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The Regional Per-Capita Solar Electric Footprint for the United States

P. Denholm and R. Margolis

Technical Report
NREL/TP-670-42463
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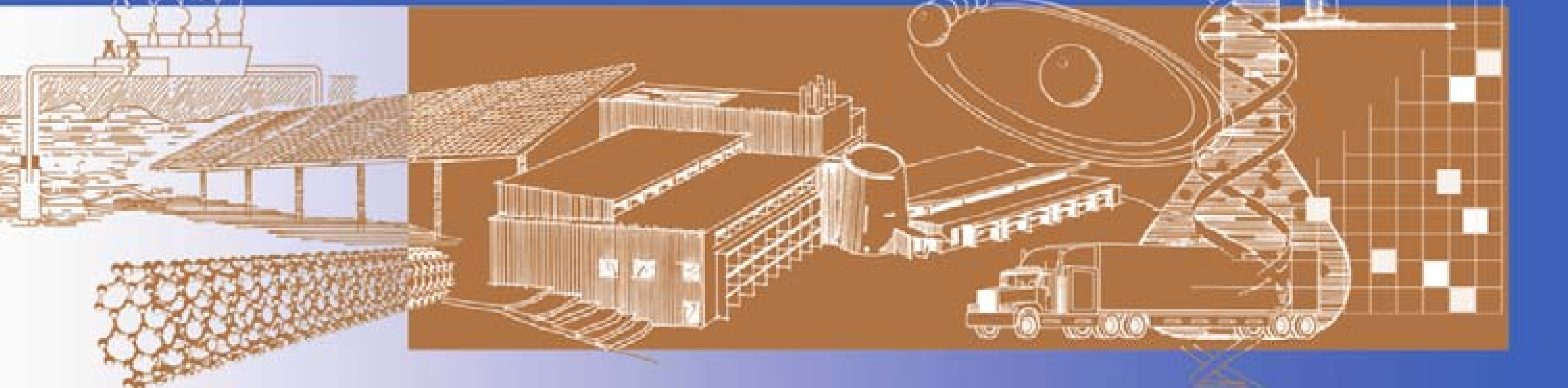

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Introduction

Solar photovoltaics (PV) offer a renewable alternative to traditional sources of electricity generation. The potential resource base for PV in the United States is enormous; however, there are a number of challenges related to realizing this potential including relatively high cost, intermittent output, and potentially significant land use. The costs of PV have been declining significantly during the past couple of decades, and there are strong prospects for further declines in cost during the next decade.[1,2] The issue of intermittency can be addressed through a number of potential means, and will likely become increasingly important as market penetration increases beyond a few percent of electricity consumption.[3,4] The issue of land use is often cited as an important issue for renewable energy technologies.[5,6] Determining the land requirements of solar PV at high penetration helps evaluate its potential to reduce both the carbon emissions and the "Ecological Footprint"[7] associated with electricity generation and use. There have been several estimates of the total land use required to meet the electricity demand from PV.[8,9,10] We go beyond these previous analyses by examining the impact of distributing the PV (and required storage) geographically throughout the United States, and by examining the impact of employing a range of array configurations (flat, fixed tilt, and tracking).

In this work, we quantify the state-by-state per-capita "solar electric footprint" for the United States, where the solar electric footprint is defined as the land area required to supply all end-use electricity from solar photovoltaics. There are four major goals of this analysis. First, we provide a state-by-state breakdown of *end-use* electricity use, accounting for the embodied energy in produced goods. In particular, we explore the impact of distributing industrial energy consumption in proportion to income rather than location of industrial activity. Second, we evaluate the solar energy density, or land use required to produce a given amount of solar energy, based on a range of PV configurations. Third, we estimate the state-by-state per-capita solar electric footprint for recent electricity use patterns and current PV system performance. Finally, we compare

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[1] Swanson, R. (2006). "A Vision for Crystalline Silicon Photovoltaics," *Progress in Photovoltaics: Research and Applications* 2006; 14:443–453.

[2] Green, M.(2006). "Consolidation of Thin-film Photovoltaic Technology: The Coming Decade of Opportunity," *Progress in Photovoltaics: Research and Applications* 2006; 14:383–392

[3] Denholm, P.; Margolis, R.M. (2007). "Evaluating the Limits of Solar Photovoltaics (PV) in Traditional Electric Power Systems," *Energy Policy*. 35, 2852-2861.

[4] Denholm, P.; Margolis, R.M. (2007). "Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies," *Energy Policy* 35 (2007) 4424–4433

[5] Nonhebel, S. (2003). "Land-use changes induced by increased use of renewable energy sources," *Global Environmental Change and Land Use:* 187-202.

[6] Rao, G. L.; Sastri, V.M.K. 1987 "Land Use and Solar Energy" Habitat International 1987 11(3) 61-75.

[7] Wackernagel, M.; Rees, W. (1996). *Our Ecological Footprint*, New Society Publishers

[8] Turner, J.A. (1999). "A Realizable Renewable Energy Future," *Science* 285:5428, p. 687.

[9] Love, M.; Pitt, L.; Niet, T.; McLean, G. (2003) "Utility-Scale Renewable Energy systems: Spatial and Storage Requirements," *Hydrogen and Fuel Cells 2003 Conference and Trade Show*, Vancouver, BC, June 8-11.

[10] U.S. Department of Energy (2004). "How much land will PV need to supply our electricity?" DOE/GO-102004-1835 www.osti.gov/bridge/servlets/purl/15006746-tqhOKf/native/15006746.pdf

this per-capita solar footprint to several other per-capita demands for land use. The solar electric footprint is based on the boundary condition of meeting the entire nation's electricity needs with solar PV. While this requirement represents an extreme (and unlikely) scenario, it does provide insight into the potential scale of land-use impacts associated with meeting a large fraction of the nation's electricity requirements from PV.

State-Level Electricity Use in the U.S.

Using state-level electricity consumption and population data for 2003-2005, we estimated the annual average per-capita electricity use. The complete electricity use data set is provided in Appendix 1. Publicly available electricity use data is divided into four end-use sectors: residential, commercial, transportation, and industrial. Transportation electricity, which accounts for about 0.2% of U.S. end-use electricity, was combined with commercial electricity. Per-capita commercial and residential electricity use was calculated by dividing total state electricity use in each sector by the state's population. For residential and commercial electricity, this is probably a reasonable allocation – if people shop, work, and conduct most business in their state of residence.

The biggest limitation of this approach is that it ignores the regional flow of embodied electricity in manufactured goods, captured largely in the "industrial" electricity category. There is a limited relationship between where industrial (which includes agriculture) products are manufactured and where they are used, and heavily industrialized states effectively export electricity embodied in goods and services. Ideally, industrial electricity could be allocated by assigning each region its actual industrial electricity use by tracking embodied electricity in manufactured products.[11] An alternative and simpler approach is to use state-level personal income as a proxy measure for consumed industrial and agricultural goods. This results in the assumption that a region with twice the annual per-capita income as another consumes twice as much goods and services per person, and correspondingly twice as much industrial electricity.[12] Based on this assumption, we assigned each state an effective industrial electricity use by multiplying its fraction of total U.S. income by the total industrial electricity used in the United States. Complete data is provided in Appendix 2. There are potential significant limitations to this approach, so we illustrate the effect of this assumption in Figure 1, the per-capita electricity use for all 50 U.S. states.

In Figure 1, each state's per-capita electricity use is shown divided into three categories. The industrial electricity bar illustrates our assumed allocation based on income. In addition, we provide an "error bar," which indicates the per-capita consumption if industrial electricity were allocated to the state of use. As discussed earlier, heavily industrialized states would have a much higher per-capita electricity use if measured using the more traditional allocation. Wyoming, in particular, would have a very high

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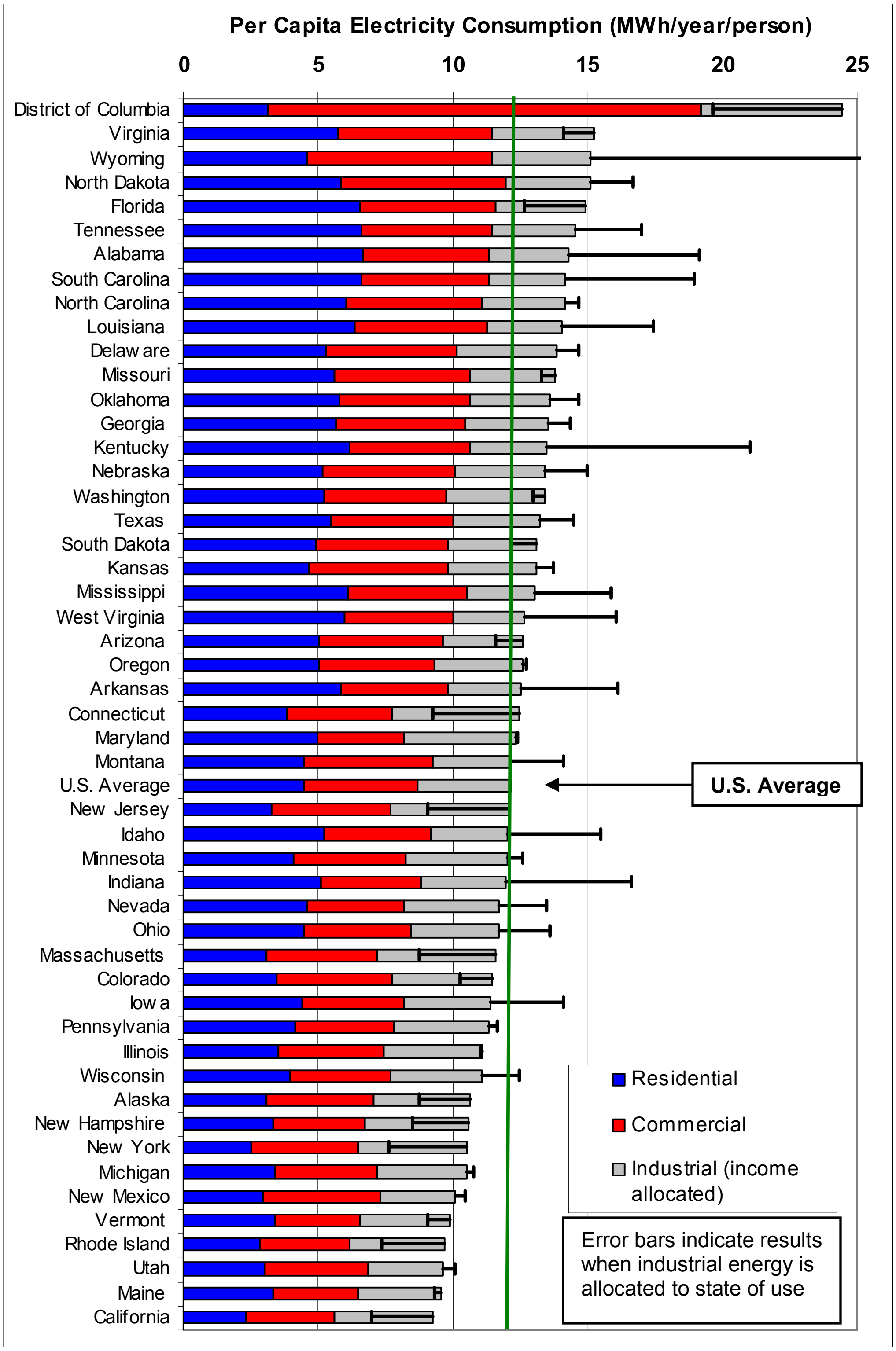
[11] A full accounting here would also include embodied electricity in internationally imported/exported goods.

[12] It may be possible to derive a more accurate distribution of the energy embodied in industrial goods, and the effective regional flows of industrial electricity, using economic activity databases such as those in the IMPLAN model (www.implan.com).

per-capita use, equal to nearly 28 MWh per person. Alternatively, Northeastern states such as Connecticut and Massachusetts are likely responsible for much more electricity use than would be accounted for using a simple per-state allocation.



Error bars indicate results when industrial energy is allocated to state of use

Figure 1. Annual Per-Capita Electricity Use in the U.S., Averaged from 2003-2005

We include the District of Columbia in our assessment due to both data availability and its usefulness in illustrating the application and limits of PV in urban areas. The large per-capita commercial electricity in Washington, D.C., is likely explained by the large number of people that work and shop in D.C. but do not live there. About 70% of the workers in the District of Columbia live outside the city; the electricity used to support these workers in office buildings and other commercial support activities results in a net export of electricity embodied in commercial activity.[13]

Solar PV Energy Density

The per-capita solar electric footprint in each location is calculated by dividing the total electricity requirement by the PV energy density:

$$\text{Solar Electric Footprint} = \frac{\text{Annual Electric Demand}}{\text{PV Energy Density}} \tag{1}$$

where the PV energy density is defined as the annual energy produced per unit of land area, equal to

$$\text{PV Energy Density} = \frac{\text{PV Array Power}}{\text{Land Area}} \times \frac{\text{Annual PV Generation}}{\text{PV Array Power}} \tag{2}$$

The first term in Equation 2 is the PV array power density, equal to PV array power deployable per unit of land area. The array consists of individual PV modules, and the nameplate (or peak) direct current (DC) power rating of an individual module is a function of module efficiency and the module collector area. The module efficiency is defined under Standard Test Conditions (STC) of 1,000 W/m^2 solar irradiance and 25°C. Typical commercially available silicon PV modules have efficiencies of about 10-15%, resulting in about 100-150 watts of peak DC output per square meter of collector area.[14] Module efficiencies vary by technology, with current thin-film modules producing efficiencies of about 6-12%, while advanced silicon modules (also commercially available) can produce efficiencies of more than15%.[15] Module efficiencies of all types are expected to increase over time, which will increase the module power density and decrease the solar electric footprint.

The total array power density depends on the array spacing as well as the individual module efficiency. If deployed horizontally with no spacing between modules, the array

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[13] According to the 2000 U.S. Census, 190,566 individuals both work and live in the District of Columbia (D.C.), while 70,318 lived in D.C. but worked outside the city. In the same time period, 481,112 individuals worked in D.C. while living outside the city. "U.S. Census 2000 County-To-County Worker Flow Files" at http://www.census.gov/population/www/cen2000/commuting.html

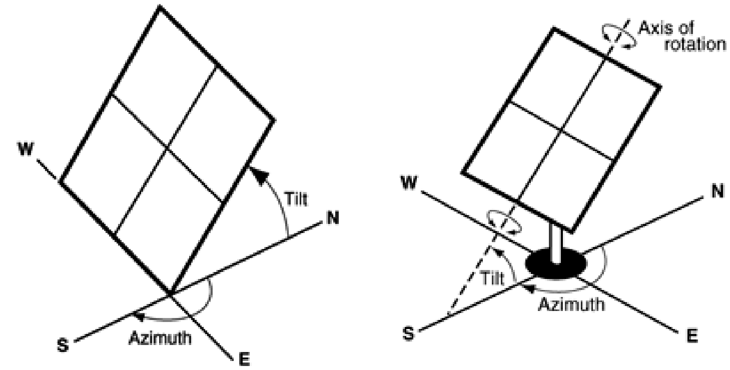
[14] Actual module efficiency can vary significantly with temperature, so the PV module may be "derated" accordingly.

[15] U.S. DOE (2007). "Solar Energy Technologies Program Multi-Year Program Plan 2007-2011."

power density would be equal to the module power density (100-150 MW/km^2 for silicon modules).

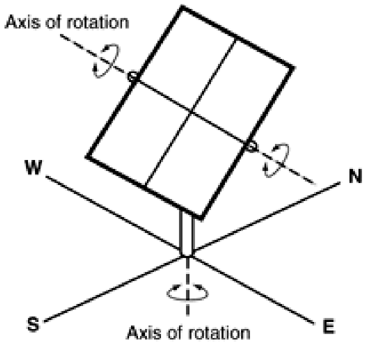
PV deployed on flat rooftops and ground-based PV arrays are typically tilted toward the south, or deployed on tracking arrays to maximize the amount of collected solar radiation per unit (MW) of deployed PV. To avoid self-shading, and to allow for maintenance, space is required around individual or sets of modules. This decreases the array power density.

Figure 2 provides an illustration of fixed and tracking PV array configurations.



PV array facing south at fixed tilt.

One axis tracking PV array with axis oriented south.



Two-axis tracking PV array

Figure 2. PV Array Configurations

Rooftop-deployed PV systems tilted at small angles can have a fairly small decrease in array power density. One example is a commercially available system using 13.5% efficient modules with a 135 W/m^2 power density when deployed flat, and an 118 W/m2 power density when deployed at a 10° tilt angle, or a drop of about 13%.[16] When deployed on ground-mounted arrays, tilt angles generally increase to increase module

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[16] Example of Powerlight "PowerGuard" and "PowerTilt" systems at http://www.powerlight.com/products/powertilt.php and http://www.powerlight.com/products/powerguard.php

energy yield. This results in even greater array spacing. In addition, there may be minimum spacing between arrays in large installations to allow maintenance vehicles to pass between long rows of PV arrays. Minimum spacing for service vehicles is about 3.5 meters between rows, with a more conservative 4-5 meters often applied.[17] For 13.5% efficient modules, this may reduce the system power density to 60-70 W/m^2 for fixed-plate systems. Tracking arrays require additional space to avoid self-shading.[18]

The second term in Equation 2 is the annual generation per unit of module power. The actual PV generation per unit of module power at any given time is the product of two factors:

$$\frac{\text{PV Generation}}{\text{Module Power}} = \text{Incident Radiation} * \text{AC Conversion Efficiency} \qquad (3)$$

The incident radiation changes as a function of time of day and weather, so calculating the annual output of the module generally involves obtaining the incident radiation for each hour and summing over all hours per year. However, it is possible to express the value as an annual average. The average solar radiation (energy per unit area, per unit time) is a function of local climate and module orientation (Figure 3).

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[17] These values are based on various project filings and discussions with several major system installers.

[18] See, for example, the Powerlight "PowerTracker" at http://www.powerlight.com/products/powertracker.php

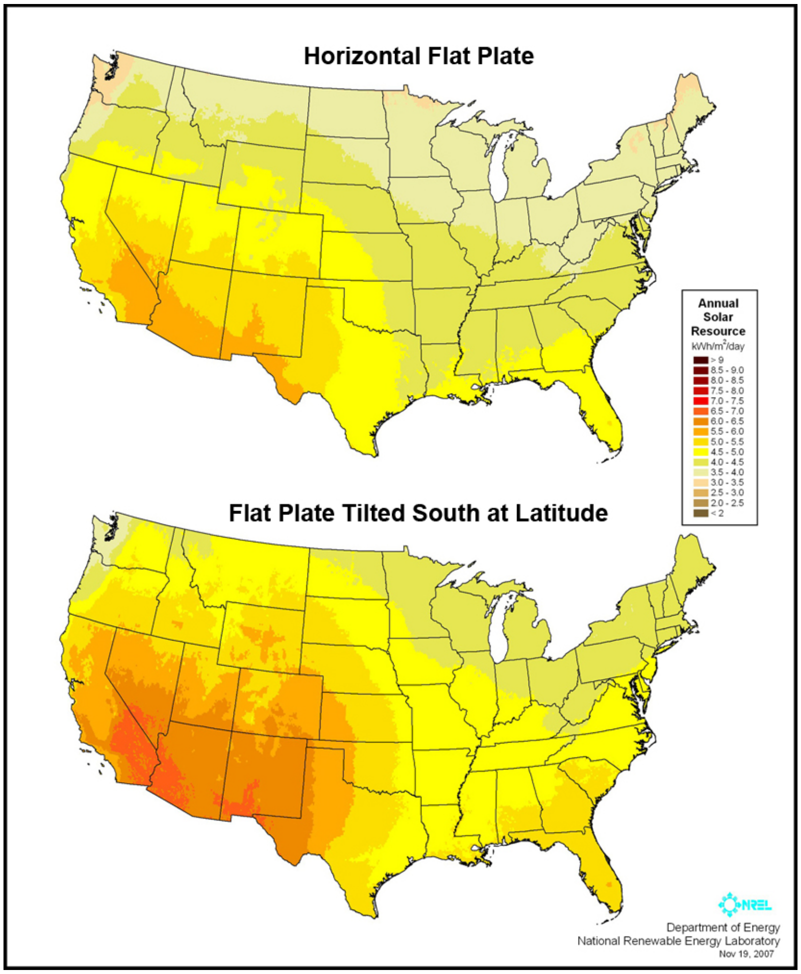

Figure 3. Average Daily Solar Radiation on Horizontal and Tilted Surfaces[19]

As illustrated above, the incident radiation on the PV array and the resulting total annual energy collected can be increased by tilting the PV array up from horizontal toward the south. Even greater collection can be gained by deploying tracking systems that continuously orient the panels toward the sun.

The second term in Equation 3 is the alternating current (AC) conversion efficiency. PV modules produce DC electricity, which must be converted to grid-compatible AC with an inverter. The overall AC-DC conversion efficiency is often described as a combination of inverter efficiency and many other factors, such as wiring losses, panel soiling, system availability, etc.[20]

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[19] Data based on 10 km, satellite modeled dataset (SUNY/NREL, 2007)

[20] The overall derate factor may vary as a function of load, so it is often necessary to perform an hour-by-hour simulation to derive an annual estimate of the actual AC energy output.

Table 1 provides the estimated system energy density for a set of system configurations and three locations that represent the range of insolations for the lower 48 U.S. states.[21] The assumed PV module efficiency is 13.5%, and average daily incident radiation for each location and orientation is derived from the "Typical Meteorological Year" (TMY) data set.[22] Calculation of energy yield was performed using the PVWatts tool, using the default average DC-AC conversion efficiency of 77%.[23]

Table 1. PV System Performance Characteristics

System Type	**PV Array Power Density (DC W/land m^2)**	**Incident Solar Radiation (kWh/ array m^2/day) low / med / high**	**Output from a 1 kW (DC) system (kWh/year) low / med / high**	**System Energy Density (kWh/ land m^2/year) low / med / high**
Flat (rooftop)	135	3.05 / 4.31 / 5.85	782 / 1113 / 1459	106 / 150 / 197
10-degree tilt, South facing (rooftop)	118	3.27 / 4.64 / 6.31	849 / 1212 / 1586	98 / 139 / 182
25-degree tilt, South facing (ground based)	65	3.42 / 4.86 / 6.62	893 / 1278 / 1668	58 / 83 / 108
1-axis tracking (0-degree tilt)	48	3.86 / 5.70 / 8.25	1024 / 1519 / 2128	49 / 73 / 102
2-axis tracking	20	4.44 / 6.60 / 9.61	1180 / 1761 / 2460	24 / 35 / 49

Table 1 illustrates the significant drop in PV array power density for tilted and tracking arrays due to shading and maintenance requirements. This drop in power density is accompanied by a greater energy yield per installed unit of module power. However, the reduced power density is much greater than the increased collector yield, so moving from flat rooftop arrays to land-based tilted and tracking arrays can reduce system energy density by more than 50%. Improvements in system energy density will be driven more by module efficiency increases than by improved array spacing because shading and maintenance requirements provide fundamental limits on array packing density, while deploying more efficient cells can substantially improve system energy densities in the future.[24]

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[21] The low-, medium-, and high-resource locations are Quillayute, Washington; Kansas City, Missouri; and Daggett, California; respectively.

[22] National Renewable Energy Laboratory (1995). *TMY2 Users' Manual*, National Renewable Energy Laboratory, Golden, Colorado. Available at http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/

[23] PVWatts performs an hourly simulation that is necessary to perform an accurate assessment of PV output, accounting for variation in module efficiency due to temperature and the variation in inverter efficiency as a function of load. Additional details are available at http://rredc.nrel.gov/solar/codes_algs/PVWATTS/.

[24] Another significant improvement in system energy density for tracking arrays would be the deployment of concentrating solar PV (CPV), which has demonstrated efficiencies of 20-26% in commercially available modules (U.S. DOE (2007) Solar Energy Technologies Program Multi-Year Program Plan 2007-2011).

The U.S. Solar Electric Footprint

The solar electric footprint for each state was calculated using Equation 1, applying the annual electric demand values as previously calculated. As discussed previously, the PV energy density is highly dependent on assumptions for system configuration.

We begin with an assumed scenario based on commercially existing PV modules with a 13.5% efficiency and the assumed array densities in Table 1. Our scenario also assumes 25% of all PV is deployed on rooftop-type systems, where 5% (of all PV) is oriented flat, 10% south facing at 10° tilt, 5% SW facing at 10° tilt, and 5% SE facing at 10° tilt. The remaining PV is deployed in ground-based arrays, with 40% deployed as south-facing arrays at 25° tilt, 25% 1-axis tracking (0° tilt), and 10% 2-axis tracking. Given the importance of array configuration, we also examine sensitivities to this assumption later in this work.

To determine the annual PV generation per unit of module power, we used hourly insolation values for 2003-2005 for 216 sites in the lower 48 U.S. states, plus one site in Hawaii from the updated National Solar Radiation Database (NSRDB).[25] For Alaska, due to limited quality of the 2003-2005 NSRDB solar data, we used historical typical meteorological year data.[26] We created 216 solar resource regions in the lower 48 U.S. states based on the proximity of census block groups to each of the stations. The location of these regions is provided in Figure 4.

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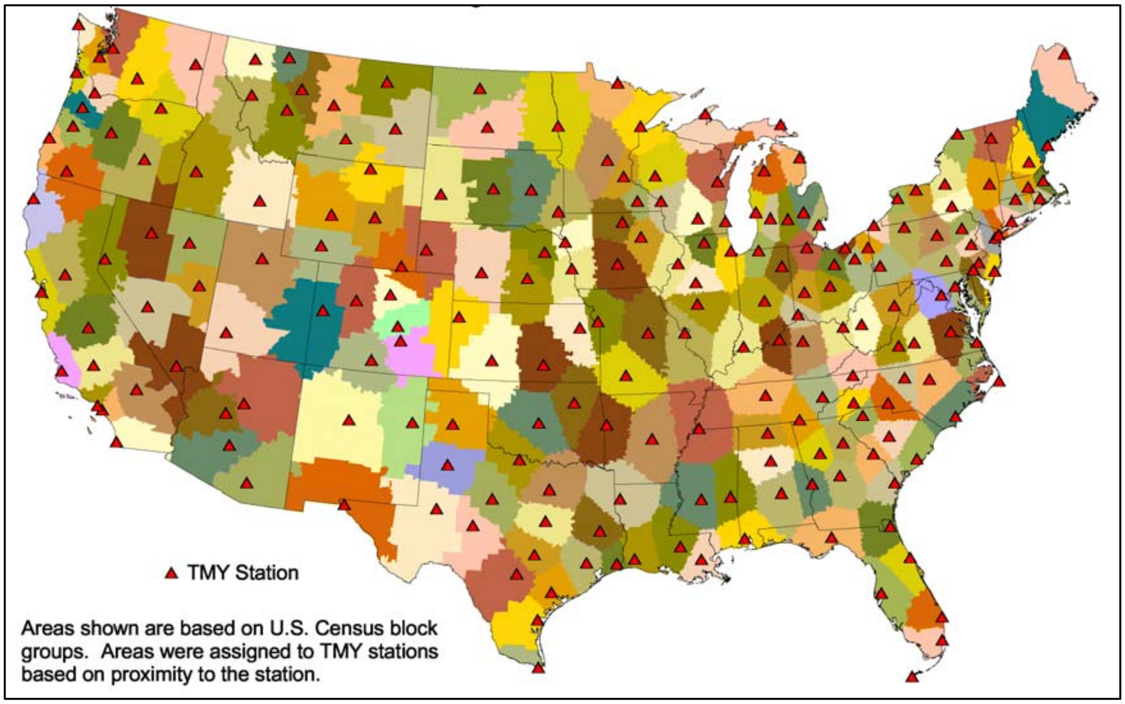
[25] The 216 locations chosen for this analysis are, with a few exceptions, the stations in the original 1961-1990 NSRDB. Although the updated (1991-2005) NSRDB contains several hundred additional sites, the 216 original sites provide adequate coverage to capture the variation in solar resources within each state. For additional detail about the NSDRB, refer to National Renewable Energy Laboratory (2007), National Solar Radiation Database 1991–2005 Update: User's Manual, NREL/TP-581-41364 http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/

[26] In addition to using noncoincident-year solar data for Alaska, we also used only a single TMY site (Anchorage) to represent the entire state. While this adds a great deal of uncertainty to our analysis, the "100% electricity from PV" scenario evaluated here is extremely unrealistic for Alaska given the poor solar resource in the state. As a result, our estimates here should be used only as a boundary condition to roughly compare the solar electric footprint in Alaska to the lower 48 states.



Areas shown are based on U.S. Census block groups. Areas were assigned to TMY stations based on proximity to the station.

Figure 4. Allocation of TMY sites to U.S. Population

To derive the solar energy production for each of the 216 sites, we performed an hourly PV simulation using the PVFORM model, assuming a 1 kW STC module.[27] The total solar resource for each state was generated by a weighted average of the resource regions based on load. This regional weighting was performed by assigning one of the 216 solar resource locations to each of the 3,277 electric service providers in the lower 48 U.S. states.[28] Location within a state was based on the fraction of load met by each of the state's utilities, and the TMY station assigned to each utility. By using the same years for both electricity loads and solar insolation, we can account for some of the correlation between load and weather. The net PV energy density for each state was calculated using the weighted average of the various power densities (based on system type) and the annual generation values (based on both system type and location within each state). The resulting state-level PV energy density values (with the assumed mix of system orientations) are provided in Figure 5. Location-weighted daily average insolation values for each state are provided in Appendix 4.

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[27] PVFORM is the PV performance model used in the PVWatts tool. While Equation 2 assumes a constant module efficiency, actual efficiency varies with temperature. PVWatts accounts for the variation in module efficiency that occurs due to changes in temperature, and the variation in inverter efficiency as a function of load. Additional details are available at http://rredc.nrel.gov/solar/codes_algs/PVWATTS/.

[28] Energy Information Administration, Form EIA-861 Database. http://www.eia.doe.gov/cneaf/electricity/page/eia861.html

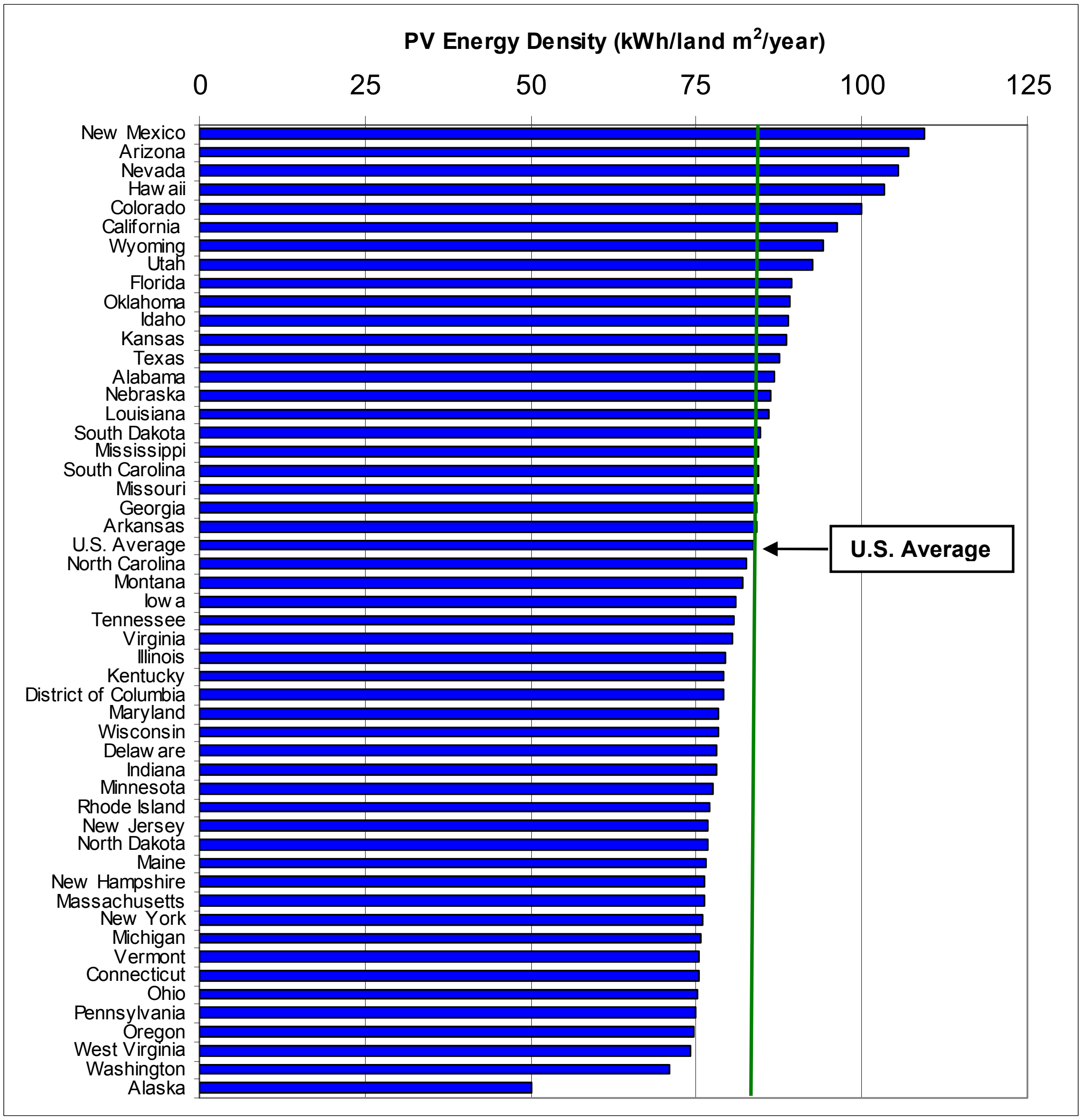

Figure 5. PV Energy Density By State

Ignoring the coincidence between PV supply and electricity demand, the per-capita solar footprint can be calculated using the data in Figures 1 and 5.

Because our solar footprint estimates are based on the extreme scenario of PV supplying 100% of the nation's electricity demand, and because solar PV generation is not entirely coincident with electricity demand, some enabling technologies must be deployed for PV to meet this entire electricity demand. Enabling technologies may include load shifting, but there are limits to the amount of load that can be shifted,[29] and we assume that energy storage is deployed to meet all mismatches between PV supply and electricity demand. Because no energy storage system is 100% efficient, energy storage losses will increase

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[29] Paul Denholm, Robert M. Margolis (2007). "Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies," *Energy Policy* 35: 4424–4433.

the amount of energy to be generated by the PV system. Each delivered kWh of electricity that is passed through an energy storage system will require PV generation equal to $1/\eta_{stor}$ where η_{stor} is the storage system efficiency. Some PV generation will be used directly (bypassing storage), so this efficiency impact applies only to the fraction of demand passing through storage f_{stor}. As a result, the multiplier or ratio of "PV generation required" to "electricity demand" can be expressed as a "storage footprint multiplier" equal to

$$\text{Storage Footprint Multiplier} = (1 - f_{\text{stor}}) + \frac{f_{\text{stor}}}{\eta_{stor}} \tag{4}$$

We assumed a round-trip storage efficiency of 75% based on existing technologies such as pumped hydroelectric storage, or batteries.[30] Determining the fraction of energy to be stored requires simulating the hourly PV supply patterns with demand patterns on a regional basis.

To determine the fraction of energy that is needed to be stored, we used the PVflex model.[31] The PVflex model compares hourly load to hourly PV supply and has the ability to charge or discharge a storage system as needed. We performed simulations for several regions around the country, and found that the energy storage fraction had a range of only about 60-70%.[32] Applying this range of values to Equation 2, the PV generation multiplier ranges from 1.20 to 1.23, a difference of just less than 3%. Because the PV footprint analysis is relatively insensitive to this range of storage values, we assume the more conservative 70% storage fraction (and the corresponding multiplier of 1.23) to all regions of the country. This storage fraction is conservative for an additional reason: It assumes storage is the only "enabling" technology used, ignoring potentially more efficient and economic means of mitigating solar PV output variability. Among these include load shifting and long-distance transmission.

It is important to note that while the fraction of energy stored does not vary significantly over a large range, the size of the required energy storage system does vary widely. While achieving 50-70% of a region's electricity from PV could theoretically be achieved with fewer than 12 hours of storage,[33] the last 10-20% would require months of storage to compensate for the seasonal mismatch between PV supply and demand. This seasonal storage requirement demonstrates that while achieving 100% of a region's electricity from PV is theoretically possible, it is not a practical goal unless very inexpensive and

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[30] Denholm, P.; Kulcinski, G.L.. (2004). "Life-Cycle Energy Requirements and Greenhouse Gas Emissions from Large-Scale Energy Storage Systems," *Energy Conversion and Management*. 45, 2153-2172.

[31] Denholm, P.; Margolis, R.M. (2007). "Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies," *Energy Policy* 35: 4424–4433

[32] We originally intended to perform simulations for a large number of regions in the country to determine the "energy storage fraction" and then assign this energy storage fraction to the corresponding states. After completing simulations for eight geographically diverse regions (Boston; Tampa; New York City; Washington, D.C.; Los Angeles; Omaha; Indianapolis; and Portland), we found that the energy storage fraction had a limited range of only about 60-70%.

[33] Denholm, P.; Margolis, R.M. (2007). "Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies," *Energy Policy* 35: 4424–4433.

very high capacity energy storage devices become available. This result also demonstrates the reality of modern electric power systems where a variety of generation technologies are used to meet the large variation in demand on both a daily and seasonal basis.

The results of the 100% solar scenario presented here can be scaled to assess the solar footprint associated with some fraction of the total electric demand. When applying any scaling factor, it is important to point out that the storage fraction may be much lower than our assumed 70% at lower PV penetration. The storage multiplier of 1.23 could drop to 1 for low penetration of PV where storage is not needed. However, the actual number depends on a variety of factors, and it is not possible to provide a simple relationship between PV penetration and the amount of storage needed for all locations. As a result, the results presented here represent a fairly conservative bounding case of solar footprint and PV land requirements.

Figure 6 provides the resulting average state-by-state per-capita solar footprint. As discussed in Section 2, the industrial footprint is based on an income-based allocation of industrial electricity, with the error bar representing the footprint for industrial electricity actually used within the state.

When comparing Figure 6 to Figures 1 and 5, it appears that electricity demand drives the relative per-capita solar footprint more than solar resource, with a few exceptions. The most obvious is Alaska, where poor solar resource results in a very high solar footprint despite its relatively low per-capita electricity use.

The overall average solar electric footprint for the United States during the years evaluated was about 181 m^2 per person, using our assumed mix of PV system types and orientations. This value is almost exactly the same for both methods of applying industrial electricity. There is no physical reason for this – if industrial electricity were used more in states with lower solar insolation, the national average footprint would increase in the "per state" allocation of industrial electricity. However, in the current distribution, industrial electricity is used less in states with both very high insolation (such as California) and regions with low insolation (such as New England). The solar footprint for 38 states and about 78% of total U.S. electric demand is within 20% of this average value.

As discussed earlier, the solar electric footprint is highly sensitive to the PV system type and does not consider expected improvements in solar collector efficiency. Compared to the assumed mix footprint of 181 m^2, the national average solar footprint is about 214 m^2 when using only 1-Axis tracking systems and about 103 m^2 when using only flat-plate systems. A list of the state per-capita footprints for the assumed configuration, and for systems deployed only as flat-plate or 1-Axis tracking, is provided in Appendix 5. This appendix also indicates the change in footprint when industrial electricity is allocated to the actual state of use.

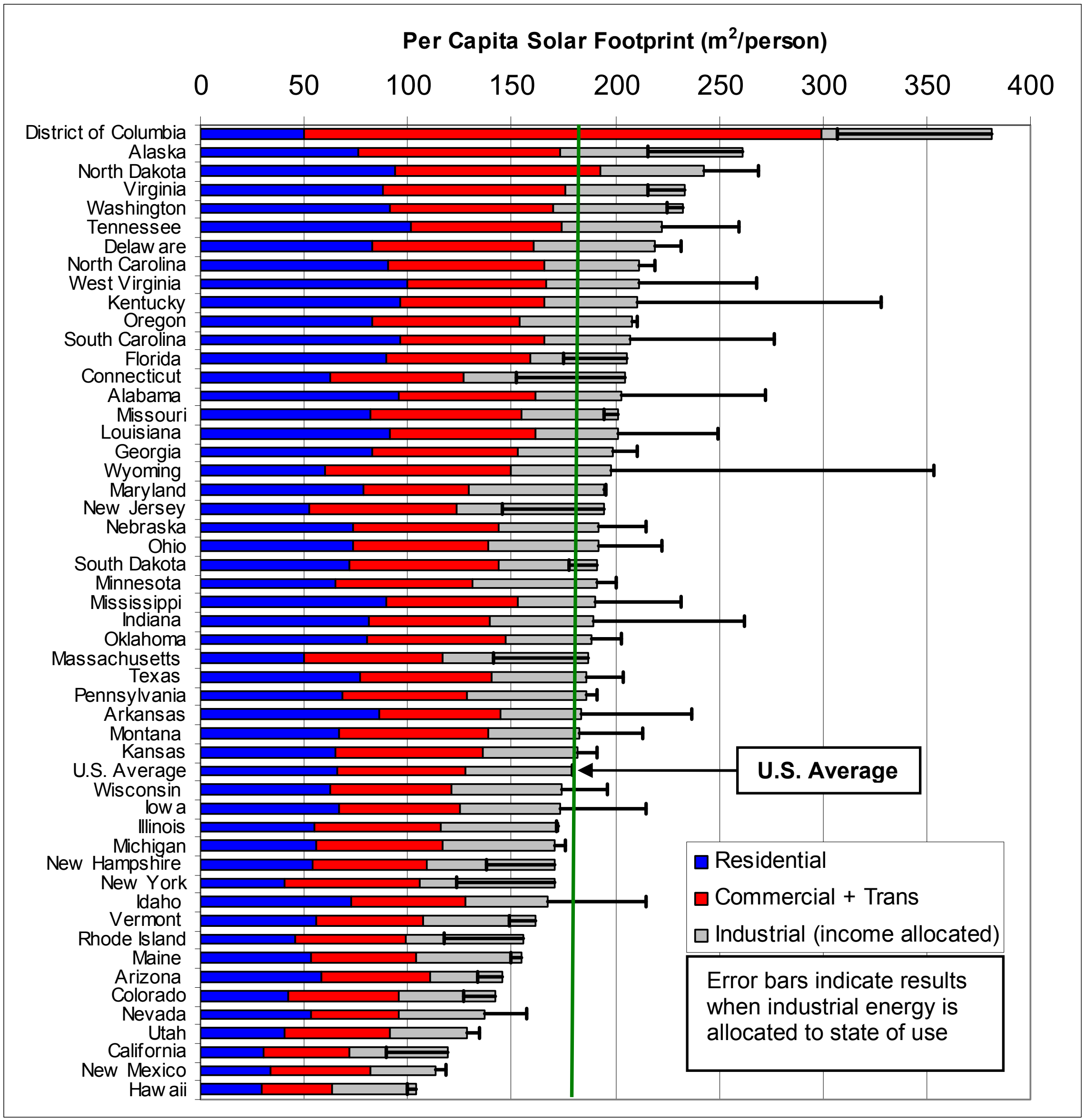

Figure 6. Per-Capita Solar Electric Footprint by State

State-Level PV Footprint in Context

The per-capita solar electric footprint can be compared to the total area available in each state. Figure 7 provides an indication of the fraction of the total state area that would be occupied by the base system configuration, based on 2005 population and electricity use data. In each state, the small square represents the total area of the solar footprint. Alaska is not drawn to scale; however, the solar footprint box within Alaska is shown on the same scale as the rest of the United States.

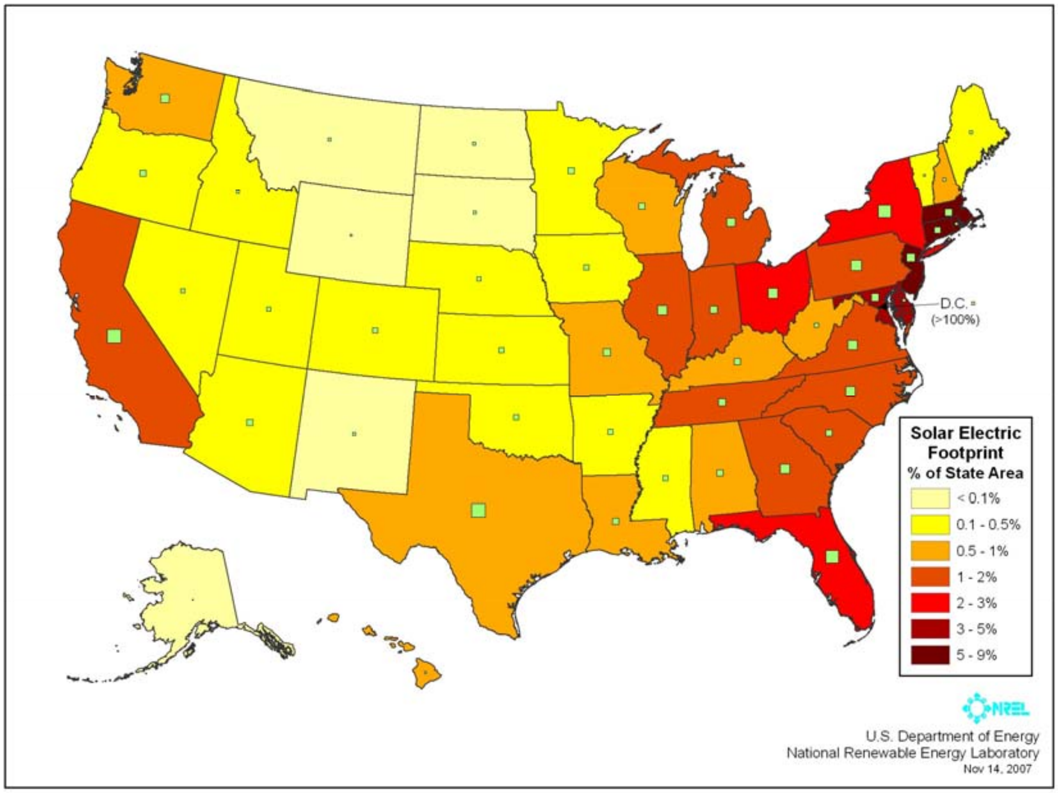

Figure 7. Per-State Solar Electric Footprint for 2005

The values in Figure 7 assume the base PV system configuration and income-based allocation of industrial electricity. Appendix 6 provides values for the flat and 1-Axis boundary cases as well as for the state-based allocation of industrial electricity.

Overall, the U.S. average solar footprint using the base system configuration is equal to about 0.6% of the total land area of the United States, or about 0.6% of each individual's "allocation" of space. In 19 states, the PV requirements of the assumed mix exceed 1% of the total land area. This is primarily a reflection of population density. In all states, where the per-capita land allocation is less than 19,000 m^2/person (except New Hampshire and Hawaii), the solar footprint exceeds 1% of the state's land area. Also of note is the land requirement for Washington, D.C., where the total solar footprint exceeds the city's total land area. This would tend to imply that with current electricity use patterns, cities themselves cannot be self-sufficient on an electricity basis using only locally generated solar energy.[34]

The total state solar footprints in Figure 7 are based on the income-weighted distribution of industrial electricity, and thus reflect this redistribution of load. If PV were actually deployed to meet the current distribution of load, it would reduce the "burden" on highly

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[34] An obvious limitation to this statement is that the majority of PV deployment in cities would be on rooftops, allowing for a greater power density. As indicated in Appendix 6, flat-roof deployment of PV in D.C. would require about 80% of the city's area using the income allocation of electricity, and about 65% if deployed to meet the actual 2005 load.

populated states in the Northeast, reflecting their lower in-state use of industrial electricity. A comparison of the total state solar footprint for industrial electricity allocated by income and by location of activity is provided in Appendix 6. In the boundary condition evaluated here, where solar PV is used to meet 100% of total demand, it might be expected that much of the high electricity intensive industrial uses (such as aluminum manufacturing) might even move to locations with better solar insolation.

To provide some context for the solar electric footprint, Table 2 provides a list of several current per-capita land uses in the United States.

Table 2. Per-Capita Solar Footprint and Other Per-Capita Land Uses

State	Per-Capita Solar Footprint (m^2/person)	Other Per-Capita Land Uses for Comparison (m^2/person)										
		Total Area	Developed Area	Urban Area	Roof Area	Major Roads	Golf Courses	Airports	Cropland	Corn	Hay	Grazing Land
Alabama	203	28,895	2452	1029	96	99	37	32	2,259	176	634	3,754
Alaska	261	2,233,457	UA	1055	70	132	17	575	178	0	127	UA
Arizona	145	49,439	1385	803	60	63	34	42	677	33	194	26,198
Arkansas	184	48,584	2382	870	87	131	40	53	11,176	274	2109	10,659
California	119	11,173	676	589	62	39	17	15	1,080	58	175	2,768
Colorado	142	57,605	1665	732	73	94	31	84	7,431	851	1303	24,777
Connecticut	205	3,584	1094	1326	48	57	31	8	200	31	72	167
Delaware	219	7,164	1311	980	69	56	30	17	2,267	806	66	117
D.C.	381	273	UA	273	58	29	6	6	0	0	0	0
Florida	206	7,861	1395	961	70	65	43	53	685	13	58	1,787
Georgia	199	16,422	2114	1133	65	90	29	23	1,920	121	281	1,430
Hawaii	104	13,065	UA	745	57	33	43	40	78	UA	UA	UA
Idaho	167	149,936	2402	792	76	203	41	68	16,137	745	4195	28,127
Illinois	173	11,277	1071	740	57	72	34	23	7,672	3564	240	854
Indiana	190	14,825	1582	936	63	91	46	29	8,703	3525	417	1,418
Iowa	173	48,794	2447	718	71	237	78	48	35,091	17099	2036	5,827
Kansas	182	77,106	3005	826	73	287	50	88	39,275	4905	4465	28,210
Kentucky	210	24,660	1967	775	92	117	41	22	5,388	1078	2386	5,943
Louisiana	201	25,031	1627	969	82	84	21	44	4,909	283	368	3,096
Maine	155	60,636	2508	696	62	138	55	49	1,190	80	429	428
Maryland	195	4,529	989	866	60	51	21	12	1,115	353	148	349
Mass.	187	3,156	988	1137	51	58	32	12	158	11	52	88
Michigan	171	14,900	1574	868	63	100	56	32	3,255	882	457	892
Minnesota	191	40,218	1857	778	65	196	59	40	16,878	5717	1621	3,510
Mississippi	190	41,770	2360	847	91	200	34	39	7,006	473	1085	5,479
Missouri	201	30,773	1920	834	70	165	36	37	9,690	1870	2868	9,909
Montana	183	403,300	4717	747	90	653	58	191	64,095	278	9682	191,855

Nebraska	192	113,243	2875	687	73	413	63	94	45,552	18537	6408	59,383
Nevada	137	117,916	857	653	64	154	28	59	1,149	6	762	15,863
New Hamp.	171	17,774	1999	1134	57	108	46	30	392	43	157	320
New Jersey	194	2,207	902	846	44	49	21	10	247	37	53	49
New Mexico	114	163,194	2942	1056	73	280	28	132	3,338	269	642	96,859
New York	171	6,331	729	535	42	51	27	12	1,127	199	319	574
N. Carolina	212	14,547	2244	1117	74	103	41	22	2,651	361	315	964
N. Dakota	243	281,509	6444	600	80	1304	89	153	155,232	10756	17311	78,474
Ohio	192	9,246	1364	911	65	95	42	20	3,978	1111	427	883
Oklahoma	188	50,190	2461	854	89	276	34	74	10,360	305	3595	32,284
Oregon	208	68,326	1492	760	78	254	34	60	4,206	56	1148	16,367
Penn.	186	9,357	1398	902	51	89	37	15	1,679	439	569	717
Rhode I.	156	2,521	826	947	49	70	28	12	76	8	27	100
S. Carolina	207	18,362	2412	1185	74	159	57	33	2,313	290	337	1,183
S. Dakota	191	253,638	5198	575	73	1124	68	133	90,517	23290	16044	129,544
Tennessee	222	17,924	1815	1095	91	135	30	21	3,295	369	1226	3,802
Texas	186	29,572	1766	853	76	145	23	51	4,674	303	887	20,822
Utah	128	85,431	1266	773	55	183	27	48	2,890	103	1127	21,962
Vermont	162	38,491	2267	624	61	225	65	29	3,837	551	1622	2,202
Virginia	233	13,557	1611	848	62	104	28	17	1,570	254	657	1,800
Washington	233	27,392	1505	911	72	145	28	33	4,287	89	487	6,648
W. Virginia	211	34,376	2264	816	80	230	40	30	1,836	100	1313	4,969
Wisconsin	174	25,447	1921	782	66	259	56	39	7,627	2658	1559	2,711
Wyoming	198	494,281	5299	884	95	1389	57	215	17,439	668	8251	237,177
U.S Average	181	30,914	1505	837	65	162	34	35	5,120	1059	835	8,021

UA= Unavailable Data

The sources and assumptions underlying the land-use estimates shown in Table 2 are discussed in detail in Appendix 7.

Overall, the U.S. average solar electric footprint of 181 m^2 per person is about 12% of the average “developed area” footprint of 1505 m^2 or 22% of the “urban area” footprint of 837 m^2 per person. Some fraction of PV deployment will occur on rooftops, building facades, and other “zero impact” areas, such as parking lot awnings. Practically, the deployment of PV on these types of areas is significantly reduced when considering shading, orientation, and other availability factors. In addition, solar PV competes with other “green” roof options, including solar water heating, daylighting, and roof-top gardens. Additional study and analysis is needed to estimate the large but uncertain potential for deployment of PV on rooftops, parking lots, and other zero/low impact areas.

If PV is deployed in land-based areas, there are some options for minimum impact deployment at Superfund and brown-field sites and other compromised land, and certain airport land.[35] There are several additional considerations when evaluating the need to deploy land-based PV on a large scale. Each of the land-use indicators in Table 2 has a substantially different impact, whether it is aesthetics, ecosystem changes, use of chemicals, etc. At worst, ground-mounted PV could have impacts approximating those of paved roads, while pole-mounted PV flat panels or tracking arrays could accommodate shade-tolerant plants underneath a large fraction of the arrays; the coexistence of PV deployment with animals grazing also has been demonstrated.[36]

As shown in Table 2, the U.S. average solar electric footprint is similar in magnitude to the land use for major roads, golf courses, and airports combined. Note that major roads do not include local roads. In addition, the U.S. average solar electric footprint is less than 2% of the land dedicated to cropland and grazing, and about 10% of the land dedicated to growing hay and corn.

One potentially notable comparison is the relative land use associated with corn ethanol. In 2006, the amount of corn dedicated to ethanol feedstocks was about 21% of corn production.[37] As a result, the national average per-capita corn ethanol area (in 2006) of about 219 m^2 exceeds the average per-capita solar electric footprint. However, this comparison is of somewhat limited value because most of the corn production is concentrated in a few states. A complete accounting of various land-use impacts is somewhat subjective, and a full analysis is beyond the scope of this report; however, it should be considered when comparing PV deployment to alternative uses.

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[35] R. Ruther, Solar Airports ReFocus, July/August 2005 30-34

[36] Solon Mover Germany http://www.solonmover.com/

[37] Food and Agricultural Policy Research Institute (2007). “FAPRI Agricultural Outlook 2007” at http://www.fapri.iastate.edu/outlook2007/

Conclusions

In this paper, we have quantified the state-by-state per-capita solar electric footprint for the United States. Major findings include:

- The use of normal state-level per-capita electricity data, where state electricity is divided by state population, may result in unrealistic estimates of the regional electric footprint. The effect of embodied energy in manufactured goods is to reduce the effective per-capita electricity demand in heavily industrialized states, and increase the per capita demand in less industrialized states.
- Besides module efficiency and local insolation, the area required per unit of annual energy output is strongly dependent on the PV array configuration. Land-based tracking arrays require much more array per unit of energy production than flat arrays due to the spacing between arrays for maintenance and avoidance of shading.
- Using existing technology for the per-capita solar electric footprint, the area required to meet the average per-capita electricity demand using solar photovoltaics is about 181 m^2 per person in the United States. This value assumes the availability of long-term (including seasonal) storage, and a mix of tracking and flat-plate PV systems.
- The area required to meet the total (2005) national electric demand with solar PV is about 0.6% of the total area of the United States. On a state-by-state basis, the solar electric footprint as a percentage of total area varies from less than 0.1% for Wyoming to about 9% for New Jersey. This total area is a relatively small fraction of the existing developed or urban area in each state. It is also less than 2% of the land dedicated to cropland and grazing in the United States.

One of the strengths of PV is that it can be deployed in a wide range of applications and locations – from central to distributed applications, and from rooftops to parking lots to field mounted systems. While the land requirements for the large-scale deployment of PV are not trivial, the ability to site PV on a range of built structures and other areas means that PV technology will not run up against "land-use" constraints in the United States for a long time. In addition, the fact that PV technology has the potential to be sited on areas not suitable for other uses (rooftops, brownfields, etc.) and in a manner that is compatible with multiple uses (i.e., grazing, growing shade tolerant crops, etc.) could minimize its impacts on land-use and ecosystem services.

Appendix 1. State Electricity End Use by Sector (2003-2005)

State	Residential (GWH)			Commercial & Transportation (GWH)			Industrial (GWH)			Total (GWH)		
	2003	2004	2005	2003	2004	2005	2003	2005	2004	2003	2004	2005
Alabama	29,416	30,109	31,315	20,411	21,166	21,608	34,017	36,279	35,595	83,844	86,871	89,202
Alaska	1,987	2,062	2,062	2,473	2,601	2,695	1,104	1,156	1,126	5,564	5,788	5,913
Arizona	27,742	28,921	30,544	25,425	26,106	27,468	10,914	11,379	11,906	64,080	66,933	69,391
Arkansas	15,598	15,619	17,134	10,568	10,731	11,366	16,942	17,665	17,322	43,108	43,672	46,165
California	82,926	83,361	85,610	110,386	119,853	118,397	49,909	50,242	48,812	243,221	252,026	254,250
Colorado	15,725	15,532	16,436	19,694	19,517	19,865	11,076	12,052	11,675	46,495	46,724	48,353
Connecticut	13,178	13,211	13,803	13,286	13,645	14,139	5,366	5,153	5,358	31,830	32,215	33,095
Delaware	4,190	4,305	4,594	3,886	4,033	4,238	4,523	3,305	3,423	12,600	11,761	12,137
D. C.	1,754	1,834	1,938	8,925	9,298	9,621	267	256	282	10,946	11,415	11,816
Florida	112,650	112,203	115,791	85,354	86,863	89,509	19,375	19,676	19,518	217,379	218,584	224,977
Georgia	48,174	51,124	52,827	40,734	42,497	44,837	34,768	34,602	35,846	123,677	129,466	132,265
Hawaii	3,028	3,162	3,164	3,517	3,632	3,463	3,846	3,912	3,937	10,391	10,732	10,539
Idaho	7,090	7,314	7,601	5,466	5,484	5,615	8,663	8,636	9,011	21,219	21,809	21,853
Illinois	43,161	43,443	48,593	50,045	47,803	50,505	43,042	45,888	48,008	136,248	139,254	144,986
Indiana	30,726	31,192	33,629	22,458	22,974	23,976	47,284	48,944	48,928	100,468	103,094	106,549
Iowa	12,768	12,625	13,571	11,637	10,840	11,271	16,803	17,915	17,437	41,207	40,903	42,757
Kansas	12,602	12,417	13,406	13,751	13,831	14,453	10,382	11,165	10,879	36,735	37,127	39,024
Kentucky	24,704	25,187	26,947	17,946	18,443	19,091	42,570	43,314	42,891	85,220	86,521	89,351
Louisiana	28,572	28,863	28,654	21,947	22,584	21,704	27,251	27,031	28,290	77,769	79,737	77,389
Maine	4,219	4,331	4,503	3,959	4,325	4,157	3,793	3,702	3,711	11,972	12,368	12,363
Maryland	26,671	27,952	28,440	17,412	17,745	18,409	27,176	21,517	21,195	71,259	66,892	68,365
Mass.	19,591	19,769	20,539	25,939	26,426	26,818	9,984	9,871	9,947	55,514	56,142	57,228
Michigan	33,669	33,104	36,095	35,395	38,635	39,605	39,813	34,745	34,867	108,877	106,606	110,445
Minnesota	20,638	20,507	21,743	20,533	20,417	22,010	21,916	22,266	22,415	63,087	63,340	66,019
Mississippi	17,670	17,580	17,953	12,593	12,750	12,666	15,281	15,282	15,702	45,544	46,033	45,901
Missouri	31,422	31,351	34,412	27,987	28,401	29,660	14,831	16,869	14,303	74,240	74,054	80,940
Montana	4,120	4,053	4,221	4,438	4,330	4,473	4,267	4,784	4,574	12,825	12,957	13,479
Nebraska	8,852	8,757	9,309	8,583	8,501	8,848	8,421	8,819	8,618	25,857	25,876	26,976
Nevada	10,340	10,673	11,080	8,168	8,275	8,524	11,624	12,897	12,364	30,132	31,312	32,501
New Hamp.	4,252	4,282	4,495	4,318	4,363	4,576	2,403	2,174	2,328	10,973	10,973	11,245
New Jersey	27,367	28,020	29,973	36,801	38,363	40,061	12,215	11,862	11,210	76,383	77,593	81,897
New Mexico	5,418	5,635	5,865	8,063	8,239	8,411	5,849	6,363	5,972	19,330	19,846	20,639
New York	47,116	47,379	50,533	75,184	77,028	79,668	21,745	19,947	20,675	144,045	145,082	150,148
North Carolina	49,349	51,717	54,073	41,672	42,864	44,161	30,314	30,101	31,075	121,335	125,657	128,335
North Dakota	3,707	3,663	3,796	3,800	3,843	3,994	2,954	3,050	3,010	10,461	10,516	10,840
Ohio	49,621	50,300	53,904	44,741	45,363	46,918	57,828	59,354	58,558	152,189	154,221	160,176
Oklahoma	20,162	19,699	21,309	16,958	17,020	17,477	13,308	14,920	14,223	50,428	50,942	53,707
Oregon	17,736	18,001	18,339	15,499	15,682	15,397	11,961	12,684	11,954	45,195	45,636	46,419
Pennsylvania	49,651	50,663	53,661	43,945	45,179	46,661	46,773	47,950	47,659	140,369	143,501	148,273
Rhode Island	2,998	3,000	3,171	3,490	3,542	3,628	1,309	1,250	1,345	7,797	7,888	8,049
South Carolina	26,422	27,910	28,676	19,336	20,113	20,498	31,296	32,080	31,886	77,054	79,908	81,254
South Dakota	3,740	3,696	3,973	3,713	3,627	3,998	1,627	1,840	1,891	9,080	9,214	9,811
Tennessee	37,697	38,526	41,132	27,481	28,250	29,148	32,278	33,625	32,885	97,456	99,661	103,905
Texas	121,355	120,330	126,562	96,784	99,697	110,855	104,547	96,841	100,588	322,686	320,615	334,258
Utah	7,166	7,325	7,567	9,048	9,370	9,444	7,646	7,989	7,816	23,860	24,512	25,000
Vermont	2,011	2,109	2,189	1,881	1,978	2,051	1,460	1,644	1,577	5,352	5,664	5,883
Virginia	40,877	42,503	44,662	41,351	43,186	44,834	19,282	19,354	19,734	101,510	105,424	108,850
Washington	31,872	32,455	33,212	28,081	28,268	28,101	18,180	22,112	19,259	78,134	79,982	83,425
West Virginia	10,473	10,756	11,384	7,136	7,221	7,456	10,687	11,312	10,942	28,297	28,919	30,152
Wisconsin	21,364	21,192	22,458	20,056	19,349	22,501	25,821	25,376	27,435	67,241	67,976	70,336
Wyoming	2,286	2,262	2,377	3,282	3,393	3,754	7,685	8,007	7,884	13,254	13,540	14,138
U.S. Total	1,275,824	1,291,982	1,359,227	1,205,537	1,237,648	1,282,585	1,012,373	1,019,156	1,017,850	3,493,734	3,547,479	3,660,969

Source: U.S. Department of Energy (2006). *Electric Power Annual 2005*, DOE/EIA-0348(2005), Energy Information Administration, Washington, D.C. (State Data Tables 1990 – 2005 at http://www.eia.doe.gov/cneaf/electricity/epa/sales_state.xls)

Appendix 2. State Population and Income (2003-2005)

State	**Population ($1000s)**			**Total State Income ($1000s)**			**Fraction of Total U.S. Income (assigned fraction of industrial energy use)**		
	2003	2004	2005	2003	2004	2005	2003	2004	2005
Alabama	4,495	4,517	4,548	118,356	126,655	134,736	1.3%	1.3%	1.3%
Alaska	648	657	663	21,184	22,259	23,588	0.2%	0.2%	0.2%
Arizona	5,582	5,746	5,953	150,582	164,122	178,706	1.6%	1.7%	1.7%
Arkansas	2,724	2,747	2,776	66,476	70,853	74,059	0.7%	0.7%	0.7%
California	35,466	35,841	36,154	1,187,040	1,268,049	1,335,386	13.0%	13.1%	13.1%
Colorado	4,546	4,599	4,663	154,829	164,673	174,919	1.7%	1.7%	1.7%
Connecticut	3,482	3,494	3,501	148,777	158,567	165,890	1.6%	1.6%	1.6%
Delaware	817	829	842	27,395	29,300	31,218	0.3%	0.3%	0.3%
D. C.	577	580	582	26,914	29,125	30,739	0.3%	0.3%	0.3%
Florida	16,982	17,367	17,768	514,378	564,997	604,131	5.6%	5.8%	5.9%
Georgia	8,750	8,935	9,133	250,806	264,728	282,322	2.7%	2.7%	2.8%
Hawaii	1,246	1,259	1,273	37,837	41,129	43,913	0.4%	0.4%	0.4%
Idaho	1,367	1,395	1,429	34,816	38,229	40,706	0.4%	0.4%	0.4%
Illinois	12,650	12,714	12,765	426,877	442,349	462,928	4.7%	4.6%	4.5%
Indiana	6,192	6,223	6,266	178,675	187,533	195,332	2.0%	1.9%	1.9%
Iowa	2,942	2,954	2,966	83,920	91,230	93,919	0.9%	0.9%	0.9%
Kansas	2,727	2,738	2,748	81,116	85,520	90,320	0.9%	0.9%	0.9%
Kentucky	4,114	4,140	4,173	106,319	111,873	117,967	1.2%	1.2%	1.2%
Louisiana	4,481	4,496	4,507	115,695	121,781	111,167	1.3%	1.3%	1.1%
Maine	1,307	1,314	1,318	37,533	39,236	40,612	0.4%	0.4%	0.4%
Maryland	5,507	5,553	5,590	205,737	220,603	234,609	2.2%	2.3%	2.3%
Mass.	6,440	6,436	6,433	253,993	267,972	279,860	2.8%	2.8%	2.7%
Michigan	10,068	10,093	10,101	313,503	320,261	331,349	3.4%	3.3%	3.2%
Minnesota	5,059	5,094	5,127	173,498	184,225	191,175	1.9%	1.9%	1.9%
Mississippi	2,874	2,893	2,908	66,305	69,450	72,862	0.7%	0.7%	0.7%
Missouri	5,712	5,753	5,798	166,129	173,054	181,066	1.8%	1.8%	1.8%
Montana	917	926	935	24,177	25,791	27,122	0.3%	0.3%	0.3%
Nebraska	1,737	1,747	1,758	53,391	55,828	57,885	0.6%	0.6%	0.6%
Nevada	2,241	2,332	2,412	71,183	79,353	86,224	0.8%	0.8%	0.8%
New Hamp.	1,286	1,298	1,307	44,327	47,248	49,356	0.5%	0.5%	0.5%
New Jersey	8,633	8,676	8,703	342,858	363,158	381,466	3.7%	3.7%	3.7%
New Mexico	1,878	1,901	1,926	46,650	50,707	53,714	0.5%	0.5%	0.5%
New York	19,238	19,292	19,316	693,533	742,209	771,990	7.6%	7.6%	7.6%
North Carolina	8,416	8,531	8,672	234,983	252,253	269,203	2.6%	2.6%	2.6%
North Dakota	633	636	635	18,179	18,509	19,899	0.2%	0.2%	0.2%
Ohio	11,438	11,461	11,471	341,146	352,588	365,453	3.7%	3.6%	3.6%
Oklahoma	3,504	3,523	3,543	92,599	100,027	106,119	1.0%	1.0%	1.0%
Oregon	3,561	3,589	3,639	105,161	111,325	117,497	1.1%	1.1%	1.1%
Pennsylvania	12,351	12,377	12,405	393,908	413,589	433,400	4.3%	4.3%	4.2%
Rhode Island	1,075	1,079	1,074	35,072	36,679	37,923	0.4%	0.4%	0.4%
South Carolina	4,142	4,195	4,247	107,203	113,632	120,123	1.2%	1.2%	1.2%
South Dakota	764	770	775	22,386	24,053	25,201	0.2%	0.2%	0.2%
Tennessee	5,834	5,886	5,956	165,402	174,452	184,443	1.8%	1.8%	1.8%
Texas	22,134	22,518	22,929	649,419	690,480	744,270	7.1%	7.1%	7.3%
Utah	2,356	2,422	2,490	59,412	63,478	68,039	0.6%	0.7%	0.7%
Vermont	619	621	622	18,711	19,519	20,362	0.2%	0.2%	0.2%
Virginia	7,376	7,472	7,564	250,605	266,751	283,685	2.7%	2.7%	2.8%
Washington	6,130	6,206	6,292	202,942	216,921	223,232	2.2%	2.2%	2.2%
West Virginia	1,809	1,811	1,814	43,841	45,819	47,926	0.5%	0.5%	0.5%
Wisconsin	5,467	5,499	5,528	168,120	176,482	183,948	1.8%	1.8%	1.8%
Wyoming	501	506	509	16,420	17,723	18,981	0.2%	0.2%	0.2%
U.S. Total	290,796	293,638	296,507	9,150,320	9,716,351	10,220,942	100.0%	100.0%	100.0%

Sources: Population data from: U.S. Census Bureau (2006). *Annual Estimates of the Population for the United States and States, and for Puerto Rico: April 1, 2000 to July 1, 2006* (NST-EST2006-01) http://www.census.gov/popest/states/NST-ann-est.html

State Income data from: Regional Economic Information System, Bureau of Economic Analysis, U.S. Department of Commerce http://www.bea.gov/regional/reis

Appendix 3. State Annual Average Per-Capita Electricity Use (kWh/person/year) (2003-2005)

State	Residential	Commercial and Trans.	Industrial by Income	Industrial by State	Total (Income Weight)	Total (State Weight)
Alabama	6,698	4,659	2,935	7,808	14,292	19,165
Alaska	3,105	3,947	3,572	1,720	10,623	8,772
Arizona	5,045	4,571	2,990	1,980	12,605	11,595
Arkansas	5,862	3,961	2,688	6,297	12,510	16,119
California	2,344	3,244	3,697	1,386	9,285	6,974
Colorado	3,454	4,279	3,753	2,520	11,486	10,252
Connecticut	3,836	3,920	4,735	1,516	12,491	9,272
Delaware	5,261	4,886	3,704	4,531	13,851	14,678
D. C.	3,177	16,008	5,228	463	24,414	19,649
Florida	6,537	5,022	3,383	1,124	14,942	12,683
Georgia	5,670	4,774	3,119	3,925	13,563	14,369
Hawaii	2,476	2,809	3,407	3,095	8,692	8,380
Idaho	5,249	3,953	2,843	6,280	12,045	15,481
Illinois	3,545	3,891	3,665	3,591	11,101	11,027
Indiana	5,114	3,715	3,153	7,770	11,981	16,599
Iowa	4,397	3,809	3,183	5,885	11,389	14,091
Kansas	4,678	5,117	3,280	3,948	13,075	13,743
Kentucky	6,182	4,464	2,836	10,362	13,482	21,008
Louisiana	6,385	4,912	2,718	6,124	14,015	17,421
Maine	3,313	3,158	3,126	2,845	9,597	9,317
Maryland	4,988	3,217	4,160	4,200	12,365	12,406
Mass.	3,102	4,101	4,354	1,543	11,557	8,746
Michigan	3,399	3,755	3,347	3,616	10,500	10,770
Minnesota	4,115	4,120	3,767	4,358	12,002	12,594
Mississippi	6,133	4,381	2,522	5,333	13,036	15,847
Missouri	5,629	4,984	3,161	2,664	13,774	13,277
Montana	4,461	4,766	2,909	4,903	12,136	14,130
Nebraska	5,135	4,947	3,344	4,932	13,425	15,014
Nevada	4,594	3,575	3,547	5,278	11,717	13,447
New Hamp.	3,348	3,407	3,798	1,775	10,553	8,531
New Jersey	3,281	4,429	4,383	1,357	12,094	9,067
New Mexico	2,965	4,332	2,775	3,187	10,072	10,484
New York	2,507	4,008	4,001	1,078	10,517	7,594
North Carolina	6,054	5,023	3,094	3,572	14,170	14,648
North Dakota	5,868	6,115	3,118	4,737	15,101	16,719
Ohio	4,475	3,987	3,233	5,113	11,695	13,575
Oklahoma	5,786	4,868	2,961	4,015	13,615	14,669
Oregon	5,012	4,318	3,245	3,392	12,575	12,721
Pennsylvania	4,146	3,656	3,504	3,834	11,307	11,637
Rhode Island	2,841	3,303	3,565	1,209	9,709	7,354
South Carolina	6,595	4,763	2,840	7,570	14,198	18,928
South Dakota	4,940	4,910	3,252	2,320	13,103	12,170
Tennessee	6,638	4,801	3,110	5,589	14,549	17,028
Texas	5,449	4,545	3,232	4,471	13,225	14,465
Utah	3,035	3,834	2,754	3,227	9,623	10,097
Vermont	3,389	3,174	3,301	2,514	9,863	9,076
Virginia	5,711	5,771	3,746	2,605	15,228	14,087
Washington	5,236	4,534	3,621	3,195	13,391	12,964
West Virginia	6,002	4,014	2,656	6,062	12,672	16,079
Wisconsin	3,942	3,753	3,361	4,768	11,055	12,462
Wyoming	4,568	6,879	3,672	15,553	15,118	26,999
U.S. Average	4,457	4,229	3,462	3,462	12,147	12,147

Appendix 4. State Average Insolation Values (2003-2005)

Weighted by Region of Use Based on 2005 Electricity Use Patterns (kwh/m^2/day)

State	Orientation						
	Flat	S 10º	SW 10º	SE 10º	S 25º	1-axis 0º	2-axis
Alabama	4.3	4.6	4.5	4.5	4.9	5.6	6.4
Arizona	5.6	6.0	5.9	5.9	6.3	7.7	8.9
Arkansas	4.3	4.6	4.5	4.5	4.9	5.7	6.5
California	4.9	5.2	5.1	5.1	5.5	6.4	7.2
Colorado	4.8	5.3	5.1	5.2	5.7	6.7	8.0
Connecticut	3.7	4.0	3.9	3.9	4.3	4.8	5.5
Delaware	3.9	4.2	4.1	4.1	4.5	5.0	5.8
District of Columbia	3.9	4.3	4.2	4.2	4.6	5.2	6.0
Florida	4.7	5.0	4.9	4.9	5.2	6.1	6.7
Georgia	4.3	4.6	4.5	4.5	4.9	5.6	6.4
Hawaii	5.5	5.7	5.7	5.7	5.8	7.1	7.7
Idaho	4.4	4.7	4.6	4.6	5.1	6.1	7.2
Illinois	3.9	4.2	4.1	4.1	4.5	5.2	6.0
Indiana	3.9	4.2	4.1	4.1	4.4	5.1	5.8
Iowa	4.0	4.3	4.2	4.2	4.6	5.3	6.2
Kansas	4.4	4.7	4.6	4.6	5.1	5.9	6.9
Kentucky	4.0	4.3	4.2	4.2	4.5	5.3	6.0
Louisiana	4.5	4.8	4.7	4.7	5.0	5.8	6.5
Maine	3.7	4.0	3.9	3.9	4.3	4.9	5.8
Maryland	3.9	4.2	4.1	4.1	4.5	5.1	5.9
Massachusetts	3.7	4.0	3.9	3.9	4.3	4.8	5.6
Michigan	3.7	4.0	3.9	3.9	4.3	4.9	5.6
Minnesota	3.7	4.1	3.9	3.9	4.4	5.0	6.0
Mississippi	4.4	4.7	4.6	4.6	4.9	5.7	6.4
Missouri	4.2	4.5	4.4	4.4	4.8	5.6	6.5
Montana	3.9	4.3	4.2	4.2	4.7	5.5	6.7
Nebraska	4.2	4.6	4.5	4.4	4.9	5.7	6.7
Nevada	5.4	5.8	5.6	5.7	6.2	7.6	8.8
New Hampshire	3.7	4.0	3.9	3.9	4.4	4.9	5.8
New Jersey	3.8	4.1	4.0	4.0	4.4	4.9	5.7
New Mexico	5.5	5.9	5.8	5.7	6.3	7.5	8.7
New York	3.8	4.0	4.0	3.9	4.3	4.9	5.6
North Carolina	4.2	4.5	4.4	4.4	4.8	5.5	6.3
North Dakota	3.7	4.0	3.9	3.9	4.3	5.0	6.0
Ohio	3.8	4.1	4.0	4.0	4.3	4.9	5.6
Oklahoma	4.5	4.8	4.7	4.7	5.1	6.0	6.9
Oregon	3.8	4.1	4.0	3.9	4.3	5.0	5.8
Pennsylvania	3.7	4.0	3.9	3.9	4.3	4.8	5.6
Rhode Island	3.8	4.1	4.0	4.0	4.4	4.9	5.7
South Carolina	4.3	4.6	4.5	4.5	4.9	5.6	6.4
South Dakota	4.1	4.4	4.3	4.3	4.8	5.5	6.6
Tennessee	4.2	4.5	4.4	4.3	4.7	5.4	6.1
Texas	4.6	4.9	4.8	4.8	5.1	6.0	6.7
Utah	4.6	4.9	4.8	4.8	5.3	6.3	7.3
Vermont	3.7	4.0	3.9	3.9	4.3	4.9	5.8
Virginia	4.0	4.4	4.3	4.2	4.6	5.3	6.1
Washington	3.6	3.8	3.8	3.7	4.1	4.7	5.5
West Virginia	3.8	4.1	4.0	4.0	4.3	4.9	5.6
Wisconsin	3.8	4.1	4.0	4.0	4.4	5.1	5.9
Wyoming	4.5	4.9	4.7	4.8	5.3	6.3	7.6

Appendix 5. Per-Capita Solar Footprint

	Per-Capita Solar Footprint m^2 (industrial electricity allocated by income)			Per-Capita Solar Footprint m^2 (industrial electricity allocated by normal use)		
State	**Base**	**1-Axis**	**Flat**	**Base**	**1-Axis**	**Flat**
Alabama	203	253	120	272	339	160
Alaska	261	314	158	215	260	131
Arizona	145	167	84	134	154	77
Arkansas	184	219	105	237	282	135
California	119	143	67	89	107	51
Colorado	142	165	84	126	147	75
Connecticut	205	251	118	152	186	88
Delaware	219	265	127	232	281	134
District of Columbia	381	459	222	307	369	178
Florida	206	246	115	175	209	97
Georgia	199	238	113	210	253	120
Hawaii	104	121	56	100	117	54
Idaho	167	192	99	215	247	127
Illinois	173	207	100	171	206	99
Indiana	190	228	109	263	316	150
Iowa	173	206	101	215	255	126
Kansas	182	215	106	191	226	112
Kentucky	210	252	120	328	393	187
Louisiana	201	241	113	250	299	140
Maine	155	185	91	150	180	89
Maryland	195	236	113	195	236	113
Massachusetts	187	229	109	142	173	82
Michigan	171	206	99	176	211	101
Minnesota	191	227	114	201	238	119
Mississippi	190	228	107	231	277	130
Missouri	201	239	117	194	230	113
Montana	183	212	110	213	247	128
Nebraska	192	227	113	215	254	126
Nevada	137	156	80	157	180	92
New Hampshire	171	206	100	138	167	81
New Jersey	194	237	112	146	177	84
New Mexico	114	132	66	118	137	69
New York	171	207	98	123	149	71
North Carolina	212	255	121	219	264	125
North Dakota	243	284	145	269	315	161
Ohio	192	231	109	223	269	127
Oklahoma	188	222	109	203	239	117
Oregon	208	246	120	210	249	122
Pennsylvania	186	226	107	192	233	110
Rhode Island	156	190	91	118	144	69
South Carolina	207	250	118	277	333	158
South Dakota	191	225	114	178	209	106
Tennessee	222	267	126	260	312	148
Texas	186	220	105	204	241	115
Utah	128	149	75	135	157	78
Vermont	162	191	95	149	176	87
Virginia	233	281	135	216	260	125
Washington	233	278	135	225	269	130
West Virginia	211	256	120	268	325	153
Wisconsin	174	208	102	197	234	115
Wyoming	198	230	119	354	410	212
U.S Average	181	214	103	181	214	103

Appendix 6. Total Solar Electric Footprint and Land Occupation Fraction

State	Total Land Per Capita (m^2)	PV occupation fraction (%) (industrial electricity allocated by income)			PV occupation fraction (%) (industrial electricity allocated by state)		
		Base	**1-Axis**	**Flat**	**Base**	**1-Axis**	**Flat**
Alabama	28,895	0.7	0.9	0.4	0.9	1.2	0.6
Alaska	2,233,457	0.01	0.01	0.01	0.01	0.01	0.01
Arizona	49,439	0.3	0.3	0.2	0.3	0.3	0.2
Arkansas	48,584	0.4	0.5	0.2	0.5	0.6	0.3
California	11,173	1.1	1.3	0.6	0.8	1.0	0.5
Colorado	57,605	0.2	0.3	0.1	0.2	0.3	0.1
Connecticut	3,584	5.7	7.0	3.3	4.2	5.2	2.4
Delaware	7,164	3.1	3.7	1.8	3.2	3.9	1.9
District of Columbia	273	140	168	81.1	112	135	65
Florida	7,861	2.6	3.1	1.5	2.2	2.7	1.2
Georgia	16,422	1.2	1.5	0.7	1.3	1.5	0.7
Hawaii	13,065	0.8	0.9	0.4	0.8	0.9	0.4
Idaho	149,936	0.1	0.1	0.1	0.1	0.2	0.1
Illinois	11,277	1.5	1.8	0.9	1.5	1.8	0.9
Indiana	14,825	1.3	1.5	0.7	1.8	2.1	1.0
Iowa	48,794	0.4	0.4	0.2	0.4	0.5	0.3
Kansas	77,106	0.2	0.3	0.1	0.2	0.3	0.1
Kentucky	24,660	0.9	1.0	0.5	1.3	1.6	0.8
Louisiana	25,031	0.8	1.0	0.4	1.0	1.2	0.6
Maine	60,636	0.3	0.3	0.2	0.2	0.3	0.1
Maryland	4,529	4.3	5.2	2.5	4.3	5.2	2.5
Massachusetts	3,156	5.9	7.2	3.5	4.5	5.5	2.6
Michigan	14,900	1.1	1.4	0.7	1.2	1.4	0.7
Minnesota	40,218	0.5	0.6	0.3	0.5	0.6	0.3
Mississippi	41,770	0.5	0.5	0.3	0.6	0.7	0.3
Missouri	30,773	0.7	0.8	0.4	0.6	0.7	0.4
Montana	403,300	0.05	0.1	0.03	0.1	0.1	0.03
Nebraska	113,243	0.2	0.2	0.1	0.2	0.2	0.1
Nevada	117,916	0.1	0.1	0.1	0.1	0.2	0.1
New Hampshire	17,774	1.0	1.2	0.6	0.8	0.9	0.5
New Jersey	2,207	8.8	10.7	5.1	6.6	8.0	3.8
New Mexico	163,194	0.1	0.1	0.04	0.1	0.1	0.04
New York	6,331	2.7	3.3	1.6	1.9	2.4	1.1
North Carolina	14,547	1.5	1.8	0.8	1.5	1.8	0.9
North Dakota	281,509	0.1	0.1	0.1	0.1	0.1	0.1
Ohio	9,246	2.1	2.5	1.2	2.4	2.9	1.4
Oklahoma	50,190	0.4	0.4	0.2	0.4	0.5	0.2
Oregon	68,326	0.3	0.4	0.2	0.3	0.4	0.2
Pennsylvania	9,357	2.0	2.4	1.1	2.0	2.5	1.2
Rhode Island	2,521	6.2	7.6	3.6	4.7	5.7	2.7
South Carolina	18,362	1.1	1.4	0.6	1.5	1.8	0.9
South Dakota	253,638	0.1	0.1	0.04	0.1	0.1	0.04
Tennessee	17,924	1.2	1.5	0.7	1.5	1.7	0.8
Texas	29,572	0.6	0.7	0.4	0.7	0.8	0.4
Utah	85,431	0.2	0.2	0.1	0.2	0.2	0.1
Vermont	38,491	0.4	0.5	0.2	0.4	0.5	0.2
Virginia	13,557	1.7	2.1	1.0	1.6	1.9	0.9
Washington	27,392	0.8	1.0	0.5	0.8	1.0	0.5
West Virginia	34,376	0.6	0.7	0.4	0.8	0.9	0.4
Wisconsin	25,447	0.7	0.8	0.4	0.8	0.9	0.5
Wyoming	494,281	0.04	0.05	0.02	0.1	0.1	0.04
U.S Average	30,914	0.6	0.7	0.3	0.6	0.7	0.3

Appendix 7. Land-Use Data

In each category, the per-capita land use was calculated by dividing the total area occupied by the use category by the state's estimated population for that year. State population data was obtained from the U.S. Census Bureau (2006). *Annual Estimates of the Population for the United States and States, and for Puerto Rico: April 1, 2000, to July 1, 2006* (NST-EST2006-01) http://www.census.gov/popest/states/NST-ann-est.html

Total Area: Source: U.S. Department of Agriculture. Economic Research Service. "Major Land Uses" http://www.ers.usda.gov/Data/MajorLandUses/ Per-capita area is the 2002 estimate of land area divided by the 2005 population estimate.

Developed Area: Source: National Resources Conservation Service. *2003 Annual National Resources Inventory.* February 2007. http://www.nrcs.usda.gov/TECHNICAL/NRI/. Area is based on year 2003 land use and 2003 population data. Developed land Definition: "A combination of land cover/use categories, Large urban and built-up areas, Small built-up areas, and Rural transportation land." From the "Glossary of Key Terms" at http://www.nrcs.usda.gov/TECHNICAL/land/nri02/glossary.html

Urban Area: Source: U.S. Department of Agriculture. Economic Research Service. "Major Land Uses" http://www.ers.usda.gov/Data/MajorLandUses/ Area is based on year 2002 land use and 2002 population data. Urban area definition: Densely-populated areas with at least 50,000 people ("urbanized areas") and densely populated areas with 2,500 to 50,000 people ("urban clusters").

Roof Area: The total roof area in each state was based on the estimates in Chaudhari, M., L. Frantzis, and T. Hoff, *PV Grid Connected Market Potential under a Cost Breakthrough Scenario*, Navigant Consulting Inc., 2004. Available at www.ef.org/documents/EFFinal-Final2.pdf. In this report, the roof area available for PV in 2010 is estimated, and includes a "derate" factor of 18% for residential roofs and 65% for commercial roofs. To calculate the total roof area, we multiplied the total roof area by an adjustment factor based on estimated population growth from 2005 to 2010 for each state, and then divided the area by the derate factors.

Major roads: Includes interstate, arterial, collector, and urban local roads. Does not include rural local and rural minor collector roads. These minor roads have a large area, but are not included due to data uncertainties, especially regarding land width. Source: http://www.fhwa.dot.gov/policy/ohim/hs05/roadway_extent.htm

Golf: The number of golf courses in each state was derived from "golfable.com" and "golflink.com" We used the lower of the two numbers (16,591 total courses at golfable.com vs. 18,703 total courses at golflink.com). We assume that each golf course occupies 0.61 km^2, from "Golf Course Adjustment Factors for Modifying Estimated Drinking Water Concentrations and Estimated Environmental Concentrations Generated by Tier I (FIRST) and Tier II (PRZM/EXAMS) Models" at http://www.epa.gov/oppefed1/models/water/golf_course_adjustment_factors.htm. Per-capita area based on 2005 population data.

Airports: A list of U.S. airports was derived from http://www.faa.gov/airports_airtraffic/airports/airport_safety/airportdata_5010/ There are 8,545 unique airports listed with an occupied land area, including only types listed as "Airports" (excluding heliports, gliderports, etc). Washington National Airport is included in D.C., although the airport is physically located in Virginia. Per-capita area based on 2005 population data.

Cropland: Source Natural Resources Conservation Service. "National Resources Inventory 2003 Annual NRU" February 2007. http://www.nrcs.usda.gov/technical/NRI/ Per-capita area based on 2003 data. Cropland definition: "A *Land cover/use* category that includes areas used for the production of adapted crops for harvest. Two subcategories of cropland are recognized: cultivated and non-cultivated. Cultivated cropland comprises land in row crops or close-grown crops and also other cultivated cropland, for example, hay land or pastureland that is in a rotation with row or close-grown crops. Non-cultivated cropland includes permanent hay land and horticultural cropland." From http://www.nrcs.usda.gov/technical/land/nri02/glossary.html

Corn and Hay: National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture. June, 2007 "Acreage" at http://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-29-2007.pdf Per-capita area based on 2006 data.

Grazing: Source Natural Resources Conservation Service. "National Resources Inventory 2003 Annual NRU," February 2007. http://www.nrcs.usda.gov/technical/NRI/ Grazing Land includes pastureland, rangeland, and grazed forest land. For additional details, see the "National Resources Inventory 2002 and 2003 Annual NRI Glossary of Key Terms" at http://www.nrcs.usda.gov/technical/land/nri02/glossary.html. Per-capita area based on 2003 data.

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In this report, we quantify the state-by-state per-capita "solar electric footprint" for the United States. We use state-level data on population, electricity consumption, economic activity and solar insolation, along with solar photovoltaic (PV) array packing density data to develop a range of estimates of the solar electric footprint. We find that the solar electric footprint, defined as the land area required to supply all end-use electricity from solar photovoltaics, is about 181 m2 per person in the United States. Two key factors that influence the magnitude of the state-level solar electric footprint include how industrial energy is allocated (based on location of use vs. where goods are consumed) and the assumed distribution of PV configurations (flat rooftop vs. fixed tilt vs. tracking). The solar electric footprint is about 0.6% of the total land area of the United States with state-level estimates ranging from less than 0.1% for Wyoming to about 9% for New Jersey. We also compare the solar electric footprint to a number of other land uses. For example, we find that the solar electric footprint is equal to less than 2% of the land dedicated to cropland and grazing in the United States.

15. SUBJECT TERMS
NREL; solar; solar electric footprint; greenhouse gas emissions; energy savings; solar photovoltaics; PV; land use; state electricity use; energy density; Paul Denholm; Robert Margolis

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