Achieving 100% renewables: supply-shaping through curtailment

Economics | How best to bridge the gap between the production of renewables such as solar and demand is the subject of much debate. Marc Perez, Richard Perez, Karl R. Rabago and Morgan Putnam argue the case for curtailment combined with storage as a cost-effective solution

Credit: BHE Renewables

Storage has long been considered the critical component to achieving high degrees of renewable penetration. This makes intuitive sense because it is readily apparent the sun doesn't always shine when energy is being used. Storage is indeed an increasingly important tool to bridge the "firm spread"—the gap between renewable production and customer demand.

Recent work has shown that we don't need as much storage as we might think to achieve high degrees of renewable energy penetration. This article demonstrates how renewable energy curtailment combined with storage enables the achievement of very high renewables penetration at much lower cost than with storage alone.

Background

A rapid decline in turnkey capital costs for solar PV systems has led it to be the fastest growing and often least-cost electricity generation resource. So-called "grid parity" of solar has already been achieved in many locations, with reports of PV PPA (Power Purchase Agreement) bids below US$0.02/kWh [2][4][19]. Contract energy prices at that level are lower than energy prices for nearly any conventional generation (nuclear, natural gas, coal, etc.).

Despite having achieved grid parity for energy prices, we must remember that not all kilowatt hours are created equal. A unit of energy supplied to the grid from a solar generator is not equivalent to a unit of energy supplied by a conventional generator. This is because renewable production is inherently variable and non-dispatchable—its production relies on the weather. Solar generation cannot therefore operate according to the preferences of the grid manager. By contrast, a conventional generator such as a combined-cycle natural gas plant is fully dispatchable. Its capacity is available whenever the plant operator decides. Energy price parity is not the same as operational equivalence.

A higher penetration of solar and wind power at a lower cost is the holy grail of the future energy system

A threshold question for high-penetration solar generation is how to "firm-up" intermittent renewables and transform them into resources that can meet load at any time. Many "firming" solutions to bridge the gap between supply and demand are under discussion. Among these solutions, Internet of Things ("IoT") load control, micro-grids, smart grids, load-shaping tariffs, and storage take prominence [1]. This article explains a counterintuitive and elegantly simple strategy that greatly reduces the need for these solutions solely to firm solar.

Energy storage: an incomplete solution

Transforming variable renewables effectively into firm generators is a necessary prerequisite to achieving their very high penetration on the grid. The issue with solar is that there exist gaps in supply when the sun isn't shining yet demand still exists. These supply/demand imbalances are present on multiple timescales. They stretch from intra-hour (passing clouds), to intra-day (rising and setting of the sun), to inter-day (weather fronts), to seasonal (rotation of the earth around the sun and axial tilt). In energy market terms, these imbalances give rise to a "firm spread". The firm spread is the differential between the cost of resources that are effectively always available to meet demand and those that are not.

Electrochemical battery storage is often cited as the solution that will transform solar into a dispatchable resource. The price of storage to firm any individual unit of solar capacity has therefore been cited as a metric to quantify the value of firm spread. Electricity storage will be a critical component to overcoming solar variability, but the combined effects of storage and solar costs will dictate that it is not the only one.

Longer-timescale solar supply gaps (in the order of weeks or seasons) require an expensive amount of storage to overcome. This is true even when assuming future electrochemical storage costs below US$100/MWh [10]. The cost is high because the amount of energy that must be stored to overcome the seasonal supply gap is large. In fact, it is more than one hundred times larger than the battery size needed to account for the shift from day to night: or to mitigate so-called duck curves. Using only battery storage as a solution to solar variability would push system costs far above grid parity.

Supply shaping through oversizing and curtailment

The least-cost pathway for effectively transforming variable PV into firm generation lies in a counterintuitive strategy: oversizing of solar generation assets and dynamically curtailing the output. Such a strategy reduces storage requirements by at least a factor of ten relative to the storage needed if it was the only solution. The effectiveness of this strategy is demonstrated in the recently-released *Minnesota Solar Pathways* study and a corresponding publication in Solar Energy Journal [8][12].

A strategy of oversizing and curtailment works because:

- Oversizing drastically diminishes the supply gaps stemming from resource variability at longer timescales;
- The cost of storage saved in so doing is much higher than the cost of oversizing renewables.

Figure 1 demonstrates the tradeoff between oversizing of renewable generation and storage. Though the figure demonstrates optimisation using future costs, this tradeoff is applicable even at today's prices.

The solid black line represents the LCOE to meet electrical demand 24/365 with an optimised blend of wind and PV, storage and 5% natural gas. This LCOE is the sum of the unconstrained RE+gas LCOE (orange line) and of the battery LCOE necessary to fill all intermittency gaps (blue line). The semi-transparent gray line represents the current [conventional] electricity production costs in the state.

At zero curtailment (i.e., no RE oversizing) the orange line is well below the grey line; i.e., it is apparently below grid parity.

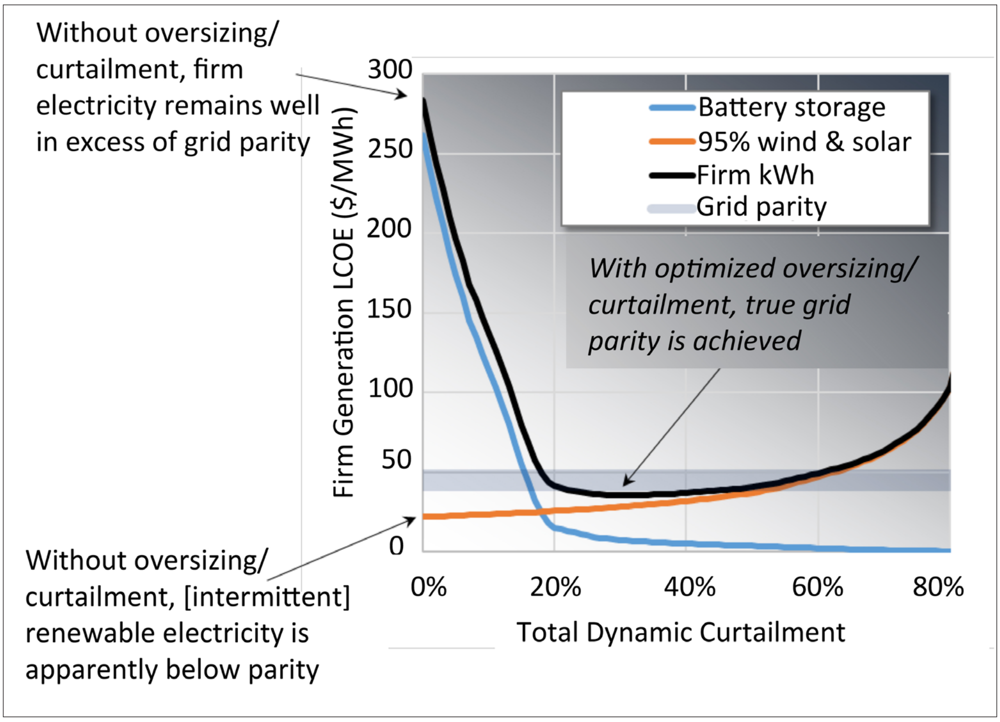


Figure 1. The levelised cost of energy (LCOE) to generate firm renewable electricity for the Minnesota power grid as a function of the fraction of oversized/curtailed renewable energy using utility-scale future (2050) PV, wind and storage cost assumptions

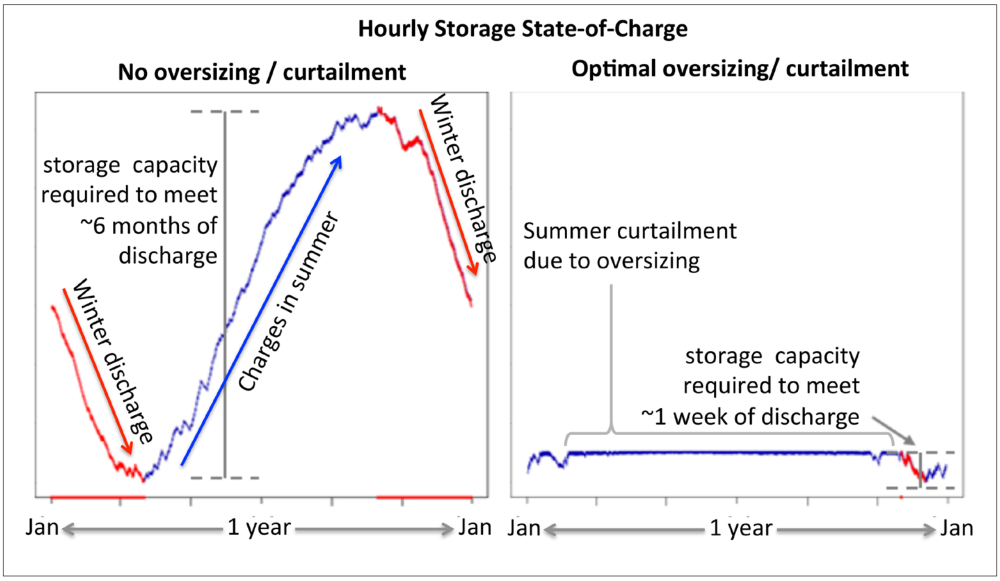


Figure 2. Hourly storage state-of-charge to meet MN utility load in the absence of oversizing (left plot) and with optimal oversizing + curtailment (right plot)

However, the storage requirements to transform unconstrained renewable energy into a firm 24/365 resource (black line) are overwhelmingly expensive. When optimally curtailing about one third of the production (i.e., oversizing RE by 50%), true grid parity is achieved.

Another way to visualise how this oversizing and curtailment strategy works is to look at the state of charge of the storage assets across a typical year. Figure 2 displays two subplots, each showing the storage state-of-charge dispatched to meet hourly utility load in Minnesota.

The plot on the left shows what this storage state of charge looks like without curtailment if 100% of a typical utility load is served by PV generation. Under such a scenario, storage must be sized to mitigate the seasonal supply-demand imbalance by soaking up excess production in the summer months and discharging all winter. The plot on the right shows what this storage state of charge looks like with cost-optimal oversizing and curtailment.

Storage size is decreased by a factor of 10 between the two scenarios pictured in Figure 2. This reduction exists because seasonal imbalance is eliminated through oversizing. By oversizing, PV produces more in the winter, mitigating the need for storage to do the same. Storage only needs to be sized to fill a roughly week-long supply gap as a result.

Complementary integration strategies

In addition to overbuilding and curtailment, other complementary strategies deliver cost reduction opportunities. These strategies include:

- Increased geographic diversity of renewable plant siting. Greater geographic diversity decreases aggregate variability [5][7][11][16].
- Synergistic blending of PV with wind where these resources are anticorrelated. See Figure 3 [1][3][8][14].
- A small degree of dispatchable conventional generation, such as gas generation operated infrequently [8][12][14][15].
- Demand-side management, including energy efficiency, demand response and dynamic load control [1][8].

It is useful to look at the magnitude of the supply/demand imbalances remedied by each of these solutions. Each solution is best suited to address variability on a timescale commensurate with its operational characteristics.

In Figure 4, the column bars represent the quantity of storage needed to overcome

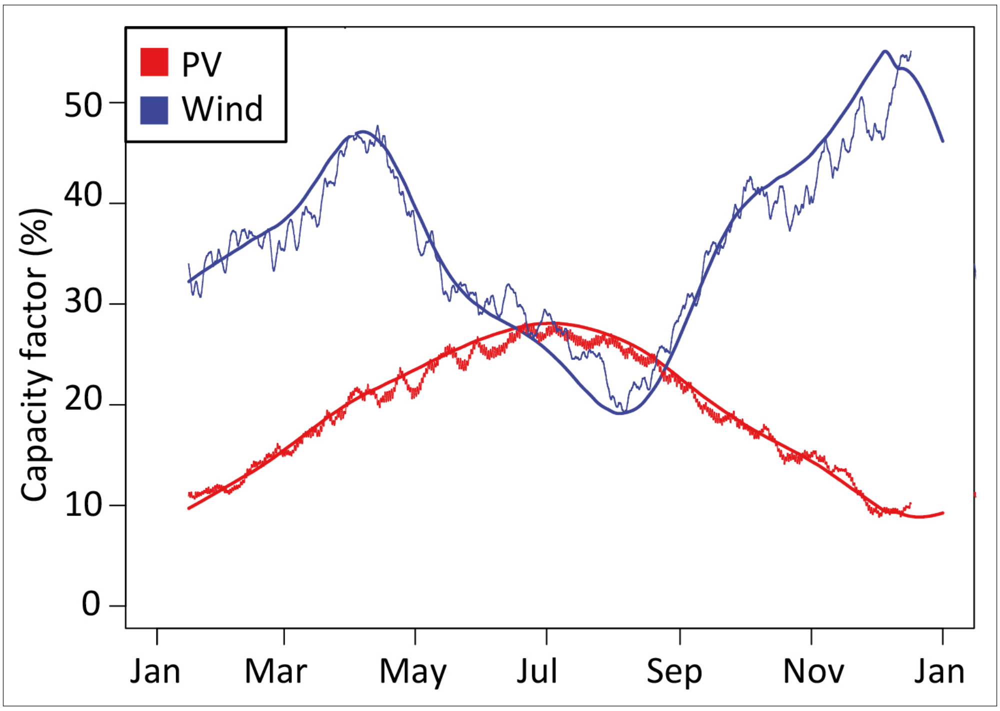


Figure 3. Solar versus wind resource across the State of Minnesota at the monthly interval in 2016. Pictured is both a 30-day moving average and locally weighted trendline for each resource. Strongly visible is the seasonal anti-correlation between the wind and solar resources across the state. Wind resource peaks in December and April (coming to a minimum in August) while the solar resource experiences its maximum and minimum at the solstices

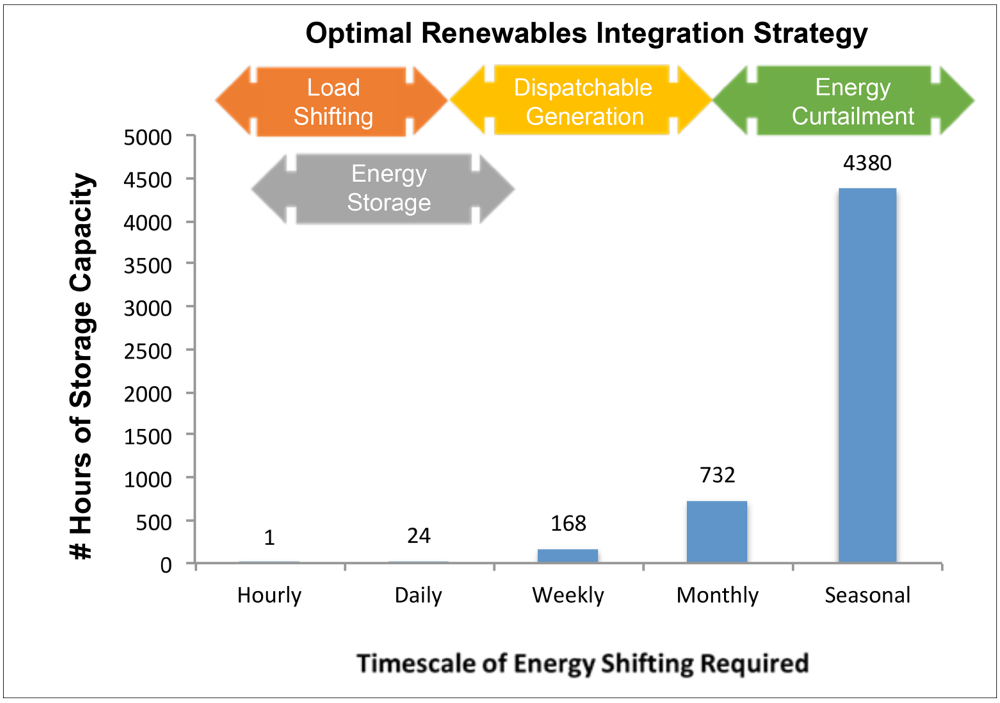


Figure 4 : Hours of storage capacity required to surmount supply/demand imbalances at various timescales (log scale) along with optimized solutions that address each of these imbalances. Note that geographic diversity of plant siting has the capability of reducing imbalances at each of these timescales if the interconnection region is large enough. Synergistic blending of PV + wind operates to reduce variability at both the daily and the seasonal levels

imbalances at various timescales, without relying on any other solution. The colored boxes near the top highlight the timescales at which a number of complementary firming solutions operate. Not surprisingly, different resources offer differing performance attributes that should be selectively applied in pursuit of an optimal solution—the right tool for the job.

Energy curtailment addresses inter-annual or seasonal imbalances. Dispatchable supplemental generation addresses weekly/monthly imbalances. And both storage and load shifting address timescales smaller than a single day. This is not to say that energy curtailment can't address variability at shorter timescales or that energy storage can't address variability at longer timescales. Figure 4 attempts to show the timescales which each of these solutions are best-suited to address given their costs and operational characteristics.

Least-cost 100% renewable energy

Using this strategy, the Minnesota Solar Pathways report shows that wind and solar can firmly meet 95% of load at costs below current wholesale market prices [8]. The report shows that these savings accrue even when demand increases due to transportation, heating and hot water electrification. The implication is that true, firm grid parity is achievable on a direct cost basis, without considering any subsidy programmes, tax credits, or the monetisation of environmental externalities.

Thanks to the synergy between overbuilding and curtailment, PV and/or wind resources are firmed—effectively transformed into dispatchable resources capable of meeting demand 100% of the time. By using such an approach, high penetrations of variable renewable resources can be seamlessly integrated into existing power grids at reasonable cost [12][13][14][15].

Policy implications for 100% renewables

At the time of writing, California, Colorado, Connecticut, Hawaii, Illinois, Maine, Nevada, New Mexico, New York and Oregon had committed to 100% renewables and/or 100% carbon-free electricity by 2050 or sooner [9][17]. Under a traditional single-solution approach of firming each incremental unit of solar capacity with storage, the intrinsic variability of solar resources stands as a fundamental barrier across multiple timescales. These 100% objectives can only be achieved if the supply gaps arising from this variability can be addressed and overcome at reasonable cost.

Curtailment is one of the primary levers to achieving 100% renewables at reasonable cost. But curtailment carries economically punitive consequences given today's regulatory structures. Renewable energy development policies, and hence the projects built under these policy structures, are largely predicated on remunerating generators based on the energy delivered, irrespective of the degree of firmness. Wholesale markets, on the other hand, do not internalise and fully price the attributes of renewable generation sought by pro-renewable development policy.

This situation threatens to penalise latecomers—the marginal PV or wind asset—as curtailment will be applied only after these facilities are built and try to operate. And regulators will be pressured by utilities to change remuneration structures, so that they are not required to pay for curtailed production.

A sound policy framework must be cognisant of the portfolio of synergistic solutions that leads to minimum-cost renewables integration. There would appear to be promise in rethinking the way in which electricity markets are structured so that they price not only day-ahead and hour-ahead time horizons, but also week-ahead and month-ahead horizons.

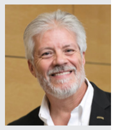
Supply-shaping through curtailment has value even before high penetration levels are reached

Oversizing renewable assets beyond what is needed on an energy basis in order to facilitate some curtailment can reduce the integration costs of both solar and wind. It does so by reducing the total amount of storage that would otherwise have been required. A small degree of oversizing results in the ability to accommodate unforeseen over-predictions in forecasted production and allows PV and wind plants to provide key ancillary grid services. This concept was recently put into operational practice by First Solar [6].

Conclusion: Oversizing coupled with curtailment is a key element in achieving high penetration renewables, and even offers benefits on the path to high penetration levels. This strategy drastically reduces the amount of storage needed to firm the effective output of renewables and thereby drastically reduces integration costs.

The Minnesota Solar Pathways study demonstrates that a 3.5¢/kWh electricity production cost to meet 95% of their electricity and transportation requirements is attainable. The policy and market frameworks necessary to support such overbuilding and curtailment are not yet in place, but there are no fundamental barriers to the approach. ■

Authors



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Morgan Putnam recently joined REsurety as VP of solar analytics. In his previous work at Clean Power Research, Morgan advanced the interconnection process for distributed solar assets, modelled high-penetration renewables futures, and co-led the MN Solar Pathways project. He started his career in the solar industry in 2005 working on next-generation solar cells at Caltech. His PhD research led to a venture-backed startup in 2010.

Richard Perez directs solar energy research at the Atmospheric Sciences Research Center of the State University of New York at Albany. He sits on the advisory board of the George Washington University's Solar Institute, and has served multiple terms on the board of the American Solar Energy Society and as associate editor of Solar Energy Journal. He has produced over 250 journal articles, book chapters and conference papers. He holds US patents on energy storage, and load management using photovoltaics. He has received several international awards.

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