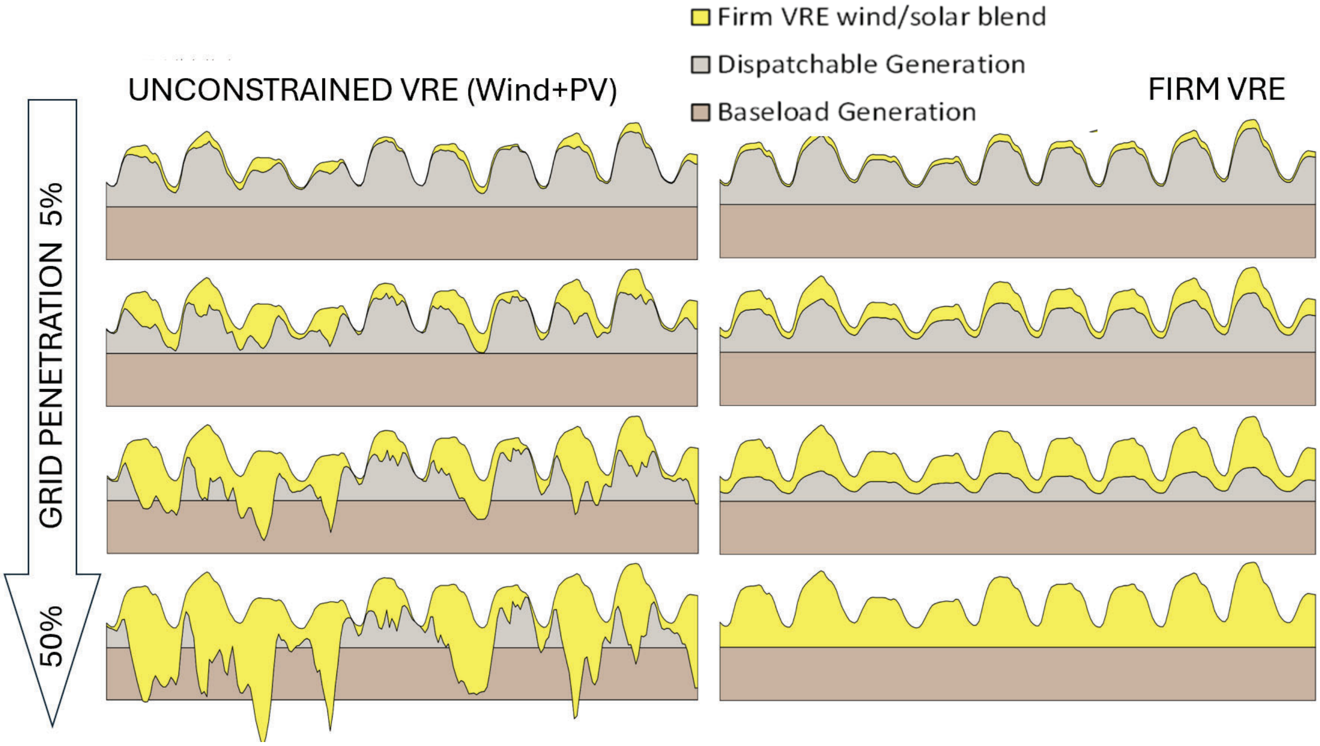

Fig. 1: Contrasting the grid penetration impact of unconstrained VRE (left) and firm VRE (right). This qualitative illustration assumes an 50/50% wind PV energy contribution on a grid traditionally served with dispatchable and baseload generation.

DPV Hosting Capacity

DPV includes user-sited residential and commercial systems, community solar systems etc., that are located on utility distribution circuits. As their number increases, congestion issues arise, increasingly leading to deployment restrictions. The well-documented California industry slowdown in residential deployments attributable to NEM3 (Balaraman, 2024) and the deployment moratoriums imposed on a growing number of distribution circuits in New Jersey [e.g., PSEG, 2024] are two symptomatic examples of this emerging issue.

The question we pose is the following: Given effective market rules enabling the deployment of regional (transmission-level) firm VRE solutions ─ with an optimized blend of PV, wind, real and implicit storage, as well as a small contribution from clean dispatchable generation (supply-side flexibility) ─ how would distribution-level hosting capacities be affected, assuming that distribution-side resources would fully participate in the regional firm power strategy (Perez, 2020; Remund et al., 2022; and Rey-Costa et al., 2023)? Distribution-side resources would consist of DPV and storage systems only, assuming that wind and thermal dispatchable units could only operate at the transmission level.

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DPV hosting capacity is typically defined in static terms as a function of the maximum DPV output and the minimum load on a distribution circuit, (e.g., Wang et al., 2022) an upper limit over which voltage and thermal overloading problems would occur. There is a growing push to consider 'dynamic' hosting capacities involving storage and a degree of DPV curtailment that would limit DPV production peaks and thereby increase a circuit's effective hosting capacity (Wang et al., 2022). Assuming a linear relationship between peak DPV and hosting capacity, the distribution hosting capacity increase, DHCI, resulting from a dynamic operation of DPV can be calculated from:

$$DHCI = \frac{\mathrm{DPVmax}_u}{\mathrm{DPVmax}_m} - 1$$

DPVmax_u represents the unconstrained DPV production peak and DPVmax_m represents the managed DPV production peak, embedding distributed storage and DPV curtailment. The firm power approach discussed in this paper is fully consistent with this dynamic view while it is also much broader, since in this case DPV curtailment and storage would not be circuit-specific but operated in the context of least-cost regional firm VRE power generation.

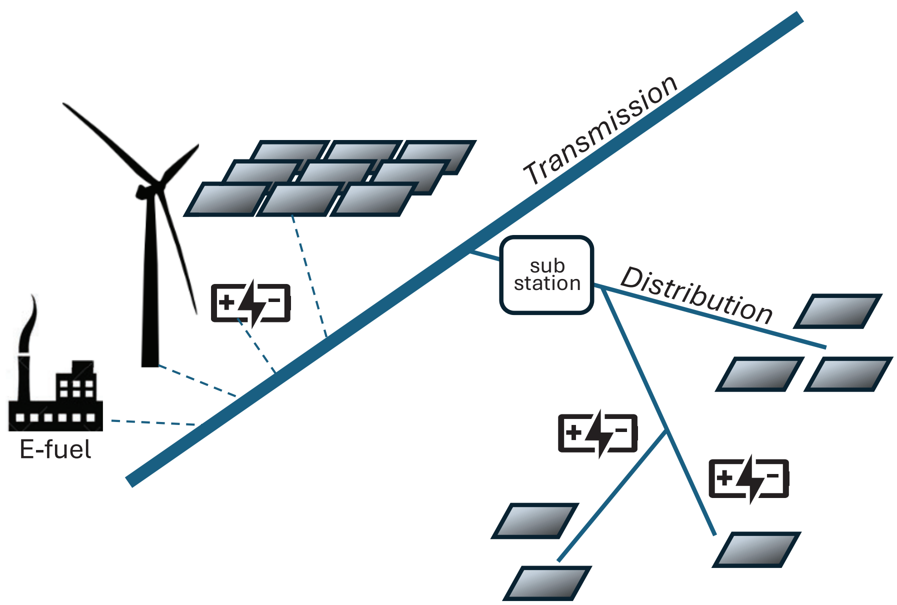

Figure 2. Distribution of firm VRE assets on a power grid. While wind and e-fuel thermal would likely be interconnected on the transmission grid, PV and storage assets can be interconnected, either upstream or downstream of distribution substations.

Illustrative Case Case Studies

We illustrate distribution hosting capacity impacts with two regional firm power case studies that were undertaken as part of IEA PVPS Task 16 for electrical regions 9 and 3 of the Midcontinent Independent System Operator (MISO), respectively corresponding to the states of Louisiana and Iowa (Perez et al., 2023). For the present case studies and for the sake of generalization, we consider that the regional firm power requirement consists of serving a constant load 24/365 (i.e., equivalent to what would be supplied by baseload generation).

Least-cost firm VRE configurations were determined by simulating 20 years' worth of hourly latitude-tilt PV generation and 90-m hub height wind power generation. Simulations apply SolarAnywhere/PVLib for PV and ERA5 reanalysis wind data extrapolated to turbine hub height using measurement using tower-validated models and nominal wind power curves (Hersbach et al., 2020; NOAA, 2003; Saint-Drenan, 2020; SolarAnywhere, 2024).

Optimum firm VRE configurations and generation LCOEs are a function of the capital and operating costs (CapEx and OpEx) of the technologies involved: PV, wind, storage, and dispatchable e-fueled powered generation (assuming a supply-side flexibility contribution of 5% for the latter). For the present case studies, we consider future (2040) costs summarized in Table 1 (NREL Annual Technology Baseline, 2023).

Table 1.

CapEx	PV	$466/kW
	Wind	$525/kW
	Battery *	$65/kWh
		$49/kW
OpEx	PV	2.3% of CapEx/yr
	Wind	4.5% of CapEx/yr
	Battery	2.5% of CapEx/yr
	e-fuel Thermal Gen	18 c/kWh

Note that Battery CapEx, unlike how it is often reported, includes two components per kW and kWh capacities.

The least-cost optimum VRE configurations and resulting firm power levelized costs of energy (LCOEs) determined for Iowa and Louisiana are presented in Table 2. The table also reports the wind and PV capacity factors in each region.

While the least-cost firm power regional VRE blend is equal part wind and solar in Iowa, it is 100% solar in Louisiana — i.e., adding any proportion of would result in higher LCOEs. While capacity factors are comparable, the small economic advantage of PV and the more pronounced wind droughts lead to a solar-only optimum.

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Table 2.

	Iowa	Louisiana
PV capacity factor	14.6%	15.4%
Wind capacity factor	41.3%	15.3%
Optimum PV energy contribution	47.5%	95%
Optimum wind energy contribution	47.5%	0%
Assumed e-fuel thermal contribution	5%	5%
Optimum VRE curtailment	24%	55%
Optimum battery storage	11.8 load hours	39 load hours
Optimum LCOE	3.9 cents per kWh	6 cents per kWh

Case Studies Results

We assume that DPV systems and associated distributed storage systems directly contribute to larger [regional transmission] grid's firm power generation objective. In effect, these distributed assets operate as part of the optimum regional VRE configuration discussed above. Dynamic curtailment, when needed, is applied to the total VRE output, and apportioned to the PV and wind output available at the time. We further assume that all PV plants on the regional grid (utility-scale and DPV) are operated in an analogous manner in terms of dynamic curtailment.

Looking at Louisiana first with its 95% PV 5% e-fuel optimum, we assume that battery storage is distributed proportionally to the installed PV capacity installed at the transmission or distribution level below a substation. In effect, all PV plants on the grid operate identically in terms of storage management, with storage possibly co-located on their DC sides, but not necessarily so. Figure 3 (top) illustrates several days' worth of DPV generation on an arbitrary feeder in MISO Region 9 (Louisiana). It shows the apportionment of DPV output between the direct feed to the circuit, the storage charge, and the curtailment. The solid black line is the sum of the direct feed of PV to the grid and storage output. It is nearly constant — matching the baseload firm power generation assumption — except for brief PV droughts when (transmission-side) e-fuel flexible power generation ensures load requirements.

However, the most important observation in this figure is the difference between unconstrained DPV and firmed DPV peaks (respectively $DPVmax_u$ and $DPVmax_m$ in the above equation). This translates into a DPV hosting capacity increase of 650% in this case study. Therefore, in effect, a regional firm VRE power strategy would increase the amount of DPV a distribution circuit can sustain by more than sevenfold.

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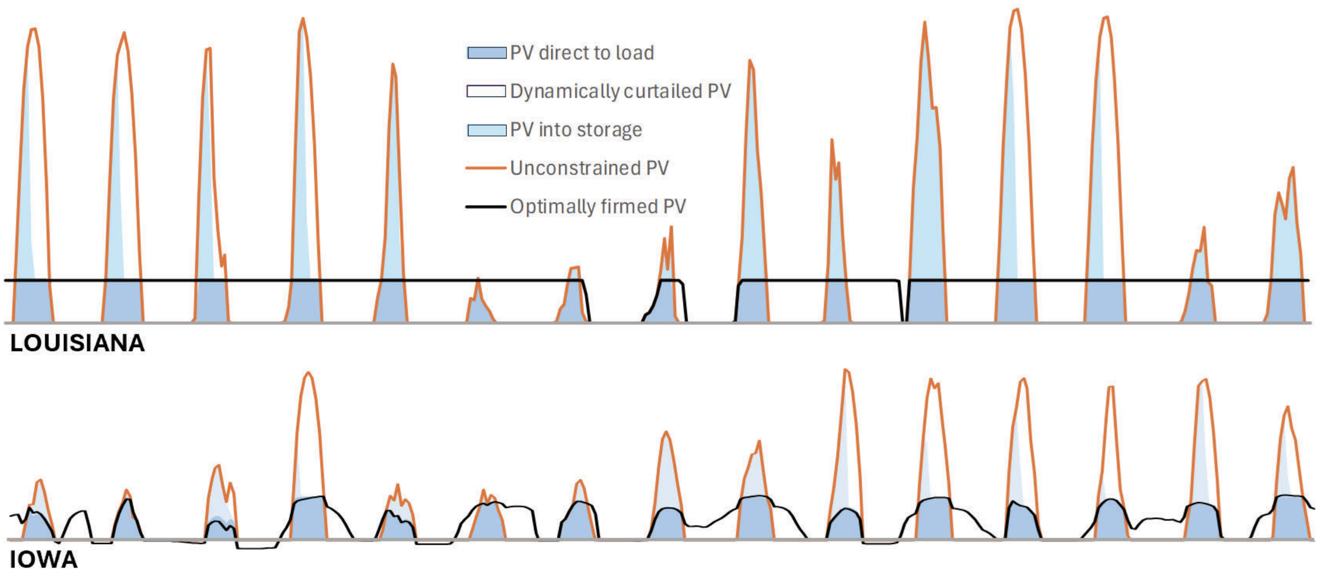

Fig. 3. Contrasting distribution-level unconstrained DPV and firm DPV contribution in two power grids, where PV is the unique VRE (top) and where VRE consists of a blend of wind and PV (bottom)

The situation in MISO Region 3 (Iowa) is illustrated in the bottom of Figure 3. This situation is more complex because the management of firm DPV must be responsive to wind output on the larger grid to maintain overall load-shape requirements. This impacts storage management on both distribution and transmission parts of the grid. Because wind and solar seasonal patterns can be different, the independent operation of storage associated with PV on the distribution side and with wind on the transmission side would result in considerably more storage (~3 times more) than if PV, wind, and storage were colocated, penalizing the optimum firm power bottom line LCOE shown in Table 2. The issue can be resolved by transferring electricity between storage units on each side of substations at the cost of small additional substation traffic (thus slightly reducing the possible hosting capacity gains). This storage-to-storage exchange is apparent in Figure 3 with the negative firm power solid black line, indicating a transfer from grid-level storage to feeder-level storage needed to maintain overall minimum storage requirements.

Nevertheless, in this more complex DPV operation case in a region with optimized PV/wind firm power operations, the distribution hosting capacity gain remains substantial at 260%.

Conclusion

The case studies analyzed, representing a limited but diverse sample of firm VRE power generation configurations, indicate that operating DPV systems to directly contribute to the regional firm power objectives, results in a multifold increase of distribution-level hosting capacities. This increase is largest when the optimum VRE blend is dominated by PV generation

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but remains remarkable when wind plays a significant role as well. An important task ahead is thus to create the regulatory and market rules environments where two major power generation benefits — (1) lowest-cost 100% renewable power generation for a region, and (2) a significant increase in DPV market size even where currently constrained — can be realized.

Conflict of Interest

The authors of this document declare no conflicts of interest related to the content presented. There are no financial, personal, or professional affiliations that could bias the information provided.

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