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ULTRA-HIGH PHOTOVOLTAIC PENETRATION: WHERE TO DEPLOY

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ABSTRACT

While it is widely known that the solar resource is sufficient to meet the world's energy demand many times over, the questions of where and how much to deploy in a realistic context do not have such clear-cut answers. The objective of this paper is to address and inform these questions in a context where solar (embodied by PV) would be applied locally to firmly meet the bulk of energy demand from regional economies. Sensible answers are important in light of growing societal mandates to displace carbon-based energy resources. We aim to provide comprehensive, realistic and actionable numbers that can effectively inform planning decisions at local and regional levels.

We focus on the continental United States (ConUS) and develop state-specific PV requirements informed by:

- A full accounting of states' energy requirements from the electric sector as well as [to be] electrified transportation and building sectors.
- Positing that the bulk of this demand will be met with an optimized blend of PV and wind with a small residual allowance for natural gas – an optimized blend informed by recent investigations in diverse climatic and socio-economic environments.
- A recognition that electrical demand must be met firmly, hence that intermittent renewables must be transformed into firm, effectively dispatchable resources available 24/365.
- A recognition that the least-cost solution to achieve this transformation implies overbuilding and proactively curtailing these resources.
- Not accounting for likely energy efficiency improvements in any of the three considered demand sectors. Therefore, the numbers developed can be considered to be conservatively high.

From these requirements we explore PV deployment options using two distinct approaches: a top-down approach assigning a fraction of plausible deployment potential to ground occupancy classes as defined by the US geological Survey, and a bottom-up approach starting from end-use applications prospectively amenable to PV deployment without change of function. In addition, we provide readers with an-online interactive capability to modify fractional ground occupancy selections applied in this article and further investigate state-specific potentials.

We conservatively conclude that the three-sector firm energy requirements could realistically be met economically by locally-deployed PV resources with ample room to grow, even in the most densely populated northeastern states. Meeting energy requirements would be reduced further with the inclusion of energy efficiency investments.

1. INTRODUCTION

Could photovoltaics power [almost] 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 massive electrification of the ground transportation and building heating sectors. Our aim is to present solid, actionable numbers that can intelligently inform societies and governments' decision-making processes.

Our analysis builds on the fundamentals of ultra-high renewable penetration by first defining a realistic renewable deployment context with the central requirement of meeting demand 24 hours a day and 365 days per year [1-5]. This fundamental deployment context builds on the premises that:

- Solar (PV) and wind are the only renewable energy (RE) resources large enough to meet the energy demand of world economies [6].
- Because they are both intermittent resources, they must be transformed to meet demand 24/365 without fail -- they must be firmed-up. We and others have demonstrated that the lowest-cost solution to achieve firmness [1 to 5] entails:
  (1) An optimization of [often complementary] wind and solar contributions and,
  (2) Substantial overbuilding and proactive operational curtailment of these resources to reduce long-term energy storage requirements to economically acceptable levels.

Here we retain a configuration that we found to be near optimal in diverse climatic environments, with an optimum RE generation mix amounting to 55% PV and 40% wind, retaining a 5% legacy natural gas contribution [2]. This optimal solution entails overbuilding of PV and wind capacity by 50%[1] -- hence proactively curtailing one third of their combined output.

We focus herein on the solar PV part of this ultra-high RE penetration mix. We have previously addressed the cost optimization question in much detail through several publications [1-5]. Here we center on the 'where' question, making only contextual economic references.

We first evaluate state-specific demand-side energy requirements before identifying PV deployment options to meet these requirements. We consider and contrast two approaches to evaluate deployment options: (1) from a land-cover distribution standpoint, and (2) from an end-use energy sector standpoint.

Originality of this work: We believe that the comprehensive approach of contrasting state-specific [firm energy] requirements and deployment options in a single comprehensive and actionable document, while essentially straightforward, is unique. Of course, detailed blueprints of solar potentiality at local scales do exist [7-11], roof deployment space has been documented in depth in several localities [e.g., 9], but this is the first continent-wide approach examining all sensible deployment options and looking at major supply-side solutions for society's new electrification requirements.

A central piece of the originality of this work resides in a clear definition of multi-sector electricity requirements, and applying demonstrated optimal solutions to meet these requirements firmly and economically around the clock and at the lowest possible cost. These solutions are based on the identification of the system capacities of wind, solar and storage that could most economically meet hourly demand firmly. These capacities are influenced by geographic location; by the temporal shape of load shifting with heating and cooling needs and by the temporal shape of supply shifting with latitude, season and topography. Where the optimum lies in terms of capacity build-outs further depends on the technological costs of system components; storage, wind and solar.

In this article, we extrapolate from results produced in diverse climatic environments applying the *Clean Power Transformation* (CPT) model [1, 3, 12-14] together with high-resolution time/site specific solar and wind resources [15] as well as demand data. The CPT model includes ultra-rapid non-brute-force Nelder-Mead optimization [16] facilitating sensitivity analyses on system component cost and technical parameters. The model is fully consistent with other recently developed analytical tools such as the Renewable Electricity Economic Optimization Model (RREEOM) described by Budischak et. al. [17] that optimized wind, PV and storage capacities to meet hourly loads in the PJM service territory. It is methodically consistent with earlier models that had been developed for remote/islanded systems optimization such as the HOMER [18] micropower model – that recently prompted the development of

[1] As will be explained below, optimum Wind/PV blend will be different and PV overbuilding for meeting the new electrified building heating loads will be set higher.

NREL's Regional Energy Deployment System (REEDS) model [19]. Its results are also consistent with simpler models applying representative days such as the Wind Water and Solar (WWS) model from Delucci and Jacobson [20] and E3's PATHWAYS [21] that are both scenario-based models that analyze the costs resulting from meeting load with defined technology portfolios and selects the one that yields the lowest cost.

Therefore, we believe that, because our approach is both comprehensive and applies state-of-the art optimized firm power generation analytics, the numbers we present constitute unique and actionable planning information for each ConUS state.

Structure of this paper: The next section summarizes our previous findings on firm PV power generation and substantiates the present PV oversizing assumptions. Section 3 defines assumptions, methods and data applied to quantify supply-side PV generation and demand-side electrical requirements for the considered (55%) fraction of three demand sectors: electricity, transportation and buildings. Section 4 dives in the central theme of this paper – where to deploy – approaching the issue from both a land-cover and an end-use sector standpoint. The concluding discussion section provides a synthesis of all results and contextualizes them from a socio-economic decision-making perspective.

2. FIRM POWER GENERATION REQUIREMENTS – THE INTERMITTENCY CHALLENGE & THE OVERBUILDING SOLUTION

In terms of magnitude, the solar resource is certainly large enough to meet the world's energy demand many times over [6], even if one considers the electrification of major energy sectors such as transportation and buildings. However, a key difficulty lies in the resource's inherent intermittency across multiple timescales, driven by stochastic meteorological processes, as well as deterministic daily and seasonal cycles. If solar photovoltaic (PV) generation is to become grid-dominant and supply electrified world economies, this intermittency issue must be addressed and resolved.

Intra-day vs. multi-day intermittency: Intraday intermittency mitigation addresses issues such as ramp rate reduction and peak supply/demand flattening [22, 23]. Energy storage (e.g., electrochemical batteries) is largely viewed as a cost-effective solution to address this short-timescale issue [24, 25]. A considerably larger challenge lies in overcoming multi-day and seasonal intermittencies, notably prolonged cloudy periods during low-yield seasons. Relying on storage alone to ensure firm power production 24/365 would be overwhelmingly expensive [2, 3, 5] – see Figure 1.

Overbuild/curtail *implicit storage* solution: In a recent series of articles, addressing cases studies in the central United States, Italy, and subtropical islands [2,4,26] we showed that overcoming PV intermittency and firmly meeting utility demand 24 hours per day and 365 days per year was economically possible well before 2050. Firm PV electricity production cost targets of the order of 5¢/kWh or less were found to be achievable on a straight financial basis[2] without recourse to technological breakthroughs. However, we also showed that these low production cost targets were contingent on one fundamental strategy: *PV resource overbuilding and proactive output curtailment*. This counter-intuitive strategy also referred to as *implicit storage* strategy [5], is key to sufficiently reducing otherwise insurmountably costly long-term energy storage requirements.

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

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

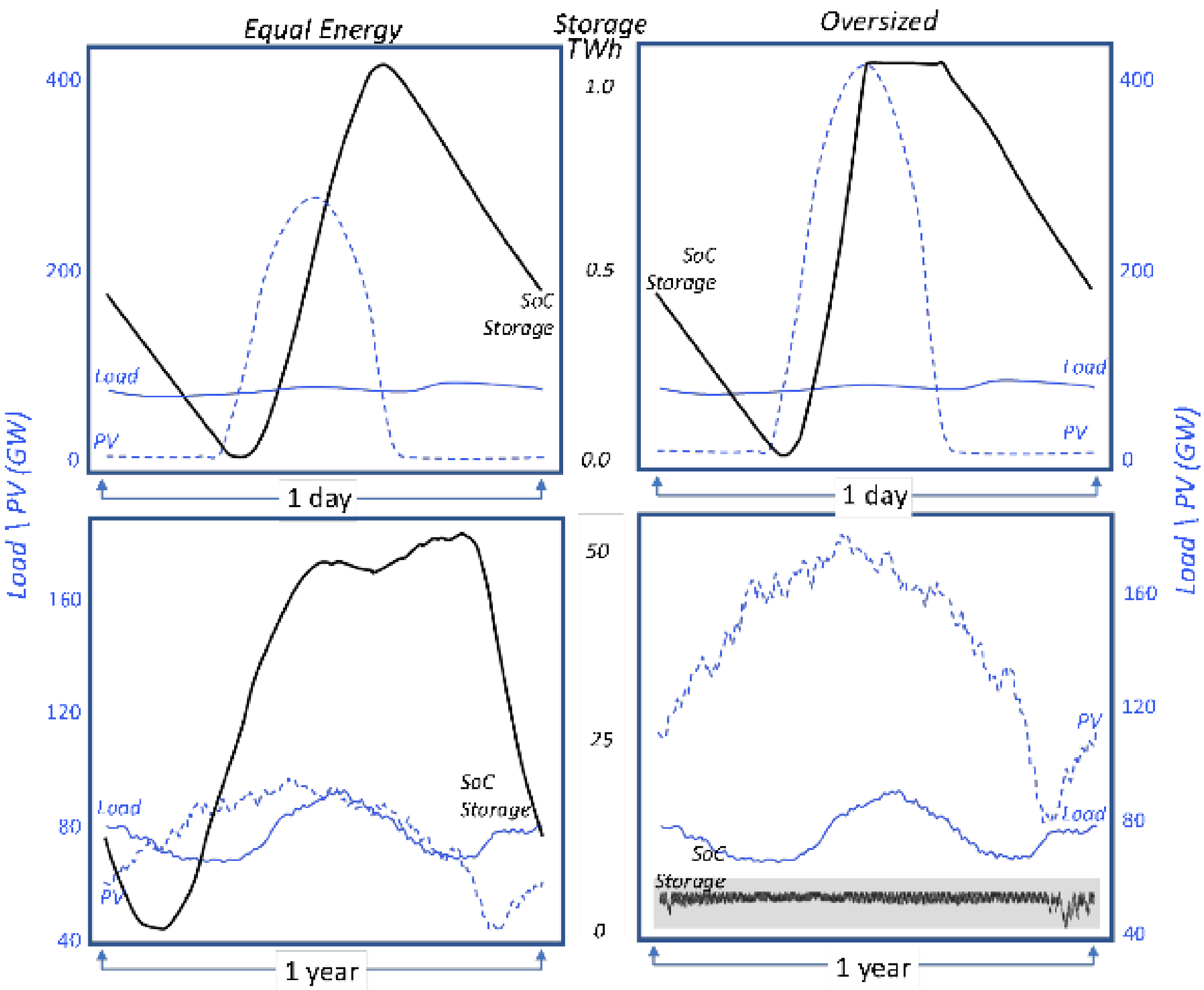

Fig. 1: Contrasting intraday intermittency (top) and multiday intermittency (bottom) and illustrating the impact of oversizing where PV is sized to meet load requirements on an energy basis (left) and PV is 2X oversized (right).

- **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.**

Figure 2 (from [1]) 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[3] given future expected costs for PV and energy storage [2,4,26], even considering the most optimistic ‘ultra-low-cost’ storage cost projections [27].

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

Further, we showed that optimally combining solar and wind resources, and allowing for some supply-side flexibility with a residual natural gas[4] fraction (<5%) could drive projected firm power generation costs well below current conventional generation costs [2].

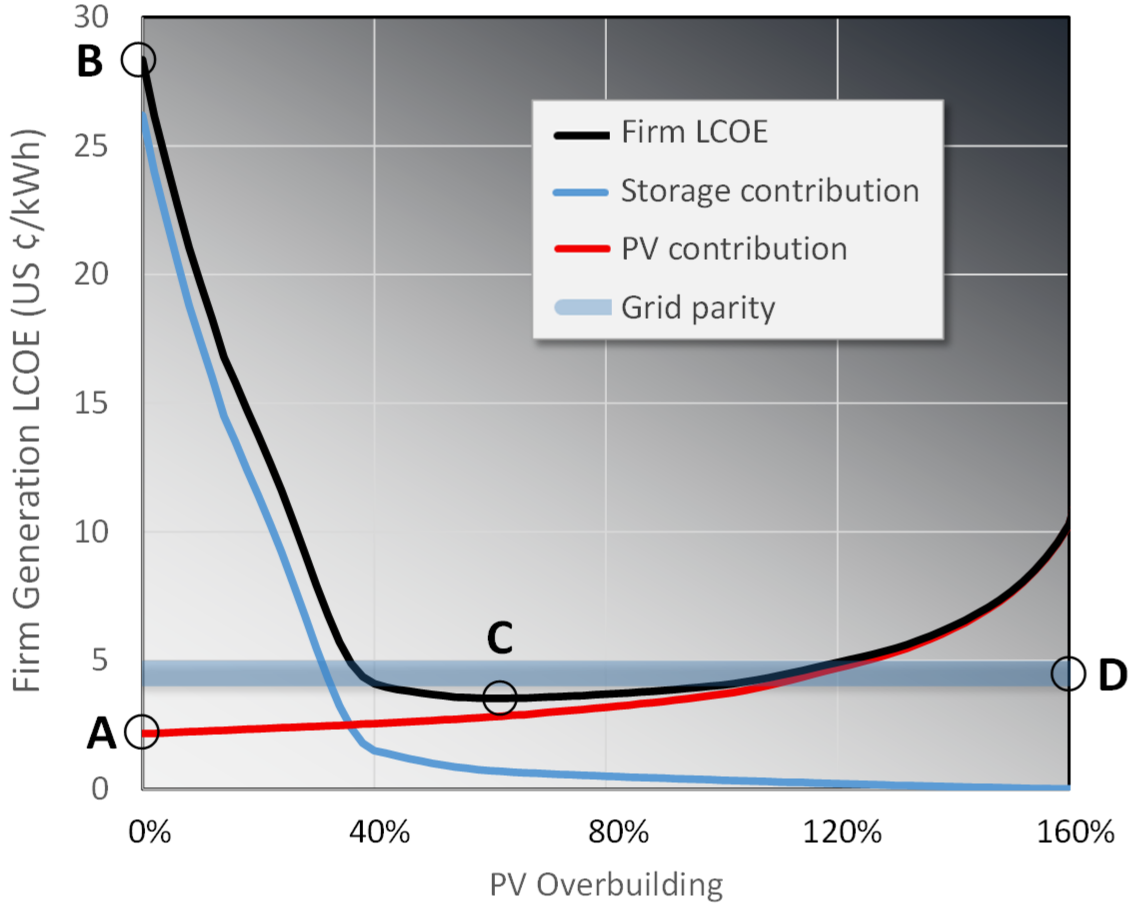

Fig. 2: While unconstrained, intermittent renewable generation costs will achieve very low targets (A) – they are already below grid parity (D) – transforming PV into the firm, effectively dispatchable resource needed by the world economies will be very costly if done with storage alone (B), even when 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 [1].

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

[4] 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.

regulatory/market-structure. In particular, we noted that in order to achieve these aims, remuneration systems would have to evolve from a marginal mindset, i.e. rewarding production maximization and treating curtailment as a loss (e.g., today's PPAs [28]) to rewarding firm production (i.e., embracing curtailment as the catalyst to least-cost firm power generation).

3. HOW MUCH PV GENERATION?

3.1 Energy Supply Side

On the PV supply-side, we will assume that ***50% oversizing***[5] of PV generation assets -- hence, 33% pro-active curtailment -- is optimal to achieve least-cost firm power generation. We have observed that this assumption was reasonable to deliver near least-cost firm power generation over a wide range of climatic/load conditions given projected PV and energy storage costs [2,4,26]. Figure 3 illustrates least-cost overbuild/curtailment results from recent studies in the central US, Italy and the Indian Ocean (La Reunion). These results show that the 50% overbuilding assumption applied in this article is conservative.

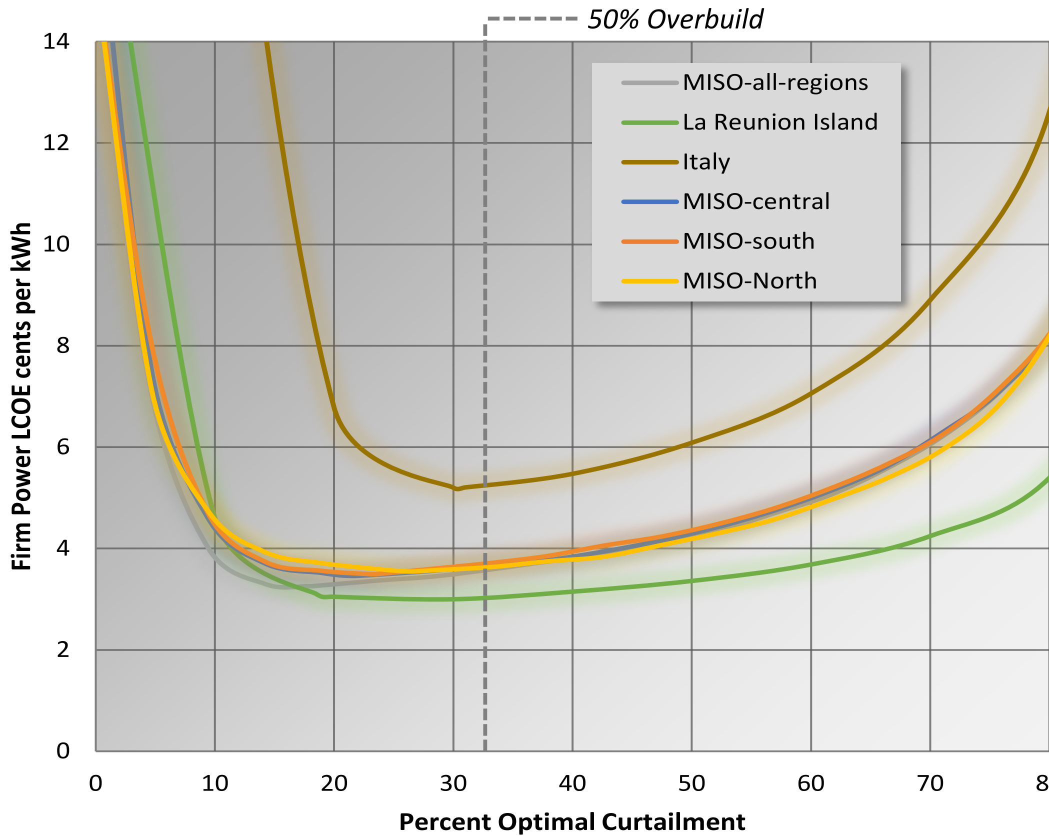

Fig. 3: Comparing least-cost firm power generation operational curtailment in the central US – Midcontinent Independent System Operator (MISO), spanning from the Gulf of Mexico to Canada – Italy, and the Island of La Réunion in the Indian Ocean. The dotted vertical line marks the 50% overbuilding assumptions (33% curtailment) conservatively used in this article.

We further assume that the least-cost ultra-high renewable penetration technology blend derived for the Minnesota Solar Pathways study [2] can be conservatively applied to all ConUS regions. This optimal blend

[5] Except for electrified building loads (see Section 3.2.3)

consists of 55% PV and 40% wind with an allowance for 5% [residual] natural gas generation. We note that this optimum blend does not differ much from the one we observed in Italy [4].

These across-the-board assumptions gloss over key factors that can influence optimum resource blend and oversizing. Chief among these factors are the relative capital and operational costs of PV, wind and storage. Other factors include the wind and solar resources' relative magnitude and annual distribution – specifically as they are able to match load – and the potential for other renewable resources like hydropower to play important roles locally as shown in Italy [4]. However, the comprehensive set of results presented in this paper could be adjusted locally to account for site-specific optimum blend/oversize solutions without fundamentally altering the overall results of this paper.

PV Technology & array configuration: We retain the high-efficiency and high-density deployment assumptions used in our recent study of PV deployment on reservoirs [29].

For conversion efficiency, we assume that the highest achieved module efficiency of nearly 25% for commercial grade crystalline modules [30] conservatively represents the mainstream efficiencies of the future. This assumption is reasonable for the medium to long-term deployment planning implied in this paper.

For array geometry, we nominally consider fixed arrays tilted southward at 10^o, although this may not strictly apply to all the considered deployment options.[6] While this nearly horizontal geometry is not optimal from an overall energy production standpoint per unit of collector area, it is nearly ideal from a ground energy density standpoint. Allowing for 20% spacing for maintenance and [minimal] row-shading considerations, the footprint conversion efficiency of the considered arrays thus reaches roughly 20% (i.e., 25% minus the non-PV areas). This amounts to a peak power density of 200 W per square meter of ground area[7] under standard test conditions.

Geographic dispersion

It is well understood that geographic solar (or wind) resource dispersion reduces variability [31-32]. This reduction in variability lessens the balancing costs required to mitigate its impacts, hence the costs of overbuild and storage incurred in supplying firm power generation.

Reinforcing the power grid is the key to unlocking geographic intermittency reduction by facilitating regional transport of variable electricity.

Here, we consider only limited geographic dispersion, contained within each state, assuming homogeneous PV deployment distribution. We have documented that this level of in-state geographic dispersion implied only minimal in-state Transmission and Distribution (T&D) upgrades entailing costs considerably lower (orders of magnitude) than the storage/implicit-storage intermittency mitigation costs [2]. One of the reasons for the observed limited T&D impacts is that power generation from locally aggregated and firmed-up PV plants can be considered at first approximation to be equivalent to the existing [in-state dispersed] conventional [firm] power plants that PV would replace.

Location-specific PV production

For each distributed PV fleet within each state, we simulated hourly PV production from high-resolution hourly SolarAnywhere® irradiance and meteorological data spanning 22 years (1998-2019) [9, 33].

[6] Note that for some of the deployment options considered below, such as vehicle-integrated PV (VIPV) the 10^o south-facing configuration would not be applicable. However this nearly horizontal geometry let us evaluate the potential of any horizontal footprint regardless of the actual systems/subsystems orientation/tilt.
[7] We acknowledge that there are interesting large-scale PV deployment solutions where PV space could be shared with other activities, in particular in the agriculture sector (e.g., under-PV cattle grazing [re]). While in such cases, the energy producing density would be less it would only be a reflection that the considered spaces would serve two or more purposes requiring solar energy input, the pure-PV energy producing density would remain as high as assumed in this article.

3.2 Energy Demand Side

On the demand side, we consider the three following 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 [34, 35, 36].

We emphasize that the purpose of this article is not to present/validate technical solutions for the electrification of the transportation and building sectors, but to estimate, provided such technical solutions will be implemented, whether PV could reasonably supply the majority of the existing and new demands (55% thereof under this article's assumption).

3.2.1. Electric Sector

Table 1 reports the current (2018) annual electric consumption of each ConUS State [37]. This ranges from 6 TWh/year in Vermont, to 425 TWh/yr in Texas. The table also reports the statewide mean annual capacity factors of the PV fleets that would operate in each state – recall that the capacity factor is the ratio of mean (AC kWh) to rated (DC kW) fleet output. These capacity factors range from 15.8% in Washington State to 23.6% in Arizona. Finally, the table reports the GW size of the 50%-oversized PV fleets that would be necessary to firmly meet the assumed 55% share of electric demand in each State. These PV requirements range from 3 GW in Vermont to 193 GW in Texas. For the ConUS, the required PV capacity would amount to 1,958 GW.

TABLE 1: PV Capacity requirement to firmly meet 55% of the ConUS electrical energy demand. Columns represent respectively state-specific electrical demand, PV capacity factors and PV capacity requirements.

State	Annual Electric Load (TWh/yr)	PV Capacity Factor	Required PV Capacity (GW)	State	Annual Electric Load (TWh/yr)	PV Capacity Factor	Required PV Capacity (GW)
Alabama	90	19.3%	44	Nebraska	31	19.0%	15
Arizona	78	23.6%	31	Nevada	38	22.1%	16
Arkansas	50	18.6%	25	New Hampshire	11	16.5%	6
California	255	22.0%	109	New Jersey	76	17.0%	42
Colorado	56	21.8%	24	New Mexico	24	23.5%	10
Connecticut	29	17.0%	16	New York	150	16.4%	86
DC	11	17.6%	6	North Carolina	138	19.0%	68
Delaware	12	17.4%	6	North Dakota	21	16.9%	12
Florida	239	20.1%	112	Ohio	153	16.4%	88
Georgia	140	19.9%	66	Oklahoma	65	20.2%	30
Idaho	24	18.8%	12	Oregon	49	18.3%	25
Illinois	143	17.1%	79	Pennsylvania	149	16.3%	86
Indiana	104	16.6%	59	Rhode Island	8	16.9%	4
Iowa	51	17.1%	28	South Carolina	82	19.7%	39
Kansas	42	19.9%	20	South Dakota	13	18.4%	7
Kentucky	77	17.6%	41	Tennessee	103	18.4%	53

Louisiana	94	18.6%	48	Texas	425	20.7%	193
Maine	12	15.9%	7	Utah	31	21.7%	14
Maryland	62	17.3%	34	Vermont	6	16.2%	3
Massachusetts	53	16.9%	30	Virginia	118	18.0%	62
Michigan	105	15.8%	63	Washington	90	15.8%	54
Minnesota	69	16.1%	40	West Virginia	34	16.9%	19
Mississippi	50	18.9%	25	Wisconsin	71	16.0%	42
Missouri	82	18.0%	43	Wyoming	17	20.2%	8
Montana	15	17.3%	8	**CONUS**	**3845**	**18.4%**	**1958**

3.2.2. Transportation Sector

The US transportation sector consumes 28% of the country's total primary energy. In 2019, this fraction amounted to 8,400 TWh worth of primary energy [38]. Of this, the terrestrial transport sectors that we assume could reasonably be electrified amounts to 82%, or 6,900 TWh [36]. If we assume that electrification entails replacing internal combustion engine (ICE) fleets averaging 25% efficiency with electric fleets averaging 80% efficiency all-around [39, 40, 41], the electrical energy requirements would amount to 1,980 TWh annually. State-specific fractions are estimated from miles driven per capita [42] and population [43].

Table 2 reports each State's population, miles driven per capita, and their resulting fraction of the considered 6,900 TWh US primary energy consumption. This fraction ranges from 0.1% in the District of Columbia to 11.1% in California. The table also reports the resulting PV capacity required to firmly meet 55% of this new electric demand, estimated as above from state-specific demand and PV capacity factors. These PV capacities range from 2 GW in DC to 103 GW in California and total 1,088 GW for the ConUS.

TABLE 2: PV Capacity requirement to firmly meet 55% of terrestrial electrified transportation energy demand. Columns represent respectively state population, miles driven per capita, state fraction of US transportation sector primary energy demand and state-specific PV capacity requirements.

State	Population (million)	Annual Miles driven per Capita (thousands)	Fraction of Transportation Energy Consumption	Required PV Capacity (GW)	State	Population (million)	Miles driven per Capita	Fraction of Transportation Energy Consumption	Required PV Capacity (GW)
Alabama	4.89	12.7	1.9%	20	Nebraska	1.93	10.6	0.6%	7
Arizona	7.28	9.7	2.2%	19	Nevada	3.03	8.8	0.8%	8
Arkansas	3.01	10.9	1.0%	11	N. Hampshire	1.36	9.7	0.4%	5
California	39.51	9.1	11.1%	103	New Jersey	8.88	8.0	2.2%	26
Colorado	5.70	9.7	1.7%	16	New Mexico	2.10	12.5	0.8%	7
Connecticut	3.57	9.0	1.0%	12	New York	19.45	6.8	4.1%	51
DC	0.70	6.1	0.1%	2	N. Carolina	10.49	11.1	3.6%	39
Delaware	0.97	10.5	0.3%	4	N. Dakota	0.76	11.2	0.3%	3
Florida	21.48	9.5	6.4%	64	Ohio	11.69	9.3	3.4%	42
Georgia	10.62	12.8	4.2%	43	Oklahoma	3.94	12.6	1.5%	15
Idaho	1.75	10.5	0.6%	6	Oregon	4.19	10.2	1.3%	15
Illinois	12.67	8.3	3.3%	39	Pennsylvania	12.80	8.3	3.3%	41
Indiana	6.69	11.7	2.4%	30	Rhode Island	1.06	8.0	0.3%	3

Iowa	3.16	10.1	1.0%	12	S. Carolina	5.08	11.4	1.8%	19
Kansas	2.91	10.5	0.9%	10	S. Dakota	0.88	11.2	0.3%	3
Kentucky	4.47	11.6	1.6%	19	Tennessee	6.77	11.6	2.4%	27
Louisiana	4.66	9.1	1.3%	14	Texas	29.21	10.6	9.6%	94
Maine	1.34	11.1	0.5%	6	Utah	3.21	10.1	1.0%	9
Maryland	6.04	9.5	1.8%	21	Vermont	0.63	11.2	0.2%	3
Mass.	6.90	8.3	1.8%	21	Virginia	8.54	10.6	2.8%	32
Michigan	9.99	9.8	3.1%	39	Washington	7.61	9.0	2.1%	28
Minnesota	5.61	10.7	1.9%	24	W. Virginia	1.81	10.6	0.6%	7
Mississippi	2.99	12.5	1.2%	12	Wisconsin	5.81	10.7	1.9%	25
Missouri	6.13	12.0	2.3%	26	Wyoming	0.58	16.4	0.3%	3
Montana	1.06	11.0	0.4%	4	**CONUS**	**326**	**9.8**	**100.0%**	**1088**

3.2.3. Residential & Commercial Building Sector:

Table 3 reports the quantity of primary energy used either directly – via combustion – or indirectly – via electricity – by the residential and commercial building sectors [44]. However, note that the end-use indirect (electric) part of energy actually consumed amounts to roughly one third of primary energy input: a result of conventional electric power generation's conversion efficiency.

TABLE 3: Residential and commercial US energy consumption

TWh / year	Residential	Commercial
Direct consumption of primary energy	1862	1311
Indirect consumption of primary energy	4159	3996

We make the approximation that the building sector's indirect use of primary energy is accounted for by the electric sector's requirements (see above), and that the direct use of primary energy consists essentially of [fossil fuel] heat requirements. Considering the prevailing efficiency of conventional heating systems and the coefficient of performance of the electric-based sources[8] that would likely replace them [e.g., heat pumps], we can reasonably assume that the required amount of electrical energy would amount to about one-third of the current primary energy consumption [45, 46, 47, 48]. These new electric requirements would thus respectively amount to 633 and 446 TWh/year for the residential and commercial sectors.

We apportion the current total US direct primary energy (i.e., heat) consumption for each state as a function of (1) their mean heating degree-days (HDDs), and (2) their population. Mean state-specific HDDs are reported in Table 4. These range from 292 ºC in Florida to 4,994 ºC in North Dakota. Resulting primary energy fractions of total US consumption, also reported in Table 4, range from 0.2% in the District of Columbia to 8.4% in New York.

Higher PV oversizing and larger proportion of wind: The 50% optimum oversizing assumption discussed above has been well documented for the electric sector demand as explained above. This oversizing assumption is arguably valid for transportation electrification since the new demand will not appreciably change seasonal load shapes. However it does not hold for heating electrification where the new electrical

[8] We considered an efficiency of 85% for the existing fleet of fossil-fuel heating systems and a conservative across the board 2.5 coefficient of performance (COP) for the heat pump systems (i.e., valid for ~ -9ºC daily temperatures and above [ii])

loads would be winter-peaking (i.e., in opposition of seasonal phase with the solar resource). The Minnesota Solar Pathway firm study [49] addressed this issue in detail. Considering the new electrified heating load alone, the least-cost optimum solar/wind blend was found to be 28%/67%, retaining the above 5% natural gas flexibility proportion. In addition, the optimum amount of oversizing for both renewable resources was found to be considerably higher, reaching about 200%.

The 200%-oversized installed PV capacity required to firmly meet 28% of the new building demand totals 572 GW across the ConUS. Individual states required PV capacities range from 1.7 GW in DC to 70 GW in New York.

TABLE 4: PV Capacity requirement to firmly meet 55% of commercial and residential building sectors heating demand. Columns represent respectively mean state heating degree-days, share of building sector primary fuel consumption and state-specific PV capacity requirements.

State	Mean Heating Degree Days (°C)	Share of Primary Fuel Consumption	Required PV Capacity (GW)	State	Mean Heating Degree Days (°C)	Share of Primary Fuel Consumption	Required PV Capacity (GW)
Alabama	1,450	1.0%	6.7	Nebraska	3,521	0.9%	6.5
Arizona	1,022	1.0%	5.8	Nevada	1,835	0.8%	4.6
Arkansas	1,863	0.8%	5.5	New Hampshire	4,021	0.7%	6.1
California	1,269	6.8%	41.6	New Jersey	2,799	3.4%	26.7
Colorado	3,963	3.0%	18.9	New Mexico	2,548	0.7%	4.2
Connecticut	3,096	1.5%	11.9	New York	3,210	8.4%	69.5
DC	2,389	0.2%	1.7	North Carolina	1,810	2.6%	18.2
Delaware	2,363	0.3%	2.4	North Dakota	4,994	0.5%	4.1
Florida	292	0.8%	5.7	Ohio	3,149	5.0%	41.0
Georgia	1,431	2.0%	13.9	Oklahoma	2,000	1.1%	7.1
Idaho	3,668	0.9%	6.2	Oregon	2,683	1.5%	11.2
Illinois	3,411	5.8%	46.2	Pennsylvania	3,115	5.4%	44.6
Indiana	3,122	2.8%	22.9	Rhode Island	3,042	0.4%	3.5
Iowa	3,813	1.6%	12.9	South Carolina	1,435	1.0%	6.8
Kansas	2,747	1.1%	7.4	South Dakota	4,239	0.5%	3.7
Kentucky	2,399	1.4%	11.1	Tennessee	2,083	1.9%	14.0
Louisiana	866	0.5%	4.0	Texas	1,010	4.0%	26.0
Maine	4,351	0.8%	6.7	Utah	3,387	1.5%	9.2
Maryland	2,458	2.0%	15.7	Vermont	4,437	0.4%	3.1
Massachusetts	3,350	3.1%	25.0	Virginia	2,337	2.7%	20.2
Michigan	3,719	5.0%	43.0	Washington	2,895	3.0%	25.6
Minnesota	4,608	3.5%	29.4	West Virginia	2,775	0.7%	5.4
Mississippi	1,314	0.5%	3.8	Wisconsin	4,178	3.3%	27.8
Missouri	2,804	2.3%	17.4	Wyoming	4,483	0.3%	2.3
Montana	4,405	0.6%	4.9	**CONUS**	**2,276**	**100%**	**762**

Table 5 summarizes installed PV requirements for the three considered deployment scenarios: (1) electricity only; (2) electricity and land-based transportation; and (3) electricity, land-based transportation, residential and commercial buildings.

TABLE 5: PV Capacity required for the three firm power generation deployment scenarios: electric only, electric and transportation, and electric, transportation and buildings.

State	Required PV GW			State	Required PV GW		
	Electric only	Electric + Transportation	Electric + Transportation + buildings		Electric only	Electric + Transportation	Electric + Transportation + buildings
Alabama	44	64	71	Nebraska	15	22	29
Arizona	31	50	56	Nevada	16	24	28
Arkansas	25	36	42	New Hampshire	6	11	17
California	109	212	253	New Jersey	42	68	95
Colorado	24	40	59	New Mexico	10	17	21
Connecticut	16	28	40	New York	86	137	207
DC	6	8	9	North Carolina	68	107	125
Delaware	6	10	12	North Dakota	12	15	19
Florida	112	176	182	Ohio	88	130	171
Georgia	66	109	123	Oklahoma	30	46	53
Idaho	12	18	24	Oregon	25	40	51
Illinois	79	118	164	Pennsylvania	86	127	172
Indiana	59	89	112	Rhode Island	4	7	11
Iowa	28	40	53	South Carolina	39	58	64
Kansas	20	30	37	South Dakota	7	10	14
Kentucky	41	60	71	Tennessee	53	79	93
Louisiana	48	62	66	Texas	193	287	313
Maine	7	13	20	Utah	14	23	32
Maryland	34	55	70	Vermont	3	6	9
Massachusetts	30	51	76	Virginia	62	93	114
Michigan	63	102	145	Washington	54	81	107
Minnesota	40	64	93	West Virginia	19	26	31
Mississippi	25	38	41	Wisconsin	42	66	94
Missouri	43	69	86	Wyoming	8	11	13
Montana	8	12	17	**CONUS**	**1958**	**3046**	**3808**

Energy efficiency and demand evolution: We do not make any assumptions regarding energy efficiency improvements in any of the three considered demand sectors. Therefore, the supply-side numbers developed above can be considered to be conservatively high since efficiency improvements and limits on demand growth are likely to lead to measurable demand-side reductions [50].

4. WHERE TO DEPLOY

4.1 Overall Space Requirements

The PV deployment space requirements presented in Table 6 are calculated from the assumed PV ground power density, state-specific PV capacity factors (Table 1) and required PV capacities presented in Table 5. For the most demanding three-sector deployment scenario spatial requirements range from 45 km^2 in Vermont to 1,566 km^2 in Texas. To put these numbers in perspective, Table 7 reports the corresponding fractions of state surface area. State percentages range from 0.02% in Montana – a large states 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.

TABLE 6: State-specific area required by PV for the three firm power generation deployment scenarios: electric only, electric and transportation, and electric, transportation and buildings.

State	Required PV area (sq.km)			State	Required PV area (sq.km)		
	Electric only	Electric + Transport.	Electric + Transport. + buildings		Electric only	Electric + Transport.	Electric + Transport. + buildings
Alabama	220	322	355	Nebraska	76	110	143
Arizona	156	251	280	Nevada	80	119	142
Arkansas	126	182	209	New Hampshire	32	57	87
California	546	1059	1267	New Jersey	210	342	476
Colorado	122	202	297	New Mexico	48	83	104
Connecticut	80	140	200	New York	430	685	1033
DC	30	38	47	North Carolina	342	535	626
Delaware	32	50	62	North Dakota	58	73	94
Florida	559	880	908	Ohio	439	649	854
Georgia	331	547	616	Oklahoma	151	228	264
Idaho	59	90	121	Oregon	127	201	257
Illinois	394	588	819	Pennsylvania	429	636	859
Indiana	295	443	558	Rhode Island	21	37	54
Iowa	141	200	264	South Carolina	196	288	322
Kansas	100	148	185	South Dakota	33	50	69
Kentucky	205	298	354	Tennessee	263	397	467
Louisiana	238	311	330	Texas	965	1435	1566
Maine	37	66	100	Utah	68	115	161
Maryland	169	274	352	Vermont	16	30	45
Massachusetts	149	256	381	Virginia	309	467	569
Michigan	313	510	725	Washington	269	407	535
Minnesota	201	319	466	West Virginia	94	130	157
Mississippi	126	188	207	Wisconsin	209	332	470
Missouri	214	343	430	Wyoming	39	54	66
Montana	40	62	86	**CONUS**	**9789**	**15228**	**19039**

TABLE 7: Fraction of state area required by PV for the three firm power generation deployment scenarios: electric only, electric and transportation, and electric, transportation and buildings.

State	Required % state area			State	Required % state area		
	Electric only	Electric + Transport.	Electric + Transport. + buildings		Electric only	Electric + Transport.	Electric + Transport. + buildings
Alabama	0.17%	0.24%	0.27%	Nebraska	0.04%	0.05%	0.07%
Arizona	0.05%	0.08%	0.09%	Nevada	0.03%	0.04%	0.05%
Arkansas	0.09%	0.13%	0.15%	New Hampshire	0.13%	0.24%	0.37%
California	0.13%	0.26%	0.31%	New Jersey	1.08%	1.76%	2.45%
Colorado	0.04%	0.07%	0.11%	New Mexico	0.02%	0.03%	0.03%
Connecticut	0.63%	1.10%	1.57%	New York	0.35%	0.55%	0.83%
DC	16.97%	21.27%	26.13%	North Carolina	0.27%	0.42%	0.49%
Delaware	0.62%	0.98%	1.22%	North Dakota	0.03%	0.04%	0.05%
Florida	0.39%	0.62%	0.64%	Ohio	0.41%	0.60%	0.80%
Georgia	0.22%	0.36%	0.41%	Oklahoma	0.08%	0.13%	0.15%
Idaho	0.03%	0.04%	0.06%	Oregon	0.05%	0.08%	0.10%
Illinois	0.27%	0.40%	0.56%	Pennsylvania	0.37%	0.54%	0.73%
Indiana	0.31%	0.47%	0.59%	Rhode Island	0.78%	1.36%	2.00%
Iowa	0.10%	0.14%	0.18%	South Carolina	0.25%	0.37%	0.41%
Kansas	0.05%	0.07%	0.09%	South Dakota	0.02%	0.03%	0.03%
Kentucky	0.20%	0.29%	0.34%	Tennessee	0.24%	0.37%	0.43%
Louisiana	0.21%	0.27%	0.29%	Texas	0.14%	0.21%	0.23%
Maine	0.05%	0.08%	0.12%	Utah	0.03%	0.05%	0.07%
Maryland	0.66%	1.07%	1.37%	Vermont	0.07%	0.12%	0.19%
Massachusetts	0.72%	1.25%	1.85%	Virginia	0.30%	0.45%	0.55%
Michigan	0.21%	0.34%	0.49%	Washington	0.15%	0.23%	0.31%
Minnesota	0.10%	0.15%	0.22%	West Virginia	0.15%	0.21%	0.25%
Mississippi	0.10%	0.15%	0.17%	Wisconsin	0.15%	0.23%	0.33%
Missouri	0.12%	0.19%	0.24%	Wyoming	0.02%	0.02%	0.03%
Montana	0.01%	0.02%	0.02%	**CONUS**	**0.13%**	**0.20%**	**0.25%**

4.2 Deployment Logistics

The modest spatial requirements presented in Table 7 indicate that well-conceived plans to deploy PV resources should not pose insurmountable ground occupancy problems. These suggest that there exist many possibilities available to planners that should alleviate any local concerns fueled by unregulated deployment [51].

In this article, we aim to inform, quantify and contextualize prospective deployment logistics by examing two possible large-scale deployment-planning approaches:

- The first approach considers current USGS ground occupancy categories in each state and assigns fractions for each category that could be reasonably assigned to PV deployment.

- The second approach identifies sector-specific footprints that are already utilized for some socio-economic activity and that could be used, all or in part, for supplementary PV generation without altering their current primary function.

4.2.2 Ground Occupancy Approach

We obtained ground occupancy data for each state from the US National Landcover Database (NLCD) [52], developed and maintained by the Multi-Resolution Land Characteristics Consortium (MRLC), a group of US Federal agencies. The NLCD classifies land-cover at 30-meter resolution across the ConUS from high-resolution decadal LandSat imagery and other sources [53]. Table 8 reports the ground occupancy categories as defined by the NLCD. Together, these categories amount to 100% of the total area of each state.

As a possible large-scale deployment scenario, we assigned a plausibly PV-developable fraction to each type of land cover. The largest assumed developable fractions are for developed (urban) areas where roofs, parking lots and miscellaneous exclusion zones could be exploited. Note that the 25% selected for high-density urbanized area is comparable to the typical building footprint for these areas (see below). We conservatively assigned 1% of cropland and pasture areas, noting that PV deployment does represent economic opportunities for an often-struggling farming sector and because of the potential for hybridizing PV with farming and animal grazing [54]. The 5% developable fraction applied to open water stems from the growth of the floating PV sector and is informed by PV deployment potential on hydropower reservoirs that we discussed in a recent publication [29]. We did not consider development of any forested areas, but a strong case could be made to convert a small fraction of forests to PV energy production considering that much of the presently forested land, particularly in the eastern part of the country, is second/third growth following farming deforestation and lumber production over a century ago.

TABLE 8: NLCD land occupancy categories and fraction that could be applied to PV deployment under the present scenario – Note: any state-specific land-cover scenario can be investigated through the link in [55]

Ground Occupancy Category	Fraction prospectively selected for PV deployment
Barren Land	1.0%
Cultivated Crops	1.0%
Deciduous Forest	0.0%
Developed, High Intensity	25.0%
Developed, Low Intensity	12.0%
Developed, Medium Intensity	15.0%
Developed, Open Space	5.0%
Emergent Herbaceous Wetlands	0.0%
Evergreen Forest	0.0%
Hay/Pasture	1.0%
Herbaceous	0.3%
Mixed Forest	0.0%

Open Water	5.0%
Perennial Snow/Ice	0.0%
Shrub/Scrub	1.0%

Table 9 contrasts the available deployable potential under this land occupancy scenario and the PV requirements to firmly meet the considered 55% of electric+transportation+building energy demand. Except for DC, all states would have considerably more than the needed developable space. For the great majority of states, the 'room to grow' beyond the considered requirements would be enough to consider a 100% PV future instead of the 55%/40%/5% PV/wind/gas blend assumed in this paper. The map in figure 4 graphically illustrates this 'room to grow' quantity.

Importantly, because the selected ground occupancy fraction, hence the results presented in Table 9, may be considered as arbitrary, excessive or insufficient depending on a multifaceted set criteria beyond the scope of this paper, we developed a web application letting readers – prospective planners and decision-makers – can interactively select ground occupancy percentages for any US state and gauge how deployment potential would be affected [55].

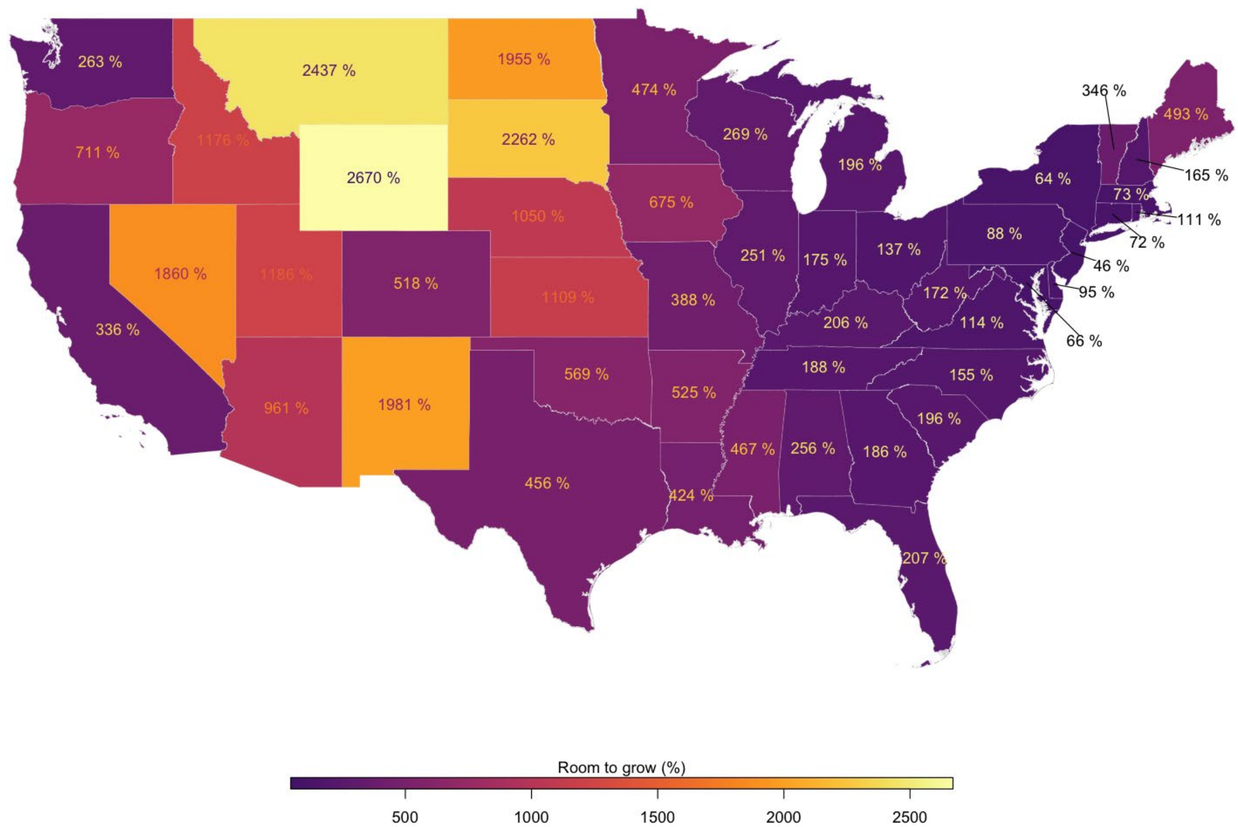

Fig. 4: PV Deployment 'room-to-grow' beyond this article's assumption to firmly meet 55% of electricity, transportation and building sectors demand with PV, given the possible deployment ground cover scenario listed in the Table 8 – Note: any state-specific land-cover scenario can be interactively investigated by linking to [55]

TABLE 9: Comparing surface area needed for PV to firmly supply 55% of the tree-sector demand compared to surface area that would be available from Table 8's deployment assumptions.

State	Required % state area			State	Required % state area		
	Area needed for PV	Area Available under Scenario	Room to grow		Area needed for PV	Area Available under Scenario	Room to grow
Alabama	355	1,263	256%	Nebraska	143	1,642	1050%
Arizona	280	2,970	961%	Nevada	142	2,777	1860%
Arkansas	209	1,308	525%	New Hampshire	87	231	165%
California	1,267	5,522	336%	New Jersey	476	695	46%
Colorado	297	1,835	518%	New Mexico	104	2,170	1981%
Connecticut	200	344	72%	New York	1,033	1,691	64%
DC	47	20	0%	North Carolina	626	1,596	155%
Delaware	62	122	95%	North Dakota	94	1,932	1955%
Florida	908	2,787	207%	Ohio	854	2,021	137%
Georgia	616	1,759	186%	Oklahoma	264	1,765	569%
Idaho	121	1,548	1176%	Oregon	257	2,085	711%
Illinois	819	2,878	251%	Pennsylvania	859	1,616	88%
Indiana	558	1,536	175%	Rhode Island	54	115	111%
Iowa	264	2,049	675%	South Carolina	322	954	196%
Kansas	185	2,236	1109%	South Dakota	69	1,621	2262%
Kentucky	354	1,084	206%	Tennessee	467	1,343	188%
Louisiana	330	1,731	424%	Texas	1,566	8,699	456%
Maine	100	591	493%	Utah	161	2,072	1186%
Maryland	352	584	66%	Vermont	45	203	346%
Massachusetts	381	661	73%	Virginia	569	1,214	114%
Michigan	725	2,144	196%	Washington	535	1,943	263%
Minnesota	466	2,674	474%	West Virginia	157	426	172%
Mississippi	207	1,173	467%	Wisconsin	470	1,735	269%
Missouri	430	2,097	388%	Wyoming	66	1,825	2670%
Montana	86	2,190	2437%	**CONUS**	**19,039**	**85,478**	**449%**

4.2.3 End-use sector approach

Here we consider a deterministic approach by looking at the ground footprint of specific applications that could be harvested for PV production without altering their primary functions. The list of prospective applications is likely exhaustive since, ultimately, PV technology could evolve to the point where every non-living surface could be harnessed. For this article, we limit our evaluation to selected sectors where PV deployment is either (1) currently explored, and/or (2) straightforward using existing technology. These sectors include:

- Railroads rights of way
- Power lines rights of way
- Expressways rights of way (center lanes)
- Gas pipelines rights of way

- Industrial/commercial/residential building envelopes
- Artificial [hydropower] reservoirs
- Vehicle-Integrated-PV (VIPV)
- Landfills /industrial/mining exclusion zones
- Parking lots

To facilitate reading flow, we grouped the tables detailing application-specific results in Appendix 1 (Tables A1 to A9).

Railroads rights of way: We acquired the length of railway tracks in each state from [56]. Assuming a typical right of way width of 15 meters (50 feet) [57], and assuming that 50% of this space could eventually be harvested for PV deployment, we estimate the deployable PV potential for each state. We contrast this potential to the requirements of the electric, transportation and building sectors reported in Table 5.

State-specific results are reported in TabIe A-1. In terms of PV capacity, the state of Texas, with more than 23,000 km of tracks, exhibits the largest potential with 35.3 GW. However, this capacity represents only 11% of PV requirements to firmly meet the anticipated 55% of the state's electricity, transportation and building demand. In relative terms, the state of Montana exhibits the largest deployable potential with 61% of the 3-sector demand. For the US, the total deployable potential is 464 GW amounting to 12% of requirements.

High-voltage powerlines' rights of way: We acquired high voltage power lines data for each State from [58, 59]. Rights of way widths typically depend on voltage, with 61 meters (200 ft) for 500 kV and up, 46 meters (150 feet) for 230 and 325 kV, 37 meters (120 feet) for 161 kV and 30 meters (100 feet) for 138 and 115 kV. From lengths and rights of way widths, we estimate PV deployment potential assuming, as above, that 75% of the space could be used for deployment. We compare this potential to the amount of PV required to meet 55% electric+transportation+building demand in each state.

Results are presented in Table A-2. High voltage power lines do offer considerably more deployable space than railroads. Seventeen states, including such large states as California, have a deployable firm PV generation potential that is larger than the anticipated demand from electricity, transportation and buildings. For the US, the powerline-deployable PV potential approaches 3,000 GW, i.e., 77% of requirements to firmly meet the 3-sector demand.

Expressways rights of way: With over 100,000 km in length, the US expressway system has a footprint approaching 4,000 km^2. However, without major and arguably expensive engineering undertakings such as canopies, only a small fraction of that space could be readily tapped for deployment. Here we assume that only the center lane space – typically 15 m or more in rural areas -- exclusive of shoulders could be assigned to low profile PV deployment. We further assume that 50% of that space would be amenable to PV deployment.

State-specific results are presented in Table A-3. The US expressway center lane deployable potential amounts to 155 GW. This is only 4% of the assumed 3-sectors demand. California exhibits the largest deployable potential in absolute terms with 13 GW. In relative-to-demand terms, Montana has the highest deployable potential with 19%.

Gas pipelines rights of way: The US has an extensive network of interstate and intrastate gas pipelines totaling over 300,000 km in length [60]. The typical construction-free right-of way width for these pipelines is 18.3 meters (60 feet). We assume, as for electrical power lines, that 75% of that space could be considered for PV deployment.

Results are presented in Table A-4. For gas-producing states with dense production networks, e.g., Oklhahoma, Wyomming or Lousiana, the right-of-way developable PV potential approaches or even exceeds the assumed electricity/transportation/building requirements. For most states, however, the developable potential only represents only a modest fraction of requirements. For the ConUS this fraction is 15%.

Commercial & residential building envelopes: We infer this deployable potential from four of the USGS ground occupancy categories presented in Table 8: developed high-density, developed medium-density, developed low-density and developed open-space. We empirically calibrated the roof-occupied fraction for each category from three recent case studies where we had also access to complete actual building (i.e., ~roofs) footprints [61, 62, 63]. These three case studies represent a diverse sample, both in terms of population density and geography:

- The city of San Francisco, California, with a population density of 7,250 inhabitants per km^2
- The City of Bloomington, Indiana, with a population density of 1,425 inhabitants per km^2
- The County of Tomkins, New York State, with a population density of 80 inhabitants per km^2

Figure 5 summarize the footprint vs. ground occupancy category trend derived from these case studies.

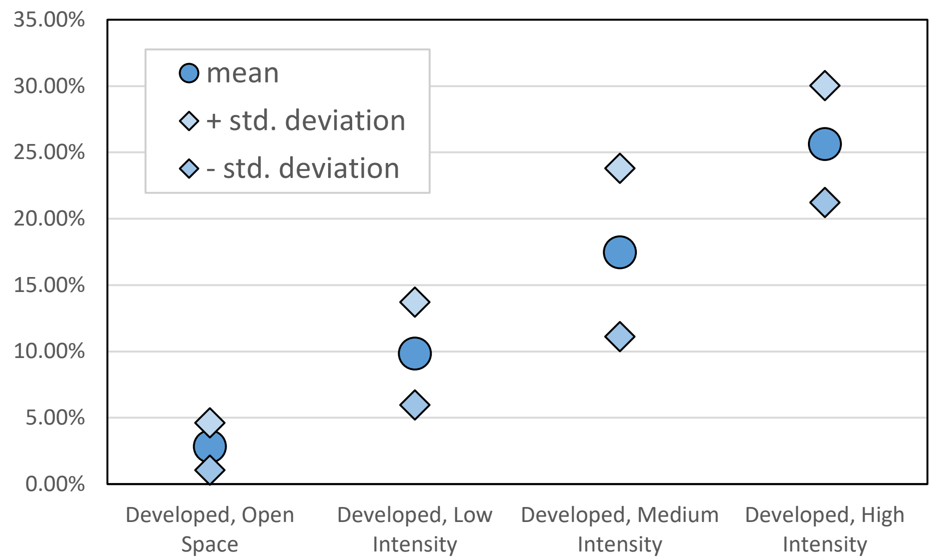

Fig. 5: Fraction of developed open space, low, medium and high intensity land-cover categories occupied by buildings

Further, based on in-depth high-resolution energy collection potential established for these three case studies [61-63], we conservatively assume that 50% of the building footprints would be economically amenable to PV deployment.

Results are presented in Table A-5 (Appendix 1). The roof PV deployment potential is arguably very large. US roofs tapped at 50% could firmly supply over 85% of the assumed three-sector demand. In absolute value, Texas exhibits the highest potential with 313 GW, enough to supply the entire sate's assumed demand. In relative terms, the largest potential occurs in South Dakota, where roofs could firmly supply nearly twice the considered demand.

Hydropower reservoirs: We specifically addressed this deployment option in a recent publication where we had analyzed the 100 largest artificial reservoirs in the US spread over 15 states [29]. Here we consider a complete list of hydropower reservoirs from USGS [64, 65] – noting that the list may be an underestimate because the USGS reports serval artificial lakes as natural lakes for reasons possibly driven by tourism industry's interests, particularly in the northeastern US.[9] We further assume that only 25% of these reservoirs' surface could be used for floating PV deployment. Results are presented in Table A-6. Deployable potential varies considerably from state to state, ranging from no potential in several coastal

[9] E.g. The Sacandaga in New York State (108 km^2) is classified as natural by USGS. In reality this lake, widely used for recreation purposes is the result of the damming of the Sacandaga River.

eastern states to very large deployable potential in north and western States (e.g., over 800% of 3-sectors energy requirements in South Dakota).

Vehicle integrated PV (VIPV): This deployment option may seem far-fetched given the nascent state of the VIPV technology [66]. Nevertheless, major car manufacturers are exploring this application, and a few top-of-the-line models already include some PV in the outer shell. The idea is that, as PV technology becomes more aesthetically versatile and less costly, it could eventually take advantage the "real estate" provided by the outer shells of vehicles, buses and semi-trailers. As fleets become electrified, and prospectively grid connected (through their very substantial storage systems), they could supply electricity directly to the transportation sector via trickle charging on the road, and to the grid at large with storage and implicit storage capability when not driven. Here we evaluate this potential assuming that, ultimately, 50% of the shell of all lightweight US vehicles (8 m^2 mean footprint on average) and 80% of the roof space of semi-trailers and buses (38 m^2 mean footprint on average) could be harvested to produce electricity. We acquired state-specific numbers of vehicles trailers and buses from [67].

Deployment potential results are shown in Table A7. Compared to other end-use sectors analyzed here, the VIPV potential is quite moderate, but it is not trivial either: VIPV could supply 6.8% of all the considered 3-sectors demand, with "vehicle-intensive" states as California reaching 13%. Looking at the transportation sector's requirements only, the potential contribution of VIPV could reach 25% US-wide and 33% in California.

Landfills/mining exclusion zones: We obtained landfill data from [68] for all US landfills. This source inventories the majority of municipal solid waste landfills in the US. The source reports tons of waste in place for all landfills, but surface area for a fraction of these landfills. We estimated area for the remaining fraction by deriving a relationship between waste in place and surface area (see appendix 2). For mining exclusion zones, we accessed a comprehensive data source inventorying all US mines by location [69] but with only sporadic surface area data. Fortunately, for one state – the State of New York – we were also able to access the exclusion surface area of its complete set mines [70]. By making the arguably conservative assumption that the size distribution of mines in New York State can be applied to other states, we were able to derive state-specific mine surface area for each state (see appendix 2).

We further assume that 50% of landfills and mining exclusion zones could be exploited for PV generation.

Detailed results are presented in Table A-8 (appendix 1). Mining/landfill deployment potential is modest but non-trivial amounting to 400 GW US-wide, i.e., ~11% of the assumed three-sector demand.

Parking lots: PV deployment over parking lots using canopies is an already mature sector of the PV industry [71]. We obtained high –resolution parking lot surface data from a recent study by Falcone & Nott [72]. We further calibrated that data using a study we had performed earlier in the eastern New York State [73] where we visually identified and spatially appraised every single parking lot. The correction factor derived for the eastern NY region was applied across the board to the entire country. We further assumed that 50% of the space would be amenable for PV deployment.

Results are presented in Table A9. Parking lot-deployment potential is comparable to the landfill-mines development potential, totaling 490 GW for the ConUS.

End-use Sector summary: In Table 10 we summed up all application-specific deployment areas. This Table is equivalent to ground occupancy-derived Table 9, comparing the deployable PV area to the area needed to firmly meet the three-sector 55% demand commitment. The 'room to grow' column quantifies how far the solar PV contribution could be pushed beyond this 55% commitment. This room to grow is positive in all locations except the District of Columbia.

Figure 6 illustrates the relative contribution of each application analyzed to the total PV deployment potential. We illustrate this relative contribution for the ConUS as well as its four largest state economies: California, Texas, New York and Florida. This figure shows that: power lines ROWs and buildings have, by far, the largest PV deployment potential; relative sector contributions are comparable in each considered major state, to the exception of hydropower reservoir deployment potential.

Overall, the end-use sector approach identifies less deployment potential than the ground-occupancy approach as it ignores important deployment opportunities such as the agricultural sector. Nevertheless, both approaches do lead to considerable deployment potential capable of supporting more that the assumed 55% demand.

TABLE 10: Comparing surface area needed for PV to firmly supply 55% of the tree-sector demand and the surface area that would be available from application-specific deployment assumptions.

State	Required % state area			State	Required % state area		
	Area needed for PV	Area Available under Scenario	Room to grow		Area needed for PV	Area Available under Scenario	Room to grow
Alabama	355	1,061	199%	Nebraska	143	673	371%
Arizona	280	1,169	318%	Nevada	142	596	321%
Arkansas	209	781	273%	N. Hampshire	87	173	98%
California	1,267	3,624	186%	New Jersey	476	497	5%
Colorado	297	851	187%	New Mexico	104	684	556%
Connecticut	200	268	34%	New York	1,033	1,248	21%
DC	47	15	0%	North Carolina	626	1,105	76%
Delaware	62	72	15%	North Dakota	94	1,070	1038%
Florida	908	1,590	75%	Ohio	854	1,502	76%
Georgia	616	1,404	128%	Oklahoma	264	1,242	371%
Idaho	121	675	456%	Oregon	257	932	262%
Illinois	819	1,626	99%	Pennsylvania	859	1,419	65%
Indiana	558	1,003	80%	Rhode Island	54	80	47%
Iowa	264	769	191%	South Carolina	322	900	179%
Kansas	185	980	430%	South Dakota	69	1,002	1361%
Kentucky	354	796	125%	Tennessee	467	1,060	127%
Louisiana	330	1,094	231%	Texas	1,566	4,226	170%
Maine	100	234	135%	Utah	161	779	383%
Maryland	352	413	17%	Vermont	45	112	147%
Massachusetts	381	549	44%	Virginia	569	910	60%
Michigan	725	1,254	73%	Washington	535	1,529	186%
Minnesota	466	932	100%	West Virginia	157	422	169%
Mississippi	207	707	242%	Wisconsin	470	869	85%
Missouri	430	1,221	184%	Wyoming	66	604	817%
Montana	86	1,095	1168%	CONUS	19,039	47,815	151%

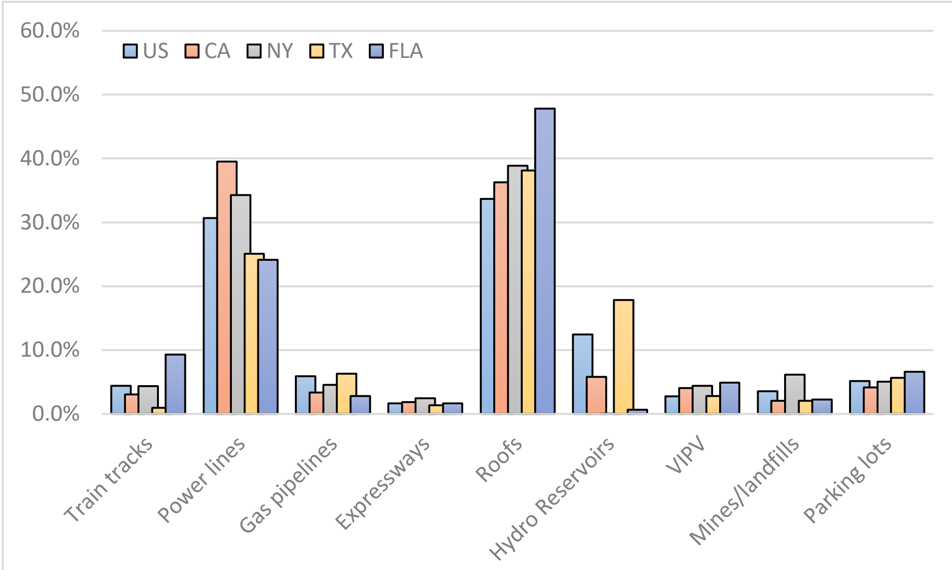

Figure 6: relative contribution of the eight considered applications to PV deployment potential – shown for the ConUS, California, New York, Texas and Florida.

5. CONCLUDING DISCUSSION

A new International Energy Agency activity on firm renewable power generation states that PV "has developed and grown at the margin of a core of dispatchable conventional generation – an expected consequence of its intermittent nature" [74]. In this article, we presented a view of PV beyond this current margin, where a mature PV resource has optimally evolved from intermittent to firm, and acquired an economically sound grid-dominant position, displacing conventional dispatchable generation.

The necessary transformation from intermittent/variable to firm at an acceptable cost implies substantially overbuilding of the resource – i.e., occupying substantially more space than a straight energy accounting would determine. 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 investigated whether an optimally oversized PV resource could reasonably be deployed to meet demand. We answered the question in a realistic context informed by recent ultra-high RE penetration studies undertaken in distinct socio economic/climatic environments and suggesting an oversized renewable mix of 55% PV, 40% wind, allowing for 5% legacy natural gas.

We contrasted two deployment approaches: (1) a top-down approach starting from global ground occupancy data, and (2) a bottom-up approaches starting from end-use application sectors prospectively amenable to PV deployment without change of function.

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. Firmly and economically supplying 55% of electricity, ground transportation and building demand 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 the densest northeastern state[10].

Both top-down and bottom-up approaches suggest that there would be substantial "room to grow" beyond the assumed 55% supply-side fraction – i.e., a 100% option could, if needed be envisaged in all states, to

[10] To the exception of the urbanized District of Columbia

the only exception of fully urbanized DC – a locality that is nevertheless well-connected to Virginia and Maryland that both have ample room to grow.

We complemented this article with an interactive web site – where the deployment assumptions could be easily modified on a state-specific basis. In particular, this application could be used to assess state-specific agricultural sector deployment options that were only sketched-out herein.

We stress that the present results represent a conservative worst-case, since we assumed 'business-as-usual' demand without considering any future demand reductions from likely to occur efficiency measures. This is particularly true for the building sector's electrified heating demand where (1) strong efficiency measures will reduce the overall electrical energy demand, and (2) possible utilization of curtailed excess PV (and wind) generation to the production of renewable fuels, e.g., via power to gas [] will increase demand flexibility and reduce oversizing requirements.

Finally, we note that while the individual questions posed in this paper can be considered straightforward, they have remained largely unanswered in practice. The comprehensive set of answers we provide can be considered innovative, particularly as these answers address head-on the often pointed-to intermittency shortcoming of PV. As such, the paper delivers effective decision-making figures that should inform solutions to entirely and economically displace conventional GHG sources. At the very least, the published figures will inform discussions in the US and elsewhere that often occur in a vacuum from lack of a comprehensive view.

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APPENDIX 1: END-USE SECTOR DEPLOYMENT TABLES

TABLE A1: State PV Deployment potential on railroads rights of way**.** Columns respectively show: the length of rail tracks in km, deployable PV capacity, and percentage of the selected (55%) fraction of electricity/transportation/ building demand this PV capacity could firmly serve

State	railroad km	PV GW	% of elec. Transp. & bldgs. reqs.	State	railroad km	PV GW	% of elec. Transp. & bldgs. reqs.
Alabama	6,666	10.2	14%	Nebraska	7,518	11.5	40%
Arizona	5,194	7.9	14%	Nevada	3,455	5.3	19%
Arkansas	5,549	8.5	20%	N. Hampshire	663	1.0	6%
California	16,011	24.4	10%	New Jersey	2,648	4.0	4%
Colorado	6,491	9.9	17%	New Mexico	4,945	7.5	36%
Connecticut	1,073	1.6	4%	New York	7,904	12.0	6%
DC	63	0.1	1%	North Carolina	6,246	9.5	8%
Delaware	546	0.8	7%	North Dakota	7,216	11.0	59%
Florida	5,709	8.7	5%	Ohio	10,824	16.5	10%
Georgia	8,601	13.1	11%	Oklahoma	6,764	10.3	20%
Idaho	3,872	5.9	24%	Oregon	5,572	8.5	17%
Illinois	15,296	23.3	14%	Pennsylvania	10,345	15.8	9%
Indiana	8,879	13.5	12%	Rhode Island	213	0.3	3%
Iowa	8,378	12.8	24%	South Carolina	4,621	7.0	11%
Kansas	10,780	16.4	44%	South Dakota	3,549	5.4	39%
Kentucky	5,672	8.6	12%	Tennessee	5,638	8.6	9%
Louisiana	5,932	9.0	14%	Texas	23,160	35.3	11%
Maine	2,222	3.4	17%	Utah	3,709	5.7	18%
Maryland	1,885	2.9	4%	Vermont	1,181	1.8	20%
Massachusetts	2,319	3.5	5%	Virginia	6,213	9.5	8%
Michigan	7,508	11.4	8%	Washington	7,284	11.1	10%
Minnesota	9,332	14.2	15%	West Virginia	4,628	7.1	23%
Mississippi	5,181	7.9	19%	Wisconsin	6,999	10.7	11%
Missouri	8,224	12.5	15%	Wyoming	4,525	6.9	52%
Montana	6,886	10.5	61%	CONUS	304,088	463.5	12%

TABLE A2: State PV Deployment potential on high voltage power lines rights of way

Columns respectively show: the lengths of power lines in different voltage categories (impacting right-of-way width) deployable PV capacity, and percentage of the selected (55%) fraction of electricity/transportation/building demand this PV capacity could firmly serve.

State	500 kV+	230 & 345 kV	161 kV	115 & 138 kV	PV GW	% of elec. Transp. & bldgs. reqs.	State	500 kV+	230 & 345 kV	161 kV	115 & 138 kV	PV GW	% of elec. Transp. & bldgs. reqs.
Alabama	1035	2910	2386	7247	76	107%	Nebraska	0	3139	219	6328	52	181%
Arizona	2809	6537	902	3176	90	161%	Nevada	443	1816	0	912	21	73%
Arkansas	968	543	5042	2874	53	128%	New Hampshire	0	738	0	1501	12	68%
California	5069	22894	1227	16666	286	113%	New Jersey	396	1903	0	1275	23	24%
Colorado	0	4181	0	6461	58	98%	New Mexico	43	3202	0	5020	45	217%
Connecticut	0	542	0	2093	13	33%	New York	5	4859	0	11404	86	41%
DC	0	12	0	3	0	1%	North Carolina	598	5938	261	4412	68	54%
Delaware	0	228	0	247	3	22%	North Dakota	0	3708	0	3237	40	214%
Florida	591	6415	0	7243	83	45%	Ohio	1	6388	0	12764	102	60%
Georgia	1558	5070	295	7984	87	71%	Oklahoma	0	1884	1629	9050	63	120%
Idaho	177	3529	497	4846	51	209%	Oregon	2944	4448	0	6817	89	172%
Illinois	0	5520	647	10676	90	55%	Pennsylvania	2310	5062	0	8548	95	55%
Indiana	0	6303	302	7345	78	70%	Rhode Island	0	91	0	362	2	21%
Iowa	0	1925	4312	1048	42	79%	South Carolina	332	3837	0	5470	54	84%
Kansas	0	2827	1072	6512	55	149%	South Dakota	0	4047	0	3170	42	308%
Kentucky	140	1182	3264	3860	45	64%	Tennessee	2568	0	9211	402	76	81%
Louisiana	942	2721	74	5216	52	78%	Texas	176	9494	18	30433	206	66%
Maine	0	618	81	1901	13	67%	Utah	85	2626	0	2790	32	98%
Maryland	551	1915	0	2100	28	39%	Vermont	0	220	0	697	5	52%
Massachusetts	0	1097	0	3519	24	31%	Virginia	865	2018	1	4893	44	39%
Michigan	0	4736	8	7220	66	45%	Washington	4519	8748	0	10464	149	139%
Minnesota	219	3752	760	5574	57	62%	West Virginia	713	804	0	4641	33	106%
Mississippi	746	1039	2164	4973	49	117%	Wisconsin	0	1850	1226	5647	45	48%
Missouri	0	2574	6745	2198	65	75%	Wyoming	0	3392	10	2950	37	279%
Montana	462	3583	2255	1927	50	290%	**CONUS**	**31,264**	**172,863**	**44,608**	**266,095**	**2,933**	**77%**

TABLE A3: State PV Deployment potential on expressways' center lanes

Columns respectively show: the lengths of expressways, the PV deployable surfaces, the corresponding deployable PV capacity, and percentage of the selected (55%) fraction of electricity/transportation/building demand this PV capacity could firmly serve

State	Expressway length (km)	Deployable space (km^2)	PV GW	% of elec. Transp. & bldgs. reqs.	State	Expressway length (km)	Deployable space (km^2)	PV GW	% of elec. Transp. & bldgs. reqs.
Alabama	1,971	15	3.0	4%	Nebraska	840	6	1	4%
Arizona	2,456	18	3.7	7%	Nevada	1,100	8	2	6%
Arkansas	1,082	8	1.6	4%	N. Hampshire	392	3	1	3%
California	8,929	67	13.4	5%	New Jersey	1,333	10	2	2%
Colorado	1,880	14	2.8	5%	New Mexico	1,858	14	3	13%
Connecticut	975	7	1.5	4%	New York	4,036	30	6	3%
D.Columbia	68	1	0.1	1%	N. Carolina	3,251	24	5	4%
Delaware	226	2	0.3	3%	North Dakota	979	7	1	8%
Florida	3,706	28	5.6	3%	Ohio	3,971	30	6	3%
Georgia	2,233	17	3.3	3%	Oklahoma	2,426	18	4	7%
Idaho	1,146	9	1.7	7%	Oregon	1,442	11	2	4%
Illinois	3,671	28	5.5	3%	Pennsylvania	3,709	28	6	3%
Indiana	2,802	21	4.2	4%	Rhode Island	299	2	0	4%
Iowa	1,434	11	2.2	4%	S. Carolina	1,386	10	2	3%
Kansas	1,537	12	2.3	6%	South Dakota	1,170	9	2	13%
Kentucky	2,773	21	4.2	6%	Tennessee	2,487	19	4	4%
Louisiana	1,518	11	2.3	3%	Texas	7,267	55	11	3%
Maine	589	4	0.9	4%	Utah	1,852	14	3	9%
Maryland	1,531	11	2.3	3%	Vermont	551	4	1	9%
Massachusetts	1,536	12	2.3	3%	Virginia	3,622	27	5	5%
Michigan	3,195	24	4.8	3%	Washington	1,774	13	3	2%
Minnesota	1,967	15	3.0	3%	West Virginia	1,020	8	2	5%
Mississippi	1,152	9	1.7	4%	Wisconsin	1,944	15	3	3%
Missouri	2,279	17	3.4	4%	Wyoming	1,644	12	2	19%
Montana	2,159	16	3.2	19%	CONUS	**103,167**	**774**	**155**	**4%**

TABLE A4: State PV Deployment potential on gas pipelines rights-of-way

Columns respectively show: the lengths of intrastate, interstate and other (e.g., gathering) pipelines in km, the corresponding deployable PV capacity, and percentage of the selected (55%) fraction of electricity/transportation/building demand this PV capacity could firmly serve.

State	Intra-state	Inter-state	other	PV GW	% of elec. Transp. & bldgs. reqs.	State	Intra-state	Inter-state	gather.	PV GW	% of elec. Transp. & bldgs. reqs.
Alabama	201	3,262	-	6	9%	Nebraska	-	5,237	-	10	34%
Arizona	124	7,244	-	13	24%	Nevada	1,654	1,146	-	5	18%
Arkansas	929	9,535	-	19	46%	New Hampshire	1	336	-	1	4%
California	11,398	1,763	-	24	9%	New Jersey	-	984	-	2	2%
Colorado	1,008	6,545	-	14	23%	New Mexico	2,370	6,667	-	17	79%
Connecticut	-	654	-	1	3%	New York	1,875	4,284	-	11	5%
DC	-	-	-	-	0%	North Carolina	1,034	349	-	3	2%
Delaware	-	389	-	1	6%	North Dakota	-	3,521	-	6	34%
Florida	200	5,016	-	10	5%	Ohio	2,719	8,252	-	20	12%
Georgia	-	3,658	-	7	5%	Oklahoma	16,264	16,475	301	60	115%
Idaho	0	1,204	-	2	9%	Oregon	165	1,733	-	3	7%
Illinois	4,355	5,616	-	18	11%	Pennsylvania	910	9,374	-	19	11%
Indiana	44	3,454	-	6	6%	Rhode Island	-	105	-	0	2%
Iowa	0	7,166	-	13	25%	South Carolina	-	2,723	-	5	8%
Kansas	258	13,665	13	25	69%	South Dakota	-	1,764	-	3	24%
Kentucky	846	4,649	-	10	14%	Tennessee	63	3,230	-	6	6%
Louisiana	7,325	21,909	0	53	81%	Texas	-	28,105	-	51	16%
Maine	160	603	-	1	7%	Utah	-	2,867	-	5	16%
Maryland	-	642	-	1	2%	Vermont	-	85	-	0	2%
Massachusetts	-	1,043	-	2	3%	Virginia	379	2,248	-	5	4%
Michigan	3,220	3,601	-	12	9%	Washington	-	2,338	-	4	4%
Minnesota	151	6,405	-	12	13%	West Virginia	309	5,056	-	10	31%
Mississippi	2,702	8,148	-	20	48%	Wisconsin	43	4,624	-	9	9%
Missouri	660	3,517	-	8	9%	Wyoming	437	9,359	854	19	148%
Montana	-	2,937	-	5	31%	CONUS	**61,803**	**243,485**	**1,168**	**561**	**15%**

TABLE A5: State PV Deployment potential on roofs

Columns respectively show: total roof surface, deployable surface, deployable PV capacity, and percentage of the selected (55%) fraction of electricity/transportation/ building demand this PV capacity could firmly serve.

State	Roof Surface Area (km2)	Deployable space (km2)	PV GW	% of elec. Transp. & bldgs. reqs.	State	Roof Surface Area (km2)	Deployable space (km2)	PV GW	% of elec. Transp. & bldgs. reqs.
Alabama	582	291	58	82%	Nebraska	403	201	40	141%
Arizona	565	282	56	101%	Nevada	277	139	28	98%
Arkansas	502	251	50	120%	N. Hampshire	151	76	15	87%
California	2,631	1,316	263	104%	New Jersey	542	271	54	57%
Colorado	525	263	53	88%	New Mexico	222	111	22	106%
Connecticut	278	139	28	70%	New York	970	485	97	47%
DC	19	9	2	20%	N. Carolina	870	435	87	69%
Delaware	78	39	8	63%	North Dakota	298	149	30	159%
Florida	1,635	817	163	90%	Ohio	1,183	592	118	69%
Georgia	1,008	504	101	82%	Oklahoma	617	308	62	117%
Idaho	217	108	22	89%	Oregon	484	242	48	94%
Illinois	1,510	755	151	92%	Pennsylvania	1,037	518	104	60%
Indiana	738	369	74	66%	Rhode Island	104	52	10	96%
Iowa	624	312	62	118%	S. Carolina	498	249	50	77%
Kansas	606	303	61	164%	South Dakota	257	129	26	188%
Kentucky	499	249	50	70%	Tennessee	695	348	70	74%
Louisiana	665	332	66	101%	Texas	3,132	1,566	313	100%
Maine	209	105	21	105%	Utah	313	157	31	97%
Maryland	355	178	36	50%	Vermont	95	47	9	104%
Massachusetts	560	280	56	73%	Virginia	676	338	68	59%
Michigan	1,282	641	128	88%	Washington	856	428	86	80%
Minnesota	780	390	78	84%	West Virginia	261	130	26	83%
Mississippi	434	217	43	105%	Wisconsin	742	371	74	79%
Missouri	821	411	82	95%	Wyoming	125	63	13	95%
Montana	292	146	29	169%	**CONUS**	**32,225**	**16,112**	**3222**	**85%**

TABLE A6: State PV Deployment potential on hydropower reservoirs

Columns respectively show: state-specific reservoir area, deployable PV area, corresponding deployable PV capacity and percentage of the selected (55%) fraction of electricity/transportation/ building demand this PV capacity could firmly serve.

State	Reservoirs Area (km²)	Deployable space (km2)	PV GW	% of elec. Transp. & bldgs. reqs.	State	Reservoirs Area (km²)	Deployable space (km2)	PV GW	% of elec. Transp. & bldgs. reqs.
Alabama	730	182	36.5	51%	Nebraska	130	33	6.5	23%
Arizona	797	199	39.9	71%	Nevada	810	203	40.5	143%
Arkansas	159	40	7.9	19%	N. Hampshire	-	-	-	-
California	837	209	41.8	17%	New Jersey	-	-	-	-
Colorado	205	51	10.2	17%	New Mexico	574	143	28.7	138%
Connecticut	-	-	-	-	New York	1	0	0.1	0%
DC	-	-	-	-	N. Carolina	266	66	13.3	11%
Delaware	-	-	-	-	North Dakota	2,334	583	116.7	621%
Florida	42	11	2.1	1%	Ohio	16	4	0.8	0%
Georgia	742	185	37.1	30%	Oklahoma	624	156	31.2	59%
Idaho	826	206	41.3	170%	Oregon	312	78	15.6	30%
Illinois	-	-	-	-	Pennsylvania	107	27	5.3	3%
Indiana	-	-	-	-	Rhode Island	-	-	-	-
Iowa	-	-	-	-	S. Carolina	883	221	44.1	68%
Kansas	336	84	16.8	45%	South Dakota	2,210	553	110.5	806%
Kentucky	474	118	23.7	33%	Tennessee	401	100	20.1	21%
Louisiana	453	113	22.6	34%	Texas	2,927	732	146.4	47%
Maine	-	-	-	-	Utah	1,278	319	63.9	198%
Maryland	-	-	-	-	Vermont	-	-	-	-
Massachusetts	176	44	8.8	12%	Virginia	507	127	25.3	22%
Michigan	-	-	-	-	Washington	559	140	28.0	26%
Minnesota	-	-	-	-	West Virginia	-	-	-	-
Mississippi	148	37	7.4	18%	Wisconsin	180	45	9.0	10%
Missouri	865	216	43.2	50%	Wyoming	685	171	34.3	260%
Montana	2,129	532	106.4	616%	**CONUS**	**23,723**	**5,931**	**1,186**	**31%**

TABLE A7: State VIPV PV Deployment Potential

Columns respectively show: number of light weight vehicles, number of semi-trailers and buses, corresponding PV deployable potential and percentage of the selected (55%) fraction of electricity/transportation/ building demand this PV capacity could firmly serve.

State	light weight cars (millions)	semi-trailers & buses (millions)	PV GW	% of elec. Transp. & bldgs. reqs.	State	Reservoirs Area (km2)	Deployable space (km2)	PV GW	% of elec. Transp. & bldgs. reqs.
Alabama	5.4	0.10	5.1	7%	Nebraska	2.0	0.04	1.9	7%
Arizona	6	0.14	5.8	10%	Nevada	2	0.06	2.4	8%
Arkansas	3	0.06	2.7	6%	N. Hampshire	1	0.03	1.3	7%
California	30	0.78	29.3	12%	New Jersey	6	0.18	5.9	6%
Colorado	5	0.11	5.0	8%	New Mexico	2	0.04	1.8	8%
Connecticut	3	0.07	2.8	7%	New York	10	0.38	11.0	5%
D.Columbia	1	0.01	0.6	6%	N. Carolina	8	0.21	8.1	6%
Delaware	1	0.02	0.9	7%	North Dakota	1	0.02	0.8	4%
Florida	17	0.42	16.6	9%	Ohio	11	0.23	10.2	6%
Georgia	8	0.21	8.2	7%	Oklahoma	3	0.08	3.0	6%
Idaho	2	0.03	1.8	8%	Oregon	4	0.08	3.6	7%
Illinois	10	0.25	10.1	6%	Pennsylvania	11	0.25	10.3	6%
Indiana	6	0.13	5.8	5%	Rhode Island	1	0.02	0.8	8%
Iowa	4	0.06	3.4	6%	S. Carolina	4	0.10	4.2	6%
Kansas	3	0.06	2.5	7%	South Dakota	1	0.02	1.0	7%
Kentucky	4	0.09	4.0	6%	Tennessee	6	0.13	5.6	6%
Louisiana	4	0.09	3.8	6%	Texas	23	0.58	22.7	7%
Maine	1	0.03	1.1	5%	Utah	2	0.06	2.4	7%
Maryland	4	0.12	4.2	6%	Vermont	1	0.01	0.6	7%
Massachusetts	5	0.14	5.1	7%	Virginia	7	0.17	7.1	6%
Michigan	8	0.20	8.1	6%	Washington	7	0.15	6.8	6%
Minnesota	5	0.11	5.1	5%	`	2	0.04	1.5	5%
Mississippi	2	0.06	2.1	5%	Wisconsin	6	0.11	5.2	6%
Missouri	6	0.12	5.4	6%	Wyoming	1	0.01	0.7	6%
Montana	2	0.02	1.5	9%	**CONUS**	**268**	**6**	**260**	**6.82%**

TABLE A8: State PV deployment potential on landfills and mine exclusion zones.

Columns respectively show: deployable landfill area, deployable mines area, corresponding PV capacity and percentage of the selected (55%) fraction of electricity/transportation/ building demand this PV capacity could firmly serve.

State	Usable Landfill Area (km2)	Usable Mines Area (km2)	PV GW	% of elec. Transp. & bldgs. reqs.	State	Usable Landfill Area (km2)	Usable Mines Area (km2)	PV GW	% of elec. Transp. & bldgs. reqs.
Alabama	5	41	9.2	13%	Nebraska	2	24	5.3	19%
Arizona	6	34	8.1	15%	Nevada	3	44	9.4	33%
Arkansas	3	28	6.1	15%	N. Hampshire	1	12	2.6	15%
California	40	74	22.8	9%	New Jersey	6	17	4.7	5%
Colorado	6	41	9.4	16%	New Mexico	2	21	4.7	22%
Connecticut	1	15	3.2	8%	New York	13	77	17.9	9%
D.Columbia	-	-	-	0%	N. Carolina	12	72	16.8	13%
Delaware	1	1	0.4	3%	North Dakota	1	3	0.8	4%
Florida	16	39	10.8	6%	Ohio	12	67	15.9	9%
Georgia	10	52	12.6	10%	Oklahoma	3	28	6.3	12%
Idaho	1	20	4.1	17%	Oregon	3	40	8.5	17%
Illinois	15	61	15.3	9%	Pennsylvania	13	83	19.1	11%
Indiana	10	48	11.5	10%	Rhode Island	1	4	0.9	9%
Iowa	4	46	10.0	19%	S. Carolina	5	31	7.3	11%
Kansas	4	35	7.8	21%	South Dakota	1	16	3.4	25%
Kentucky	5	34	7.8	11%	Tennessee	9	66	14.9	16%
Louisiana	6	10	3.0	5%	Texas	30	83	22.6	7%
Maine	1	14	2.9	15%	Utah	3	33	7.2	22%
Maryland	6	19	5.0	7%	Vermont	0	19	3.8	42%
Massachusetts	4	20	4.7	6%	Virginia	9	39	9.6	8%
Michigan	11	38	9.8	7%	Washington	5	48	10.6	10%
Minnesota	4	30	6.7	7%	W. Virginia	2	10	2.4	8%
Mississippi	3	19	4.4	11%	Wisconsin	6	46	10.3	11%
Missouri	6	62	13.7	16%	Wyoming	1	11	2.4	18%
Montana	1	16	3.5	20%	**CONUS**	**312**	**1,691**	**401**	**11%**

TABLE A9: State PV deployment potential on parking lots.

Columns respectively show: deployable area, corresponding PV capacity and percentage of the selected (55%) fraction of electricity/transportation/ building demand this PV capacity could firmly serve.

State	Parking km2	PV GW	% of Elec. Transp. & Bldgs. reqs.	State	Parking km2	PV GW	% of Elec. Transp. & Bldgs. reqs.
Alabama	51	10.1	14%	Nebraska	41	8.2	29%
Arizona	53	10.6	19%	Nevada	38	7.6	27%
Arkansas	40	8.0	19%	New Hampshire	9	1.8	10%
California	149	29.8	12%	New Jersey	30	6.1	6%
Colorado	53	10.6	18%	New Mexico	43	8.5	41%
Connecticut	14	2.7	7%	New York	63	12.5	6%
D.Columbia	1	0.2	2%	North Carolina	72	14.3	11%
Delaware	5	1.0	8%	North Dakota	40	7.9	42%
Florida	112	22.5	12%	Ohio	73	14.6	9%
Georgia	76	15.2	12%	Oklahoma	52	10.4	20%
Idaho	32	6.3	26%	Oregon	44	8.9	17%
Illinois	84	16.9	10%	Pennsylvania	72	14.5	8%
Indiana	51	10.1	9%	Rhode Island	4	0.8	7%
Iowa	51	10.3	19%	South Carolina	39	7.8	12%
Kansas	57	11.5	31%	South Dakota	39	7.8	57%
Kentucky	40	8.0	11%	Tennessee	51	10.3	11%
Louisiana	42	8.5	13%	Texas	232	46.4	15%
Maine	17	3.4	17%	Utah	35	7.0	22%
Maryland	26	5.2	7%	Vermont	7	1.3	15%
Massachusetts	24	4.8	6%	Virginia	56	11.2	10%
Michigan	69	13.8	10%	Washington	48	9.7	9%
Minnesota	61	12.3	13%	West Virginia	19	3.8	12%
Mississippi	37	7.5	18%	Wisconsin	49	9.8	10%
Missouri	70	13.9	16%	Wyoming	30	6.1	46%
Montana	52	10.5	61%	**CONUS**	**2,454**	**490.7**	**13%**

APPENDIX 2: LANDFILL SURFACE AREA vs WASTE IN PLACE RELATIONSHIP

The figure below illustrates the relationship between waste-in-place and landfill area for the ~25% fraction of US landfills where both characteristics were available. The variable A represents landfill area (in acres) and the variable T represents waste in place (in tons). This relationship was applied to the remaining landfills were we only had access to waste in place data.