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Impacts of Array Configuration on Land-Use Requirements for Large-Scale Photovoltaic Deployment in the United States

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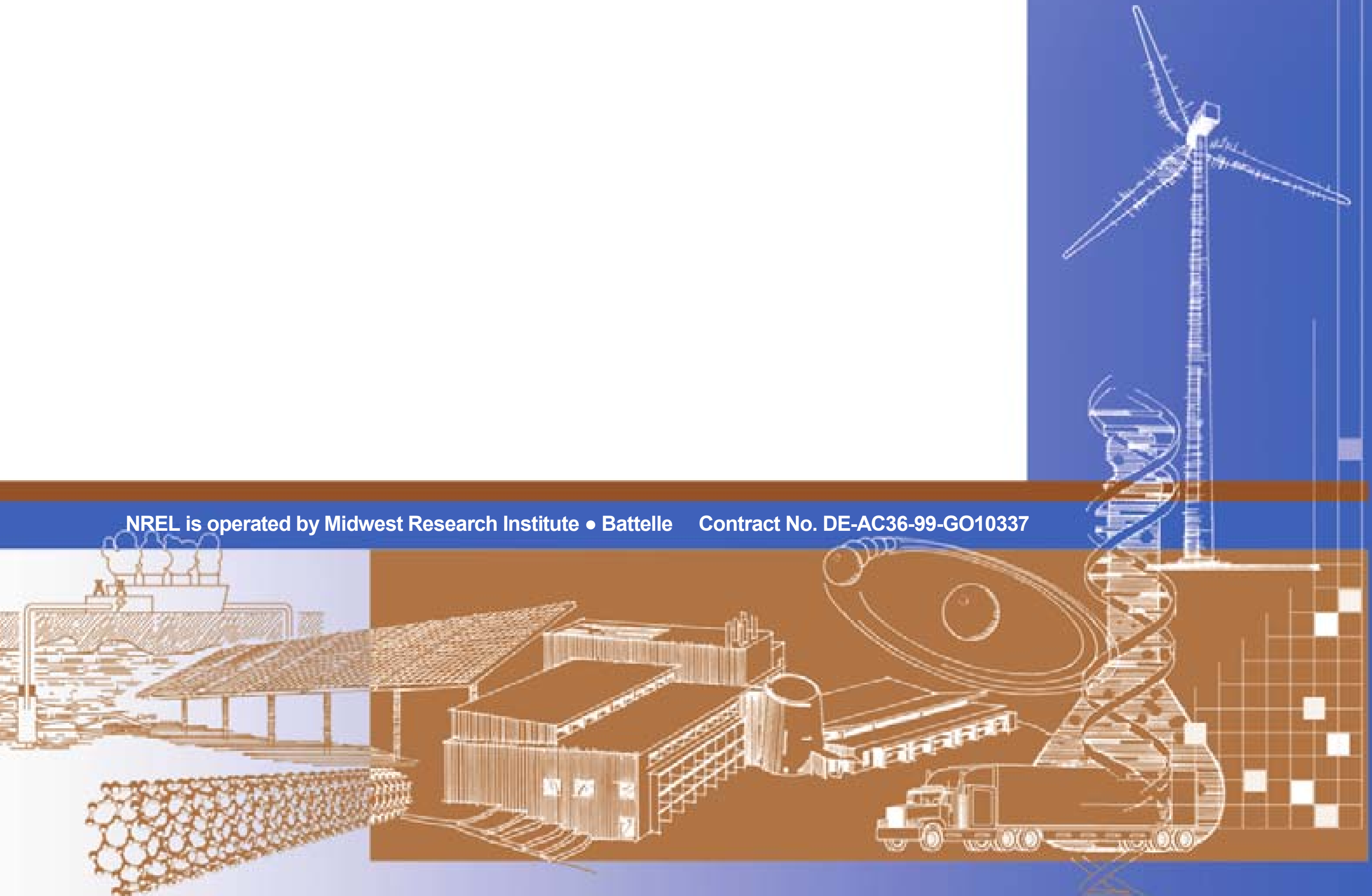

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IMPACTS OF ARRAY CONFIGURATION ON LAND-USE REQUIREMENTS FOR LARGE-SCALE PHOTOVOLTAIC DEPLOYMENT IN THE UNITED STATES

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ABSTRACT

Land use is often cited as an important issue for renewable energy technologies. In this paper we examine the relationship between land-use requirements for large-scale photovoltaic (PV) deployment in the U.S. and PV-array configuration. We estimate the per capita land requirements for solar PV and find that array configuration is a stronger driver of energy density than regional variations in solar insolation. When deployed horizontally, the PV land area needed to meet 100% of an average U.S. citizen's electricity demand is about 100 m^2. This requirement roughly doubles to about 200 m^2 when using 1-axis tracking arrays. By comparing these total land-use requirements with other current per capita land uses, we find that land-use requirements of solar photovoltaics are modest, especially when considering the availability of zero impact "land" on rooftops. Additional work is need to examine the tradeoffs between array spacing, self-shading losses, and land use, along with possible techniques to mitigate land-use impacts of large-scale PV deployment.

1. INTRODUCTION

The installed price of PV systems has dropped considerably over the past couple of decades and is expected to continue to decline over the next two decades. As the price approaches grid-parity, PV systems are likely to become a significant component of future electric power systems. The fact that solar energy is a diffuse resource, in particular compared to fossil and nuclear fuels, is both a strength and a potential liability. It is a strength in that solar energy can be captured and utilized to provide energy services where these services are needed, and it is a potential liability in that it may need to compete with other uses for limited land areas. In this paper we examine the land area required for PV to contribute a significant fraction of a region's electricity demand in the U.S.

The actual land requirements are driven by both the solar resource and the configuration of the PV system. Several aspects of the land-use requirements of solar PV are considered in this analysis. First, we quantify the relationship between PV energy yield and land use, considering various array configurations and spacing. Second, we quantify the actual land area required to meet the electricity demand in several regions of the United States using PV in different configurations. Finally, we discuss the implications of this land use, and consider further steps needed to understand and potentially minimize land-use and environmental impacts from large-scale PV deployment.

2. PV POWER AND ENERGY DENSITY

A major consideration for land-use requirements is the PV energy density, or the energy yield per unit of land (or surface area) occupied by a PV system. The energy density is a function of the array power density (power per unit land area occupied) and the PV generation (energy generated per unit of power). For any given site and PV module, the energy density is ultimately a function of how the system is configured. If PV systems are tilted (or mounted on tracking arrays) the energy yield per unit of module power increases, but the spacing between modules needs to increase in order to avoid self-shading and to allow for maintenance. Ground-based arrays have the additional complication of requiring minimum spacing between rows to allow for service vehicles.

To determine the PV array energy density for different regions of the U.S., we used data from the National Solar Radiation Database (NSRDB) for the years 2003-2005

(1). We used the NSRDB data in conjunction with the PVWATTS/PVFORM model (2), assuming a 1-kW (Standard Test Conditions) module, and an average system DC-AC conversion efficiency of 77%. We then calculated an average PV array energy density over the 3 year period 2003-2005, aggregated at the state level by weighing each weather station site by the amount of electricity demand in the assigned region. Figure 1 illustrates the allocation of weather stations in the southwestern United States by census tract. A more detailed discussion of the modeling methodology is provided in reference 3.

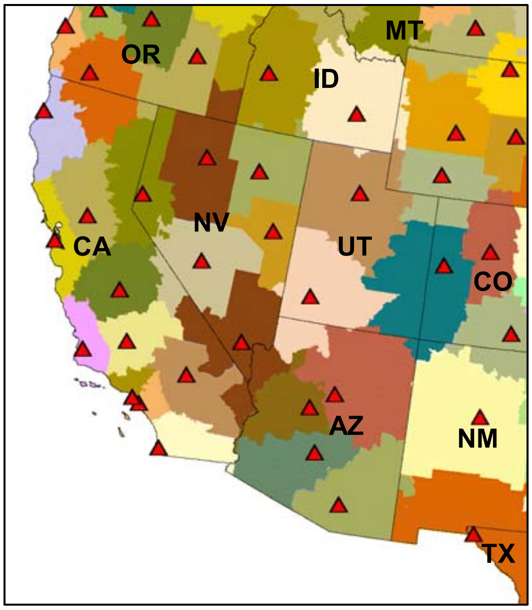

Figure 1. Allocation of the NSRDB Weather Station Data in the Southwestern United States by Census Tract

Figure 2 illustrates the resulting PV array energy density for four states (Arizona, California, Missouri, and New Jersey), and the national average, as a function of array configuration. The most notable feature of this figure is the strong dependence of energy density on system configuration, which is significantly greater than the dependence of energy density on the difference in solar resource.

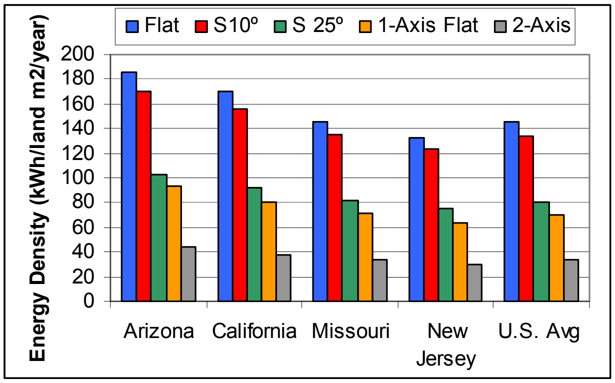

Figure 2. PV Energy Density in Four States by Array Configurations.

The highest deployable energy density is a flat array configuration, an approach often used on large commercial building rooftops. However, there are numerous tradeoffs between energy yield, mounting requirements, roof loading limits, etc., which often lead to deployment of PV systems at a low tilt angle in order to increase the collector yield. Rooftop-type systems with a 10º tilt angle increased collector yield by about 10% with a modest decrease in overall system energy density.

Increasing the tilt angle, or deploying tracking arrays can considerably increase the yield per unit of collector area – by over 50% moving from flat to 2-axis tracking. However, in terms of energy density, the increased yield from using tilted and tracking arrays does not make up for the significant additional land area required to avoid self shading. The energy density for tilted- and single-axis tracking arrays are around half of the energy density of a flat, rooftop system, while 2-axis tracking system may produce about 1/3rd of the energy per unit of land area. Ultimately, this represents a tradeoff between land costs and PV-collector costs. PV costs are such that a premium is placed on maximizing yield from each installed unit. This tends to encourage array designs that minimize self-shading. It also promotes the use of tracking arrays, especially when the value of additional yield exceeds the incremental cost of the added mechanical and structural components.

3. TOTAL LAND AREA REQUIREMENTS

The impact of array configuration on total land requirements of PV can be examined by comparing system energy density to total regional electricity use. The annual electricity production in each state was compared to the annual simulated yield from PV for the years 2003-2005 (4). We estimated the boundary condition land-use requirement, i.e., where PV provides 100% of each state's electricity demand. Meeting this condition requires the use of energy storage. In estimating the energy storage requirements, we assumed a 75% round trip storage efficiency, and that 70% of all consumed electricity would pass through storage, resulting in a required electricity production equal 1.23 times the actual demand.

Two land-use metrics are useful for understanding the potential land-use requirements. The first is the per-capita land-use requirement, which could be considered part of the ecological footprint associated with each individual's electricity use if derived from PV.

Figure 3 illustrates the per-capita land-use requirement for several states in the U.S.

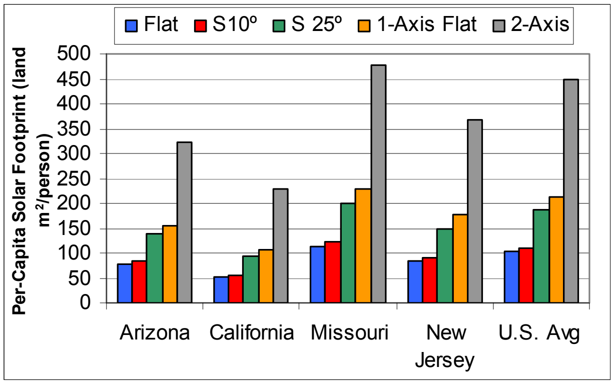

Figure 3. Solar PV Per Capital Land-use Requirement for Four States.

As shown in figure 3, when deployed horizontally, the PV land area needed to meet 100% of an average U.S. citizen's electricity demand is about 100 m^2 with California having the lowest requirement at about 50 m^2 per person due not only to good solar resource, but also the lowest per capita electricity consumption in the nation. When using 1-axis tracking arrays, the U.S. per capita PV area roughly doubles to over 200 m^2 on average, and about 100 m^2 per person in California.

In states with a low population density, this per-capita area represents a relatively small fraction of the total state area. However, in states with a high population density, this per-capita area can be a significant fraction of total state area. Figure 4 illustrates the fraction of land required by solar arrays in various configurations to meet the 100% boundary condition. In the mid-western and western states, this is a relatively small fraction of total land area. However in some eastern states, the combination of lower insolation and higher population density would require a substantial fraction of the state's area to meet the entire electricity demand with solar PV.

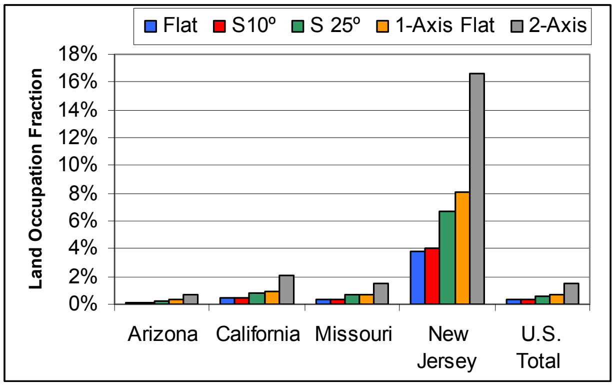

Figure 4. Fraction of Land Required to Meet 100% of Electricity Demand in Four States.

4. IMPLICATION OF PV LAND USE

The potential use of large amounts of area for PV raises a number of questions regarding the availability of land for and the potential land-use impacts of wide-scale PV deployment. Perhaps the most obvious issue is the availability of zero-impact "land" on rooftops. There is, however, considerable uncertainty in the estimates of available rooftop space that is suitable for PV in the U.S. While no comprehensive study has been performed, several estimates of the rooftop space appropriate for PV are available. One estimate assumes that 18% of all residential roofspace and 65% of all commercial roofspace are available and suitable for PV deployment (5). This results in a national average of about 65 m^2 of rooftop area available per person in the U.S. Assuming flat deployment, this number would imply that rooftop PV deployment alone could provide around two-thirds of the nation's electricity supply. However, this estimate does not take into account the sub-optimal orientation of many buildings and assumes that the PV system on each building is sized to completely fill the available roofspace, as opposed to applying a typical size to meet the economic needs of the individual building. This number is also unsatisfactory in that it assumes a uniform shading factor throughout the United States, which is extremely unlikely given the variation in vegetation between the eastern and western U.S. A more recent estimate splits the country into two zones, increasing the overall estimate of roofspace available in the southern and southwestern United States (6).

Despite tremendous uncertainty in overall availability, it is clear that roofspace could provide a significant fraction of the total area needed for PV to become a major contributor to the nation's electricity supply. It should be noted that rooftop space is not entirely without opportunity costs, since rooftop PV will compete with other applications, such as solar water heating, green roofs, daylighting etc.

Beyond rooftops, if it assumed that large-scale ground based PV systems will be deployed, then some consideration of actual land use and land-use impacts should be considered. Several land-use applications provide a useful comparison. Golf courses and airports each currently occupy about 35 m^2 per person in the United States, while land used to grow corn for ethanol production exceeds 200 m^2 per person, although this land is concentrated in a fairly small number of states.

Comparisons between PV and other land uses must be placed in context of the actual degree to which they impact the land and potentially alter local ecosystems. Deploying tightly packed PV arrays would create the most disruption but would require the least amount of land area. In contrast, the use of pole-mounted 2-axis arrays would require significantly more land but could be substantially less disruptive. This difference is important, especially when considering the extremely low energy density of 2-axis arrays. The substantial amount of land surrounding each 2-axis array could potentially support multiple land uses such as grazing and the cultivation of shade tolerant crops.

5. CONCLUSIONS AND FUTURE WORK

The land-use requirements for wide-scale deployment of PV are modest when considering both the large area of rooftop availability and when compared to other uses of land in the United States. Additional studies are needed to better understand the potential opportunities and impacts of PV on land use. First, a more comprehensive estimate of rooftop availability is needed on a national basis. This includes detailed statistical sampling of homes and commercial buildings, considering the distribution of rooftop orientation, pitch, shading, and other availability factors. Second, better understanding of actual shading impacts of ground based PV arrays is required. Installers may be conservative when performing shading analysis, spacing arrays to produce every last possible kWh out of the system. It may be that actual shading impacts, considering real weather patterns during periods of low sun angle may not warrant the large array spacing calculated by traditional shading analysis. This could allow for increased packing density and a corresponding reduction in land-use impacts, limited of course by maintenance requirements. Evaluation of increased array density and increased shading losses at low sun angles could also consider the potentially lower value of electricity during these typically off-peak time periods. Finally, actual ecosystem impacts of large-scale PV deployment need to be evaluated. This includes studies and evaluation of shade tolerant native and beneficial species that could be grown under large-scale PV arrays. This also includes evaluation of best practices to minimize the use of herbicides and other chemicals, and the use of installation and maintenance techniques to provide minimum impact such as soil compaction and erosion.

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