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ORIGINAL PAPER

Utility-Scale Solar PV in South Carolina: Analysis of Suitable Lands and Geographical Potential

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Abstract The purpose of this study is to determine prospective locations for the implementation of utility-scale solar photovoltaic (PV) technologies and the associated geographical potential of solar energy in South Carolina. By considering limitations imposed by land use, land type, protected areas, and topography, the absolute solar potential was restricted to areas physically, socially, and environmentally favorable for utility PV projects. Using a geographical information system-based suitability model, lands were ranked from 0 (unsuitable for development) to 100 (most suitable). The available solar resource was then calculated for lands with suitability values of at least 50, 70, and 90, with contiguous area requirements of 0.18 and 0.036 km^2 (consistent with approximately 5 MW_{AC} and 1 MW_{AC} capacity systems, respectively). The results indicate that, with a 5 MW_{AC} capacity requirement, 3253 km^2 (approximately 4.2 % of state land area) obtains the mid-range suitability value of 70. These lands annually receive 5460 TWh of energy from the sun. The analysis and results can facilitate the identification of potential land areas for implementation of utility-scale solar development and demonstrate the maximum solar flux extractable on these lands.

Keywords Suitability analysis · Photovoltaics · Geographical potential · Solar resource · Land-use planning · Renewable energy potential

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Introduction

The U.S. solar industry, practically non-existent before the year 2000, has experienced tremendous growth in the past decade. Between 2006 and 2015, the annual net generation from solar PV and thermal facilities grew from approximately 508 MWh to 38,614 MWh (EIA 2016). Of the total installed solar capacity, utility-scale PV systems constitute the largest majority and have the highest potential for further developments (Bolinger and Seel 2015). Lopez et al. (2012), for example, estimated that rural, utility-scale PV has a technical capacity potential of 153,000 GW, more than 24,500 times current US installed capacity of 6236 MW_{AC} (Bolinger and Seel 2015). Of this technical potential, Jacobson et al. (2015) calculates that 2326 GW of solar PV (covering a land area footprint of 17,383 km^2) could contribute to a 100 % clean energy society by 2050. Considering the solar industry's large potential for continued expansion, it is increasingly critical to identify land areas that maximize resource potential while minimizing environmental and social conflict. Due to its current market dominance and bourgeoning technical potential, this study focuses specifically on identifying suitable areas and the associated resource potential of utility-scale solar PV, using the state of South Carolina as an example.

In South Carolina, a lack of political momentum[1] coupled with restrictive utility company business models has limited the state from experiencing the growth of solar development seen in the rest of the country. Though Jacobson et al. (2015) estimates that 6.7 GW of utility PV could enable South Carolina to meet 2050 end-use loads with 100 % clean energy, at the time of this writing, the state has just 0.25 % (17 MW) of this installed solar capacity (SEIA 2016). Current state policies, such as a renewable portfolio standard of just 2 % of electric utilities' installed nameplate generation capacity by the year 2021 (Bill 1189 2014), are inadequate to facilitate expansion of solar development. However, in light of agreements such as the 2015 Paris Agreement, in which the USA pledged to reduce greenhouse emissions by 26–28 % below 2005 levels by 2025, it can be expected that increased priority will be given to renewable energy developments such as solar across the USA (U.S. Cover Note 2015; EPA 2015).

With the anticipation of increased solar developments, the question remains as to where these developments should take place. In this study, we use geospatial land use, slope, aspect, and solar data to proactively identify low-conflict and topographically suitable areas for the development of utility-scale solar PV in South Carolina, and quantify the solar resource available on these lands. The maps presented here can inform projects that minimize environmental damage and decrease development costs. The associated calculations of geographical potential can serve as an initial gauge of possible progress toward high shares of renewables and national and state emissions targets.

Background

In order to facilitate the increased deployment of solar technologies, a realistic assessment of the available solar resource and suitable lands is needed. Assessments of the potential of energy sources can be defined in many ways, depending on the considered parameters and constraints. Several of the most common, based on categories utilized by Hoogwijk (2004), include theoretical, geographical, technical, and economic potentials. For solar, the theoretical potential represents the natural upper limit of the solar energy flux, while the geographical potential is the reduction of this energy flow to areas that are considered suitable and available for production. Technical potential is the reduction of the geographical potential due to system performance losses during conversion to secondary energy sources, and the economic potential is the amount of this energy that can be obtained at competitive cost levels.

Several reports, by Lopez et al. (2012), Black & Veatch (2012), and La Capra Energy Associates (2007), have quantified the technical potential—which considers system performance along with resource strength—of solar PV in South Carolina, whereas our study focuses on the geographical potential. Other sources, such as the Eastern Interconnection States' Planning Council (EISPC) Energy Zones Mapping Tool, provide geospatial data and visualizations of factors influencing solar development (Koritarov et al. 2013). Denholm and Margolis (2007) estimate the per-capita land area needed to supply all end-use electricity with solar PV to be 207 m^2 in South Carolina. Our analysis builds upon aspects of these studies in order to provide more specific geospatial data for the siting of solar facilities, and calculations of the exploitable solar resource independent of technological and economic assumptions.[2]

Each of the previously mentioned studies employs unique methodologies and assumptions, with greatly varying results (summarized in Table 1). On one extreme, La Capra and GDS Associates (2007) concluded that deployment of solar power was not feasible in the state, citing inhibitive cost and technological barriers[3] in their reasoning. A second report, prepared by Black & Veatch for the South Carolina Energy Advisory Council (2012), calculated the technical potential for utility PV to be 29,900 MW and generation technical potential to be 39,300 GWh/year. Lopez et al. (2012) determined nearly 32,400 km^2 in South Carolina to be suitable for rural, utility-scale PV development, and an associated technical potential of approximately 1500 GW, or 2755 TWh/year. As shown in Table 1, each study assumed a differing power density (PD) for solar PV plants, thereby influencing land area, capacity, and generation potential estimates. These three studies demonstrate the large variance in estimates for solar electricity output in South Carolina, as a result of differing assumptions about technical efficiencies, solar resource availability, and land-use suitability.

The EISPC EZ Mapping Tool enables the visualization of areas suitable for utility-scale solar PV by allowing stakeholders to select minimum allowable thresholds for resource quality and other ecological, topographical, technical, and social criteria. Suitability models are

[1] The SC Distributed Energy Resource Program Act, signed into law June 2014, provides the first major state incentive for solar installation. However, the law has been criticized for providing an unfair advantage to utility companies, and its success in increasing solar capacity cannot yet be judged.

[2] It should be noted that our study indirectly incorporates a technical assumption in the application of a minimum contiguous land area requirement for utility-scale solar (see Methodology, *Application of Minimum Land Area Requirement*).

[3] The La Capra (2007) study assumed a net energy conversion efficiency of 10 % for PV systems. However, contemporary commercial wafer-based silicon modules now have efficiencies near 15 % (many are up around 20 %).

Table 1 Summary of relevant findings and parameters from several analyses of solar potential in South Carolina

Report title	US renewable energy technical potentials: a GIS-based analysis[a]	South Carolina resource study	Analysis of renewable energy potential in South Carolina	Energy zones mapping tool[c]
Institution/ Author (Year)	Lopez et al. (2012)	Black & Veatch (2012)	La Capra Energy Associates and GDS Associates (2007)	Eastern Interconnection States' Planning Council (2013)
Total potential land area (% state land)	32,399 km^2 (42 %)	16,887 km^2 (22 %)	N/A	27,000 km^2 (35 %)
Capacity potential (GW)	1555	29.9	Infeasible	N/A
Generation potential (TWh/year)	2755	39.3	N/A	N/A
Main technical and economic assumptions[b]	PD = 48 MW/km^2, CF = 0.202, MCLA = 1-km^2	PD = 35 MW/km^2, CF = 0.15, MCR = 1 MW	PD = 24.7 MW/km^2, CF = 0.19–0.20, MCR = 1–10 MW, CE = 10 %, LC = \$164–\$309/ MWh, AIC = \$4000/kW	N/A
Included or excluded land categories	Excluded: slopes > = 3 %, federally protected lands, inventoried roadless areas, areas of critical environmental concern	Included (percent assumed available): pasture/hay (5 %), row crops (5 %), and quarries/ strip mines/gravel pits (10 %)	N/A	Excluded: Open water, perennial snow/ice, developed open space, slopes > = 11 %[d]

Some caution is needed when directly comparing the above results; this table is not a comprehensive summary of the various methodologies and assumptions applied in these studies

[a] Values in this table are associated with an analysis of rural, not urban, utility-scale PV

[b] Assumption abbreviations: *PD* Power density, *CF* capacity factor, *MCLA* minimum contiguous land area requirement, *CE* PV system net energy conversion efficiency, *MCR* minimum capacity requirement, *LC* Levelized Cost, *AIC* Average Installed Cost

[c] Land area results calculated for areas with overall suitability value of at least 50

[d] Refer to page A-23 of report for detailed land suitability values

produced by the weighted overlay of input layers depicting land attributes, each layer with suitability values ranging from 0 (unsuitable) to 100 (best suitability). The suitability values determined for utility-scale solar are detailed by Koritarov et al. (2013). A report generated for utility-scale PV in South Carolina, using the default suitability values, shows that 35 % of state land, or approximately 27,000 km^2, has a suitability value of at least 50. Approximately 1200 km^2, or 1.5 % of South Carolina land area, has a value of at least 70, and no land area obtains a value of 90 or above. The tool does not identify specific potential areas for development or provide estimates of resource potential, as we do.

Our analysis provides a source for comparison to these past results and addresses several perceived limitations of previous assessments of the potential for utility-scale PV in South Carolina. Primarily, the study does not make assumptions about the efficiency of PV technologies (with the exception of a minimum land area requirement) or state-specific capacity factors. Our results, therefore, correspond with a geographical, as opposed to theoretical, technical, or economic potential for solar. As done in previous studies, several land-use types were deemed to be unsuitable for utility PV and thus excluded from this analysis (Lopez et al. 2012, Black & Veatch 2012). However, similar to Koritarov et al. (2013), a suitability analysis approach was subsequently employed by weighting the remaining lands based on their land type and use, slope, and aspect values. This allowed for consideration of land types not considered by Black & Veatch (e.g., deciduous forest and cultivated crop areas), as well as greater granularity in the suitability of remaining land areas than that applied by Lopez et al. (2012), which treated all un-eliminated land areas equally. Furthermore, we use global horizontal irradiance (GHI) data to calculate the energy flux on suitable lands, as opposed to assuming either a uniform, state-wide capacity factor or land-use requirement, to calculate solar potential.

The identification of lands that are geographically promising without being socially or environmentally contentious should facilitate the implementation of solar projects in South Carolina. A similar process in Nevada, in which the Bureau of Land Management developed the Western Solar Plan with 19 designated Solar Energy Zones (SEZ), has successfully contributed to the lowest power purchase agreement between a utility and solar company in the USA, at just $0.0384 per kWh (after an investment tax credit of 30 %) of electricity produced[4] (PUCN 2015). The establishment of SEZs has also allowed for a more efficient permitting process, reducing the waiting time from over 2 years to just 10 months. The results shown in our report can facilitate the development of a similar plan for South Carolina.

Methodology

A GIS-based, suitability analysis was used to determine which South Carolina lands hold the greatest potential for the development of utility-scale solar PV systems. GHI data was then used to quantify the annual solar energy available on these lands. Through the assignment of suitability values to land attributes and weighted combination of layers, this process inherently involved a quantification of social and environmental factors that influence the suitability of land for utility-scale solar PV. These assumptions greatly affect the results of the suitability study and have therefore been detailed. The process was divided into the following steps:

1. Data preparation
2. Creation of analysis mask
3. Identification and reclassification of relevant land attributes
4. Weighting of attributes and combination into suitability layer
5. Calculation of geographical potential at minimum suitability values
6. Application of minimum land area requirement

The full Model Builder process used to perform this analysis in ArcGIS can be found in Fig. 6 in the Appendix. Although ArcGIS was used for this analysis, the general methodology employed here can be applied using any appropriate geospatial program for any region, provided data are available.

[4] This 20-year, fixed-escalator price includes the present-day investment tax credit of 30 % on the total cost of the solar system.

Data Preparation

Many factors influence a specific land parcel's suitability for utility-scale solar development. We considered: (1) land use, including protected natural environments, parks, and urban areas; (2) the type of land cover; (3) land slope and aspect; and (4) solar irradiation. Table 2 details the sources and file types of the data used.

The Universal Transverse Mercator (UTM) system divides the globe into 60 north and south zones, each spanning 6° of longitude. This coordinate system uses the cylindrical Transverse Mercator projection. The state of South Carolina lies entirely in Zone 17 of this projection. The coordinate system Clarke 1866 UTM Zone 17 N with Transverse Mercator projection was used for the data because it has minimal distortion of area and shape. In order to ensure all layers were properly overlaid, added datasets were projected in this coordinate system in ArcGIS.

Creation of Analysis Mask

As detailed by Patton et al. (2013), utility-scale solar development can have adverse impacts related to land use; ecological resources; air, soil, and water quality; esthetics; cultural resources; and hazardous waste, all of which can be minimized by intelligent site selection. In our study, therefore, solar development was excluded on several land types, including urban areas; national, county, state, regional, and local parks; airports; national forests; historic sites; national wildlife refuges; wilderness areas; and protected marine environments. The corresponding datasets used are shown in Table 2, and specific land areas selected for elimination from the U.S. National Atlas Federal and Indian Land Areas layer can be found in the Appendix, Table 8. The five datasets were merged into a "No Build Zone" shown in Fig. 1, in which solar development was not considered.[5]

This layer was excluded from the South Carolina analysis area to create a resulting analysis mask, which excludes areas upon which, for social and environmental reasons, it has been deemed to be infeasible to build utility-scale solar PV systems. Of the remaining land, clearly some will be more desirable for solar development. The next steps detail the suitability analysis used to make this determination.

[5] Note: Because this data was available as vector files, the creation of an analysis mask was used as an alternative to reclassifying the layers with 0 suitability, as is done with several attributes of the land use, slope, and aspect raster files in Sect. 2 of the methodology.

Table 2 Data type, source, and file type of data used in geospatial analysis using ArcGIS

Data	Source	File type
State Boundary	ArcGIS Data and Maps	Polygon
Land Cover	U.S. Geological Survey (Homer et al. 2015)	Raster
Statewide Digital Elevation Model (DEM) for SC	SC Department of Natural Resources (2006)	Raster
Urban areas	ArcGIS Data and Maps	Polygon
U.S Parks (national, county, state, regional, local)	ArcGIS Data and Maps	Polygon
Airport areas	ArcGIS Data and Maps	Polygon
Protected Marine Environment	ArcGIS Data and Maps	Polygon
U.S. National Atlas Federal and Indian Land Areas	ArcGIS Database	Polygon
Global Horizontal Irradiance (10 km resolution) 1998 to 2009	National Renewable Energy Laboratory (2012a)	Polygon

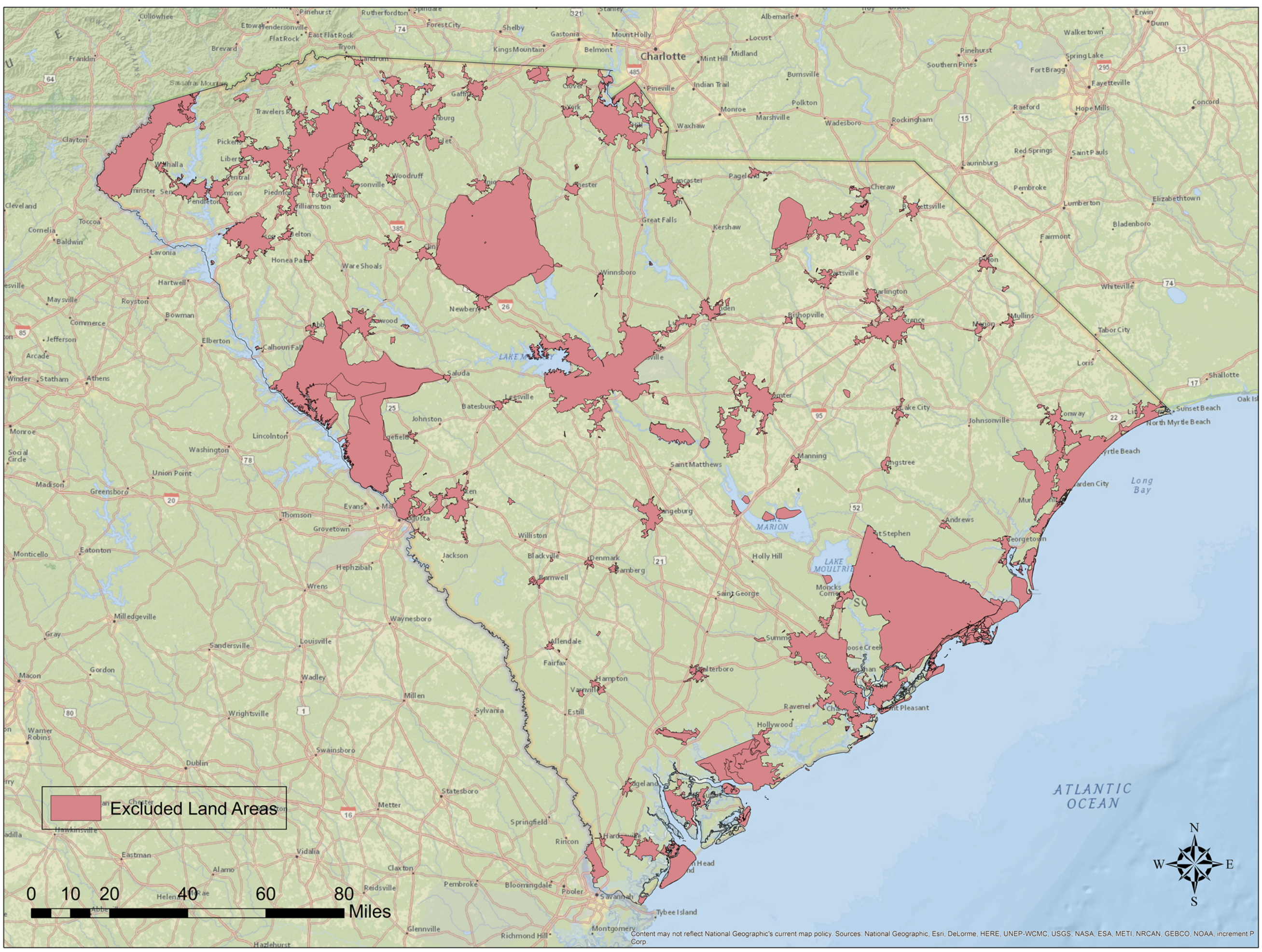

Fig. 1 South Carolina land areas excluded from consideration for the development of utility-scale solar PV facilities

Identification and Reclassification of Relevant Land Attributes

Physical, site-specific land attributes have a significant impact on the success of a large-scale solar project. The variables that we considered were land use, slope, and aspect. In order to compare and utilize the impact of these factors, the data in each layer were reclassified to a common scale of 0 (unsuitable for utility-scale PV) to 100 (most suitable) using the methodology detailed in this section. The suitability values assigned in this analysis relate to their influence on strength of solar resource, cost of development, and the social and environmental feasibility of development.

Land Use

Land cover data were obtained from the U.S. Geological Survey (USGS) Land Cover Institute (LCI) (Homer et al. 2015). The USGS survey classified lands into the 17 categories shown in Table 3. Land Cover Class Definitions can be referred to for full descriptions of these land types (USGS Land Cover Institute 2012). Land types were assigned reclassification values based on the default suitability criteria used by EISPC in the EZ Mapping Tool, utility-scale PV suitability model (Koritarov et al. 2013). The values indicate the relative physical, economic, and environmental feasibility of installing utility-scale PV on each respective land type. For example, developing PV on woody or herbaceous wetlands (suitability value of 5), which are saturated in water and provide environmental benefits such as flood protection and wildlife habitat, would likely result in greater construction and maintenance costs and environmental degradation than on developed areas of low intensity (suitability value of 50). It should be noted that in present day, land classified as hay/pasture and cultivated crops are appealing to solar developers (suitability values of 80 and 70, respectively) for their expansive flatness and lack of tree cover. In North Carolina, for example, farmers leased approximately 28.3 km^2 of pasture and cropland to solar developers between 2013 and 2016 (Ryan 2016). Furthermore, the potential for co-development exists, meaning that the high suitability value does not necessarily indicate that the entire area, but rather selected sites, can be used to deploy solar. However, as agricultural land requirements increase to satisfy the needs of a burgeoning global population, the suitability values assigned to areas classified as hay/pasture (80) and cultivated crops (70) may need to be revisited. This model's flexibility allows for such adjustments. The resulting map, showing reclassified land-use values, can be found in Fig. 2 at the end of this section.

Table 3 Land use types and assigned suitability values *Source* Koritarov et al. (2013)

Category	Suitability value
Unclassified	100
Open water	0
Perennial snow/ice	0
Developed, open space	0
Developed, low intensity	50
Developed, medium intensity	15
Developed, high intensity	10
Barren land	100
Deciduous forest	20
Evergreen forest	10
Mixed forest	10
Shrub/scrub	25
Herbaceous	10
Hay/pasture	80
Cultivated crops	70
Woody wetlands	5
Emergent herbaceous wetlands	5

Slope and Aspect

Slope and aspect layers were derived in ArcGIS from the statewide Digital Elevation Model (DEM) for South Carolina and were reclassified based on their suitability for utility-scale solar PV development. The designation of these values is explained here.

Slope In general, "relatively level" slopes ($\sim$1–3 %) are preferred for utility-scale PV development, as they receive greater solar radiation and require lower installation costs (Mancini 2008). However, different mounting systems and installation techniques can allow for successful installations on steeper slopes.[6] Furthermore, analyzing the data collected by a USDA Forest Service study shows that at latitude of 30° North (that of South Carolina), solar resource is not significantly depleted until slope increases to greater than 30° (Buffo et al. 1972). Considering these varying reports and the fact that our study is not specific to one particular PV technology or mounting system, the reclassification values in Table 4 were determined. Note that the slope values considered acceptable for utility-scale solar are greater than those considered in the previously mentioned Lopez et al. (2012) and EISPC studies (Koritarov et al. 2013). Figure 2 depicts the resulting map layer with reclassified slope values.

Aspect Aspect is the compass direction that a slope faces. In the Northern Hemisphere, south-facing slopes receive the greatest amount or solar radiation, and north-facing receive the least. As shown in Table 5, aspect values were first modeled with a horizontally shifted cosine curve, to place aspects of 180° at the highest point on the curve, then normalized and scaled to range from 0 to 100.

[6] The company Schletter Inc, for instance, advertises that their GYAK hydraulic ram can install mounting systems on slopes up to 20°.

Table 4 Reclassification of land slope with assigned suitability values

Slope (°)	Suitability values
0	100
1	100
2	95
3	90
4	80
5	70
6	55
7	35
8	20
9	10
10	0
>11	0

Weighting of Attributes and Combination into Suitability Layer

Once all three datasets were reclassified to a common scale of 0–100, layers were weighted based on their relative importance to site selection and combined to produce a suitability layer. Each 30 m by 30 m land parcel in the resulting layer has a suitability value for utility-scale solar PV development ranging from 0 (unsuitable) to 100 (most suitable). The resulting suitability value indicates the relative confidence with which a particular land area can be used to deploy utility-scale solar PV, considering the land use, slope, and aspect attributes of the area.

Land use was considered to be the most important factor in selecting a site for utility-scale solar development due to its relatively large influence on the social, environmental, and economic impacts of development (Patton et al. 2013), as well as the feasibility of permit acquisition.[7] Aspect and slope were considered the second and third most influential factors, respectively. In reality, site-specific available solar energy is a complex function of slope, aspect, and other factors, as exemplified by Chandrakar and Tiwari (2013). The weighting shown in Eq. 1 simplifies this relationship, but maintains a slightly larger influence of aspect, as is it is well-established that in the northern hemisphere south-facing orientation is optimal for maximizing solar irradiance, while “no definite value is given by researchers for the optimum tilt angle” (Chandrakar and Tiwari 2013) and current mounting systems allow for slight correction of unfavorable slopes. The weighting factors are given in Eq. 1:

$$\text{Suitability} = 0.70 \cdot \text{land use} + 0.20 \cdot \text{aspect} + 0.10 \cdot \text{slope} \tag{1}$$

The distribution of the resulting suitability values for South Carolina is shown in Fig. 3. In ArcGIS, one suitability value was calculated for each 900-m^2 section of a grid overlaying the state.

In order to illustrate the results’ sensitivity to the applied minimum suitability value, areas with suitability values over 50, 70 and 90 on a scale of 0–100 were analyzed separately for their geographical solar potential.

Calculation of Geographical Potential at Minimum Suitability Values

Solar Irradiance Data

The availability of solar resource is one of the most important considerations for a potential solar PV development. Solar resource can be quantified in several ways: direct normal irradiation, diffuse horizontal irradiation, or global horizontal irradiation. We used GHI data, as it includes both the direct and diffuse components of solar radiation, both of which can be utilized by solar PV systems. As shown in Fig. 4, the average annual GHI in South Carolina ranges from 4.34 to 4.89 kWh/m^2/day. Considering that utility-scale PV systems have been installed in areas in the Northeastern United States with much lower solar resource,[8] all values in South Carolina are sufficient for the development of utility PV systems, and no land areas need be excluded due to limited solar resource.

Solar Resource Calculations

Using GHI data provided by NREL (2012a, b), the annual terawatt hours (TWh/year) of solar energy available for utility-scale solar PV development on suitable lands was calculated. This was accomplished by multiplying the solar resource layer by a binary suitable land layer (with values of 1 where suitability values are above the selected minimum and 0 elsewhere), as shown in Eq. (2). The geographical potential was calculated at three minimum suitability rankings: 50, 70, and 90.

[7] Studies, such as that of the Universidad Politécnica de Valencia, quantify the relatively high risk to project developers of social consequences and permitting delays associated with land acquisition—influenced primarily by land use – as compared to system performance losses or plant operation costs, which are associated with a site’s slope and aspect (Aragonés-Beltrán et al. 2009).

[8] According to NREL’s Solar Prospector Tool (2012b), New Jersey and New York receive an annual average GHI of approximately 3.5–4.5 kWh/m^2/day. As documented in NREL’s Open PV Project (2016), these states have, respectively, 1505.98 and 285.82 MW of installed PV capacity.

a

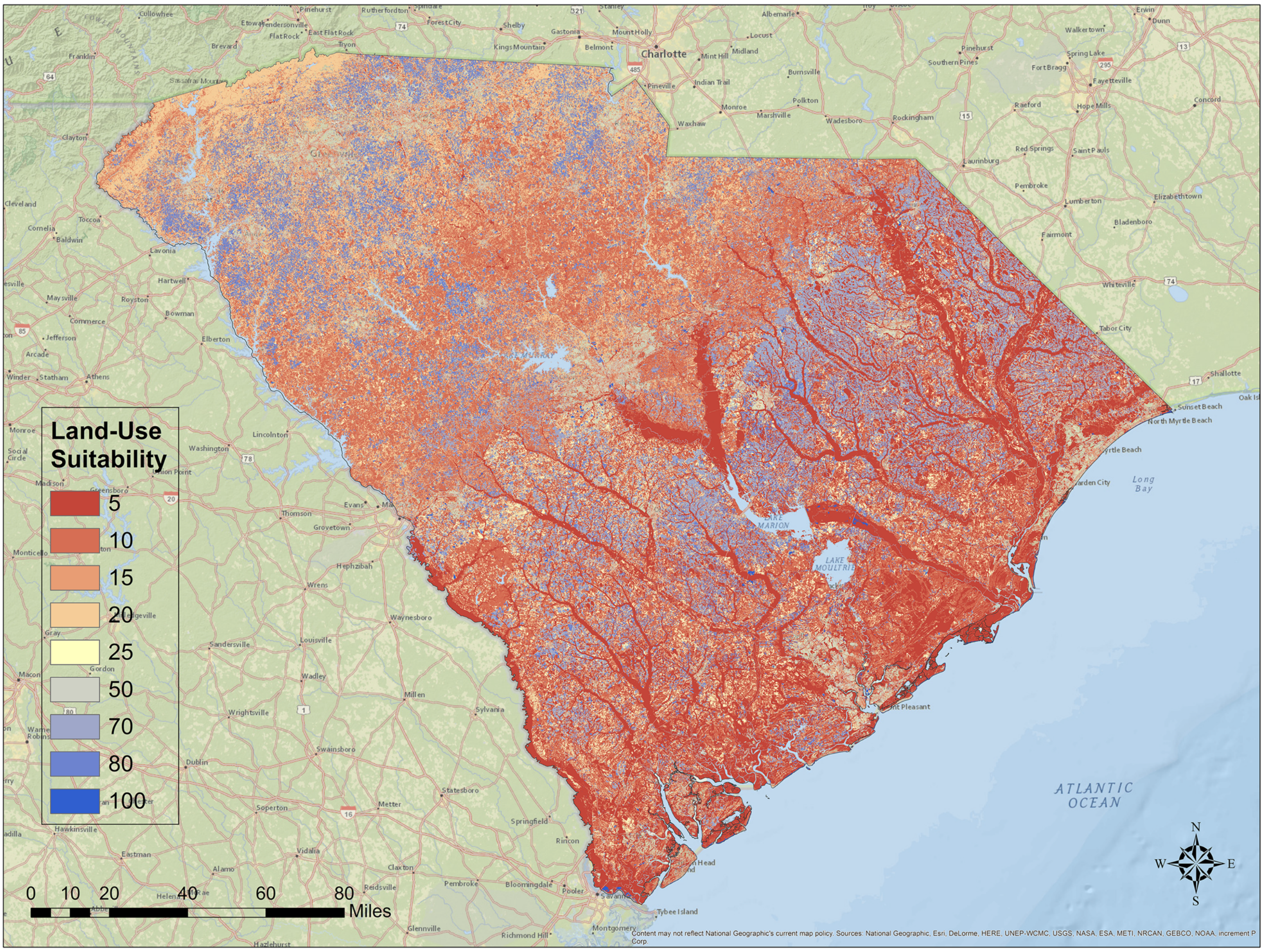

Fig. 2 Reclassified land cover and slope layers for South Carolina

$$\text{Total annual energy}\left(\frac{\text{TWh}}{\text{year}}\right) = \text{State}\sum\left[B\cdot\text{GHI}\left(\frac{\text{kWh}}{\text{m}^2\cdot\text{day}}\right)\cdot 365\left(\frac{\text{days}}{\text{year}}\right)\cdot\text{cell area}\left(900\text{m}^2\right)\cdot\text{conversion factor}\left(10^{-9}\frac{\text{TWh}}{\text{kWh}}\right)\right] \quad (2)$$

where B is a binary variable such that B equals one if the minimum suitability value is met and zero otherwise.

Application of Minimum Land Area Requirement

The total annual available solar energy on suitable lands was further restricted based on established definitions of "utility-scale" solar developments. As defined by Bolinger and Weaver (2015), "utility-scale" solar projects are those with nameplate capacities larger than 5 MW_{AC}. The Energy Information Administration (EIA), however, reports utility-scale development data for all projects larger than 1 MW_{AC} in capacity (Bolinger and Weaver 2015). To analyze the sensitivity of the final geographical solar potential to this minimum capacity requirement, both a 1 MW_{AC} and 5 MW_{AC} minimum were used.

In order to apply this capacity requirement in ArcGIS, approximate equivalent contiguous land areas were needed. The power density, or area required for 1 MW of installed solar capacity, is impacted by technology choices, topography of the site, panel spacing, and intensity of the solar resource. An analysis of utility-scale solar projects in the USA determined a total-area capacity-weighted average for all solar power plants to be 0.036 km^2 per MW_{AC} (Ong et al. 2013). Therefore, this study used contiguous land areas of approximately 0.18 and 0.036 km^2 to satisfy the 5 MW_{AC} and 1 MW_{AC} minimum capacity requirements, respectively. Only contiguous land areas larger than these minimum areas were considered for final potential calculations.

b

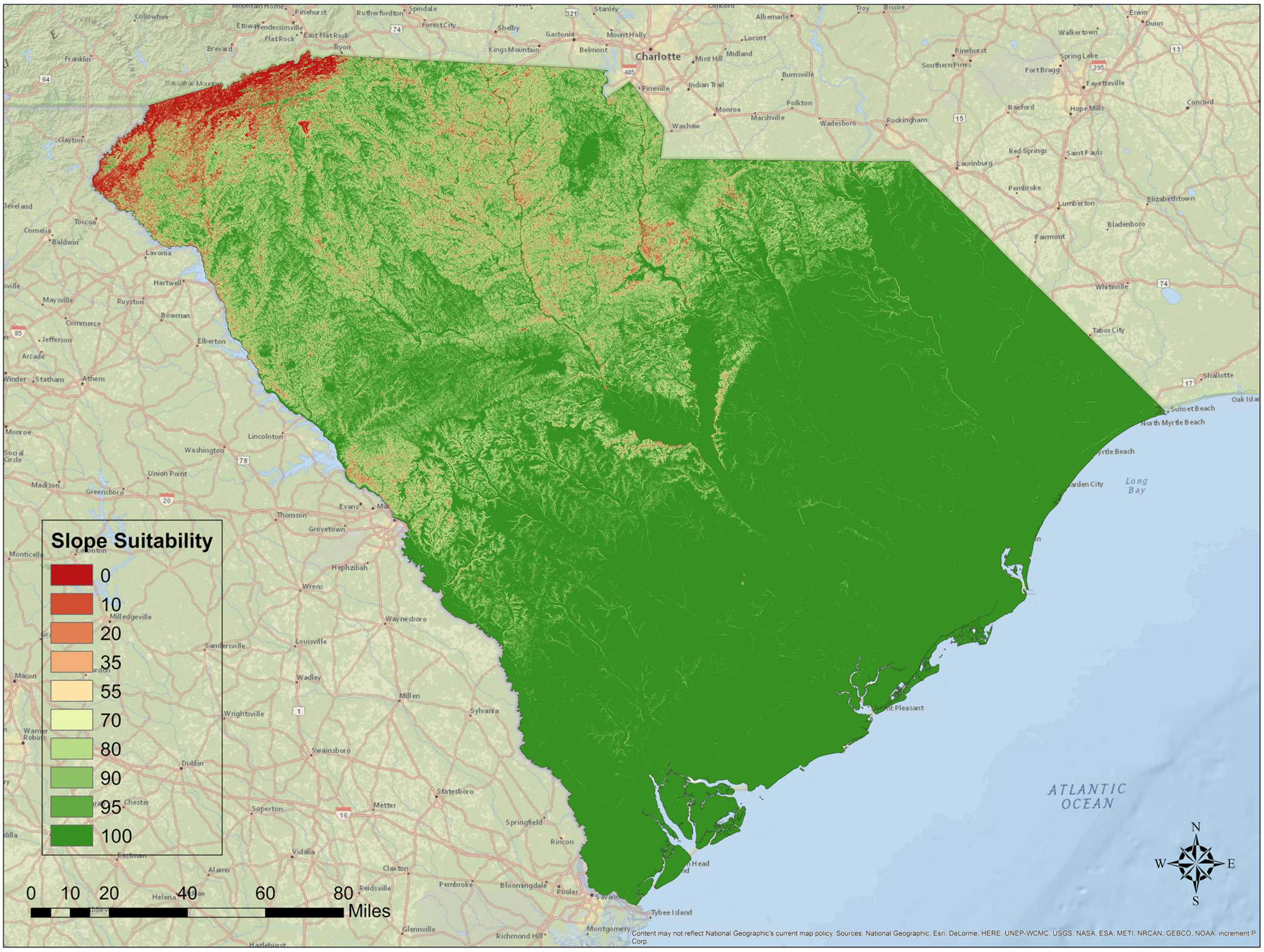

Fig. 2 continued

Table 5 Reclassification of land aspect with assigned suitability values

Aspect (°)	Cos($x+\pi$) + 1[a]	Normalized value	Suitability value
342–18	0.00	0.00	0
18–54	0.19	9.55	9
54–90	0.69	34.55	34
90–126	1.31	65.45	65
126–162	1.81	90.45	90
162–198	2.00	100.00	100
198–234	1.81	90.45	90
234–270	1.31	65.45	65
270–306	0.69	34.55	34
306–342	0.19	9.55	9

[a] Values in this column were calculated using the average of the adjacent aspect range

It should be noted that in light of recent technology improvements, the applied area requirement is conservative. A recently approved Stuttgart Solar project in Alabama, for example, has a nameplate capacity of 81 MW and will cover approximately 500 acres (0.025 km^2/MW) (APSC 2015). It can be expected that higher solar cell efficiencies will continue to drive down area requirements for utility-scale PV plants. This model can be adapted to account for technology improvements by adjusting the minimum contiguous land area requirement.

Results

The total annual solar energy available, total qualifying land area, and percentage of state land use are reported along two dimensions: three minimum suitability values and two minimum contiguous land area requirements, for a total of six results in each category. As previously detailed, the suitability values correspond to the relative confidence with which a given land parcel can be used to develop utility-scale solar PV, on a scale of 0–100, given the area's

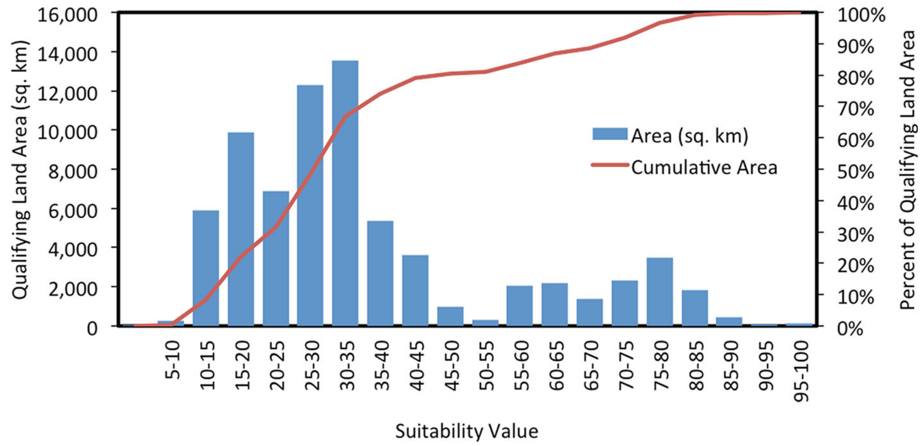

Fig. 3 Area and cumulative percent of SC lands with listed suitability values for utility-scale solar PV, calculated for 900-m^2 land parcels using a weighted combination of land use, aspect, and slope

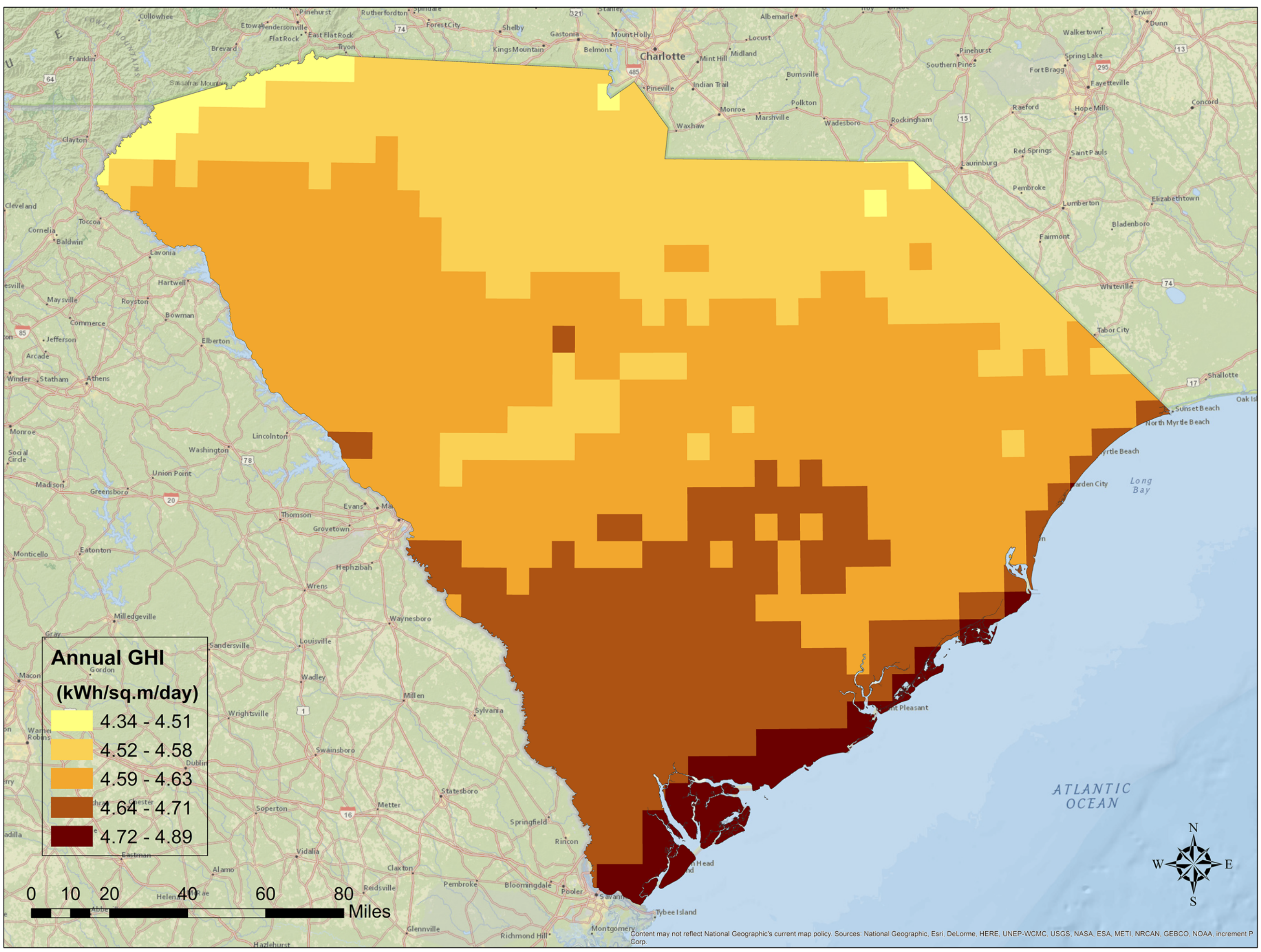

Fig. 4 Solar resource availability in South Carolina, measured as GHI (kWh/m^2/day)

slope, aspect, and land type. The minimum contiguous land area requirements of 0.18 and 0.036 km^2 correspond to two established definitions of "utility-scale" solar projects—5 MW_{AC} and 1 MW_{AC}, respectively. All results are summarized in Table 6.

Figure 5a depicts contiguous land areas large enough for a 5 MW_{AC} solar PV development (0.18 km^2) at suitability cutoffs of 50, 70, and 90, with previously established "No Build Zones" eliminated. The three land areas are overlayed, as those with higher suitability values are simply

Table 6 Available energy and land use for six suitability scenarios

Minimum suitability rank	Min capacity	Minimum contiguous land area (km^2)	Total annual energy available (TWh)	Land area (km^2)	State land use (%)
50	5 MW_{AC}	0.18	14,434	8600	11.1
	1 MW_{AC}	0.036	18,699	11,143	14.3
70	5 MW_{AC}	0.18	5460	3253	4.2
	1 MW_{AC}	0.036	10,168	6059	7.8
90	5 MW_{AC}	0.18	37	22.1	0.03
	1 MW_{AC}	0.036	107	63.6	0.08

a

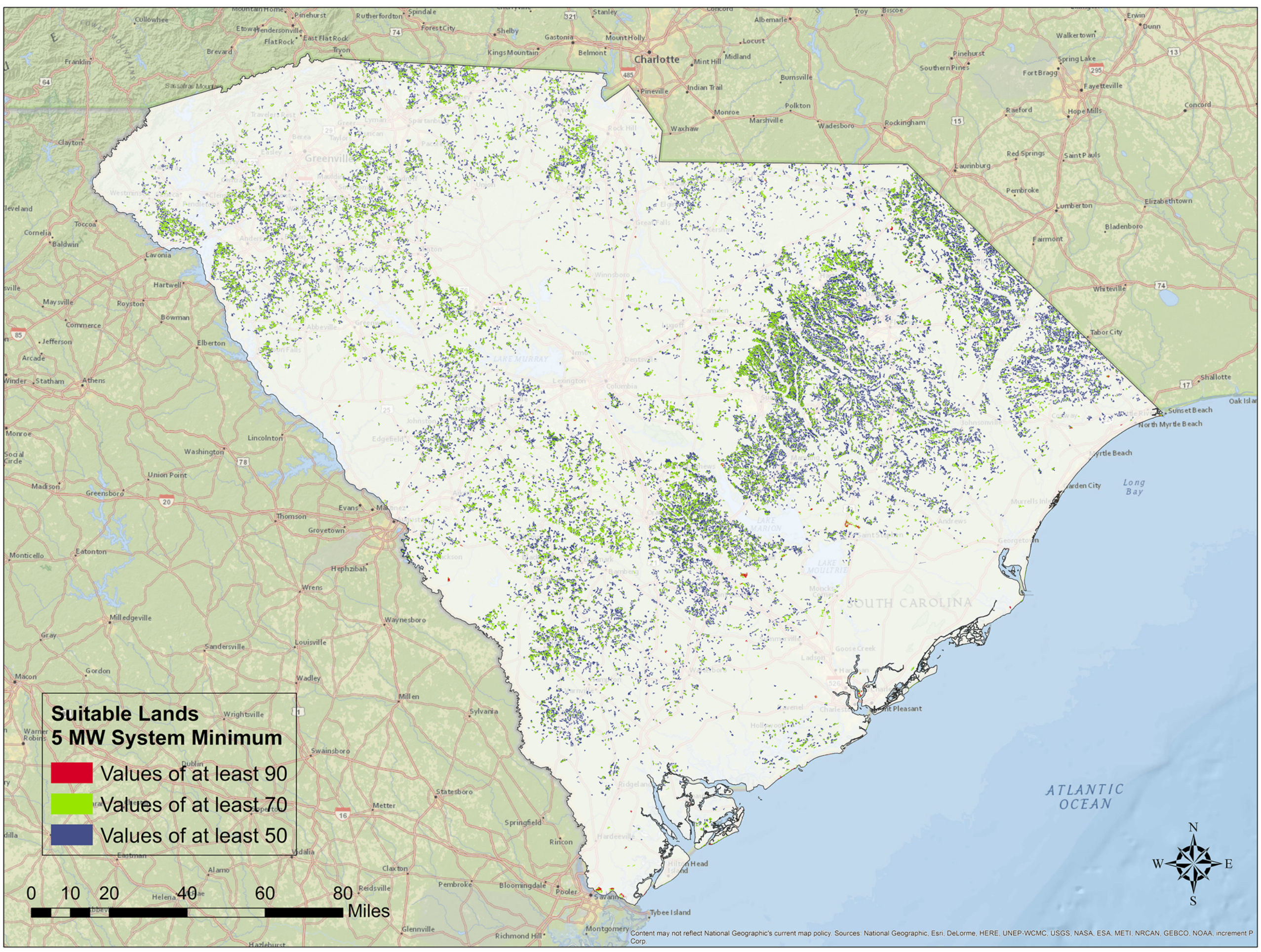

Fig. 5 Land areas with suitability scores of at least 50, 70, and 90 (*Note*: Land areas with a suitability score of at least 90, though present, are difficult to discern at this resolution), with a minimum capacity requirement of 5 MW_{AC} (**a**) and 1 MW_{AC} (**b**)

restricted portions of those with low suitability cutoffs. Figure 5b depicts suitable land areas with an applied 1 MW_{AC} capacity (0.036 km^2 land area) requirement.

As shown in the final maps (Fig. 5), most suitable land areas are dispersed across almost all of the state, but especially concentrated in the northeast. Most coastal land area is unsuitable for the development for utility-scale solar, likely due to the presence of low-lying wetlands.

Discussion

The resulting land area values and available solar energy potentials vary greatly depending on the applied minimum capacity and suitability value requirements—ranging from 37 TWh/year on 22 km^2 of land to 18,699 TWh/year on 11,143 km^2. A mid-range scenario of land with suitability values of at least 70 and an applied 1 MW_{AC} capacity b

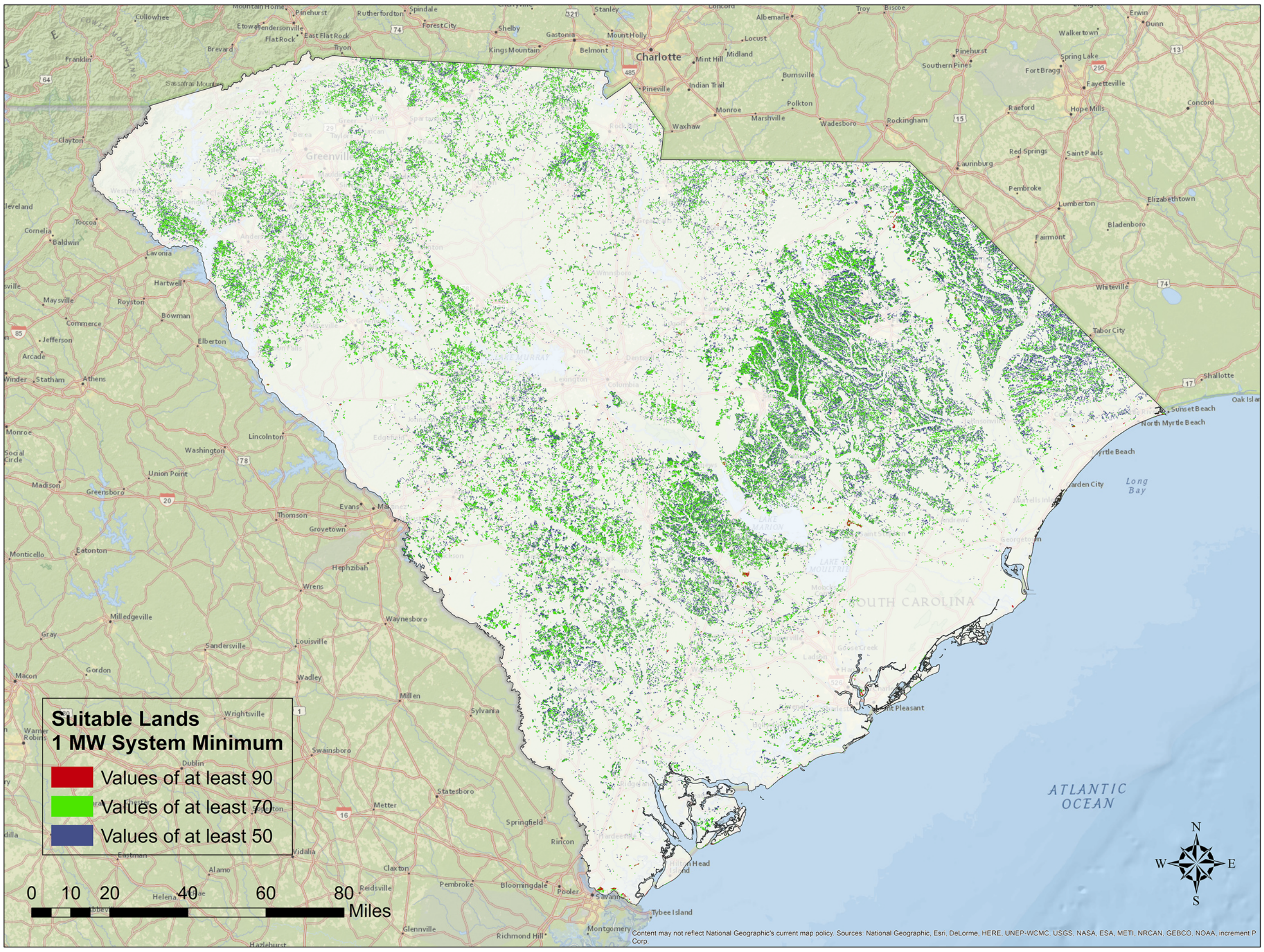

Fig. 5 continued

minimum shows 10,168 TWh/year on 6059 km^2 of qualifying land—an area slightly smaller than the state of Delaware. This equates to approximately 1.16 TW of raw capacity. Assuming 15 % module efficiency and a ground cover ratio of 0.4, this 69.6 GW of solar capacity well exceeds the 6.7 GW estimated by Jacobson et al. (2015) to be needed to contribute to a 2050 clean energy economy in South Carolina. Although very few land areas have suitability values above the most stringent cutoff (suitability value of 90), the analysis of these lands does provide insight as to which land parcels are most preferable and should be considered first by developers for large-scale solar projects. Furthermore, reducing the minimum capacity requirement from 5 MW_{AC} to 1 MW_{AC} dramatically increases the amount of qualifying land areas, suggesting that it may be efficacious to implement smaller distributed solar projects to meet load demands.

The EISPC EZ Mapping Tool model run for utility-scale PV reports a considerably greater land area with suitability values of at least 50 ($\sim$27,000 km^2), but a smaller area for lands with a minimum suitability value of 70 ($\sim$1200 km^2), indicating that most land areas in the EISPC model obtained more moderate suitability values than those we have obtained (Koritarov et al. 2013). Areas above a suitability value of 90 in this report (22.1 and 63.6 km^2) are just slightly greater than the 0 km^2 obtained by the EISPC model. A complete comparison of these results can be found in Table 7. Differences in these results could be influenced by the fact that the EISPC model considered distance to transmission lines, did not include land aspect, assigned different suitability values and layer weightings to

Table 7 Comparison of suitable land area results to those obtained from EISPC *EZ Mapping Tool* utility-scale PV model run, at differing minimum suitability values and capacity requirements

Minimum suitability value	50	70	90
EISPC EZ Mapping Tool (km^2)	27,000	1200	0
Our results (1 MW_{AC} minimum) (km^2)	11,143	6059	63.6
Our results (5 MW_{AC} minimum) (km^2)	8600	3253	22.1

all layers except land use, and did not include a minimum contiguous area requirement.

The amount of land considered suitable at suitability values of at least 50 and 70 is significantly greater than the area obtained by Black & Veatch (850 km^2), likely due to the fact that our report assigned a range of suitability values to many land types completely excluded by the Black & Veatch report. Conversely, the land area considered for utility-scale development by Lopez et al. (2012) (32,400 km^2) is nearly three-fold greater than the highest estimate reported here (11,143 km^2). Although, as in our report, this calculation excluded urban areas and areas of high social and ecological value, it was much less stringent on the consideration of various land types, only excluding water and wetlands, and also did not consider land aspect in its analysis (Lopez et al. 2012).

It is important to note that the assumptions made in this analysis in regard to the reclassification of slope, aspect, and land-use values, as well as the relative importance of these factors in utility-scale PV development, greatly influence the findings. In reality, these factors will have much more complex relationships than are modeled in this study. For instance, on land areas with very steep slopes, the influence of land aspect may be much greater than on shallow slopes. Further study should be done to more accurately determine the interrelatedness of these factors, how to model such relations, and the sensitivity of the results to different weighting schemes.

The results shown in this report can facilitate the implementation of utility-scale solar projects in South Carolina. Considering the potential for mandatory emissions reduction and clean energy requirements in the near-term, policymakers, utility companies, and solar developers should look to regional planning studies to begin analyzing where technologies such as solar can be best utilized without compromising environmental and societal values.

Conclusions and Next Steps

We show land areas with the highest resource potential and lowest environmental and social conflict. Using a suitability analysis, which considered land use and type, slope, and aspect, three suitability scenarios were evaluated at two minimum capacity requirements, for a total of six scenarios. These results include the total area of South Carolina lands with a calculated suitability value of at least 50, 70, and 90 on a scale of 0–100, as well as the annual amount of solar energy available on these land areas. With a minimum capacity requirement of 5 MW_{AC}, the total area of land that surpasses the most stringent suitability cutoff is 22.1 km^2, and 37 TWh/year of solar energy befalls these lands. These areas offer the greatest geographical potential for utility-scale solar projects and should be scrutinized more rigorously for potential developments. With a 1 MW_{AC} capacity requirement, the total area of land with suitability values of at least 50 was 11,143 km^2, and 18,699 TWh/year of solar energy is theoretically extractable across these areas. All specific land areas are visible in Fig. 5 of this report.

With the exception of the applied minimum contiguous area requirement, which indirectly accounts for module efficiency, factors such as proximity to infrastructure, socio-political influence of government policies, performance parameters of current PV technologies, and financial costs of solar development are not taken into consideration in this analysis of geographical potential. As the energy market evolves and module efficiencies increase, these factors will increasingly influence the technical potential for solar to meet statewide energy needs. This initial study, however, is less dependent on such variable factors and can be used as a starting point to locate specific areas for implementation or further analysis and to demonstrate the maximum solar flux extractable on these lands. Our results should indicate to policymakers that solar offers a viable way for South Carolina to diversify its fuel mix while reducing emissions, and the maps should indicate to potential developers the specific land parcels which will be most efficacious in terms of utility-scale solar power production. The Model Builder process shown in the Appendix allows this same analysis to be run on any chosen land area.

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Appendix

See Table 8; Fig. 6.

Table 8 South Carolina land areas selected (with Definition Query in ArcGIS) from U.S. National Atlas Federal and Indian Land Areas as No Build Zones

Feature name	Feature type
Francis Marion National Forest	National Forest FS
Nantahala National Forest	National Forest FS
Sumter National Forest	National Forest FS
Ninety-Six National Historic Site	National Historic Site NPS
Kings Mountain National Military Park	National Military Park NPS
Ace Basin National Wildlife Refuge	National Wildlife Refuge FWS
Cape Romain National Wildlife Refuge	National Wildlife Refuge FWS
Carolina Sandhills National Wildlife Refuge	National Wildlife Refuge FWS
Pinckney Island National Wildlife Refuge	National Wildlife Refuge FWS
Santee National Wildlife Refuge	National Wildlife Refuge FWS
Savannah National Wildlife Refuge	National Wildlife Refuge FWS
Ellicott Rock Wilderness	Wilderness FS
Ellicott Rock Wilderness	Wilderness FS
Hell Hole Bay Wilderness	Wilderness FS
Little Wambaw Swamp Wilderness	Wilderness FS
Wambaw Creek Wilderness	Wilderness FS
Wambaw Swamp Wilderness	Wilderness FS
Cape Romain Wilderness	Wilderness FWS
Congaree Swamp National Monument Wilderness	Wilderness NPS

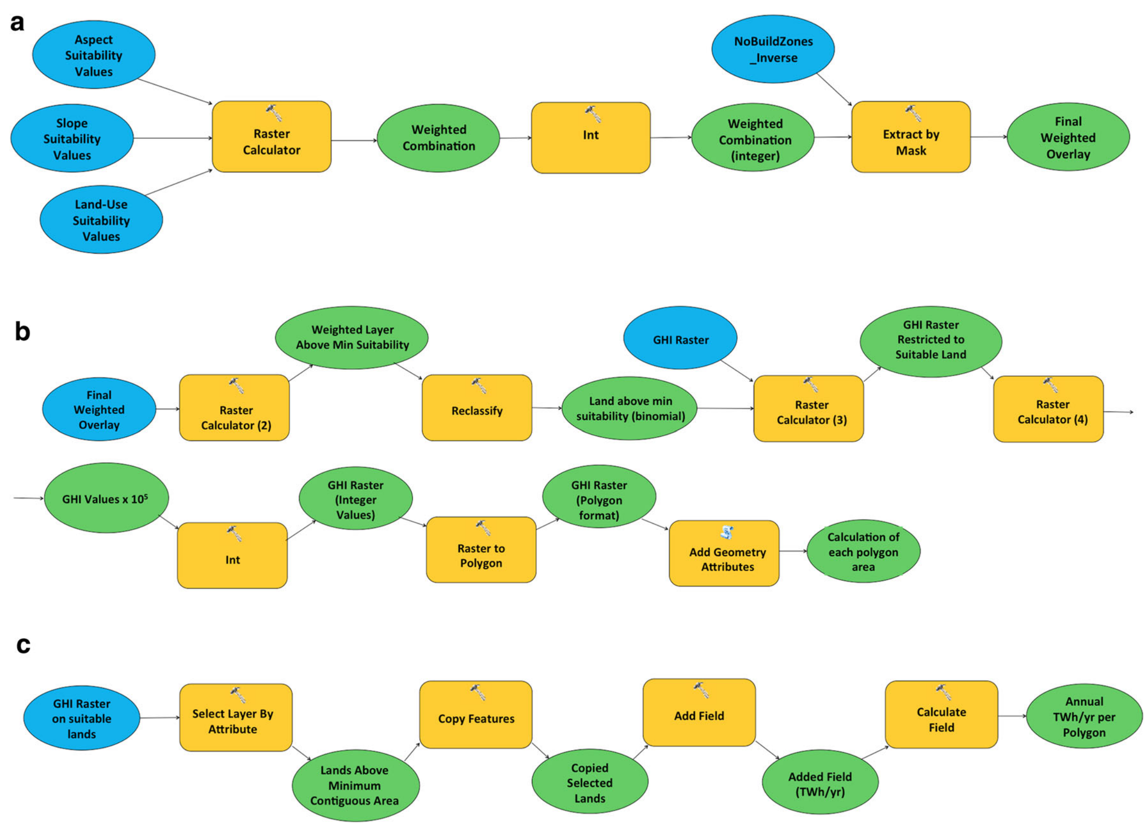

Fig. 6 Model Builder diagram of process used in ArcGIS to **a** create a weighted combination of reclassified slope, aspect, and land-use values, excluding previously established "No Build Zones," **b** determine the solar flux on land areas above a minimum suitability value, and the area of each land parcel, and **c** select lands above a minimum contiguous land area requirement and calculate the final TWh per year on these lands

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