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Achieving Very High PV Penetration

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The need for an effective electricity remuneration framework and a central role for grid operators

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ABSRTRACT

This article argues that optimally deployed intermittency solutions could affordably transform solar power generation into the firm power delivery system modern economies require, thereby enabling very high solar penetration and the displacement conventional power generation. The optimal deployment of these high-penetration enabling solutions imply the existence of a healthy power grid, and therefore imply a central role for utilities and grid operators.

This article also argues that a value-based electricity compensation mechanism, recognizing the multi-facetted, penetration-dependent value and cost of solar energy, and capable of shaping consumption patterns to optimally match resource and demand, would be an effective vehicle to enable high solar penetration and deliver affordable firm power generation.

1. INTRODUCTION

Solar energy is a vast renewable energy resource with a minimal environmental footprint. It is also rapidly becoming one of the least costly electrical energy generation resources on a straight energy basis and as such, represents an important economic opportunity for all actors in the energy sector.

However, exploiting this vast potential requires the deployment of technological and logistical solutions that can overcome solar energy's intermittency and transform this inherently non-dispatchable resource into a firm power delivery system.

In this article we present five of these solutions and argue that their optimal deployment can reliably deliver firm electricity affordably. This, in turn, will make very high solar penetration an acceptable proposition to all energy actors, particularly the utility sector.

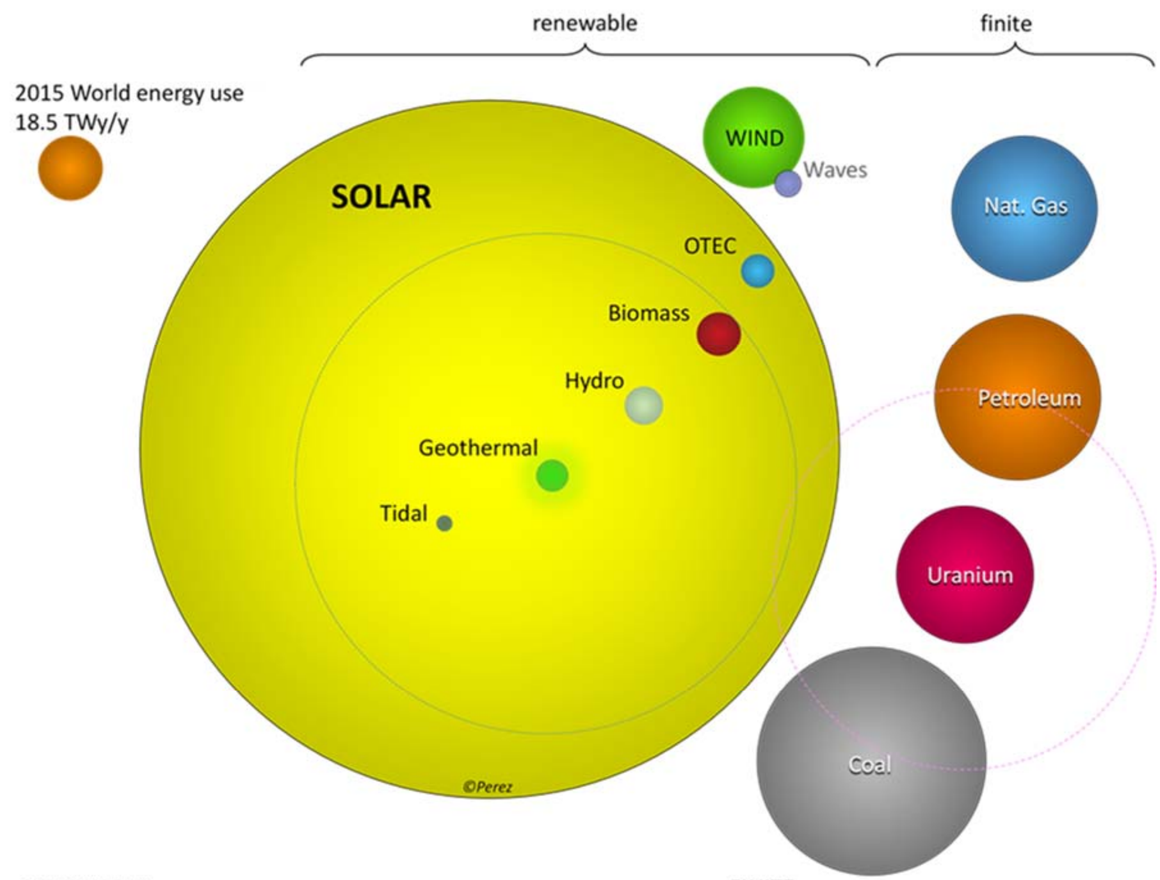
A key catalyst to the deployment of these high-penetration-enabling solutions is the implementation of a suitable electrical energy remuneration system on both supply and demand sides. On the supply-side (production), remuneration should embed both the evolving value of solar power generation and the evolving cost of overcoming intermittency as penetration increases. On the demand side (consumption) the cost of retail energy should reflect the [real-time] availability of the solar resource so as to shape loads and increase their solar synchronicity.

Finally, we argue that the nature of both the enabling solutions and the remuneration systems imply a central role for grid operators with the likely outcome of easing the current tensions between the solar and utility industries, tensions arising from a remuneration system that is not adapted for solar growth.

2. PV: a massive potential for least cost electricity generation

The solar potential is vast compared to the energy reserves of the planet. Indeed the deployable potential of this renewable and clean energy resource is orders of magnitude larger than all other energy resources combined, both renewable and finite [1].

The high cost of solar electricity generation via photovoltaics (PV) or thermal technologies has historically been the main barrier to deployment. PV, however, is rapidly becoming one of the lowest cost resources for electricity production on a pure energy basis [2]. Unsubsidized utility scale PV LCOE is now approaching $60/MWh. This is on par with or better than all other renewable and non-renewable electrical energy generating resources except large scale wind and natural gas (if externalities are not included) [3].



RENEWABLE				FINITE	
Solar	23,000 TWy/y	Biomass	2-6 TWy/y	Nat. Gas	220 TWy
Wind	75-130 TWy/y	Hydro	3-4 TWy/y	Petroleum	335 Twy
Waves	0.2-2 TWy/y	Geotrm	0.2-3++ TWy/y	Uranium	185++ TWy
OTEC	3-11 TWy/y	Tidal	0.3 TWy/y	Coal	830 TWy

Figure 1: Comparing the energy resources of the planet. Yearly resource is shown for the renewables and total reserves are shown for the finite resources[1] (source** [1]**).

3. Intermittency: the remaining challenge to high solar penetration

Whereas cost is a disappearing issue, intermittency remains an issue. This is because the solar resource is modulated by clouds, weather, seasons and daily cycles. It is not dispatchable, and its variability cannot always be accurately predicted [4]. It is often viewed by grid operators as being unreliable and not capable of contributing to bulk power generation.

[1] The dashed outline around the uranium sphere represents the achievable potential if 100% of all fission byproducts were ideally reprocessed. The dotted outline around geothermal sphere represents what future yet highly environmentally questionable, deep hydro-fracking-based enhanced geothermal systems could deliver. These technologies do not currently exist.

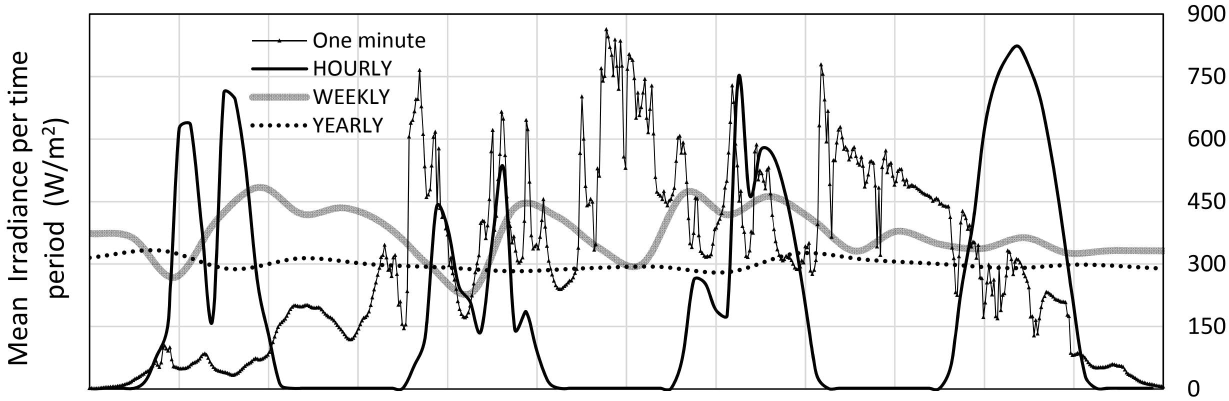


Figure 2: Illustrating the variability of the solar resource at different time scales for a given location (source** [4]**)

The intermittency of PV does not represent a major challenge at low penetration. In addition, PV can claim capacity credit at moderate penetration in regions where peak demand is driven by commercial air conditioning usage, which is fueled by solar gain [5].

Intermittency at very high penetration, however, poses major energy supply and demand mismatch problems. Figure 3 illustrates how increasing PV penetration impacts utility loads. This example shows two high demand weeks of load for the New York metropolitan area. The top of the figure presents no PV. The middle presents moderate penetration. The bottom presents high penetration. PV at moderate penetration would be effective at reducing summer peak demand, and at displacing the most expensive generation assets. This would no longer be the case at very high penetration, where the demand-supply imbalances would require a considerable amount of backup generation with often unpredictable weather-driven ramps and dispatching schedules. Mid-season and winter loads would exhibit similar high-penetration imbalances without the benefit of moderate penetration capacity relief.

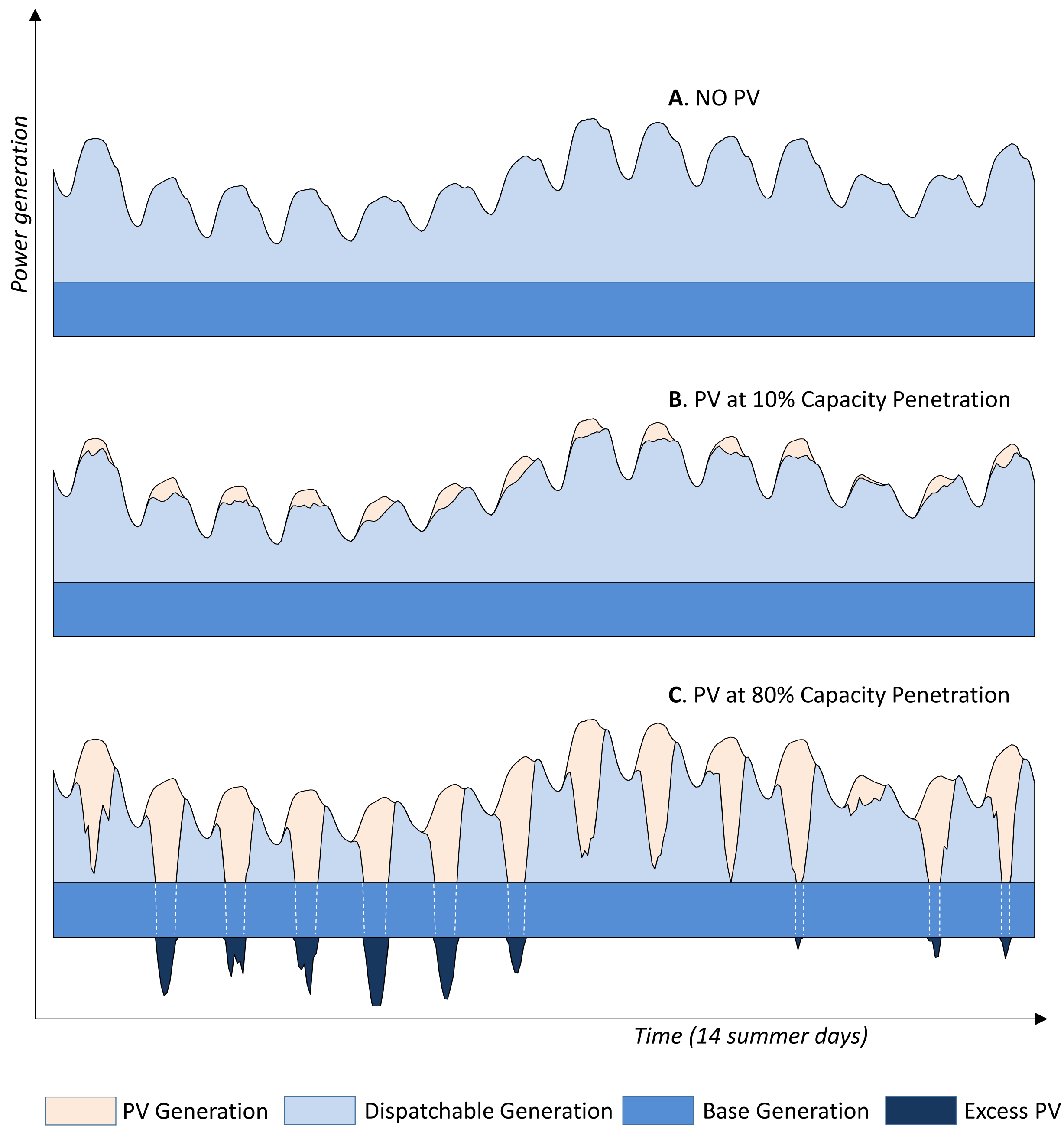


Figure 3: Illustrating PV grid penetration. This example shows:

- ***(A) 2 weeks of demand and power generation for the New York metro are in a summer peak period.***
- ***(B) At moderate penetration, PV generation is effective at reducing peak demand***
- ***(C) At high penetration, PV generation creates demand-supply imbalance issues that must be addressed.***

4. Solutions to intermittency's problems

Fortunately, solutions exist to transform the vast potential of the solar resource into a firm electricity production system capable of meeting electrical demand with operational guarantees, i.e., capable of eliminating the need for dispatchable backup generation as illustrated in Fig. 3. These solutions include:

- Electric storage: Excess solar production above current load requirements can be stored for later use. Two problems are addressed with storage: the removal of excess generation, and the provision of renewable energy when renewable generation is unavailable. Electric storage technologies cover a wide spectrum of capabilities. Very fast response storage includes low reserve fly-wheels and capacitors. Slower response storage includes massive energy reserve technologies such as pumped hydro. Storage with electrical batteries occupies the middle ground [6]. All storage technologies are rapidly evolving (e.g., [7], [8]). Downward trends in storage costs and upward trends in performance (efficiency, lifetime) are underway.
- Smart curtailment: Excess solar production beyond what can be consumed or stored can be spilled (e.g., by partially reducing inverter power output). This type of curtailment is distinct from the reactive curtailment practice based on ramp rate constraints for transmission stability and already imposed by some grid operators. It is also distinct from curtailment based on distribution system needs, such as backfeed prevention and local voltage control. This type of curtailment is also different than tripping renewable sources offline. Rather, it reduces output partially to a level that is situation-appropriate.
- Load shaping: This is a proactive form of demand response encouraging electrical consumption when the solar resource is locally abundant and discouraging it when it is not, such as through appropriate electricity consumption tariffs and/or controllable loads. It also may take advantage of thermal storage capabilities that allow the shift of consumption to different time periods with minimal impact to end users.
- Geographic dispersion: Solar energy generation can be pooled locally, regionally, or beyond [9], to lessen the effects of weather-induced variability [4]. Taking advantage of geographic dispersion may require additional transmission resources [10].
- Combining solar with wind and/or biomass generation: Wind is another very large-scale variable renewable resource. Although its ultimate potential is smaller than solar, it has the advantage of often being uncorrelated to, and in many cases complementary to solar on intraday and seasonal scales [11]. Although a limited resource, biomass can provide dispatchable or baseload power similar to the way that fossil and nuclear power can.

Four of these [solar-only] solutions – storage, curtailment, load-shaping and dispersion -- are qualitatively illustrated in Fig. 4.

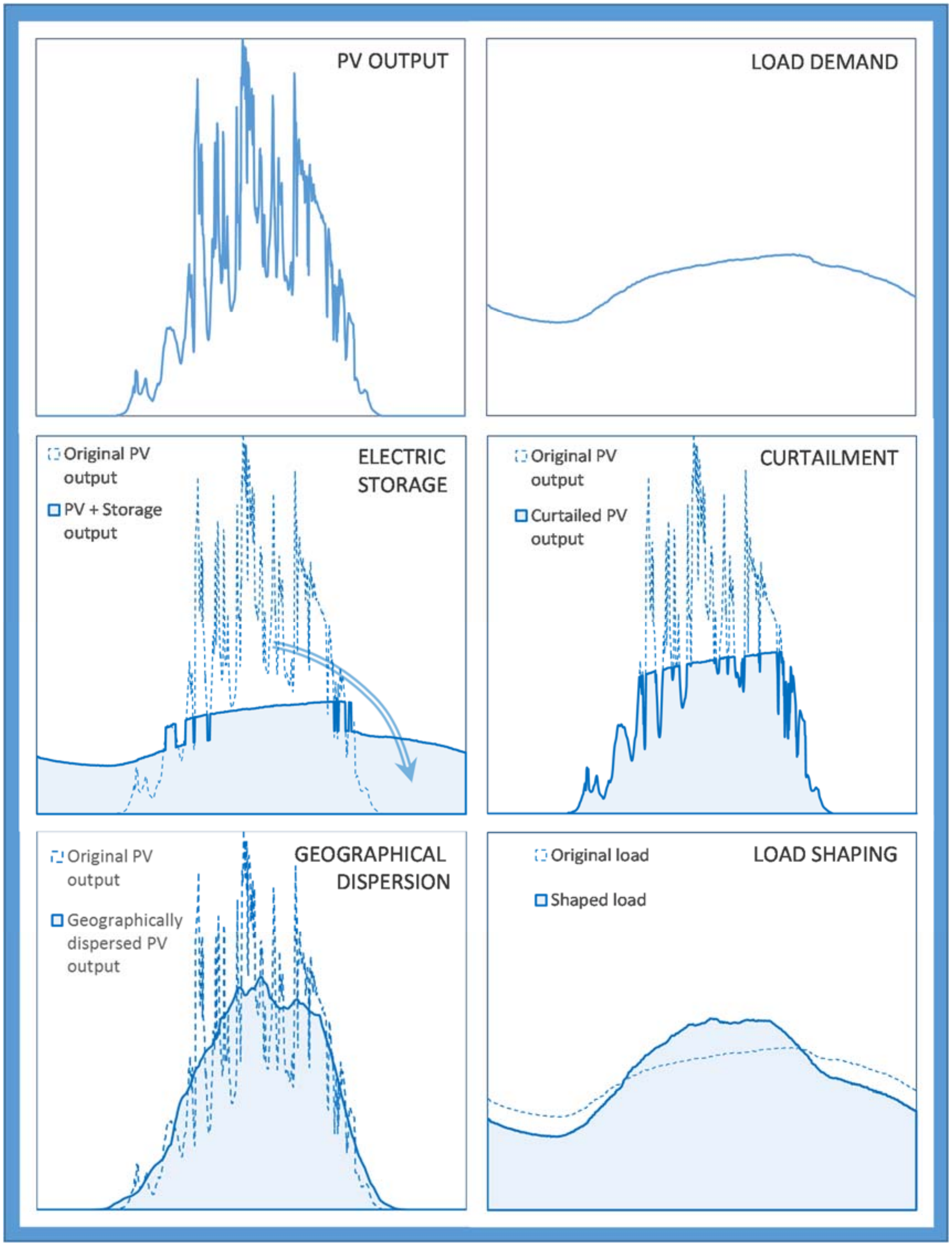


Figure 4: Illustrating four solutions to firmly meeting load demand requirements at very high PV penetration: storage, output curtailment, geographic dispersion and load shaping. The first two graphs at the top illustrate the variable solar supply (A) and a typical demand profile that must be firmly served (B). Storage (C) redistributes the resource to periods when it is not available. Curtailment (D) and geographic dispersion (E) mitigate both intra-day and day-to-day variability. Load shaping (F) changes the demand profile to enhance its coincidence with the solar supply.

The only solution that, alone, could eliminate the need for conventional generation backup at any penetration level is electric storage. This is because storage is the only solution that can guarantee output at any point in time to make up for lack of resource (e.g., at night). Whereas storage alone would make high penetration prohibitively expensive (e.g., see [12]), firm power delivery at high PV penetration could be made reliable and affordable by optimally combining storage with the other solutions. The IEA PVPS recently analyzed the cost of producing firm baseload generation with solar in the Central US by optimally combining regional dispersion (within a 1000 km radius), storage, curtailment and demand response [13]. The study showed that a stringent baseload firm power delivery objective[2] could be achieved for below 10 cents per kWh even without including wind generation in the mix. Fig. 5 illustrates the main result of this analysis.

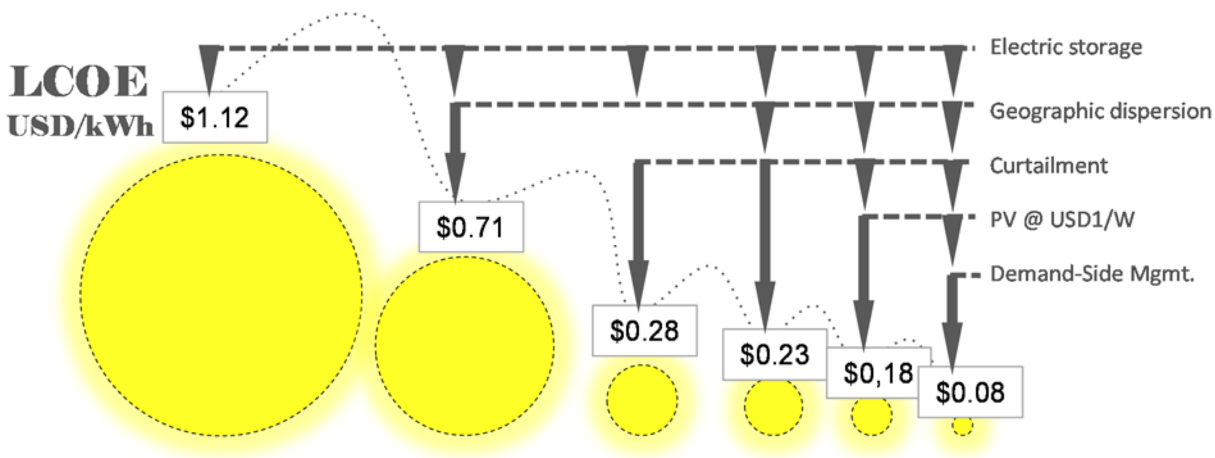


Figure 5: LCOE for providing firm, constant power output (i.e., baseload generation-equivalent) from PV generation in the central United States, using one or more optimally mixed high penetration solutions (source [13]***). The figure includes, from left to right:***

1. ***Storage alone***
2. ***Storage and geographic dispersion;***
3. ***Storage and smart curtailment;***
4. ***Storage, geographic dispersion and smart curtailment;***
5. ***Same as 4, but with turnkey PV cost achieving USDOE SunShot's objective of $1/W;***
6. ***Same as 5, but with load shaping.***

[2] Baseload power delivery objective: this objective is constant power delivery night and day and throughout the year, equivalent to the output of a nuclear power plant with no down time.

5. The role of utilities and grid operators will be essential

The inherent dispersed nature of PV generation and the solutions to intermittency outlined above imply that a healthy, well-managed power grid will be central to high solar penetration.

- Geographic dispersion will require enhanced transmission grid capabilities to support regional transfers of solar energy production.
- Storage, curtailment, load shaping/demand response, and renewable resource mixing will be most efficiently managed and economically implemented from a grid operator standpoint, rather than through the actions of individual customer-producers. The approaches envisioned by, e.g., ConEdison (virtual PV system aggregation), or Iberdrola (utility control/dispatch of renewable systems) [14] in response to the New York's DPS REV Initiative [15] are early pragmatic steps along the path towards a comprehensive optimum high penetration PV management/control system.

It is important to recognize that it will be difficult for a large fraction of electricity residential, industrial and commercial customers (e.g., in urban areas) to be solar producers. Most of these customers will only be able to access and consume solar-generated electricity through the power grid in a high PV penetration context. Very high PV penetration cannot exist without addressing these electricity customers.

Utilities and grid operators must be key actors/implementers of high penetration because a highly interconnected, intelligent, and transparent electric grid is key to a very high-penetration renewable future.[3] It follows that the ramp-up of renewables must enable utilities and grid operators to remain economically healthy so that they can make the investments in infrastructure and develop the new management capabilities that are required.

6. A catalyst to high penetration: effective electricity remuneration

Affordable solutions to transform the vast, intermittent solar resource into a firm power delivery system exist. Enabling these solutions will require new thinking about how solar electrical energy is purchased and consumed. Supply-side and demand-side electricity tariffs could optimally drive the deployment of solar resources and the implementation of high-penetration enabling solutions.

6.1 Supply-side: The remuneration of solar generation should reflect both its evolving value and its evolving integration cost as penetration increases. Integration costs reflect the expense of deploying the optimum mix of intermittency mitigation solutions necessary to firmly ingest increasing amounts of solar onto the grid. An effective remuneration vehicle could consist of [net] Value Of Solar (VOS) tariffs, which, if properly assessed and implemented, would reflect the composite net value of solar electricity (e.g., see [16], [17], [18], [19], [20], [21], [22]).

Value of Solar analysis reflects two broad categories of avoided cost components. First, some components are directly relevant to utility ratepayers as a whole, such as avoided energy and capacity requirements, avoided congestion, loss savings, energy price risk mitigation, and intermittency

[3] Although new renewable energy and storage technologies could possibly enable a highly "islanded" energy system, such a system would lose the benefits of several of the combined measures discussed above and continued substantial reliance on fossil fuels would then be needed to ensure reliable power to all.

mitigation costs. Second, some components are more relevant to the society at large (e.g., environment and economic development benefits). Thus, regulators may decide that utility ratepayers should only pay for a part of the VOS through utility rates, while the other part should come from the tax base or other vehicles.[4] Fig. 6 shows an example of a VOS net value "stack" with one such division of ratepayer and societal components.

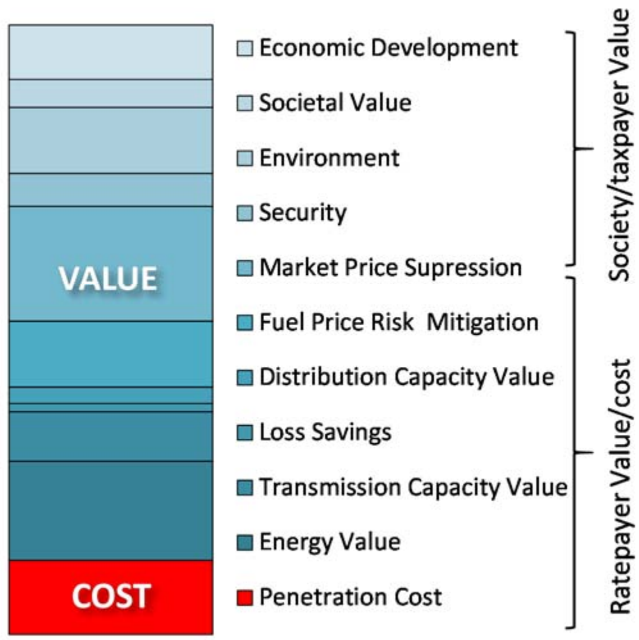


Figure 6: Example of composite taxpayer/ratepayer value and cost of PV (source [23]***).***

The ratepayer items will reflect the costs of implementing the high penetration solutions discussed above when properly valued using locational factors. These value/cost items are modulated by three fundamental factors:

- <u>Location</u>: Where solar electricity is injected on the grid. For example, PV sited on congested day-time, summer-peaking power lines and feeders carry a higher local transmission and/or distribution benefit than on uncongested winter-peaking power lines.

[4] Note that under the current solar remuneration paradigm, a sizeable fraction of revenues already comes from the tax base in the form of income tax credits and other tax-based vehicles (e.g., MACRS). However this across-the-board approach does not account for solar value fundamentals (see below).

- Penetration: The gross and relative amount of solar locally injected on the power grid. Increasing penetration saturates the grid with intermittent solar energy, reduces value depending on the conditions at the injection point, and increases ingestion costs.
- System design attributes: Array orientation and on-site dispatchability/curtailability (e.g., via batteries and smart inverters). Design attributes can enhance (or degrade) the manageability of the solar resource and hence, increase (or decrease) its value.

Pricing solar electricity to reflect its net value and accounting for the fundamental drivers of this value will foster the optimal deployment of PV (i.e., the right geographical and technical combination of location, penetration, and system design attributes), and reflect the costs of applying high-penetration solutions including storage, curtailment, geographic dispersion via grid strengthening, and demand-response/load shaping. In addition, properly calibrated[5] supply-side VOS tariffs that account for penetration effects will enable the long-term managed growth of PV without the boom/bust disruptions that have been observed in major markets around the world.

One important aspect of VOS tariffs is that they would be readily applicable to all forms of solar generation ownership, including customer, independent energy producer, utility, and community solar ownership. Notably, the latter enables all utility customers to acquire high value PV assets, even if their load location cannot support deployment or is a low-value location.

6.2 Demand-side tariffs would encourage loads to coincide with the solar resource supply, i.e., low retail energy cost when solar resource is locally abundant and high cost when it is not. As such, they would facilitate high-penetration through load shaping, and would maximize the injection of lowest cost solar power on the grid. These tariffs are general consumption tariffs that are not limited to customers with onsite PV generation, and would apply to the entire utility customer base.

Current developments in operational solar forecasts (e.g., [24]) and in demand-based distributed energy resource planning tools, e.g. [25], combined with the growth of electric transportation could enable users to take full advantage of load shaping tariffs while also reducing their net energy footprint to near zero. The example in Fig. 7 shows the case of a California home whose load (including transportation) could not only be net-zeroed, but could be combined with efficiency investments and controls to result in a desirable load profile from the utility's perspective. This approach could be applied to carve loads in the most appropriate way so as to maximize the direct utilization of solar energy on power grids.

[5] Note: When VOS would exceed the investment cost of deploying PV (LCOE), the former would have to be managed and/or capped near the latter to avoid building rushes that could lead to overbuilding. Further studies should investigate operational solutions such as, for instance capping VOS tariffs where needed and developing utility-managed solar dividend funds to be applied at a later date if and when VOS fall below deployment cost.

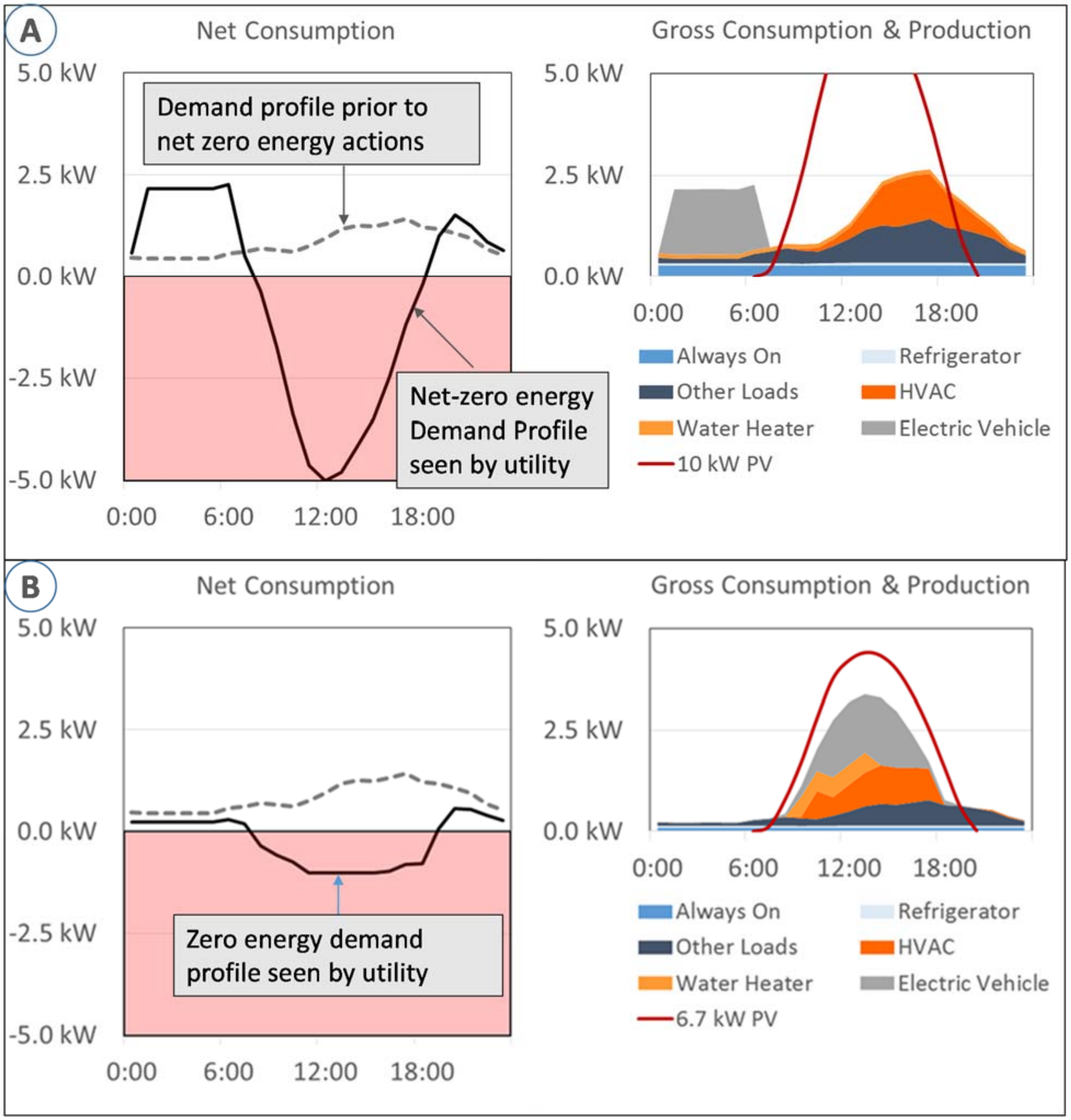


Figure 7: Example of net zero energy utility customer load coupled with load shaping. The example at the top (A) shows the load profile an existing California home that has been refitted with PV and all-electric energy systems including transportation. Although this home is net-zero on an aggregate basis, its load profile contributes to the type of power grid imbalances identified in Fig. 4. The example at the bottom (B) shows the same home where loads have been minimized and scheduled to occur in sync with available solar resource, yielding a demand profile that has been shaped to take advantage of appropriate demand side-tariffs designed to minimize grid supply-demand imbalances. Note that this example is for a customer where PV generation and loads are co-located. In practice the same effect could be achieved without colocation of PV generation and load [25]**.**

These high-penetration-enabling demand-side (load shaping) and supply-side (VOS) tariffs define and imply a central role for the utilities/grid operators who would administer them. They also imply a critical role for regulators to design these tariffs to ensure both a healthy management of the power grid and result in a healthy growth of solar.

As an effective exploratory step in this direction, now could be the time for regulators and service providers to locally quantify and optimize VOS[6] and load-shaping tariffs, and to ascertain the effectiveness of their implementation via pilot programs.

6.3 Current Solar electricity remuneration system: The remuneration system for PV generation in 2015 is largely underwritten by rigid tax incentives and, for customer-owned systems, by net energy metering (NEM). Although US solar policy has been effective at growing solar capacity, traditional NEM rates lead to tensions between the solar and utility industries as PV penetration becomes significant. NEM is not reflective of location, penetration, or PV design attributes, and, more importantly, the resultant financial transaction bypasses the grid operator. This second part is unsustainable on two fronts: (1) NEM implies the existence of a healthy power grid by definition, and (2) NEM-based PV growth will require, but not implicitly account, or capture the costs for a strengthened and healthy grid, particularly as penetrations increase.

Although the problems with NEM are being recognized along with the growth in solar deployment that it has promoted, transition to new models is challenging. Some ideas proposed in California's important "NEM 2.0" proceeding [26], fail to address these problems sufficiently, [27] and instead encourage maximum self-consumption. Maximum self-consumption, however, retains the same solar growth-limiting consequences as NEM. These problems arise wherever tariff design fails to reflect the fundamentals of PV value; that is, the importance of location in particular, and the potential elimination of the financial and physical interaction with the grid for some customers,[7] while leaving other customers (the majority in some areas) without access to solar via a grid that is not healthily evolving.

Another challenge of NEM is that it does not differentiate supply-side and demand-side. Unlike NEM, two-part tariffs would offer the possibility of enabling those unable to locate PV at their location to own PV generation anywhere (e.g., at high-value interconnection points), possibly as part of community ownership. This desirable outcome is more difficult with current regulatory constructs, such as virtual NEM, that value solar electricity at the retail owner/customer location and not at the injection site.

7. Final Remarks: Economic Development, Secondary Market Opportunities and Resiliency

7. 1 Economic opportunities & secondary markets: A high-penetration paradigm with optimized remuneration systems enabling technical solutions will go hand in hand with economic development opportunities. The growth of the energy storage market (featuring both stationary and mobile electric vehicle storage) is the most obvious, but the growth of services and technologies enabling electricity

[6] In particular a delineation of all value items attributable to solar – including but not limited to those illustrated in Fig.6, e.g., impact of solar on commodity prices – and a determination of which are relevant to utility operations (ratepayers) and which are relevant to societal objectives.

[7] Short of rigid and controversial fixed charges.

users to load shift/shape should also be manifest. The utility industry, providing a central role in high penetration solutions, should also take part in these opportunities.

Optimized PV output curtailment could also open the door to new business opportunities. Indeed curtailed PV energy is leftover spilled energy, and available for applications outside the grid at near zero marginal cost. This energy could be utilized locally in innovative secondary applications/markets –e.g., applications such as desalination, or hot water resistance heating that require little time specificity.

7.2 Resiliency: High-penetration-enabling supply-side VOS tariffs are fully consistent with, and could also be catalysts to increased local resiliency. Outage-resilient PV systems capable of operating (islanding) in micro- or nano-grid emergency load configurations could be fostered with VOS supply side tariffs. While the grid at-large (i.e., ratepayers) would benefit only marginally[8] from locally event-resilient installations, these installations have a measurable societal/taxpayer value[9] which could be reflected in appropriate supply-side tariffs as illustrated in Fig. 8.

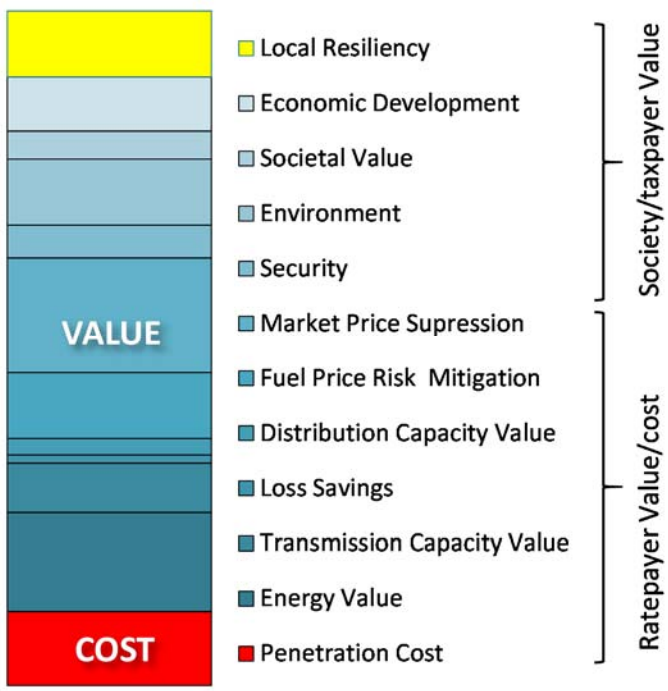


Figure 8: Same as Fig. 6, hypothetically illustrating how locally resilient capability could be enabled as a logical extension of VOS tariffs.

[8] Locally resilient installations could provide a degree of relief to utilities/grid operators at times of outage recovery operations.

[9] As seen in disaster events such as superstorm Sandy where much of the disaster cost was traceable to widespread power outages, localized resiliency can benefit society (taxpayers) above and beyond the owners of a resilient systems, e.g., by keeping local businesses and critical services up, and by allowing resident-owners of resilient systems to remain economically active.

8. Conclusions

Solar energy is the largest resource available in the world. Its environmental footprint is minimal. It is also rapidly becoming one of the cheapest resources on a straight energy basis and as such represents a very large economic opportunity for all actors in the energy sector.

Developing this vast potential economically, however, will depend on an optimal deployment of the technological and logistical solutions which can transform this variable, non-dispatchable resource into a firm power delivery system.

This article argues that a high solar penetration, firm power delivery system can be achieved affordably if it is the desired objective. However, the development of this delivery system requires recognition of the fact that the power grid is central to the deployment of the intermittency solutions that will enable high-penetration solar. Therefore, the role of grid operators and regulators will be essential.

This article also argues that a value-based compensation mechanism, recognizing the multi-facetted, penetration-dependent value and cost of solar energy and capable of shaping consumption patterns to optimally match resource and demand, would be an effective vehicle to achieve the desired affordable high-penetration objective.

Acknowledgement

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