Efficient use of land to meet sustainable energy needs

Rebecca R. Hernandez\textsuperscript{a,b,1}, Madison K. Hoffacker\textsuperscript{a,b}, and Christopher B. Field\textsuperscript{a,b}

\textsuperscript{a}Department of Global Ecology, Carnegie Institution for Science, Stanford, USA 94035
\textsuperscript{b}Department of Environmental Earth System Science, Stanford University, Stanford, USA 94305
\textsuperscript{1}To whom correspondence should be addressed. E-mail: rebecca.hernandez@stanford.edu, Website: www.rebeccarhernandez.com

Table of Contents

1.0 Results
  1.1 Open Water & Perennial Ice/Snow
  1.2 Slope, Transmission, and Roads
  1.3 Effect of Individual Resource Opportunities and Constraints on Land Area and Solar Energy Potential

2.0 Methods
  2.1 Overview
  2.2 Theoretical Solar Energy Potential
  2.3 The Carnegie Energy and Environmental Compatibility Model
  2.4 Technical Solar Energy Potential
  2.5 Effect of Resource Opportunities and Constraints on Land Area and Solar Energy
  2.6 Realized Generation-based Solar Energy Potential
  2.7 Sensitivity Analysis
  2.8 Carnegie Energy and Environmental Compatibility Index

3.0 Literature Cited

4.0 Supplemental Tables
  4.1 Supplementary Table 1
  4.2 Supplementary Table 2
  4.3 Supplementary Table 3
  4.4 Supplementary Table 4
  4.5 Supplementary Table 5
  4.6 Supplementary Table 6
  4.7 Supplementary Table 7
  4.8 Supplementary Table 8
  4.9 Supplementary Table 9
  4.10 Supplementary Table 10
1.0 Results

1.1 | Open Water & Perennial Ice/Snow. Excluding coastlines, the state of California (USA) includes over 5,348 km² of open water and 41 km² of perennial ice and snow. If we consider areas of perennial snow and ice to be negligible (0.77%), areas with open water have an approximate capacity-based generation potential of 11,000 TWh y⁻¹ for photovoltaics (PV; Supplementary Table 1). However, PV systems can be deployed on water (known as “floatovoltaics), conferring reduced water evaporation and enhanced panel efficiency up to 8 - 10%¹.

1.2 | Slope, Transmission, and Roads. Within both developed and undeveloped regions of California, we found approximately 150,000 km² where slopes were 5% or less and approximately 72,000 km² are available for concentrating solar power (CSP) development where slopes are 3% or less. Excluding areas where slopes were too steep renders 310,423 TWh y⁻¹ and 187,389 TWh y⁻¹ of capacity-based generation potential for PV and CSP, respectively (Supplementary Table 1).

There are over 56,317 km of operating transmission lines in California where 38,835 km are high voltage lines (≥ 69 kV). For PV, 224,260 km² is land within 10 km of an existing transmission corridor, rendering 481,081 TWh y⁻¹ of capacity-based generation potential, and for CSP 155,838 km² is land within 10 km of transmission, rendering 395,025 TWh y⁻¹ of capacity-based generation potential (Supplementary Table 1).

There are approximately 704,500 km of roads in California, including 700,914 km of roads operational for vehicles. Areas for PV development within 5 km of roads comprise 390,088 km² with a capacity-based potential of 839,379 TWh y⁻¹. Areas for CSP development within 5 km of roads comprise 292,626 km² with a capacity-based potential of 752,351 TWh y⁻¹ (Supplementary Table 1).

1.3 | Effect of Individual Resource Opportunities and Constraints on Land Area and Solar Energy Potential. Individual resource opportunities and constraints have a unique effect on the amount of land available for development, and the technical potential of the solar resource properties therein (Supplementary Table 2). The development of PV is
most limited by topography; slope reduces the amount of favorable land and solar energy potential in California by approximately 64% respectively. The next limiting constraint is proximity to transmission infrastructure. Access to transmission reduces both land area availability and solar energy potential by approximately 45%.

Unique to CSP technologies, the availability of adequate levels of direct normal irradiance (DNI) reduced the total area in California by 24.5%—from 409,443 km² to 309,209 km²—engendering a reduction in capacity-based solar energy potential of 20.5% (Supplementary Table 2). Like PV technologies, the most limiting resource constraint for CSP development in California is slope; total area and electrical potential in California is reduced by more than 75% when siting land with favorable topography. Access to transmission is also limiting, reducing available land and solar energy potential by half. Remaining resource constraints reduce total land area and solar energy potential by less than five percent.

2.0 Methods

2.1 | Overview. To identify areas meeting land, energy, and environmental (LEE) compatibility for small- and utility-scale solar energy (USSE) in the state of California, we developed the Carnegie Energy and Environmental Compatibility (CEEC) Model to quantify the:

(i) Quantify the capacity-based technical potential (i.e., satellite-based estimates of PV and CSP technologies operating at their full, nominal capacity over 0.1 degree surface cells);

(ii) Quantify the (accessible) generation-based technical potential (i.e., realized potential incorporating a satellite-based capacity factor model with 0.1 x 0.1 degree surface resolution) for PV and CSP. Owing to California’s limited water resources, we model dry-cooled CSP parabolic trough technology. Photovoltaic technologies included three sub-types: fixed tilt (TILT25), single-axis (AX1FLAT), double axis (AX2);
Create a compatibility index (i.e., “compatible,” “potentially compatible,” and “incompatible”) to categorize and quantify land resources meeting LEE compatibility for solar energy infrastructure; and lastly,

Determine to what extent energy and climate change goals can be met therein.

All analyses were conducted in R (R: A Language and Environment for Statistical Computing) and ArcGIS (10.2, Redlands, CA).

2.2 | Theoretical Solar Energy Potential. Theoretical potential is the irradiance incident on Earth’s terrestrial and aquatic surfaces that can be utilized for solar energy. We calculated the solar energy theoretical potential for PV and CSP in California using the radiation model developed by Perez et al. (2002) and the National Renewable Energy Laboratory (NREL). This model incorporates geostationary weather satellite imagery, daily snow cover data, and monthly atmospheric water vapor, trace gas, and aerosol data as well as ground measurement validation (1998-2005) to calculate annual average daily total solar resource over 0.1 degree surface cells (~10 km in size). Concentrating solar power uses direct-beam sunlight that is captured using solar thermal collectors. Consequently, we used a direct normal irradiance (DNI) dataset to assess CSP energy potential. In contrast, a PV system can employ both direct and diffuse components of solar radiation and thus we used radiation values representative of a flat plate collector with a south-oriented panel at an angle from horizontal equal to the latitude of the collector location. Theoretical generation potential (kWh m\(^{-2}\) day\(^{-1}\)) was (i) averaged for all cells within and intersecting California and (ii) integrated across space within the clip feature (California) to calculate total theoretical potential (TWh y\(^{-1}\)) for PV and CSP solar technologies.

2.3 | The Carnegie Energy and Environmental Compatibility Model. The CEEC model is an adaptable geographic information system (GIS) decision support tool that calculates technical solar energy potentials for areas of interest, including solar energy hotspots, incorporating selected user-specified development opportunities and resource constraints (for potential inputs see Supplementary Table 7). In this study, we adapted the CEEC model for the state of California (USA), integrating the aforementioned satellite-based...
radiation models and hydrologic, socioeconomic (i.e., land-cover), topographical, energy infrastructure, and ecological resource opportunities and constraints to derive intermediate outputs of interest (Figure 1) and a final spatial output (Figure 2) classified according to a LEE compatibility index (described below).

2.4 | Technical Solar Energy Potential. We calculated total land area potential (km²) and capacity-based generation potential (TWh y⁻¹) for solar energy technologies using the CEEC model (Stanford, CA). Land area and capacity-based solar energy potential were calculated at various steps throughout the CEEC model workflow, following the same methods used to calculate theoretical potential but instead incorporating development opportunities (e.g., land-cover classified as built environment) and constraints.

First, areas within California with DNI values less than 6 kWh m⁻² day⁻¹ were considered unfavorable locations for CSP technology⁵ and such areas were removed from the analyses. No minimum value restrictions were prescribed for PV installations since these systems utilizes both DNI and diffuse horizontal irradiance at levels that is sufficient throughout the entire state.

Next, we procured data from the National Land Cover Database (NLCD) created by the Multi-Resolution Land Characteristics Consortium⁶, to identify and eliminate water bodies and areas with perennial snow and ice. Before eliminating these attributes, we calculated total area (km²) and energy potential (TWh y⁻¹) for PV and CSP technologies on these land-cover types exclusively, incorporating the minimum solar radiation requirements for CSP (Supplementary Table 1). As energy and water are inextricably linked, future studies could use CEEC model methods to explore interactions between water availability and solar energy technical potential, however, this was beyond the scope of this study.

Then, we integrated socioeconomic development opportunities using data from the NLCD to identify human-modified landscapes in California and particularly as a resource opportunity for “compatible” sites. Such areas within the built environment are classified under four levels of development intensity, including high (> 79% impervious surfaces),
medium (50 - 79%), low (20 - 49%), and open space (< 20%; see Supplementary Table 8 for details). High and medium developed regions were eliminated for possible CSP sites owing to its incompatibility with dense urban environments. Total land area potential (km²), capacity-based generation potential (TWh y⁻¹), and realized generation potential (TWh y⁻¹) were calculated for each land-use type for PV schemes and for low and open space land-use types for CSP schemes.

Our topographic constraint included elevation data (3 to 30 m resolution) from the National Elevation Dataset produced by the United States Geological Survey (USGS) to identify areas that are most suitable for solar energy systems; where slopes are 3% and 5% or less, for CSP and PV installations, respectively. Construction costs (e.g., leveling) are considered prohibitive when slopes are greater and are typically more conservative for CSP installations; however, values vary across studies (Supplementary Table 9). We used the average of CSP and PV slope thresholds from eight studies and areas with steeper slopes removed as potential sites.

Energy infrastructural constraints included transmission infrastructure and road access. We prioritized a ≤ 10 km development zone on each side of all transmission lines (Supplementary Table 5) and a ≤ 5 km zone along each side of all roads of interest (Supplementary Table 5; for a description of road types and those used in the study see Supplementary Table 10), as these areas minimize infrastructural and environmental costs associated with new construction activities and materials. These development zone values were informed from the results of the sensitivity analyses (explained below). Previous studies of technical potential including proximity to transmission infrastructure and roads are absent or vary greatly (Supplementary Table 9). Only high voltage transmission lines (≥ 69 kV) were included in the analysis following several other studies’ methodology (Supplementary Table 9).

Lastly, we integrated ecological resource constraints into the model. Areas where road construction is federally prohibited (“inventoried roadless areas”) were identified using data from the U.S. Department of Forest and Agriculture’s Forest Service Geospatial Service and Technology Center (Supplementary Table 5), and these regions were
excluded from the analysis. Also excluded from potential areas for solar energy
development were critical habitat of threatened and endangered species (United States
[U.S.] Fish and Wildlife Service, **Supplementary Table 5**) and federally protected areas
(Protected Areas Database of the U.S.; **Supplementary Table 5**). For the latter, we
excluded only areas managed for biodiversity where disturbance events proceed (Code 1),
are mimicked (Code 2), or suppressed as designated by the USGS (Code 3; see
**Supplementary Table 5** for class type details).

To determine potential for USSE infrastructure, we eliminated parcels of insufficient size.
The minimum parcel size for a 1 MW power plant is 28,490 m² at a land-use efficiency
of 35.1 Wm⁻² for PV and 29,500 m² at a land-use efficiency of 33.9 Wm⁻² for CSP¹⁰.

### 2.5 | Effect of Resource Opportunities and Constraints on Land Area and Solar Energy. **Potential**

We were interested in determining the influence of each individual
opportunity and constraint on the land area (km²) available for solar energy development
and the solar energy potential (TWh y⁻¹) therein. We calculated the absolute effect, i.e.,
percent reduction, of land and energy that resulted after implementing each constraint
individually, where the absolute effect = \( \frac{\text{area unavailable for solar energy development}}{\text{total land area}} \times 100 \). For the hydrology constraint, “total land area” was the total
area in California (404,443 km²). For all remaining constraints, “total land area” was
404,062 km², which is the area of California excluding areas of open water and perennial
ice and snow, and for CSP, areas where DNI < 6 kWh m⁻² d⁻¹. Effect of parcel-size
minimum for USSE development was not assessed because it is not an independent
constraint but instead results from the output of all other resource opportunities and
constraints.

### 2.6 | Realized Generation-based Solar Energy Potential.

We calculated the realized
generation-based solar energy potential at various steps throughout the CEEC model
workflow (**Supplementary Table 3**) and according to the compatibility index. For PV,
realized generation potential was calculated by multiplying the capacity-based solar
energy potential with a spatially-explicit capacity factor—developed with NREL PV
Watts model by Drury et al.¹¹—for identical cells of the same size and for three PV
system types: (i) fixed mount, south-facing with a 25° tilt; (ii) one-axis tracking, rotating east-west with a ± 45° maximum tracking angle; and (iii) two-axis tracking, rotating east-west and north-south of the sun across the horizon. We used five DNI classes of capacity factors for CSP estimated by Lopez et al. (2012)\textsuperscript{12} for a trough system to estimate a spatially-explicit generation-based CSP technical potential (Supplementary Table 6).

2.7 | Sensitivity Analysis. Other studies assessing the potential of renewable energy development vary in values used for distance to road and transmission criteria, with some not using any such constraints to identify potential development areas (Supplementary Table 9). In this study, a sensitivity analysis was performed to observe trends in area and capacity-based technical potential using incremental criteria values for distance to roads and transmission. Specifically, we incrementally increased each input by 10 km on each side of all transmission lines (ranging from 1 to 30 km) and 1.5 km on each side of all roads (ranging from 1 to 10 km). Like other analyses, areas of open water and perennial ice and snow for PV and CSP and areas where DNI < 6 kWh m\textsuperscript{-2} d\textsuperscript{-1} for CSP were not included in the total potential.

2.8 | Carnegie Energy and Environmental Compatibility Index. The final component of the CEEC model consists of the LEE Compatibility Index to classify the area of interest according to its suitability for solar energy development by technology type. For this study, our index categorized space and land resources for solar energy infrastructure—indeedely for PV and CSP—in California as follows: 1) \textit{compatible} – areas that meet the hydrology criteria and those that are exclusively within the built environment, 2) \textit{potentially compatible} – areas beyond (i.e., not including) compatible areas that meet all hydrologic, topographic, energy infrastructural, and ecological resource constraints, and 3) \textit{incompatible} – all remaining areas. For CSP, areas identified as compatible and potentially compatible had to meet the parcel size minimum of a one-megawatt installation. For each class and technology type, we calculated the total land area potential (km\textsuperscript{2}), capacity-based generation potential (TWh y\textsuperscript{-1}), and realized generation potential (TWh y\textsuperscript{-1}).
3.0 Literature Cited


**Supplementary Table 1** | Total land area (km²) and capacity-based solar energy potential (TWh y⁻¹) available for photovoltaic (PV) and concentrating solar power (CSP) technologies in California within each model resource constraint and opportunity using the Carnegie Energy and Environmental Compatibility Model (CEEC). Ecologically sensitive, federally protected habitat constraints are not shown as they represent, in part, areas excluded from potential solar energy development.

<table>
<thead>
<tr>
<th>CEEC Model Resource Constraint or Opportunity</th>
<th>PV</th>
<th>CSP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (km²)</td>
<td>Capacity-based Potential (TWh y⁻¹)</td>
</tr>
<tr>
<td>California</td>
<td>409,443</td>
<td>881,604</td>
</tr>
<tr>
<td>DNI ≥ 6 kWh/m²/d&lt;sup&gt;a&lt;/sup&gt;</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Open water, ice/snow</td>
<td>5,389</td>
<td>11,379</td>
</tr>
<tr>
<td>Developed, high intensity&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1,578</td>
<td>3,244</td>
</tr>
<tr>
<td>Developed, medium intensity&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6,827</td>
<td>14,204</td>
</tr>
<tr>
<td>Developed, low intensity&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6,509</td>
<td>13,749</td>
</tr>
<tr>
<td>Developed, open space&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12,372</td>
<td>25,902</td>
</tr>
<tr>
<td>Slope&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>142,056</td>
<td>310,423</td>
</tr>
<tr>
<td>Transmission line (≤ 10km)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>224,260</td>
<td>481,081</td>
</tr>
<tr>
<td>Roads (≤ 5km)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>390,088</td>
<td>839,379</td>
</tr>
</tbody>
</table>

<sup>a</sup>DNI = direct normal irradiance
<sup>b</sup>Reported area and solar potential do not include areas of open water, perennial ice and snow, and for CSP areas where DNI is < 6 kWh/m²/d
<sup>c</sup>Slope must be ≤ 5% and ≤ 3% for PV and CSP, respectively
**Supplementary Table 2** | Absolute effect (i.e., percent reduction) of each model constraint (if positive) or opportunity (if 0), individually, on total land area and solar energy potential for photovoltaic (PV) and concentrating solar power (CSP) technologies in California.

<table>
<thead>
<tr>
<th>CEEC Model Resource Constraint or Opportunity</th>
<th>PV (%)</th>
<th>CSP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area</td>
<td>Solar Energy Potential</td>
</tr>
<tr>
<td>DNI ≥ 6 kWh/m²/d&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Open water, ice/snow</td>
<td>1.32</td>
<td>1.29</td>
</tr>
<tr>
<td>Developed, high intensity&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Developed, medium intensity&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Developed, low intensity&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Developed, open space&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Slope&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>64.84</td>
<td>64.33</td>
</tr>
<tr>
<td>Transmission line (≤ 10km)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>44.50</td>
<td>44.72</td>
</tr>
<tr>
<td>Roads (≤ 5km)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.46</td>
<td>3.55</td>
</tr>
<tr>
<td>Inventoried roadless areas</td>
<td>4.42</td>
<td>4.38</td>
</tr>
<tr>
<td>ET species habitat&lt;sup&gt;d&lt;/sup&gt;</td>
<td>13.00</td>
<td>13.19</td>
</tr>
<tr>
<td>Federally protected areas</td>
<td>23.60</td>
<td>24.77</td>
</tr>
</tbody>
</table>

<sup>a</sup>DNI = direct normal irradiance
<sup>b</sup>Reported percent reduction is referenced to the total area and solar energy potential of California excluding areas of open water and perennial ice/snow and for CSP areas where DNI is < 6 kWh/m²/d
<sup>c</sup>Slope must be ≤ 5% and ≤ 3% for PV and CSP, respectively
<sup>d</sup>Endangered and threatened species habitat
**Supplementary Table 3** | Total land area (km$^2$) and realized generation-based solar energy potential (TWh y$^{-1}$) available for photovoltaic (PV) and concentrating solar power (CSP) technologies in California for each model resource constraint or opportunity using the Carnegie Energy and Environmental Compatibility Model (CEEC). Ecologically sensitive, federally protected habitat constraints are not shown as they are, in part, areas excluded from potential solar energy development.

<table>
<thead>
<tr>
<th>CEEC Model Resource Constraint or Opportunity</th>
<th>PV Area (km$^2$)</th>
<th>Generation-based Potential (TWh y$^{-1}$)</th>
<th>CSP Area (km$^2$)</th>
<th>Generation-based Potential (TWh y$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TILT25</td>
<td>AX1FLAT</td>
<td>AX2</td>
<td></td>
</tr>
<tr>
<td>All California</td>
<td>409,443</td>
<td>169,461</td>
<td>209,790</td>
<td>240,520</td>
</tr>
<tr>
<td>DNI ≥ 6 kWh/m$^2$/d$^a$</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Open water, ice/snow</td>
<td>5,389</td>
<td>2,147</td>
<td>2,652</td>
<td>3,037</td>
</tr>
<tr>
<td>Developed, high intensity$^b$</td>
<td>1,578</td>
<td>592</td>
<td>705</td>
<td>797</td>
</tr>
<tr>
<td>Developed, medium intensity$^b$</td>
<td>6,827</td>
<td>2,622</td>
<td>3,145</td>
<td>3,559</td>
</tr>
<tr>
<td>Developed, low intensity$^b$</td>
<td>6,509</td>
<td>2,575</td>
<td>3,122</td>
<td>3,545</td>
</tr>
<tr>
<td>Developed, open space$^b$</td>
<td>12,372</td>
<td>4,828</td>
<td>5,894</td>
<td>6,711</td>
</tr>
<tr>
<td>Slope$^{b,c}$</td>
<td>142,058</td>
<td>59,735</td>
<td>73,790</td>
<td>84,454</td>
</tr>
<tr>
<td>Transmission line (≤ 10km)$^b$</td>
<td>224,260</td>
<td>91,523</td>
<td>112,824</td>
<td>128,972</td>
</tr>
<tr>
<td>Roads (≤ 5km)$^b$</td>
<td>390,088</td>
<td>161,094</td>
<td>199,311</td>
<td>228,493</td>
</tr>
</tbody>
</table>

$^a$DNI = direct normal irradiance

$^b$reported area and solar potential do not include areas of open water, perennial ice and snow, and for CSP areas where DNI is < 6 kWh/m$^2$/d

$^c$slope must be ≤ 5% and ≤ 3% for PV and CSP, respectively

© 2015 Macmillan Publishers Limited. All rights reserved.
### Supplementary Table 4 | Consumption (2012) and production (2011) of energy by type for California

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Consumption (Trillion Btu, TWh)</th>
<th>Production (Trillion Btu, TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>43.8 (12.8)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Liquified Petroleum Gas</td>
<td>2456.3 (719.9)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Residual Fuel</td>
<td>1690.2 (495.3)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Other Renewables</td>
<td>523.2 (153.3)</td>
<td>812.8 (238.2)</td>
</tr>
<tr>
<td>Biomass</td>
<td>535.7 (157.0)</td>
<td>25.0 (7.3)</td>
</tr>
<tr>
<td>Other Petroleum</td>
<td>57.3 (16.8)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Nuclear Electric Power</td>
<td>167.1 (49.0)</td>
<td>383.6 (112.4)</td>
</tr>
<tr>
<td>Hydroelectric Power</td>
<td>310.6 (91.0)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Distillate Fuel Oil</td>
<td>193.9 (56.8)</td>
<td>1123.4 (329.2)</td>
</tr>
<tr>
<td>Jet Fuel</td>
<td>255.4 (74.9)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Net Interstate Flow of Electricity</td>
<td>260.7 (76.4)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Motor Gasoline excl. Ethanol</td>
<td>289.6 (84.9)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>828.6 (242.8)</td>
<td>279.7 (82.0)</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>7612.4 (2231.0)</strong></td>
<td><strong>1501.1 (769.2)</strong></td>
</tr>
</tbody>
</table>

1. United States Energy Information Administration, State Energy Data System
2. Crude oil
**Supplementary Table 5** | Satellite-based models and hrology, socioeconomic, topographical, infrastructural, and ecological data used as input parameters for calculating solar energy technical potential in study.

**SATELLITE-BASED RADIATION MODELS**

**Parameter:** Solar energy technical potential for photovoltaic technology  
**Dataset Title:** NREL Radiation Model (diffuse/direct normal irradiance)  
**Online Linkage:** http://www.nrel.gov/gis/data_solar.html  
**Description:** This model incorporates geostationary weather satellite imagery, daily snow cover data, and monthly atmospheric water vapor, trace gas, and aerosol data as well as ground measurement validation (1998-2005) to calculate annual average daily total solar resource over 0.1 degree surface cells (~10 km in size) in both latitude and longitude. This third-generation model has improved capability to handle cloud detection over desert areas and was used to assess solar potential for photovoltaic technologies.  
**Geographic Coverage:** 48 contiguous United States  
**Author/Institution(s):** Perez et al., 2002 / National Renewable Energy Laboratory  
**Publication Date:** 2007  
**Date Last Updated:** 2012  
**Dataset Confidentiality:** None  
**Geospatial Data Presentation Form:** Vector digital data  
**Resolution:** 10km  
**Projection Parameters**  
- **Datum:** World geodetic system (WGS) 1984  
- **Geographic Coordinate System:** WGS 1984  
- **Units:** Decimal Degrees  
**Contact Information:** ray_george@NREL.gov; 303-275-4669

**Parameter:** Solar energy potential for concentrating solar power technology  
**Dataset Title:** NREL Radiation Model (direct normal irradiance)  
**Online Linkage:** http://www.nrel.gov/gis/data_solar.html
**Description:** This model incorporates geostationary weather satellite imagery, daily snow cover data, and monthly atmospheric water vapor, trace gas, and aerosol data as well as ground measurement validation (1998-2005) to calculate annual average daily total solar resource over 0.1 degree surface cells (~10 km in size) in both latitude and longitude. This third-generation model has improved capability to handle cloud detection over desert areas and was used to assess solar potential for concentrating solar power technologies.


**Geographic Coverage:** Hawaii and the contiguous United States

**Author/Institution(s):** Perez et al., 2002 / National Renewable Energy Laboratory

**Publication Date:** 2012

**Date Last Updated:**

**Dataset Confidentiality:** None

**Geospatial Data Presentation Form:** Vector digital data

**Resolution:** 10km

**Projection Parameters**
- **Datum:** WGS 1984
- **Geographic Coordinate System:** WGS 1984
- **Units:** Decimal Degrees

**Contact Information:** ray_george@NREL.gov; 303-275-4669

**Parameter:** Capacity factor for photovoltaic installations in the United States

**Dataset Name:** (Perez9805-PVWatta20MW.shp)

**Website:** [http://www.nrel.gov/gis/data_solar.html](http://www.nrel.gov/gis/data_solar.html)

**Descriptive Summary:** Authors simulate hourly PV generation using PVWatts for three types of PV systems: (i) fixed mount PV systems that are oriented to face south with a 25° tilt, (ii) horizontal one-axis tracking PV systems (axes of rotation are parallel to the ground) that rotate from east to west with a 45° maximum tracking angle, and (3) two-axis tracking systems that follow both the east–west and north–south motion of the sun across the horizon.

**Associated Documentation/Article(s):** Easn Drury, Anthony Lopez, Paul Denholm, Robert Margolis (2013) Relative performance of tracking versus fixed tilt photovoltaic systems in the USA. Progress in Photovoltaics, doi: 10.1002/pip.2373
**Geographic Coverage:** Contiguous United States  
**Authors/Institution:** Easn Drury, Anthony Lopez, Paul Denholm, Robert Margolis/National Renewable Energy Laboratory  
**Date Released:** 2013  
**Date Last Updated:** not applicable  
**Dataset Confidentiality:** none  
**Geospatial Data Presentation Form:** Vector digital data  
**Resolution:** NA  
**Projection Parameters**  
  - **Datum:** North American 1983  
  - **Projection:** Albers  
  - **Projected Coordinate System:** USA Contiguous Albers Equal Area Conic  
  - **Geographic Coordinate System:** NAD 1983  
  - **Units:** Decimal degrees  
**Contact:** easan.drury@NREL.gov

**HYDROLOGY**

**Parameter:** Land-cover of open water/perennial ice and snow  
**Dataset Title:** NLCD 2006 Land Cover  
**Online Linkage:** http://www.mrlc.gov/nlcd2006.php  
**Description:** The National Land Cover Dataset consists of a 16-class land cover classification scheme that captures images and releases data with a 5-year time lag.  
**Geographic Coverage:** United States  
**Author/Institution(s):** Fry et al. 2011 / Multi-Resolution Land Characteristics (MRLC) Consortium  
**Publication Date:** 2011  
**Date Last Updated:**  
**Dataset Confidentiality:** None  
**Geospatial Data Presentation Form:** Raster digital data  
**Resolution:** 30m
Projection Parameters

- **Datum**: North American Datum of 1983
- **Spatial Reference**: Albers Conical Equal Area
- **Units**: meters

**Contact Information**: mrlc@usgs.gov; 605-594-6151

---

**SOCIOECONOMICS**

**Parameter**: Land-cover of developed regions

**Dataset Title**: NLCD 2006 Land Cover

**Online Linkage**: http://www.mrlc.gov/nlcd2006.php

**Description**: The National Land Cover Dataset consists of a 16-class land cover classification scheme that captures images and releases data with a 5-year time lag.


**Geographic Coverage**: United States

**Author/Institution(s)**: Fry et al. 2011 / Multi-Resolution Land Characteristics (MRLC) Consortium

**Publication Date**: 2011

**Date Last Updated**: not applicable at the time

**Dataset Confidentiality**: None

**Geospatial Data Presentation Form**: Raster digital data

**Resolution**: 30m

**Projection Parameters**

- **Datum**: North American Datum of 1983
- **Spatial Reference**: Albers Conical Equal Area
- **Units**: meters

**Contact Information**: mrlc@usgs.gov; 605-594-6151
TOPOGRAPHY

Parameter: Elevation (NED)
Dataset Title: National Elevation Dataset (NED)
Online Linkage: http://ned.usgs.gov/
Descriptive Summary: The National Elevation Dataset (NED) is the primary elevation dataset of the United States Geological Survey. It is the best raster elevation data of the coterminous United States, including Alaska, Hawaii, and territorial islands.
Date Last Updated: updated on a nominal two month cycle
Geographic Coverage: Conterminous United States
Author/Institution(s): United States Geological Survey
Publication Date: 2011
Dataset Confidentiality: None
Geospatial Data Presentation Form: Raster digital data
Resolution: 3-30 meters
Projection Parameters
  Datum: North American Datum of 1983
  Geographic Coordinate System: North American 1983
  Units: Decimal Degrees
Contact Information: webmapping@usgs.gov; 1-800-252-4547, 605-594-6151

ENERGY INFRASTRUCTURE

Parameter: California Electric Transmission Grid, Substations, and Operational Power Plants
Dataset Title: Statewide Electric Transmission Lines and Substations and Statewide Operational Power Plants
Online Linkage: NA
Description: All transmission lines, substations, and operational power plants including attribute information for the state of California.
Associated Documentation/Article(s): None
Geographic Coverage: California
Author/Institution(s): California Energy Commission
Publication Date: 2010
Date Last Updated:
Dataset Confidentiality: Confidential, requires CEC non-disclosure agreement
Geospatial Data Presentation Form: Vector digital data
Resolution: NA
Projection Parameters
  Datum: North American 1983
  Projection: Albers
  Projected Coordinate System: North American datum of 1983 California Teal Albers
  Geographic Coordinate System: North American 1983
  Units: Meter
Contact Information: Siting Transmission & Environmental Protection Division, Cartography Unit, 916-654-3902

Parameter: Road
Dataset Title: TIGER/Line Shapefile
Online Linkage: http://www.census.gov/geo/maps-data/data/tiger-line.html
Description: Topologically Integrated Geographic Encoding and Referencing (TIGER) data are informed from the Census Bureau’s MAF/TIGER database for the United States. Features are exhaustive and include boundaries, roads, address information, water features, population counts and more.
Geographic Coverage: United States
Author/Institution(s): United States Department of Commerce, United States Census Bureau, Geography Division
Publication Date: 2013
**Parameter:** Roadless

**Dataset Title:** USFS Inventoried Roadless Areas for contiguous US

**Online Linkage:** [http://www.arcgis.com/home/item.html?id=2dd4cfcf14e34bc8bd9d3bd7e13b1091](http://www.arcgis.com/home/item.html?id=2dd4cfcf14e34bc8bd9d3bd7e13b1091)

**Description:** This coarse resolution dataset encompasses all National Forest Inventoried Roadless Areas for the lower 48 states and Puerto Rico. Roadless areas are classified as the following:

- Inventoried Roadless Areas where road construction and reconstruction is prohibited
- Inventoried Roadless Areas that are recommended for wilderness designation in the forest plan and where road construction and reconstruction is prohibited
- 1C-Inventoried Roadless Areas where road construction and reconstruction is not prohibited

**Associated Documentation/Article(s):**

**Geographic Coverage:** Lower 48 states including Puerto Rico

**Author/Institution(s):** USDA Forest Service – Geospatial Service and Technology Center

**Publication Date:** 2003

**Date Last Updated:**

**Dataset Confidentiality:** None

**Geospatial Data Presentation Form:** Vector digital data

**Resolution:** NA

**Projection Parameters**
- **Datum:** WGS 1984
- **Projection:** Mercator Auxiliary Sphere
Parameter: Threatened and endangered species habitat
Dataset Title: Critical Habitat (polygon)
Online Linkage: http://ecos.fws.gov/crithab/
Description: When a species is proposed for listing as endangered or threatened under the Endangered Species Act (ESA), the United States Fish and Wildlife Service must consider whether there are areas of habitat believed to be essential to the species' conservation. Those areas may be proposed for designation as "critical habitat." Critical habitat is a term defined and used in the Endangered Species Act. It is specific geographic areas that contain features essential to the conservation of a threatened or endangered species and that may require special management and protection. Critical habitat may include areas that are not currently occupied by the species but that will be needed for its recovery. As of March 1, 2013, critical habitat has been designated for 661 of the 1,499 U.S. species listed as threatened or endangered species. Service rules normally exclude by text developed areas such as buildings, roads, airports, parking lots, piers, and other such facilities. Within areas occupied by the species, biologists consider physical and biological features needed for life processes.

These include:
• space for individual and population growth and for normal behavior;
• cover or shelter;
• food, water, air, light, minerals, or other nutritional or physiological requirements;
• sites for breeding and rearing offspring; and
• habitats that are protected from disturbances or are representative of the historical geographical and ecological distributions of a species.
Biologists also consider unoccupied areas that are essential for the conservation of the species.

Associated Documentation/Article(s):
**Geographic Coverage:** United States  
**Author/Institution(s):** Fish and Wildlife Services  
**Publication Date:** 2013  
**Dataset Confidentiality:** None  
**Geospatial Data Presentation Form:** Vector digital data  
**Resolution:** NA  
**Projection Parameters**  
- **Datum:** WGS 1984  
- **Geographic Coordinate System:** WGS 1984  
- **Units:** Decimal Degree  
**Contact Information:** CNO@fws.gov

**Parameter:** Federally protected land  
**Dataset Title:** Protected Areas Database of the United States (PAD-US)  
**Online Linkage:** http://gapanalysis.usgs.gov/padus/  
**Description:** A national inventory of the U.S. terrestrial and marine protected areas that are dedicated to the preservation of biological diversity and to other natural, recreation and cultural uses, managed for these purposes through legal or other effective means. Lands in PAD-US are typically open space/resource lands owned in fee by agencies and non-profits. The current data set includes the “gap ranks” of these lands, indicating how they are being managed for conservation purposes. PAD-US includes all federal and most state conservation lands, and many areas at regional and local scales, with plans underway to expand these holdings in the database. Codes include the following:

- 0 Unknown
- 1 Disturbance events proceed or are mimicked
- 2 Managed for biodiversity, disturbance events suppressed
- 3 Managed for multiple uses, subject to extractive (e.g. mining or logging) or OHV use
- 4 No known mandate for protection

**Associated Documentation/Article(s):**  
**Geographic Coverage:** United States
Author/Institution(s): United States Geological Survey Gap Analysis Program (GAP)
Publication Date: 2012
Dataset Confidentiality: None
Geospatial Data Presentation Form: Vector digital data
Resolution: NA
Projection Parameters
  Datum: North American Datum of 1983
  Projection: Albers Conical Equal Area
  Projected Coordinate System: USA Contiguous Albers Equal Area Conic
  Geographic Coordinate System: North American 1983
  Units: meter
Contact Information: lduarte@uidaho.edu; 208-885-3013
**Supplementary Table 6** | Direct normal irradiance classes and associated capacity factors generated\(^1\) by Lopez et al. (2012)\(^2\) for a dry-cooled trough system with six hours of storage (solar multiple = 2, land-use efficiency = 32.8 MW km\(^{-2}\)).

<table>
<thead>
<tr>
<th>Class</th>
<th>Direct Normal Irradiance (Kwh m(^{-2}) d(^{-1}))</th>
<th>Capacity Factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.00 ≤ DNI &lt; 6.25</td>
<td>0.315</td>
</tr>
<tr>
<td>2</td>
<td>6.25 ≤ DNI &lt; 7.25</td>
<td>0.393</td>
</tr>
<tr>
<td>3</td>
<td>7.25 ≤ DNI &lt; 7.50</td>
<td>0.428</td>
</tr>
<tr>
<td>4</td>
<td>7.50 ≤ DNI &lt; 7.75</td>
<td>0.434</td>
</tr>
<tr>
<td>5</td>
<td>DNI &gt; 7.75</td>
<td>0.448</td>
</tr>
</tbody>
</table>

\(^1\)Using NREL's Systems Advisor Model with the National Solar Radiation Database Typical Meteorological Year 3 (see: http://sam.nrel.gov/).

**Supplementary Table 7** | Potential hydrologic, socioeconomic, topographical, infrastructural, and ecological input parameters (influencing factors) for calculating solar energy technical potential in the Carnegie Environmental Energy Compatibility Model (CEEC). Parameters are not exhaustive.

<table>
<thead>
<tr>
<th>Hydrologic</th>
<th>Socioeconomic</th>
<th>Topographical</th>
<th>Infrastructural</th>
<th>Ecological</th>
</tr>
</thead>
<tbody>
<tr>
<td>atmospheric aerosols</td>
<td>culturally sensitive land</td>
<td>aspect</td>
<td>capacity factor</td>
<td>biodiversity</td>
</tr>
<tr>
<td>atmospheric</td>
<td>electricity price</td>
<td>elevation</td>
<td>communication cables and sites</td>
<td>biomass</td>
</tr>
<tr>
<td>greenhouse gases</td>
<td>energy incentives</td>
<td>parcel size</td>
<td>pipelines</td>
<td>land-cover</td>
</tr>
<tr>
<td>albedo</td>
<td>energy demand</td>
<td>slope</td>
<td>roads</td>
<td>ecologically protected land</td>
</tr>
<tr>
<td>cloud cover</td>
<td>energy legislation</td>
<td></td>
<td>substations</td>
<td>land-cover change</td>
</tr>
<tr>
<td>evaporation</td>
<td>land-use</td>
<td></td>
<td>technology type</td>
<td>soil carbon</td>
</tr>
<tr>
<td>groundwater</td>
<td>land-use change</td>
<td></td>
<td>transmission</td>
<td>fire</td>
</tr>
<tr>
<td>perennial snow and ice</td>
<td>land-use history</td>
<td></td>
<td>rooftop area</td>
<td>ecological corridors</td>
</tr>
<tr>
<td>soil precipitation</td>
<td>population</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>solar radiation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>surface water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>trace gases</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>water vapor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wind</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Supplementary Table 8** | Land-cover types characterizing California including their description, total area (km²), and percent cover (%). Land cover type descriptions are informed from the National Land Cover Database (Fry et al. 2011).

<table>
<thead>
<tr>
<th>Land-cover type</th>
<th>Description</th>
<th>Total area (km²)</th>
<th>Percent cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open water</td>
<td>All areas of open water, generally with less than 25% cover of vegetation or soil</td>
<td>5,350.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Perennial ice and snow</td>
<td>All areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover</td>
<td>40.7</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Developed, open space</td>
<td>Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover; these areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes</td>
<td>12,371.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Developed, low intensity</td>
<td>Includes areas with a mixture of constructed materials and vegetation; impervious surfaces account for 20-49 percent of total cover; these areas most commonly include single-family housing units</td>
<td>6,508.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Developed, medium intensity</td>
<td>Includes areas with a mixture of constructed materials and vegetation; impervious surfaces account for 50-79 percent of the total cover; these areas most commonly include single-family housing units</td>
<td>6,827.4</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Supplementary Table 8 | Land-cover types characterizing California including their description, total area (km²), and percent cover (%). Land cover type descriptions are informed from the National Land Cover Database (Fry et al. 2011).1

<table>
<thead>
<tr>
<th>Land-cover type</th>
<th>Description</th>
<th>Total area (km²)</th>
<th>Percent cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed, high intensity</td>
<td>Includes highly developed areas where people reside or work in high numbers; examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to 100 percent of the total cover</td>
<td>1,577.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Barren land (rock/sand/clay)</td>
<td>Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material; generally, vegetation accounts for less than 15% of total cover</td>
<td>20,266.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Deciduous forest</td>
<td>Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover; more than 75 percent of the tree species shed foliage simultaneously in response to seasonal change</td>
<td>3,545.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Evergreen forest</td>
<td>Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover; more than 75 percent of the tree species maintain their leaves all year; canopy is never without green foliage</td>
<td>82,713.7</td>
<td>20.2</td>
</tr>
<tr>
<td>Mixed forest</td>
<td>Areas dominated by trees generally</td>
<td>10,095.2</td>
<td>2.5</td>
</tr>
</tbody>
</table>
**Supplementary Table 8** | Land-cover types characterizing California including their description, total area (km²), and percent cover (%). Land cover type descriptions are informed from the National Land Cover Database (Fry et al. 2011).1

<table>
<thead>
<tr>
<th>Land-cover type</th>
<th>Description</th>
<th>Total area (km²)</th>
<th>Percent cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrub/Scrub</td>
<td>Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation; this class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions</td>
<td>163,366.8</td>
<td>39.9</td>
</tr>
<tr>
<td>Grassland/Herbaceous</td>
<td>Areas dominated by grammanoid or herbaceous vegetation, generally greater than 80% of total vegetation; these areas are not subject to intensive management such as tilling, but can be utilized for grazing</td>
<td>53,097.7</td>
<td>13.0</td>
</tr>
<tr>
<td>Pasture/Hay</td>
<td>Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle; pasture/hay vegetation accounts for greater than 20 percent of total vegetation</td>
<td>7,450.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Cultivated crops</td>
<td>Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and</td>
<td>33,330.6</td>
<td>8.1</td>
</tr>
</tbody>
</table>
**Supplementary Table 8** | Land-cover types characterizing California including their description, total area (km²), and percent cover (%). Land cover type descriptions are informed from the National Land Cover Database (Fry et al. 2011).1

<table>
<thead>
<tr>
<th>Land-cover type</th>
<th>Description</th>
<th>Total area (km²)</th>
<th>Percent cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woody wetlands</td>
<td>Areas where forest or shrubland vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water</td>
<td>851.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Emergent herbaceous wetlands</td>
<td>Areas where forest or shrubland vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water</td>
<td>2,048.5</td>
<td>0.5</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>409,443.0</td>
<td>100</td>
</tr>
</tbody>
</table>

**Supplementary Table 9 | A selection of A) concentrating solar power (CSP) and B) photovoltaic (PV) land suitability analysis studies and associated parameter constraints.**

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Date</th>
<th>Minimum DNI (kWh/m²/d)</th>
<th>Proximity to Roads (mi)</th>
<th>Proximity to Transmission (mi)</th>
<th>Minimum Voltage (kV)</th>
<th>Slope</th>
<th>Minimum Parcel Unit (km²)</th>
<th>Distance to Population Center</th>
<th>Area of Study Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1Kirby et al.</td>
<td>2003</td>
<td>≥ 5</td>
<td>50</td>
<td>50</td>
<td>69 ≤ x ≤ 345</td>
<td>≤ 5%</td>
<td>0.16</td>
<td>--</td>
<td>Western USA</td>
</tr>
<tr>
<td>2Karstaedt et al.</td>
<td>2005</td>
<td>≥ 5</td>
<td>25*</td>
<td>25</td>
<td>69 ≤ x ≤ 345</td>
<td>&lt; 5%</td>
<td>0.16</td>
<td>--</td>
<td>USA</td>
</tr>
<tr>
<td>3Bravo et al.</td>
<td>2007</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&lt; 2%**</td>
<td>4</td>
<td>--</td>
<td>Spain</td>
</tr>
<tr>
<td>4Pletka et al.</td>
<td>2007</td>
<td>&gt; 6.75</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&lt; 1%</td>
<td>5</td>
<td>--</td>
<td>USA</td>
</tr>
<tr>
<td>5Dahle et al.</td>
<td>2008</td>
<td>≥ 5</td>
<td>25*</td>
<td>25</td>
<td>≥ 69</td>
<td>&lt; 3%</td>
<td>2</td>
<td>--</td>
<td>USA</td>
</tr>
<tr>
<td>6Fluri et al.</td>
<td>2009</td>
<td>≥ 7</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&lt; 1%</td>
<td>2</td>
<td>South Africa</td>
<td></td>
</tr>
<tr>
<td>7Cameron et al.</td>
<td>2012</td>
<td>7</td>
<td>--</td>
<td>--</td>
<td>&lt; 1%, &lt; 3%, &lt; 5%</td>
<td>1</td>
<td>1</td>
<td>CA, USA</td>
<td></td>
</tr>
<tr>
<td>8Lopez et al.</td>
<td>2012</td>
<td>≥ 5</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>≤ 3%</td>
<td>1</td>
<td>--</td>
<td>USA</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>--</td>
<td><strong>5.8</strong></td>
<td><strong>33.3</strong></td>
<td><strong>33.3</strong></td>
<td><strong>≥ 69</strong></td>
<td><strong>2.9</strong></td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>PV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kirby et al.</td>
<td>2003</td>
<td>≥ 5</td>
<td>--</td>
<td>50</td>
<td>115 ≤ x ≤ 345</td>
<td>&lt; 10%</td>
<td>--</td>
<td>--</td>
<td>Western USA</td>
</tr>
<tr>
<td>Karstaedt et al.</td>
<td>2005</td>
<td>≥ 5</td>
<td>25*</td>
<td>25</td>
<td>69 ≤ x ≤ 345</td>
<td>&lt; 5%</td>
<td>0.16</td>
<td>--</td>
<td>USA</td>
</tr>
<tr>
<td>Bravo et al.</td>
<td>2007</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&lt; 2%**</td>
<td>4</td>
<td>--</td>
<td>Spain</td>
</tr>
<tr>
<td>Pletka et al.</td>
<td>2007</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>USA</td>
</tr>
<tr>
<td>Dahle et al.</td>
<td>2008</td>
<td>5</td>
<td>--</td>
<td>25</td>
<td>69 ≤ x ≤ 345</td>
<td>--</td>
<td>≤ 100 miles</td>
<td>USA</td>
<td></td>
</tr>
<tr>
<td>Cameron et al.</td>
<td>2012</td>
<td>7</td>
<td>--</td>
<td>--</td>
<td>&lt; 1%, &lt; 3%, &lt; 5%</td>
<td>1</td>
<td>--</td>
<td>CA, USA</td>
<td></td>
</tr>
<tr>
<td>Lopez et al.</td>
<td>2012</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>≤ 3%</td>
<td>1</td>
<td>--</td>
<td>USA</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>--</td>
<td><strong>5.5</strong></td>
<td><strong>25</strong></td>
<td><strong>33.3</strong></td>
<td><strong>≥ 69</strong></td>
<td><strong>4.6</strong></td>
<td><strong>1.5</strong></td>
<td></td>
</tr>
</tbody>
</table>

*includes roads and railways
**additional slope rules apply to SE and SW aspects (see paper)
### Supplementary Table 10 | Road codes and descriptions for road types included in the Carnegie Energy and Environmental Compatibility model.

<table>
<thead>
<tr>
<th>MTFCC¹ (Code)</th>
<th>Description</th>
<th>Included</th>
<th>Excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1100</td>
<td>Primary road</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1200</td>
<td>Secondary road</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1400</td>
<td>Local neighborhood road, rural road, city street</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1500</td>
<td>Vehicular trail (4WD)</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1630</td>
<td>Ramp</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1640</td>
<td>Service drive usually along a limited access highway</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1710</td>
<td>Walkway/pedestrian trail</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1720</td>
<td>Stairway</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1730</td>
<td>Alley</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1740</td>
<td>Private road for service vehicles (logging, oil fields, ranches, etc)</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1750</td>
<td>Private driveway</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1780</td>
<td>Parking lot road</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1820</td>
<td>Bike path or trail</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1830</td>
<td>Bridle path</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S2000</td>
<td>Road median</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

¹MAF/TIGER Feature Class Code (see [http://www.census.gov/geo/maps-data/data/tiger.html](http://www.census.gov/geo/maps-data/data/tiger.html) for more details)