IMPLICIT STORAGE
Optimally Achieving Lowest-Cost 100% Renewable Power generation

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

[1] Clean Power Research, Napa, California (USA)

[2] State University of New York, Albany, New York, (USA)

Abstract

Implicit storage – aka overbuilt and operationally curtailed variable renewable energy (RE) resources – is a synergistic complement to [real] energy storage for transforming these resources from intermittent to firm, at the lowest possible cost. Firm power generation is an indispensable requirement of ultra-high RE penetration when demand must be met 24/365 without reliance on a core of conventional baseload and dispatchable generation. Analyzing data from a large US TSO, we show that implicit storage is by far the most effective strategy to achieve this intermittent-to-firm transformation compared to other strategies that can reduce RE's intermittency: RE blending, demand flexibility, and geographic dispersion.

Keywords: 100% renewables, storage, intermittency, firm power generation

1. Resolving Renewables' Intermittency with Real and Implicit Storage

Transforming intermittent wind and solar – the two easily-accessible renewable resources large enough to massively displace conventional fossil-based generation – into firm, effectively dispatchable generation is a prerequisite for these resources to acquire a grid-dominant position. Both resources are intermittent, driven by weather and seasons. At current levels of penetration, they operate at the margin of a core of conventional dispatchable and baseload generation. An ineluctable requirement for their growth beyond the margin is their transformation from intermittent to firm, i.e., their capability to meet demand 24/365 without fail and without reliance on underlying dispatchable generation.

1.1. Energy Storage

Energy storage, under any of its possible embodiments – batteries, pumped hydro, hydrogen/e-fuels, etc. – is generally considered essential for this intermittent-to-firm transformation.

It is convenient to regroup current and future storage grid applications into three categories: (1) regulation/ancillary services; (2) intra-day peak shaving and ramp management; (3) long term storage for firm power generation. The first two are directly or indirectly monetizable within the context of existing markets and regulations, e.g., via targeted remunerations, or price arbitrage. The third application is fundamental to ultra-high RE penetration – the subject of this article – but is not yet directly monetizable.

- Regulation Ancillary services: storage is deployed to correct small demand/supply mismatches, that occur because of e.g., RE supply or demand forecast uncertainties. Storage systems can contribute effectively to frequency control, spinning reserves and operating reserves (e.g., Rebours et al., 2007). The stored energy transfer involved in ancillary services typically amount to an infinitesimal fraction of the total demand – i.e., a small market for storage overall. Monetary vehicles exist today to monetize this service (Fitzgerald et al., 2015, Mendelsohn & Weiss, 2021) but market size is limited (at most equal to the volume of the fluctuations) [c].
- Ramp management and peak shaving: storage is deployed to tackle intraday load shape issues that are increasingly enhanced by renewable deployments. Managing the peaks and steep ramps surrounding the solar

"duck curve" is a well-known example of this type of management (Wan et al., 2020, Udin et al., 2017, State of Maryland, 2018). Storage can already be applied economically in many locations with access to appropriate remuneration pathways (e.g., The sizes of storage involved for these applications are considerably larger than for ancillary services (Wang et al., 2019, Torabi et al., 2019, Denholm, et al., 2015). However, while power capacities can amount to a substantial fraction of the load, energy capacities remain a small fraction of the overall load.

- Firm RE power generation: storage is applied to enable intermittent RE to displace underlying conventional dispatchable and baseload resources. This task requires large quantities of long-term storage, to make up for any renewable production "droughts", e.g., for solar at higher latitudes, extended cloudy periods during winter. The quantities of storage involved can amount to many days' worth of renewable production. Applying storage alone has been shown to be prohibitively expensive, even when applying the most optimistic future storage technology cost estimates (Perez et al., 2019).

1.2. Implicit Storage

We recently introduced the term implicit storage (Perez et al., 2020) to designate the overbuilt and operationally curtailed portion of renewable power plants. Curtailment is still largely viewed as something that must be avoided. This is because current remuneration systems foster a maximization of renewable energy production. However, as counterintuitive as it may appear, overbuilding and shedding a substantial portion of renewable energy production is central to achieving least-cost firm power generation.

Indeed, overbuilding – analogous to Installed Reserve Margin or IRM, in grid operator parlance – drastically reduces the quantity of long term-storage required to deliver firm power 24/365. Several recent studies by the authors and others have demonstrated that the extra cost of overbuilding (implying having to "waste" potential power generation) more than makes up for the decreased cost of required long term storage (Perez et al., 2019). This is qualitatively illustrated in Figure 1. The term implicit storage embodies the catalyst attribute of overbuilding: enabling [real] energy storage to perform its function: firmly supplying power when the renewable resource is insufficient, but at a considerably lower cost. As shown in, e.g., the MISO high renewable penetration study, (Perez, M., 2020), the difference in firm power generation LCOE between a no-curtailment storage-only configuration, and implicit storage configuration can approach one order of magnitude.

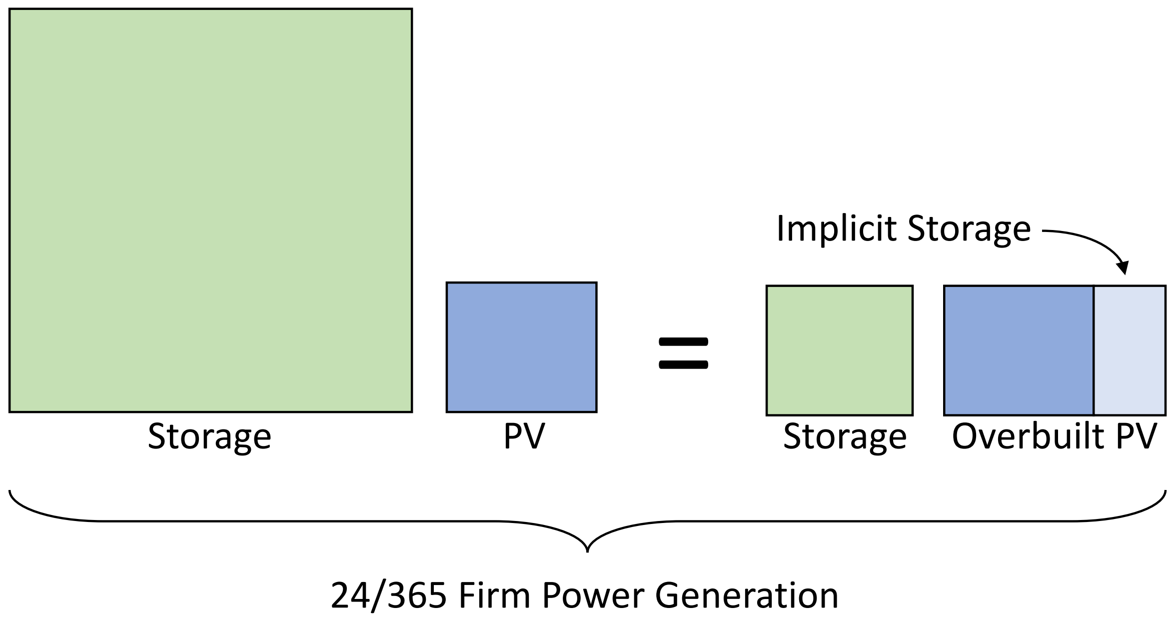

Fig. 1: Achieving firm power generation with PV. Left: PV and storage alone; maximized production with no curtailment (also referred as "dump" PV). Right: Overbuilt, curtailable "flexible" PV including optimized real and implicit storage.

The optimum amount of implicit storage is the amount that minimizes the firm levelized cost of energy (LCOE) for meeting demand 24x365. This amount depends (1) on the capital and operational costs of the considered intermittent renewable resources compared to storage, as well as (2) on the availability of these renewable resources vis-a-vis the load to be served.

In practice implicit storage optimization requires time/site-matching data time series for the nominal production of the considered renewable(s) and for load demand. The cost of meeting demand without implicit storage is first determined by calculating – and pricing – the quantity of storage necessary to make up for all renewables deficits with respect to demand. The size of the implicit storage is then gradually increased, and the storage determination process is repeated stepwise until the firm production cost reaches a minimum. Increasing implicit storage (i.e., overbuilding the renewable resources and producing more energy than required) implies that a fraction of the output will not be needed to meet demand either directly or via storage, hence will be operationally curtailed. When more than one renewable resource are involved, this process will also involve a least-cost optimization of the their respective contributions.

We illustrate the implicit storage determination in the simple case of PV-only in Figure 2. The Y axis represents the LCOE for meeting demand 24x365. The X axis represents the amount of PV output that is operationally curtailed. Implicit storage and proactive operational curtailment are linked by the following relationship:

$$\boldsymbol{IS = 1 - \ 1/((1 - OC))}$$

where *IS* represents the implicit storage expressed as a fraction of installed PV, and where *OC* represents the fraction of proactively curtailed (i.e., non-monetized) PV output

The stepwise process of increasing implicit storage defines a U shape curve. The least-cost firm power is achieved at the minimum of the curve, thus defining the size of implicit storage relative to the uncurtailed fraction of PV.

This illustrative example is for the central US region referred in section 2 assuming a homogenous geographic dispersion of the PV resource, and assuming a (future) turnkey PV cost of $400/kW and a storage cost of respectively $50/kWh for energy capacity and $150/kW for power capacity. Experimental data time series applied to this example consist of hourly load data and time/site-specific PV simulated from high-resolution SolarAnywhere irradiances and meteorological data (SolarAnywhere, 2021). The experimental data cover the year 2016. Note that all LCOE calculation assume a 4% cost of capital representative of the US utility industry at the time of this writing.

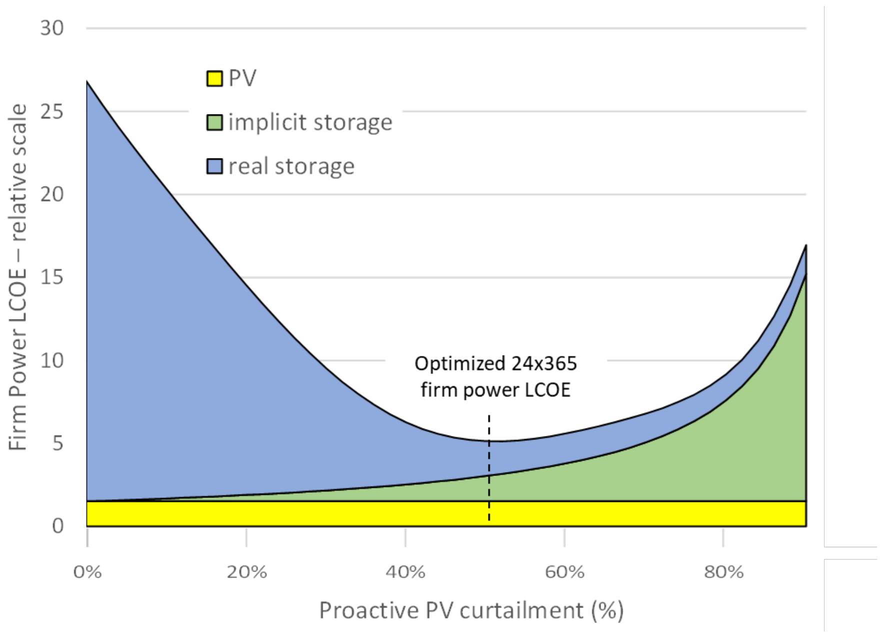

Fig. 2: Firm Power LCOE as a function of proactive operational curtailment (OC) in the case of a PV-only configuration. The cost contributions of PV, implicit storage and actual storage add up to the LCOE.

2. Implicit Storage vs. other enablers of firm power generation

While implicit storage is an impactful system design configuration to decrease the cost of firm renewable power generation, it is not the only one. Other configuration/strategies that can be combined with implicit storage include:

- RE blend optimization: wind and solar often have complementary availability profiles both a on a daily and seasonal basis. These complementarities reduce the required quantity of real and implicit storage, hence the cost of firm power.
- Flexibility: reduces the firm power requirements by allowing a small fraction of the load to be met by conventional dispatchable resources (supply-side flexibility) or load reduction (demand-side flexibility).
- Geographic dispersion: the geographic smoothing effect reduces the variability of both wind and solar resources, hence also reduces the size of real/implicit storage required to supply firm 24/365 power.

Figure 3 compares the impacts of implicit storage, wind/solar blending, flexibility, and geographic dispersion for a selected electrical region in the Midcontinent Independent System Operator (MISO) interconnected area, starting with a 100% solar/no-curtailment/storage-only configuration, and successively applying implicit storage, wind/solar optimum blending, 5% of supply-side flexibility from dispatchable natural gas, and continent-wide RE geographic dispersion through the entire MISO territory. As for solar above, the wind power generation data are time/site-specific and extrapolated from the majority of wind farms operational throughout the MISO region (Perez, 2020).

Starting at left of Figure 3, we first consider MISO region # 4 with a homogeneously dispersed PV resource at \$400/kW. We calculate the LCOE of unconstrained (no-curtailment) PV output with battery storage (\$50/kWh) as the only resource to deliver 24x365 firm power. This LCOE corresponds to the the leftmost point in Figure 2's curve with an LCOE of ~ 28 ¢/kWh. We then optimize PV oversizing/curtailment and battery storage using the stepwise approach mentioned above to arrive at the minimum LCOE cost of 6 ¢/kWh for region #4. Enter wind power generation at \$800/kW; nominal wind power hourly production data, extraploated from time/site specific wind farms operating in region #4 (Perez, 2020), are added to hourly nominal solar production data to perform a two dimentional stepwise optimization – wind/solar blend and curtailment/storage. This leads to the third column in figure 3 at 4.2 ¢/kWh. When gas is dispatched in this model, it occurs deterministically when aggregate storage resources are entirely empty; this allows gas assets to do some of the energy work which otherwise would be placed on the storage; thereby reducing its necessary size. We assume fully depreciated legacy natural gas resources with an operational cost of 2.8 ¢/kWh. This leads to a resource blend firm power LCOE of 3.5 ¢/kWh. Finally we repeat the combined four steps for the entire MISO region that covers nearly 20% of the USA from the Gulf of Mexico to Canada. Despite assuming no additional transmission costs, the large regional resource spread only produces a modest gain in bottom line LCOE at 3 ¢/kWh,

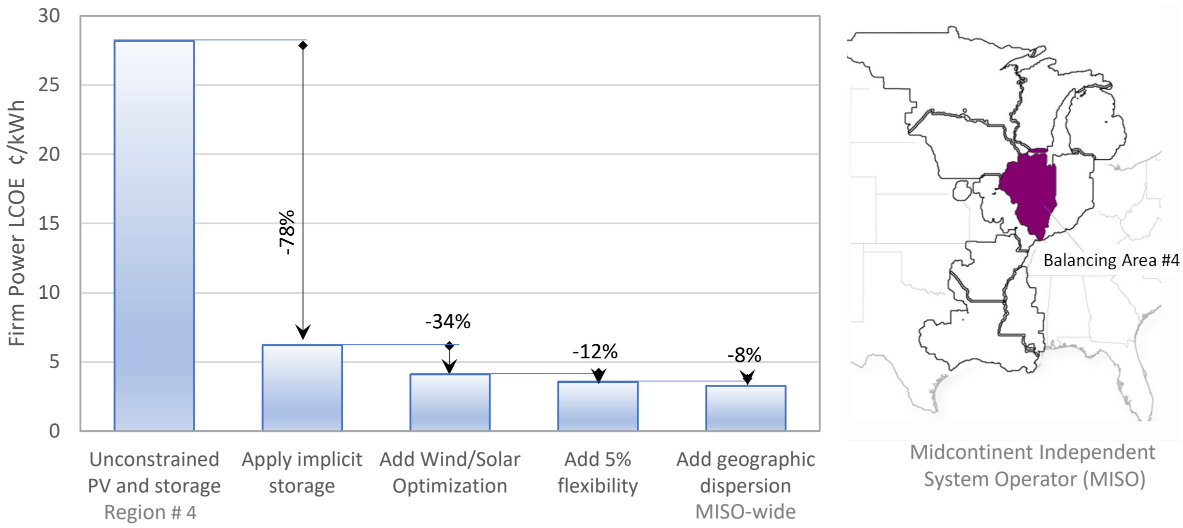

Fig. 3: Contrasting the cumulative influences of implicit storage (overbuild/curtail), wind/solar blending, load flexibility and TSO-wide geographic dispersion on firm power generation Levelized Cost of Energy (LCOE).

3. Least-Cost Enabling Regulations Needed

The above example shows that, for the considered mid-latitude region, the implementation of implicit storage is the most effective system design configuration required to achieving regional firm power generation at an acceptably low cost. (Importantly, the relative cost reductions from one configuration to the next do not depend appreciably on their implementation order.) The effectiveness of this strategy will vary based on latitude and the associated seasonality of the solar resource as one distances from the equator but it is valuable in reducing costs no matter the location.

Unfortunately, current regulation and the remuneration systems they enable do not currently target renewable firm power generation objectives, hence do not enable the most effective solutions that could reach these objectives effectively. Renewable deployment strategies are entirely driven by the way in which existing regulatory policy frames the market: market structure incentivizes actors to deploy capital in specific ways which may not be optimal from a long-term economically sound perspective. Appropriate RPS-like structures specifying optimum deployment of renewable blends and real/implicit storage, or firm-power tariff structures – implying the deployment of implicit storage as a least-cost design solution – are two regulatory strategies that could effectively foster this objective. It is important to stress that the later such strategies will be implemented, the higher the cost of ultra-high RE penetration will be. The longer deployments of unconstrained RE (i.e., w/o implicit storage) continue, the larger the burden – i.e., cost – of future systems will be to achieve firm power generation.

4. References

Denholm, P., M. O'Connell, G. Brinkman, and J. Jorgenson, 2015. Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart National Renewable Energy Laboratory Technical Report NREL/TP-6A20-65023 November 2

Fitzgerald A., J. Garrett, J. Mandel, J. Morris, and H. Touati, 2015. The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid. Rocky Mountain Institute, September 2015.

Mendelsohn M., & A. Weiss, 2021. The Next Big Thing: Grid-Tied Batteries. How to Maximize Value. https://www.ascendanalytics.com/blog/the-next-big-thing-grid-tied-batteries-how-to-maximize-value

Perez M., et al., 2019. Overbuilding & curtailment: enablers of firm PV generation. Sol. Energy 2019, 180.

Perez, R.; Perez, M.; Schlemmer, J.; Dise, J.; Hoff, T.E.; Swierc, A.; Keelin, P.; Pierro, M.; Cornaro, C., 2020. From Firm Solar Power Forecasts to Firm Solar Power Generation an Effective Path to Ultra-High Renewable Penetration a New York Case Study. Energies 2020, 13, 4489. https://doi.org/10.3390/en13174489

Perez M., 2020. Pathways to 100% Renewables across the MISO Region. http://mnsolarpathways

Rebours, Yann G., et al., 2007. A survey of frequency and voltage control ancillary services—Part I: Technical features. Power Systems, IEEE Transactions on 22.1 (2007): 350-357

Sackler, D., 2021. New battery storage on shaky ground in ancillary service markets https://www.utilitydive.com/news/new-battery-storage-on-shaky-ground-in-ancillary-service-markets/567303/

SolarAnywhere, 2016. https://www.solaranywhere.com/

State of Maryland, 2018. Energy Storage in Maryland https://dnr.maryland.gov/pprp/Documents/Energy-Storage-In-Maryland.pdf

Torabi, R., A. Gomes, and F. Morgado-Dias, 2018. The Duck Curve Characteristic and Storage Requirements for Greening the Island of Porto Santo, 2018 Energy and Sustainability for Small Developing Economies (ES2DE), 2018, pp. 1-7, doi: 10.1109/ES2DE.2018.8494235.

Uddin, Moslem & Romlie, Mohd & Abdullah, M.F. & Abd Halim, Syahirah & Bakar, Ab & Kwang, Tan. 2017. A review on peak load shaving strategies. Renewable and Sustainable Energy Reviews. 82. 3323-3332. 10.1016/j.rser.2017.10.056.

Wan, Y., X. Liu, X. Wu, & Q. Liu, 2020. Economic Analysis Method for Peak Shaving of Wind Storage Combined System Considering Energy Storage Participating in Peak Shaving. 431-434. 10.1109/ICITBS49701.2020.00093.

Wang Q, Chang P, Bai R, Liu W, Dai J, Tang Y. 2019. Mitigation Strategy for Duck Curve in High Photovoltaic Penetration Power System Using Concentrating Solar Power Station. Energies. 2019; 12(18):3521. https://doi.org/10.3390/en12183521