Where and How Much?
Land Use Implications for High-Penetration PV

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Abstract

It is widely known that the solar resource is many times larger than world's primary energy demand. Despite this, questions of where and how much to deploy in a realistic context do not have such clear-cut answers. This article addresses this question in a context where solar PV is applied locally to firmly meet the bulk of energy demand from regional economies across the continental US. We provide comprehensive, realistic and actionable numbers regarding land use and installed capacities to meet present and future load that can inform planning decisions at local and regional levels. We contextualize PV deployment and corresponding land use by assigning a fraction of plausible deployment potential to land use classes as defined by the US Geological Survey. In addition, we provide readers with an online-interactive capability to select land-use deployment availability by class and further investigate state-specific potentials.

1. Introduction

Could photovoltaics power everything? Where could this resource be deployed? How much would such an investment cost? These are central questions as world economies face urgent and far-reaching decarbonization decisions.

In this article, we examine the case of photovoltaics (PV) supplying the majority of primary energy needs for the continental US (CONUS), including the electrification of the ground transportation and building sectors.

We first evaluate state-specific demand-side energy requirements before identifying PV deployment options to meet these requirements. We assume that meeting this demand is most-economically achieved through overbuilding renewable assets by 50% past what is needed on an energy basis: a strategy known as implicit storage (Perez, 2020). This degree of overbuilding has been identified as the cost-optimal amount needed to overcome intrinsic resource intermittency when firmly meeting 95% of demand in locations as diverse as the central United States, Italy and Réunion island. (Pierro, 2020; Tapaches, 2020)

2. Firm Power – Resolving Intermittency with Overbuilding and Storage

The solar resource is more than large enough to meet the world's energy demand many times over (Perez, 2015). This is true even if one considers the electrification of major energy sectors such as transportation and buildings. Intrinsic resource intermittency across multiple timescales, driven by stochastic meteorological processes, as well as deterministic daily and seasonal cycles poses the primary barrier to achieving high-penetration. If solar photovoltaic (PV) generation is to become grid-dominant and supply electrified world economies, this intermittency barrier must be crossed.

Intra-day vs. multi-day intermittency: Issues like ramp rate reduction and peak supply/demand flattening (Chen, 2020; Martins, 2019) can be considered intra-day issues. Energy storage is often employed as a cost-effective solution to address the intra-day intermittency driving these issues (Fan, 2020; Telaretti, 2020). From an energy balance perspective, multi-day and seasonal intermittencies drive a much more significant and costly issue to solve. Of interest is retaining stability during prolonged cloudy periods during low-yield seasons. Relying on storage alone to resolve these multi-day issues and ensure firm power production 24/365 would be overwhelmingly expensive– see Fig 1.

Overbuild/curtail *implicit storage* solution: We showed in a recent series of articles (Perez, 2020; Pierro, 2020; Tapaches, 2020) that overcoming PV intermittency and firmly meeting utility demand 24 hours per day and 365 days per year was economically possible well before 2050 in many global regions. Firm PV electricity production costs (LCOE) of the order of 5¢/kWh or less were found to be achievable on a straight financial

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basis[1] without major technological breakthroughs. However, we also showed that these low production costs were contingent on one fundamental strategy: *PV resource overbuilding and proactive output curtailment*. This counter-intuitive strategy also referred to as the *implicit storage* strategy, is key to sufficiently reducing otherwise insurmountably-costly long-term energy storage requirements. Other authors have recently employed optimized overbuilding of variable renewable capacities and curtailment in their renewable optimizations for purposes of designing a cost-optimal high-renewables-penetration system but they are each subject to scenario-based constraints more stringent than the CPT model which allows for any capacity of wind, PV and storage to be built to eventually meet load.

Fig. 1 illustrates the impact of oversizing on storage requirements. The [relatively small] amount of storage required to supply power and alleviate intraday imbalances does not change appreciably with oversizing (top part of the figure). By contrast, the multi-day (annual) storage requirements are reduced by over an order of magnitude (bottom part of the figure).

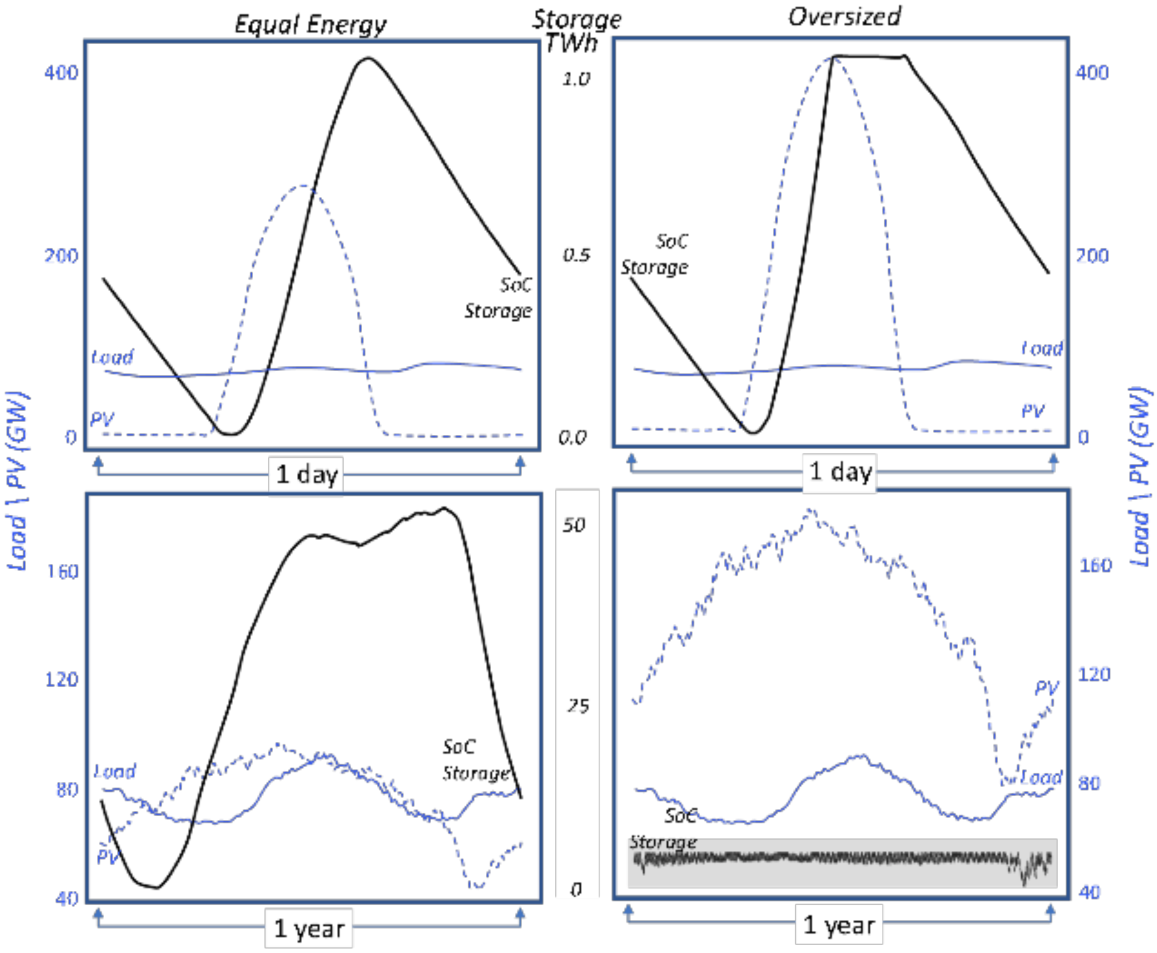

Fig. 1: Contrasting intraday intermittency (top) and multiday intermittency (bottom) and illustrating the impact of oversizing where PV is sized to meet load requirements on an energy basis (left) and PV is 2X oversized (right).

- **The top left graph contrasts typical PV production to load requirements intraday. PV is sized to meet load requirements on an energy basis. When applying storage (solid black line) PV energy can be stored and released appropriately to meet intraday (here night time) demand.**
- **The bottom left graph contrasts [30 day-smoothed] annual PV production and load demand. As above PV is sized to meet annual load on an annual basis. Applying storage can enable PV to meet load at all time. However, the quantity of storage required is nearly 50 times larger than the amount required to resolve intraday supply-demand mismatch.**
- **At right top, oversizing PV does not sensibly modify intraday storage requirements**
- **However, the bottom right draft shows that oversizing can meet demand with drastically reduced long-term storage requirements compared to equal energy-sized PV.**

[1] 'Straight business' production costs before tax, without including any environmental benefits or any other incentives.

Fig. 2 from (Perez, 2019) illustrates the economic impact of overbuilding PV. It shows how this is central to achieving acceptable least-cost firm power generation. Across the case studies analyzed, oversizing factors of the order of 50% were found to be conservatively optimal[1] given future expected costs for PV and energy storage (Pierro, 2020; Tapaches, 2020), even considering the most optimistic 'ultra-low-cost' storage cost projections (Dhieber, 2020).

Further, we showed that optimally combining solar and wind resources, and allowing for some supply-side flexibility with a residual natural gas[2] fraction (<5%) could drive projected firm power generation costs well below current conventional generation costs.

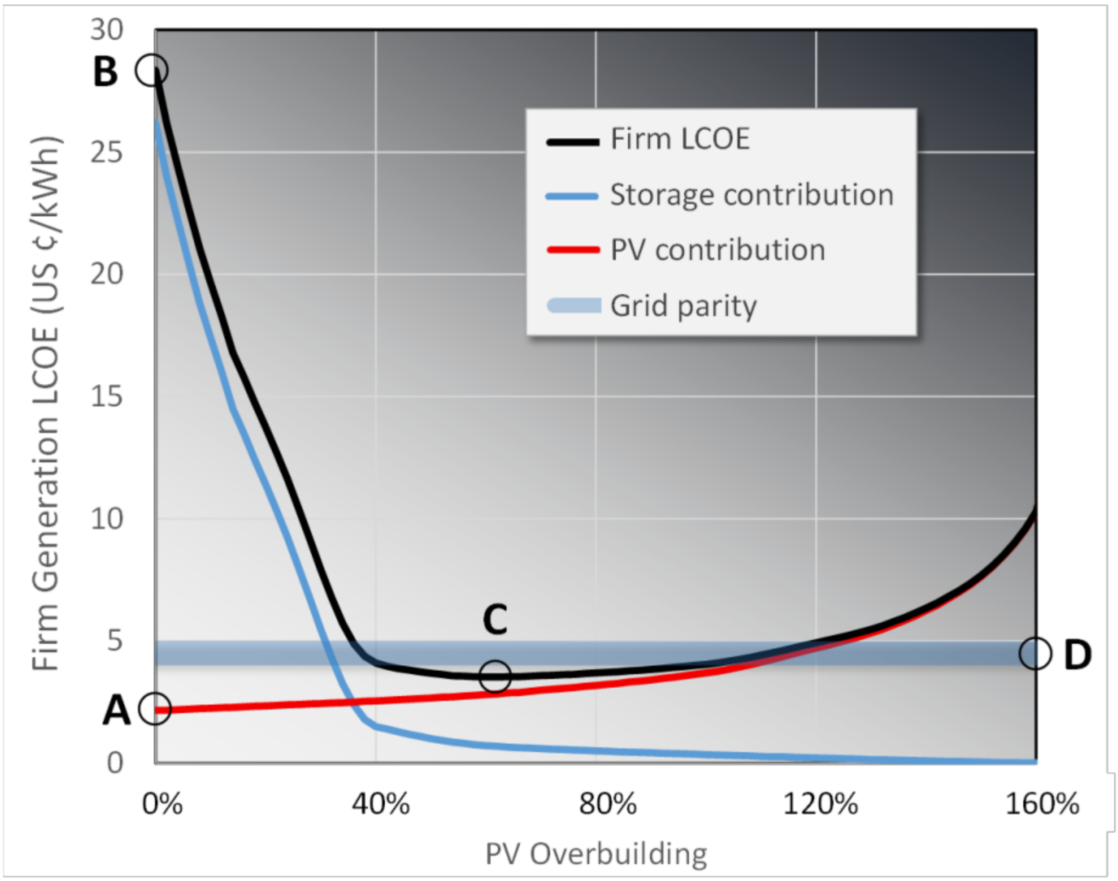

Fig. 2: While unconstrained, intermittent renewable generation costs will achieve very low targets (A) – they are already below grid parity (D) – transforming PV into the firm, effectively dispatchable resource needed by the world economies will be very costly if done with storage alone (B), even when considering the most aggressive future cost projections for storage. Overbuilding renewables can reduce the storage requirements, to the point where "true" below parity firm generation will be attainable (C) – source (Perez, 2019).

These low prospective firm power generation costs let us envision an economically sound transition from business-as-usual fossil-based energy sources, to renewable sources -- even before accounting for external environmental benefits. Importantly, we also argued that, once firmed-up – i.e., rendered effectively dispatchable – intermittent renewable resources become operationally equivalent to conventional dispatchable, baseload, or peaking generation. Overbuilding allows renewables facilities to ramp up and curtailment allows these facilities to ramp down at multiple timescales, as needed by supply and demand conditions. Optimally minimized storage manages the remaining imbalance. Ultra-high penetration deployments could therefore occur without fundamental power grid restructuring.

Finally, we underscored that evolving from the current [intermittent] marginal PV generation paradigm – relying on a core of conventional baseload and dispatchable generation -- to a [firm] grid-dominant paradigm would depend less on technological innovations than on innovative thinking surrounding regulatory/market-structure. In particular, we noted that in order to achieve these aims, remuneration systems would have to

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[1] Higher wind proportion and overbuilding will be assumed for electrified heating loads (see below).

[2] Here natural gas is a stand-in for flexible, dispatchable generation capable of ramping up and down in short order; cleaner alternative like power-to-gas via H_2 electrolysis and hydroelectric power all have the potential to fill this role.

evolve from a marginal mindset, i.e. rewarding production maximization and treating curtailment as a loss (e.g., today's PPAs as outlined in Mendocino, 2019) to rewarding firm production (i.e., embracing curtailment as the catalyst to least-cost firm power generation).

3. Demand Requirements: How Much PV Generation?

We assume 25% for PV conversion efficiency—reflective of commercial-grade crystalline modules and used in the literature (Cousins, 2010). For array geometry, we nominally consider fixed arrays tilted southward at 10º for increased packing factor. This leads to a peak power density of 200 W per square meter of ground area under standard test conditions. PV fleets are sized according to these assumptions to meet the identified present and future energy demands in each state subject to 50% capacity overbuilding. For each identified fleet, hourly PV production is simulated from high-resolution hourly-interval SolarAnywhere® irradiance and meteorological data spanning 22 years (1998-2019).

The present and future demands fall under three scenarios: (1) Supplying the existing electric sector only (2) Supplying the existing electric and transportation sectors – assuming a complete transformation of the latter to electric, with the exception of air and maritime transport. (3) Supplying the existing electric, electrified transportation, and building sectors (residential/commercial) – with the assumption that the current non-electric building sector HVAC loads (i.e., chiefly heating) would be electrified (Waite, 2020).

2.1 Electric Sector

We first tabulate the existing electrical consumption for each state in the CONUS. This ranges from 6 TWh/yr in Vermont, to 425 TWh/yr in Texas. For each state, we also calculate the capacity factor (kWh_{AC} / kW_{DC}) for PV fleets based on resource availability and the other assumptions outlined above. These capacity factors range from 15.8% in Washington State to 23.6% in Arizona. We then infer the power capacity of PV fleets (including overbuilding) necessary to meet 55% of the loads in each state. Capacities range from 3 GW in Vermont to 193 GW in Texas wile the required PV capacity to serve 55% of the CONUS would amount to 1,958 GW.

2.2 Transportation Sector

The US transportation sector consumes 28% of the country's total primary energy. In 2019, this fraction amounted to 8,400 TWh. The terrestrial transport sectors that we assume could reasonably be electrified amount to 82% of this total, or 6,900 TWh (Waite, 2020). Electrifying transport will yield significant efficiency increases. We assume internal combustion engine (ICE) fleets average 25% efficiency will be replaced with electric fleets averaging 80% efficiency (Helms, 2010). The electrified transport demand would amount to 1,980 TWh annually. Allocating this CONUS wide value by state is performed by using miles driven per capita and population. The PV capacity required to meet 55% of the electrified transportation demand ranges from 2 GW in DC to 103 GW in California and totals 1,088 GW across the CONUS.

2.3 Residential & Commercial Building Sector

The CONUS currently uses 3,173 TWh/year of primary heat energy across the residential (1,862 TWh) and commercial (1,311 TWh) building sectors. Electrification will save 2/3 of this energy given the efficiency of heat-pumps (Tian, 2005)These new electric requirements would thus, respectively amount to 633 and 446 TWh/year for the residential and commercial sectors. We allocate the current total US primary heat energy consumption for each state as a function of (1) their mean heating degree-days (HDDs), and (2) their population. Mean state-specific HDDs range from 292 ºC in Florida to 4,994 ºC in North Dakota. Importantly for heating, we assume that PV capacity is both more overbuilt (200%) and supplies only 28% of the new heating load given seasonal anticorrelation – the balance is met by wind. The PV capacity required to firmly meet the demand ranges from 1.7 GW in DC to 70 GW in New York and totals 572 GW across the CONUS.

4. Where to Deploy

For the most demanding three-sector deployment scenario (electric + transport + buildings), spatial requirements range from 45 km^2 in Vermont to 1,566 km^2 in Texas. To put these numbers in perspective, we also calculate what percentage this surface area represents relative to the size of each individual state. State percentages range from 0.02% in Montana – a large state with low population – to 26% in Washington DC –

a small, almost completely urbanized region. For the entire CONUS, the Electric + transportation + buildings scenario would require 0.25% of total area.

Our approach to contextualize PV deployment considers current USGS ground occupancy categories in each state and assigns reasonable fractions of each category available for PV deployment (the *developable fraction*). The ratio between the surface area available and the surface area required to meet 55% of all load with PV we term '*room to grow*.'

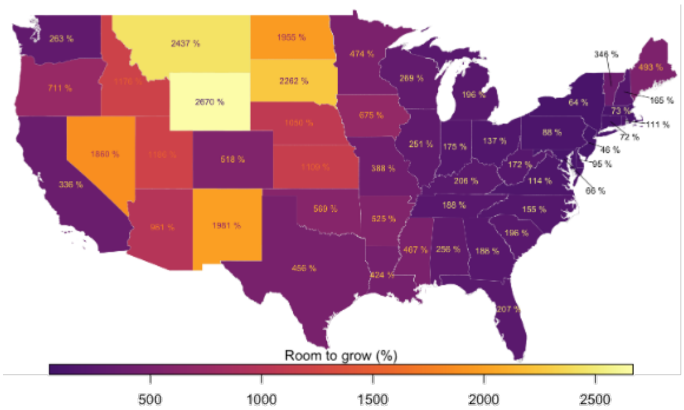

Fig. 3: PV Deployment 'room-to-grow' beyond this article's assumption to firmly meet 55% of electricity, transportation and building sector demand with PV, given the possible deployment ground cover scenario listed in the Table 8 – Note: any state-specific land-cover scenario can be interactively investigated by linking to Perez (2021).

Land-use categorization was obtained from the LandSat-derived, 30-m resolution US National Landcover Database (USGS, 2020). The largest assumed developable fraction is for urban landcover where we assume that 15-25% of roofs, parking lots and exclusion zones can be covered depending on density. We entirely exclude forests or wetlands and at the low end include as deployable, 0.3% of herbaceous land.

Except for DC, all states have considerable room to grow. For the great majority of states, the room to grow is such that a 100% PV future instead of the assumed 55%/40%/5% PV/wind/gas blend is conceivable. The map in Fig. 3 graphically illustrates this 'room to grow' quantity. Because the developable fraction is somewhat qualitative and subject to debate, we developed a web application allowing users to interactively set specifics for any US state and groundcover class and assess how deployment potential would be affected (Perez, 2021).

5. Conclusions

In this article, we present a view of a grid-dominant PV sector capable of providing firm power and displacing conventional generation—in line with global research at the International Energy Agency. Firming up intermittent renewables at reasonable cost implies substantially overbuilding generation capacity and therefore occupying substantially more space than needed on an energy basis. The central question of this paper – where to deploy – thus becomes even more pressing.

Considering demand from the US electric sector as well as electrified transportation and building sectors, we investigate whether an optimally oversized PV resource could reasonably be deployed to meet demand. We assume the same resource breakdown as other recent studies: 55% PV, 40% wind, and 5% dispatchable generation. We examined a deployment approach which starts from global land use data derived from LandSat and some reasonable assumptions regarding which fractions of land class types can be used for PV deployment.

We provided solid evidence that a PV-dominant future supplying the majority of the energy demand from three large sectors of the economy was highly realistic from a deployment standpoint. Firmly and economically supplying 55% of these three sectors could require as little as 0.23% of the country's surface with state-specific fractions ranging 0.03% in low-density sunny states, to 2.3% in most densely-populated northeastern state.

Using these numbers for each state and assumptions regarding the deployable surface for each land-use category, we identified the "room to grow" beyond the assumed 55% supply-side fraction assumed to be met by PV. Indeed, a 100% PV option could be considered in all states within the CONUS from a land-use perspective with the exception of fully-urbanized DC. We complemented this article with an interactive web site – where the deployable surface assumptions could be easily modified on a state-specific basis.

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