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Maximizing DPV Hosting Capacity with Regional Firm VRE Power Generation

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***Abstract*— A growing body of work demonstrates that firm wind/solar power generation capable of meeting current and future electric demand 24/365 can be affordable if enabled by effective regulations. The question we pose here is whether DPV hosting capacities would be increased if DPV systems actively participated in the larger grid's firm power generation objective. We show, based on 20 years of hourly wind/solar data and two Central US case studies, that this is indeed the case with the possibility of multifold DPV hosting capacity increases.**

Keywords*— *firm power photovoltaics, wind, grid integration, transmission, distribution.

I. FIRM VRE POWER GENERATION & DPV HOSTING CAPITY

Firm power Generation: The IEA [1] defines firm power generation as the capability for a generating resource or an ensemble of resources to meet electrical demand 24x365. 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. Figure 1-left illustrates the intensifying VRE supply/demand imbalance as penetration increases.

A growing body of work [1] shows that it is possible to economically transform VREs from intermittent to firm so their output can match demand (Figure 1-right), removing imbalances and enabling a seamless gradual displacement of underlying conventional resources. The transformation requires a blend of technologies and strategies that include energy storage, coupling solar and wind, load requirements flexibility, and most importantly, overbuilding and proactively curtailing (i.e., apparently wasting) a portion of the VRE generation. The overbuilding/curtailment (aka 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 [e.g., 2, 3, 4] suggest that, by 2040 or before, so 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. However, the overbuilding strategy that is central to achieving this objective, cannot be implemented today because remuneration pathways for VREs are guided by merit order energy markets that inherently penalize curtailment. As a result, VREs continue to deploy unconstrained at the margin (left side of Fig. 1) contributing to limiting their own growth beyond said margin. A recent article by the IEA team of experts [5] 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.

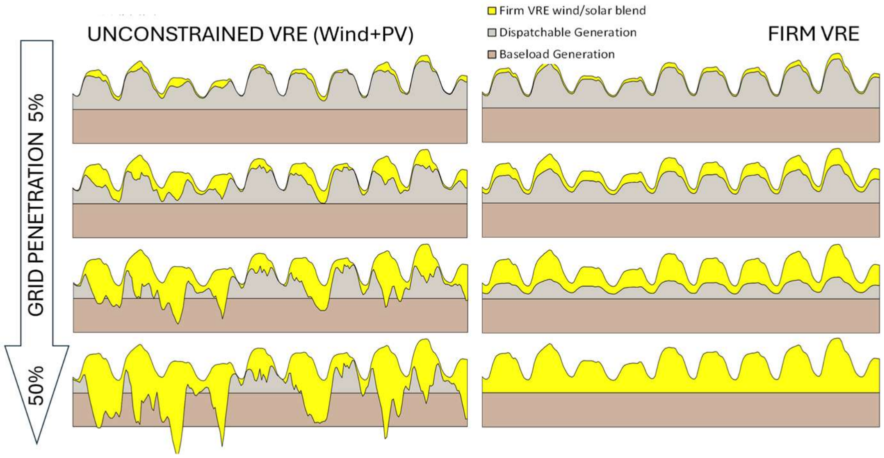

Figure 1: Contrasting the grid penetration impact of unconstrained VRE (left) and firm VRE (right). This qualitative illustration assumes an 50/50% wind PV energy contribution on a grid traditionally served with dispatchable and baseload generation.

DPV hosting Capacity: This article focuses on distribution circuits and distributed PV (DPV, including user-sited residential and commercial systems, community solar systems etc.,) where congestion issues are rising and leading to deployment restrictions. The well documented California slow-down in residential deployments attributable to NEM3 [6] and the de-facto deployment moratoriums imposed on a growing number of distribution circuits in New Jersey [e.g., 7] 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 objectives as envisioned in [e.g., 2, 3, 4] — with an optimized blend of PV, wind, real and implicit storage, as well as a small contribution from clean thermal 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? (Distribution-side resources would consist of DPV and storage systems only, assuming that wind and thermal units could only operate at transmission level.)

Stricto sensu, 'static' DPV hosting capacity has been defined in relation to the maximum DPV output and the [minimum] load on a distribution circuit (e.g., [8]) an upper limit over which voltage and thermal overloading problems would occur. However, 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 [8]. Assuming a linear relationship between peak DPV and hosting capacity, the distribution hosting capacity increase, DHCI, resulting from a dynamic operation of DPV would thus be:

$$\mathrm{DHCI} = \mathrm{DPVmax}_u / \mathrm{DPVmax}_m - 1 \quad (1)$$

Where DPVmax_u represents the unconstrained DPV production peak and DPVmax_m represents the managed DPV production peak (embedding associated storage and curtailment operations). The firm power approach discussed in this paper is fully consistent with this dynamic view while it is also much broader, since DPV curtailment/storage would not be circuit-specific but operate in the context of least-cost regional firm VRE power generation as illustrated in Figure 2.

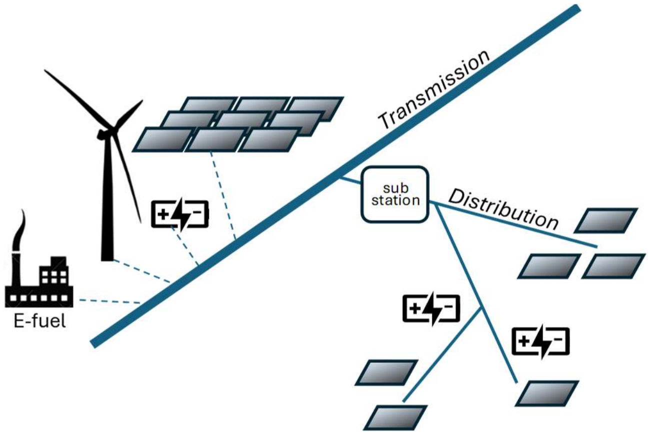

Figure 2. Distribution of firm VRE asset on a power grid. While wind and e-fuel thermal can only be interconnected on the transmission grid, PV and storage can be interconnected either upstream or downstream of distribution substations.

II. 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 [1] in Iowa and Louisiana, corresponding to MISO regions 3 and 9, respectively. For simplicity and generalization, we consider that regional firm VRE generation requirements consist of serving a constant load (i.e., equivalent to what would be supplied by baseload generation). Least-cost firm VRE configurations are determined by simulating 20 years' worth of hourly latitude-tilt PV generation and 90 m hub height wind generation. Simulations apply SolarAnywhere/PVLib [9] for PV, and reanalysis wind data extrapolated to turbine hub height using measurement tower-validated models [10] and nominal power curve from [11]. Optimum firm VRE configurations and generation LCOEs are a function of the capital and operating costs of the technologies involved: PV, wind, storage, and thermal power generation (assuming a supply-side flexibility contribution of 5% for the latter). For this abstract, we consider future (2040) costs [12] summarized in Table 1.

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 often reported, includes 2 components per kW and KWh capacities

The optimum VRE configurations and resulting firm power 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 solar in Iowa, it is 100% solar in Louisiana — adding any proportion of wind is more expensive there (while capacity factors comparable, the small economic advantage of PV and the more pronounced wind droughts lead to a solar-only optimum)

Table 2

	Iowa	Louisina
PV capacity factor	14.6%	15.4%
Wind Capcity 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

III. DPV HOSTING CAPACITY PRELIMINARY RESULTS

We assume that DPV systems are an integral part of the larger grid firm VRE power operations. Dynamic curtailment, when needed, is applied to the total VRE output, and

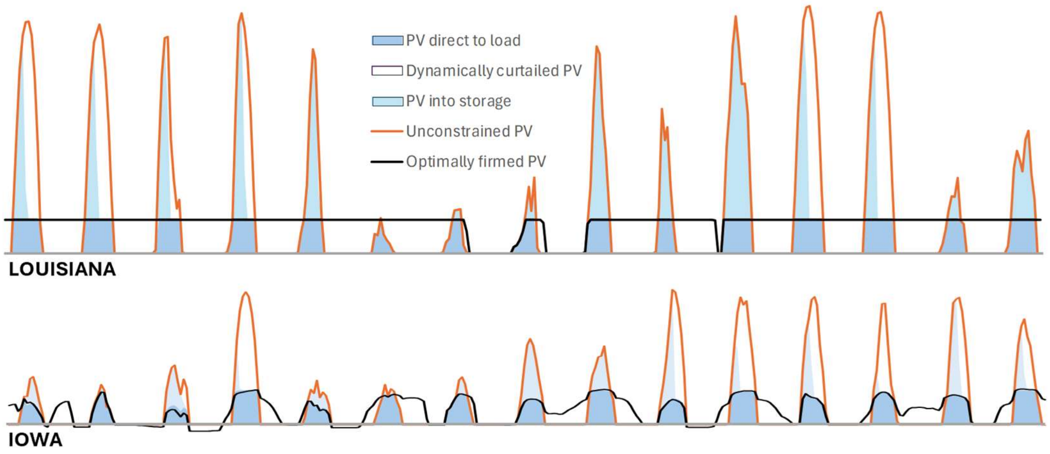

Figure 3. Contrasting distribution level unconstrained DPV and firm DPV contribution in two power grids where PV is the unique VRE (top) and where VRE consists of a blend of wind and PV (bottom)

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 whether at the transmission or distribution level. In effect all PV plants on the grid operate identically in terms of storage management (possibly co-located on their DC side, but not necessarily so). Figure 3 (top) illustrates several days' worth of DPV generation on any given feeder in Louisiana. It shows the apportionment of DPV output between direct feed to the circuit, storage charge, and curtailment. The solid black line is the sum of the direct feed of PV to the grid and storage output. It is nearly constant (because of the baseload firm power generation assumption), except for brief droughts when (transmission-side) e-fuel flexible power generation insures load requirements. The most important observation in this figure is the difference between unconstrained DPV and firmed DPV peaks. Per equation (1) this corresponds to a DPV hosting capacity increase is equal to 650%. In effect a regional firm VRE power strategy would increase the amount of DPV circuit can sustain by more than sevenfold.

The situation in 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 collocated, 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 can be seen in Figure 3 by the negative firm power solid black line, indicating a transfer from grid level storage to feeder level storage to maintain overall minimum storage requirements. Nevertheless, DPV hosting capacity gains still amount to 260% in this environment where regional firm power generation involves a large fraction of wind.

IV. CONCLUDING REMARKS

We have shown, based on 20 years of hourly site/time specific PV and wind generation data, that DPV systems operated in the context of generating firm high penetration renewable power on the larger grid would result in a multifold increase of distribution-side hosting capacities. The increase is largest when the optimum VRE blend is dominated by PV generation but remains remarkable when wind plays a significant role. An important task ahead is thus to create a regulatory environment where these benefits (least cost high VRE penetration on the grid, and substantial increase of DPV hosting capacities) can be realized.

REFERENCES

[1] Perez R, M. Perez, J. Remund et al. (2023) : Firm Power Generation. IEA-PVPS Technology Collaboration Report T16-04:2023 Eds. J. Remund & R. Perez

[2] Perez, M., (2020): Pathways to 100% Renewables across the MISO Region. Report DOE-MNCOMM-7659-4

[3] Remund J., M Perez & R Perez (2022): Firm PV Power Generation in Switzerland IEEE 49th PVSC.

[4] Rey-Costa E., et al., (2023): Firming 100% renewable power: Costs and opportunities in Australia's National Electricity Market. Renewable Energy Volume 219, Part 1, December 2023, 119416

[5] J Remund, R Perez, M Perez, M Pierro, D Yang (2023) : Firm photovoltaic power generation: Overview and economic outlook. Solar RRL, 2300497

[6] Balaraman K. (2024): California rooftop solar had a tough year following NEM 3.0. Utility Dive

[7] PSE&G (2024): Power Suitability Map

[8] Wang W. et al, (2022): PV Hosting Capacity Estimation: Experiences with Scalable Framework; National Renewable Energy Laboratory. NREL/CP-6A40-81851.

[9] SolarAnywhere, (2024)

[10] NOAA (2003): LLLJP Wind Shear Formula

[11] Saint-Drenan, Y., R. Besseau, M. Jansen, I. Staffell, A. Troccoli, L. Dubus, J. Schmidt, K. Gruber, S. Simões, S. Heier, (2020): A parametric model for wind turbine power curved incorportating envionmental conditions. Renewable Energy Volume 167.

[12] Annual Technology Baseline (2023); https://atb.nrel.gov/electricity/2023/data