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# Geospatial and techno-economic analysis of wind and solar resources in India

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## Abstract

Using geospatial and economic analysis, we identify abundant renewable resources in India — 850-3,400 GW for onshore wind, 1,300-5,200 GW for utility-scale solar photovoltaic (PV), 160-620 GW for concentrated solar power (CSP, with 6h-storage). However, these resources are concentrated in the western and southern regions. Deriving capital costs from India's 2017-18 auction prices, we estimate the 5th and 95th percentiles of levelized costs of energy generation ranging from USD 47-52 per MWh for solar PV and USD 42-62 per MWh for wind. Karnataka, Maharashtra, Tamil Nadu, and Telangana are the best states for access to high-voltage substations, but transmission investments in Gujarat, Rajasthan, Andhra Pradesh, and Madhya Pradesh are needed to harness significant renewable resources. More than 80% of wind resources lie on agricultural lands where dual land use strategies could encourage wind development and avoid loss of agriculturally productive land. Approximately 90% of CSP resources and 80% of solar PV resources are in areas experiencing high water stress, which can severely restrict deployment unless water requirements are minimized. Finally, we find co-location potential of at least 110 GW of wind and 360 GW of solar PV, which together could meet 35% of electricity demand in 2030.

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## 1. Introduction

India’s greenhouse gas emissions rank third in the world [1]. More than 30% of these emissions are from coal-based electricity generation [1], which until recently, was the cheapest source of electricity. Technological advances and recent cost declines in solar photovoltaic (PV) and wind technologies have made these alternatives increasingly cost-competitive with coal generation [2, 3, 4]. If costs of wind and solar PV continue to fall, India could cost-effectively deploy and integrate very high renewable energy (RE) capacity, which could significantly reduce local and global environmental impacts of its electricity system. As of 2017, India had already installed 32.8 GW of wind (6.4% of the global wind capacity of 514 GW) and 19.3 GW of solar PV (5% of the global solar PV capacity of 391 GW) [5]. Further, the Government of India (GoI) has set ambitious targets for grid-connected RE—60,000 MW of wind and 100,000 MW of solar capacity by 2022 [6]. In addition, in its Nationally Determined Contribution (NDC), the GoI committed to a target of 40% of installed generation capacity from non-fossil fuel sources by 2030 [6].

Despite India’s ambitious RE goals, there is little understanding of the siting barriers and opportunities in the scale up of wind and solar generation in India. Wind and solar resources depend on weather patterns and are often unevenly distributed across space. Therefore, quantifying regional potential is important for setting regional policies such as state-specific RE targets. Identifying suitable areas for RE deployment is also critical for land-use and transmission planning. If wind and solar technologies are to each supply half of India’s electricity demand in 2030, direct land requirements for wind and solar plants could be as large as 25% and 10% of India’s present urban area, respectively [7, 8].<sup>2</sup> Land acquisition in India has been a challenge, and land conflicts due to large infrastructure projects are common [9, 10].<sup>3</sup> Identify-

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<sup>2</sup>Assumptions of land use factors are 9 MW/km<sup>2</sup> for wind and 30 MW/km<sup>2</sup> for both solar PV plants. Actual direct land-use requirements of wind plants, which mainly includes roads, turbine footprint, and transformer, is significantly smaller than the entire area occupied by a wind plant. Total and urban area estimates for India are from the World Bank.

<sup>3</sup>In a study analyzing 289 land-related conflicts in 2016, 15% of the total conflicts were

ing areas with high quality RE resources but with limited competing values such as agriculture or biodiversity can limit potential conflicts and accelerate deployment. Further, identifying best quality resources relative to existing grid infrastructure can enable prioritizing potential RE projects based on existing transmission infrastructure and early planning of high-voltage high-capacity transmission lines, which typically take longer to construct than RE plants [11]. Pursuing opportunities to co-locate wind and solar PV plants can reduce the overall land requirements for RE deployments and capitalize on transmission line extensions. Vast areas in India are under water stress [12], and avoiding solar plant development in such areas would be critical to limit competition for scarce water resources.

For India, most studies estimating renewable resource potential have focused on wind energy [13, 14, 15, 16, 17, 18, 19], with few studies providing estimates of solar potential [20, 21]. However, none of the India-focused studies have quantified the technical potential of all three RE technologies—wind, solar PV, and CSP—using the same methodological framework and assumptions, which precludes a comparison of siting barriers between technologies. To our knowledge, no existing study has estimated potential costs of developing these resources.

In this study, we spatially identify and quantify the techno-economic potential for electricity generation from onshore wind, utility-scale solar PV, and concentrated solar power (CSP, with 6hr-storage) technologies in India using various siting assumptions and physical and environmental constraints. To enable strategic spatial planning, we identify land-use and water siting constraints and explore co-location opportunities for informed solar and wind power plant siting. Numerous studies have quantified RE resource potential using geographic information systems (GIS) [22, 23, 24, 25]. We also estimate the levelized cost of electricity (LCOE) generation, interconnection costs using the nearest transmission substation, and costs to connect each project to the road network. Further, we evaluate risks posed by competing land-uses and water scarcity to future RE development in the country. Finally, we quantify synergies between RE technologies in India, specifically potential for co-locating wind and solar plants to make better use of land and transmission resources.

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found to be in the electricity sector [9].

## 2. Methods

We adapted and built upon the Multi-criteria Analysis for Planning Renewable Energy (MapRE) modeling framework, which was first developed for and applied to regions in Africa [26]. MapRE is a spatial energy systems modeling framework that integrates renewable resource assessment and estimation of multiple criteria for decision making analysis [26]. The three stages of the MapRE methodology are shown in the flowchart in Figure .

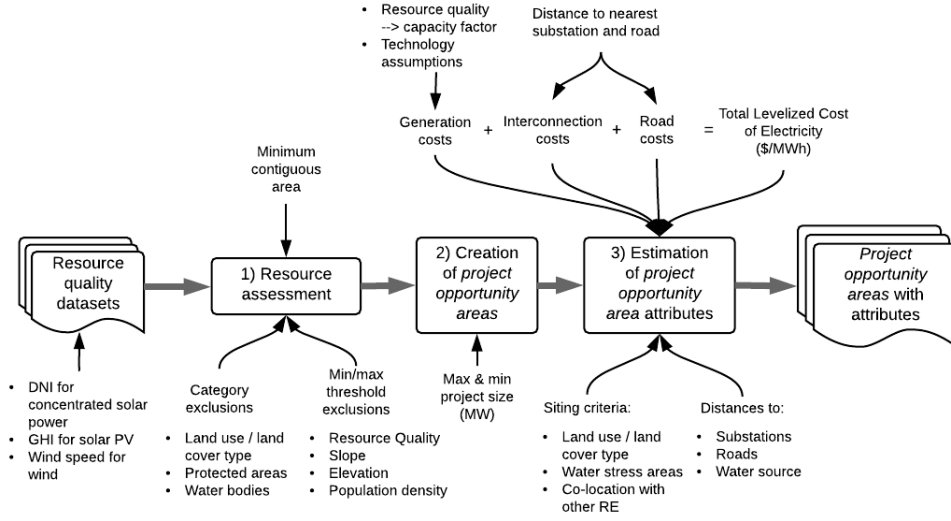


Figure 1: Methodology flow chart. Adapted from Wu et al. 26.

### 2.1. Renewable Energy Resource Assessment

We first identified areas that meet baseline technical, environmental, economic, and social suitability criteria for RE development. We relied on a combination of global and India-specific spatial and non-spatial datasets (Table A.7 in SI A). Using Python and the Arcpy package for spatial analysis, we estimated the resource potential by linearly combining exclusion criteria after applying industry-standard [22, 15, 14, 25, 27, 28] thresholds and

77 buffers for the following data types: techno-economic (elevation, slope, re-  
78 newable resource quality, water bodies), environmental (land-use and land-  
79 cover, protected areas), and socio-economic (population density) (Table 1  
80 and Table A.7 in SI A). To identify economically-viable resources, we chose  
81 resource quality thresholds of 5.5 m/s wind speed or 200 W/m<sup>2</sup> power den-  
82 sity for wind and 4.9 kWh/m<sup>2</sup>/day or ~1800 kWh/m<sup>2</sup>/y Global Horizontal  
83 Irradiance (GHI) for solar PV and Direct Normal Irradiance (DNI) for CSP.<sup>4</sup>  
84 We then imposed a minimum contiguous area of 2 km<sup>2</sup> for both wind and  
85 solar. The technology-specific land-use and land-cover (LULC) categories  
86 are listed in Table 1. We included agricultural land for wind because turbine  
87 footprints occupy only a small fraction of total plant area, leaving the rest  
88 for other uses. Although farmers could choose to install solar plants on agri-  
89 cultural areas for economic reasons, we chose to exclude those areas for solar  
90 to avoid conflict between energy and food. All analyses were performed at  
91 500 m resolution using South Asia Albers Equal Area Conic projection.

92 We used empirical values of installed capacity per unit area (land use effi-  
93 ciency) of 9 MW/km<sup>2</sup> for wind, 30 MW/km<sup>2</sup> for solar PV, and 17 MW/km<sup>2</sup>  
94 for CSP with 6-hour storage to estimate the potential for installed genera-  
95 tion capacity on the remaining areas deemed suitable for energy development  
96 [29, 26]. Unlike some studies, we did not exclude areas occupied by roads,  
97 railroads, and airports because of uncertainties in available data. To reflect  
98 uncertainties in land availability due to the presence of other infrastructure  
99 as well as ground realities such as land ownership and conflict areas, we ap-  
100 plied a land use discount factor of 75% for both wind and solar technologies  
101 [28].

## 102 2.2. Project opportunity area attributes

103 Using a 5 x 5 km grid, we divided large contiguous suitable resource areas  
104 into representative utility-scale projects that we term “project opportunity  
105 areas” (POAs). These POAs range from 2 km<sup>2</sup> - 25 km<sup>2</sup> and have the  
106 potential to accommodate 4.5 - 56.25 MW size wind plants and 9 - 187.5  
107 MW size solar power plants (assuming land use factors of 2.25 MW/km<sup>2</sup> for  
108 wind, 7.5 MW/km<sup>2</sup> for solar PV, and 4.25 MW/km<sup>2</sup> for CSP with 6-hour

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<sup>4</sup>Wind speed threshold results in approximately a 20% capacity factor cut-off, similar to [22, 14, 15]. GHI threshold covers approximately all solar PV resources in India. DNI threshold is low relative to other studies [25, 21], but results in 18% capacity factor cut-off for CSP without storage.

Table 1: Included (In) categories from the National Remote Sensing Centre’s land-use and land-cover data for all technologies.

Code	Class Name	Solar PV and CSP	Wind
1	Built-up (urban)		
2	Kharif (cropland: June-October)		<b>In</b>
3	Rabi (cropland: November-April)		<b>In</b>
4	Zaid (cropland: April-June)		<b>In</b>
5	Double/Triple (irrigated cropland)		<b>In</b>
6	Current fallow (cropland)		<b>In</b>
7	Plantation/orchard		
8	Evergreen forest		
9	Deciduous forest		
10	Scrub/degenerated forest		
11	Littoral swamp		
12	Grassland	<b>In</b>	<b>In</b>
13	Other wasteland	<b>In</b>	<b>In</b>
14	Gullied		
15	Scrubland	<b>In</b>	<b>In</b>
16	Water bodies		
17	Snow covered		
18	Shifting cultivation		<b>In</b>
19	Rann (Salt marsh in Kutch district, Gujarat state)	<b>In</b>	<b>In</b>

Kharif, Rabi, and Zaid are cropping seasons.

storage after applying a 75% land use discount factor). These sizes were selected to represent utility-scale wind and solar power plants.

For each POA, we estimated several technical and economic attributes (Table 2). We calculated average values for these attributes determined either by spatial overlap with other data (water stress areas, agricultural land, other RE resources for co-location opportunities) or distances from features such as substations, roads, and water bodies (see Figure 1). We used the resource quality to estimate capacity factors, which we then used along with two of the siting criteria—distances to transmission and road infrastructure—to estimate each POA’s generation, transmission, and road components of the levelized cost of energy (LCOE) for each technology.

### 2.2.1. Capacity factor

*Solar PV.* Annual average capacity factor (CF) for each POA is the ratio of the estimated output of a power plant over a whole year to the potential

Table 2: Description of estimated project opportunity area (POA) attributes.

Attribute	Description
Area	Total area of the POA in units of square kilometers
Resource quality	Mean resource quality in terms of wind speed (m/s) or solar irradiance (kWh/m <sup>2</sup> -day).
Capacity factor	Mean annual capacity factor of the POA for each technology estimated using average resource quality.
Electricity generation	Average annual electricity generation (MWh) estimated using each technology's capacity factor, land use factor, and land area.
Distance to nearest location	Straight-line distance from each POA to the nearest substation (with 1.3 terrain factor applied); road (with 1.3 terrain factor applied); and surface water body.
Generation LCOE	Average levelized cost of electricity (in INR/MWh or USD/MWh) for the generation component. Values were estimated using the location and technology's capacity factor and capital and operations and maintenance cost assumptions.
Transmission interconnection LCOE	Average levelized cost of electricity (in INR/MWh or USD/MWh) for the transmission component for each technology using distance to nearest substation and transmission infrastructure unit cost assumptions.
Road LCOE	Average levelized cost of electricity (in INR/MWh or USD/MWh) for the road component, using distance to nearest road, road infrastructure unit cost assumptions, and assuming 50 MW of installed capacity per POA.
Total LCOE	Average total levelized cost of electricity (in Rs/MWh or USD/MWh) estimated by summing the individual component LCOEs for generation, transmission infrastructure (nearest substation), and road.
Co-location potential	A binary score of 0 or 1, with 1 indicating that a POA is suitable for the development of another renewable energy technology. A score was determined for wind and solar PV technologies, which can be co-located.
Water stress score	A "Baseline Water Stress Score" from the World Resources Institute's Aqueduct Water Risk Atlas, which varies from 0 to 5, with 4-5 indicating "Extreme Water Stress" and 3-4 indicating "High Water Stress".

123 output of that plant if it were to generate continuously at its rated capacity.  
124 In addition to the resource quality, CFs for solar PV depend on the type of  
125 system. Single and dual axis tracking systems will have higher CFs but also



greater costs compared to fixed tilt systems. Although single-axis tracking systems dominated the U.S. utility-scale solar market in 2015 [30], the Indian market still preferred fixed tilt systems, likely due to reasons such as lower steel and labor costs (IHS, 2015). In this study, we assumed that all solar PV systems are south-facing fixed tilt systems, with their tilt equal to the latitude of the location. The CF depends on the solar irradiance on the tilted surface of PV panels, which in turn depends on the GHI and the latitude of the location. We had access to high spatial resolution (10 km) annual average GHI data across India but high temporal resolution (hourly) solar radiation data, essential to estimate irradiance on the tilted surface, for only a limited number of locations. To estimate the non-linear relationship between GHI and CF, we first manually chose 617 locations spatially well-dispersed across suitable solar resource areas to capture locations across India’s widely varying latitudes. We then estimated annual average CFs for those locations using hourly solar radiation, temperature, and wind speed data from the National Solar Radiation Database (NSRDB) [31] in the System Advisor Model (SAM) [32] (see Table 3 for solar PV-specific assumptions).<sup>5</sup> We then spatially associated each POA to the nearest location with a simulated CF and resource quality and estimated each POAs CF by proportionally adjusting the closest simulated CF using the POA’s average resource quality.

*CSP.* Other than the DNI, the CF for a CSP plant mainly depends on the type of technology (e.g. parabolic, solar power tower) and the amount of thermal storage. Thermal storage can enable CSP plants to provide a valuable service of shifting energy generation to times of high energy prices [38]. In this study, we assume a generic CSP plant with 6-hour storage.

Similar to solar PV, only annual average DNI data were available at a high spatial resolution across India. Unlike solar PV, CF of CSP plants, reflectors of which track the sun, are not significantly affected by latitude of the location. Therefore, a relatively small number of locations with detailed CF simulations were deemed sufficient to estimate the relationship between DNI and annual CF. Assuming a generic CSP plant with 6 hours of storage and a solar multiple of 2.1, we first simulated CFs for 19 locations across

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<sup>5</sup>The solar radiation data in NSRDB were developed by the National Renewable Energy Laboratory (NREL) using the State University of New York (SUNY) semi-empirical model and the meteorological data are from the National Aeronautics and Space Administration (NASA)’s Modern-Era Retrospective Analysis for Research and Applications (MERRA).

Table 3: Parameters in capacity factor and levelized cost of electricity estimates

Parameters	Wind	Solar PV	CSP
Land use factor [MW/km <sup>2</sup> ]	2.25 <sup>a</sup> – 9 <sup>b</sup>	7.5 <sup>a</sup> – 30 <sup>c</sup>	4.25 <sup>a</sup> – 17 <sup>c,d</sup>
<b>Wind-specific</b>			
Hub height	80meters	-	-
Array and collection loss ( $\eta_a$ )	15% <sup>e</sup>	-	-
Outage rate ( $\eta_o$ )	2% <sup>f</sup>	-	-
<b>Solar PV-specific</b>			
DC-to-AC ratio	-	1.1	-
Tilt of fixed-tilt system	-	Latitude	-
Azimuth	-	180°	-
Inverter efficiency losses	-	4% <sup>f</sup>	-
Wiring, soiling, availability losses	-	14% <sup>e</sup>	-
Ground cover ratio	-	0.4 <sup>f</sup>	-
<b>CSP-specific</b>			
Solar multiple	-	-	2.1
Auxiliary consumption including losses	-	-	10% <sup>f</sup>
Outage rate	-	-	4% <sup>f</sup>
Storage duration	-	-	6hours
<b>Costs</b>			
Generation capital [USD/kW] ( $c_{g,t}$ )	1,250 <sup>g</sup>	850 <sup>g</sup>	7500 <sup>h</sup>
Generation fixed O&M [USD/kW] ( $o_{f,g}$ )	15 <sup>i</sup>	10 <sup>i</sup>	100 <sup>i</sup>
Transmission interconnection capital [USD/MW/km] ( $c_i$ )	450 <sup>j</sup>	450 <sup>j</sup>	450 <sup>j</sup>
Transmission interconnection fixed O&M [USD/km] ( $o_{f,i}$ )	-	-	-
Substation capital [USD/MW] ( $c_s$ ) (for 2 substations)	70,000 <sup>j</sup>	70,000 <sup>j</sup>	70,000 <sup>j</sup>
Road capital [USD/km] ( $c_r$ )	407,000 <sup>k</sup>	407,000 <sup>k</sup>	407,000 <sup>k</sup>
Road fixed O&M [USD/km] ( $o_{f,r}$ )	-	-	-
Economic discount rate ( $i$ )	7% <sup>l</sup>	7% <sup>l</sup>	7% <sup>l</sup>
Lifetime [years] ( $n$ )	25 <sup>m</sup>	25 <sup>m</sup>	25 <sup>m</sup>

<sup>a</sup> Applied 75% land-use discount factor to higher land-use factor to account for greater spread of wind turbines and uncertainties in land availability for all technologies [33].

<sup>b</sup> Assumption used by National Institute of Wind Energy, India [19] and [22].

<sup>c</sup> Mean of U.S. empirical values [29]

<sup>d</sup> Estimated from no-storage land use factor by multiplying by the ratio of no-storage to 6-hr-storage solar multiples (2.1/1.2).

<sup>e</sup> [34]

<sup>f</sup> System Adviser Model (SAM) [32]

<sup>g</sup> Capital costs estimated using 2017-18 auction prices as benchmarks.

<sup>h</sup> Capital costs derived from IRENA 2017 estimates for CSP with 4-8 hour storage [3].

<sup>i</sup> O&M costs from IRENA 2017 estimates [3].

<sup>j</sup> Average of 132 kV, 220 kV, and 400 kV transmission line and substation costs [35].

<sup>k</sup> [36] Costs are for two lane bituminous road, and inflation adjusted.

<sup>l</sup> Average real interest rate from 2014-16 for India from The World Bank [7]

<sup>m</sup> [37]

158 suitable CSP resource areas using hourly DNI data in the System Advisor

159 Model [32].<sup>6</sup> We then chose to fit a logarithmic equation to the CFs and  
 160 average DNI data because of known increased efficiency losses at the higher  
 161 end of the DNI range (Figure C.11 in SI C). Using the fitted logarithmic  
 162 curve equation (Eq. 1,  $R^2 = 0.998$ ) and spatially averaged DNI, we estimated  
 163 CFs for a 6-hr-storage CSP power plant for each POA.

$$cf_{CSP} = 0.369 \cdot \ln(DNI) - 0.225 \quad (1)$$

164  
 165

166 *Wind.* The CF of a wind turbine depends on wind speed distribution at the  
 167 turbine hub height, air density, and the turbine power curve. In this analysis,  
 168 we estimated CFs from wind speeds at a turbine hub height of 80 m.

169 On-shore wind turbines are generally classified into three International  
 170 Electrotechnical Commission (IEC) classes depending on the wind speed  
 171 regimes. We used normalized wind turbine power curves for the three IEC  
 172 classes developed by NREL [39] and scaled them for a 2000 kW rated tur-  
 173 bine. For each of the three turbine classes, we adjusted the power curves  
 174 for the entire range of possible air densities (0.775-1.275 kg/m<sup>3</sup> in 0.5 kg/m<sup>3</sup>  
 175 increments) by scaling the wind speeds of the standard curves according to  
 176 the International Standard IEC 61400-12 [40, 41].

177 To compute the CF for each 3.6 km grid cell (the native resolution of  
 178 Vaisala data), we used methods described in [26]. We first assigned IEC  
 179 classes based on each grid cell's annual average wind speed [42]. Second, to  
 180 account for the effect of air density on power generation, we estimated the  
 181 air density using elevation and average annual temperature for each grid cell.  
 182 We then selected the appropriate air-density-adjusted power curve given the  
 183 average wind speed, which determines the IEC class, and the air density,  
 184 which determines the air-density adjustment within the IEC class. For each  
 185 grid cell, we discretely computed the power output at each wind speed given  
 186 its probability (using a Weibull distribution with a shape factor of 2) and  
 187 summed the power output across all wind speeds within the turbines oper-  
 188 ational range to calculate the mean wind power output ( $\bar{P}$ ). The capacity

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<sup>6</sup>The DNI solar resource data for India were developed by NREL using satellite imagery and a numerical model developed at the State University of New York (SUNY) with the weather data from the Integrated Surface Database maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA).

189 factor ( $cf_{wind}$ ) is simply the ratio of the mean wind power output to the rated  
 190 power output of the turbine ( $P_r$  or 2000 kW), accounting for any collection  
 191 losses ( $\eta_a$ ) and outages ( $\eta_o$ ) (Eq. 2).  
 192

$$cf_{wind} = \frac{(1 - \eta_a) \cdot (1 - \eta_o) \cdot \bar{P}}{P_r} \quad (2)$$

193

194

### 195 2.2.2. Levelized Cost of Electricity (LCOE) estimation

196 LCOE is the average cost of electricity for every unit of electricity gener-  
 197 ated over the lifetime of a project at the point of interconnection. Using the  
 198 economic and technical parameters listed in Table 3 and the CFs and dis-  
 199 tances to nearest substation and road estimated for each POA, we calculated  
 200 the generation, interconnection and road components of the levelized cost of  
 201 electricity (LCOE in USD/MWh) (equations 3, 4, 5). The total LCOE is  
 202 simply the sum of the generation, transmission, and road cost components.

203 Rapidly changing economics of wind and solar PV technologies makes it  
 204 difficult to accurately estimate average capital costs. Thus, for determining  
 205 capital costs of these two technologies, we used recent auction prices for RE  
 206 in India as benchmarks. From Jan 2017 to Jan 2018, 5.2 GW of solar PV  
 207 capacity and 5 GW of wind capacity was procured through various state and  
 208 central government auctions. For the auction-winning project, we first as-  
 209 sumed a nominal CF at the 90th percentile of all POA's annual average CFs.  
 210 Using this CF along with assumptions for fixed operations and maintenance  
 211 (O&M) cost, discount rate, and plant lifetime (Table 3) and the capacity-  
 212 weighted mean auction price in equation 3 provided us with a nominal capital  
 213 cost for each technology (Table 3; rounded to two significant figures). The  
 214 generation LCOE for each POA was then estimated using the capacity fac-  
 215 tor for that POA, the nominal capital cost, and assumptions for fixed O&M  
 216 costs, discount rate, and lifetime (Table 3) in equation 3.

217 We derived the average capital cost for CSP with 6 hour storage from  
 218 estimates provided by [3]. However, capital costs of CSP vary significantly  
 219 because of a wide variation in technology among plants, e.g. type of collectors  
 220 and receivers, single or double axis tracking, and amount and type of storage.  
 221 Commercial CSP plants are also few in number, with limited public data on  
 222 costs. Hence, our estimates are subject to significant uncertainties.

223 For transmission and road costs, we estimated distances of POAs from  
 224 nearest high-voltage substation (220 kV and above) and nearest road. To  
 225 account for terrain and other development constraints that would dictate  
 226 the actual path of the extended road or transmission line, we then applied a  
 227 terrain factor of 1.3 to the estimated distances.

228 We calculated the capital cost of transmission as a function of its length  
 229 alone, holding all other cost parameters constant. To this cost, we added  
 230 the cost of the substations, which does not vary by distance (see Table 3  
 231 for parameter values). We then used this total capital cost to estimate the  
 232 transmission interconnection component of the LCOE using equation 4.

233 Road LCOE was estimated using a fixed capital cost per km of additional  
 234 road needed to service the project, and is expressed per unit of electricity  
 235 output from the project (equation 5). Road costs can vary widely depending  
 236 on the type of road, terrain, and region-specific factors such as labor costs  
 237 and financing. We assumed costs for a two lane bituminous road (Table  
 238 3). We also assumed that one road will be built for every 50 MW capacity  
 239 project, which is a reasonable size for a utility-scale project.

$$LCOE_{generation,t,x} = \frac{(c_{g,t}i_{cr} + o_{f,g,t})}{8760 \cdot r_{t,x}} \quad (3)$$

$$LCOE_{interconnection,t,x} = \frac{(d_{i,x}(c_i i_{cr} + o_{f,i}) + c_s i_{cr})}{8760 \cdot r_{t,x}} \quad (4)$$

$$LCOE_{road,t,x} = \frac{d_{r,x}(c_r i_{cr} + o_{f,r})}{8760 \cdot r_{t,x} \cdot 50MW} \quad (5)$$

240

241

$$i_{cr} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (6)$$

242

243

244 Where  $c_{g,t}$  is the capital cost of generation for technology  $t$ ;  $c_i$  is the  
 245 capital cost of transmission interconnection ( $i$ );  $c_s$  is the capital cost of two  
 246 substations ( $s$ );  $c_r$  is the capital cost of road;  $r_{t,x}$  is the capacity factor of  
 247 technology  $t$  and POA  $x$ ;  $o_{f,g,t}$  is the fixed operations and maintenance cost  
 248 of generation for technology  $t$ ;  $o_{f,i,t}$  is the fixed operations and maintenance  
 249 cost of interconnection ( $i$ ) for technology  $t$ ;  $o_{f,r}$  is the fixed ( $f$ ) operations

250 and maintenance cost of roads ( $r$ ). The capital recovery factor ( $i_{cr}$ ) converts  
251 a present value to a uniform stream of annualized values given a discount  
252 rate and the number of interest periods (Eqn. 6).  $n$  is the number of years  
253 in the lifetime of a power plant.

254 To address evolving cost assumptions, we examined the sensitivity of  
255 total LCOE to key parameters by varying values of those parameters within  
256 realistic ranges. We used median, minimum, and maximum estimates for  
257 CFs and distances to nearest road and substation as base case and minimum  
258 and maximum limits for the sensitivity analysis. We derived the range of  
259 capital costs from India's highest and lowest auction prices in 2017-18 for  
260 wind and solar PV, and varied CSP capital costs by 20%. We varied the  
261 real discount rate by 3 percentage points from the base value of 7%. The  
262 remaining parameters were varied by 20% of their base value. We did not  
263 include land costs because of lack of data.

### 264 2.2.3. Other attributes

265 We estimated the following additional attributes for each POA that in-  
266 form the constraints to and opportunities for RE development: overlap with  
267 agricultural cropland, water stress level, and potential for co-location with  
268 another RE technology. To evaluate potential conflict of RE development  
269 with agriculture, wind POAs located in agricultural areas were identified by  
270 their overlap with any of the six cropland land-use land-cover categories of  
271 the NRSC data - kharif, rabi, zaid, double/triple, current fallow, and shift-  
272 ing cultivation (Table 1; [43]). Agricultural lands are excluded from solar  
273 suitable areas in this study.

274 Water availability is crucial for solar PV and CSP plants. CSP technolo-  
275 gies using recirculating evaporative cooling tower, one of the most widely  
276 used cooling technologies in thermal power plants, consume the most wa-  
277 ter (3000-3800 liters/MWh) [44] among RE technologies considered in this  
278 study. Dry-cooled CSP plants could reduce water consumption significantly  
279 to 100-300 liters/MWh [44], but these plants have higher costs and lower  
280 efficiencies compared to evaporative cooling technologies. Utility-scale solar  
281 PV power plants, on average, require about 100 liters/MWh [44], mainly for  
282 cleaning panels to prevent soiling [45], which is much lower than CSP plants,  
283 but is still significant in water-stressed areas. Wind plants have insignificant  
284 water use requirements.

285 To assess the vulnerability of solar plants to water scarcity, we overlaid  
286 the water-stressed areas identified in the World Resources Institute's (WRI)

287 Aqueduct Water Atlas using estimates of Baseline Water Stress (BWS) or  
288 relative water demand [12]. We focused on the “Extremely High Stress” and  
289 “High Stress” areas, where annual water withdrawal is  $>80\%$  and  $40\%-80\%$   
290 of blue water or surface water availability respectively.

291 Co-locating wind and solar PV plants can enable greater land and trans-  
292 mission utilization, especially when the temporal profiles of generation from  
293 the two technologies are complementary. To estimate the potential for co-  
294 locating two RE technologies, we simply identified POAs with overlapping  
295 wind and solar resources. We limited this analysis to only wind and solar PV  
296 technologies because PV panels can occupy areas between wind turbines.

### 297 3. Results

#### 298 3.1. Technical potential of wind and solar resources

299 Abundant wind, solar PV, and CSP potential exists within India. These  
300 resources, however, are distributed unevenly across the country. Because  
301 RE targets are set by state-specific policies and states are the first tier of  
302 balancing areas in India’s interconnected national electricity grid, we use the  
303 state as the sub-national geographical unit of analysis to present our results.  
304 See Tables 4, 5, 6 for the technical potential in each state.

305 India’s wind energy generation potential is greater than three times its  
306 annual energy demand forecast for 2030 [8] assuming a land-use factor of  
307  $9 \text{ MW /km}^2$ . If a land-use factor of  $2.25 \text{ MW /km}^2$  is assumed ( lowered  
308 to account for uncertainties and ground-realities not captured in geospatial  
309 data), the wind potential is about  $80\%$  of the 2030 energy demand forecast.  
310 Wind resources are concentrated mainly in the western states (Gujarat, Ma-  
311 harashtra, and Rajasthan) and southern states (Andhra Pradesh, Karnataka,  
312 Tamil Nadu, and Telangana), together accounting for over  $95\%$  of total wind  
313 potential (Table 4, Figure 2). The highest quality resources are concentrated  
314 in Tamil Nadu and Gujarat.

Table 4: State-wise technical potential for electricity generation and capacity for wind

State	Area (km <sup>2</sup> )	Land use factor: 9 MW/km <sup>2</sup>		Land use factor: 2.25 MW/km <sup>2</sup>	
		Generation Potential (TWh)	Capacity Potential (GW)	Generation Potential (TWh)	Capacity Potential (GW)
Andhra Pradesh (AP)	64,000	1,300	580	330	150
Chhattisgarh (CT)	840	16	8	4	2
Gujarat (GJ)	35,000	760	320	190	79
Karnataka (KA)	89,000	1,800	800	450	200
Kerala (KL)	910	24	8	6	2
Madhya Pradesh (MP)	2,300	42	21	10	5
Maharashtra (MH)	77,000	1,600	690	390	170
Odisha (OD)	8,000	160	72	40	18
Rajasthan (RJ)	23,000	430	210	110	52
Tamil Nadu (TN)	60,000	1,400	540	350	140
Telangana (TG)	15,000	270	130	67	33
India Total	376,000	7,800	3,400	2,000	850

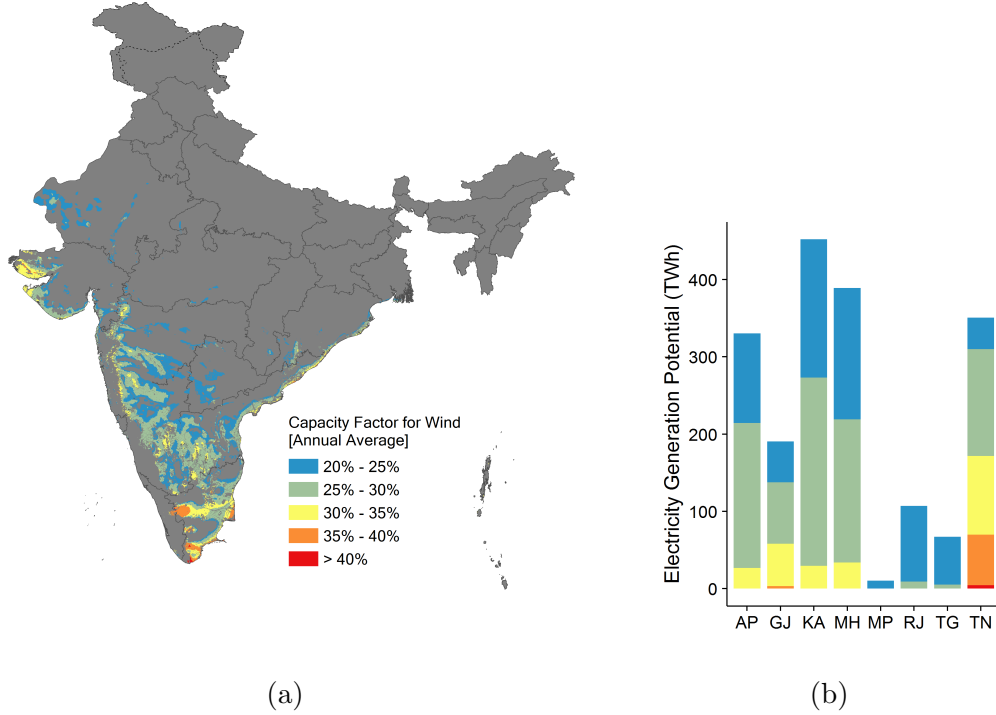


Figure 2: Spatial distribution (a) and state-wise potential (b) of wind electricity generation for a range of annual capacity factors, estimated for wind turbines with 80m hub heights. Wind speed resource threshold is 5.5 m/s and land use factor is 2.25 MW/km<sup>2</sup>.



315 Total solar PV energy generation potential for utility-scale power plants  
 316 with expected capacity factors of at least 17% is greater than four times  
 317 India's energy demand forecast for 2030 [8] assuming a land-use factor of  
 318 30 MW /km<sup>2</sup> (Table 5, Figure 3). If a land-use factor of 7.5 MW /km<sup>2</sup>  
 319 (lowered to account for uncertainties) is assumed, this potential is similar  
 320 to the 2030 forecast of total electricity demand. While solar PV resources  
 321 are distributed across several states, the five states of Rajasthan, Gujarat,  
 322 Maharashtra, Madhya Pradesh, and Andhra Pradesh account for over 80% of  
 323 these resources. Almost half the solar PV resources are located in Rajasthan  
 324 alone. Solar PV resources in the rest of India are limited primarily because  
 325 of constraints on land use (e.g. agricultural land) and slope rather than poor  
 326 resource quality. This is evident from the relatively few areas with capacity  
 327 factors below 18% (Figure 3).

Table 5: State-wise technical potential for electricity generation and capacity for solar PV.

State	Area (km <sup>2</sup> )	Land use factor: 30 MW/km <sup>2</sup>		Land use factor: 7.5 MW/km <sup>2</sup>	
		Generation Potential (TWh)	Capacity Potential (GW)	Generation Potential (TWh)	Capacity Potential (GW)
Andhra Pradesh (AP)	10,100	510	300	130	76
Bihar (BR)	750	36	22	9	6
Gujarat (GJ)	20,200	1,100	610	260	150
Haryana (HR)	1,300	61	38	15	10
Jammu & Kashmir (JK)	570	33	17	8	4
Jharkhand (JH)	1,500	72	44	18	11
Karnataka (KA)	4,700	240	140	61	35
Madhya Pradesh (MP)	14,400	720	430	180	110
Maharashtra (MH)	20,400	1,040	610	260	150
Odisha (OD)	2,100	100	62	25	15
Punjab (PB)	770	37	23	9	6
Rajasthan (RJ)	80,300	4,200	2,400	1,000	600
Tamil Nadu (TN)	3,500	180	100	44	26
Telangana (TG)	4,300	220	130	55	32
Uttar Pradesh (UP)	5,400	260	160	64	40
Uttarakhand (UT)	300	14	9	4	2
West Bengal (WB)	1,800	87	55	22	14
India Total	173,000	8,900	5,200	2,200	1,300

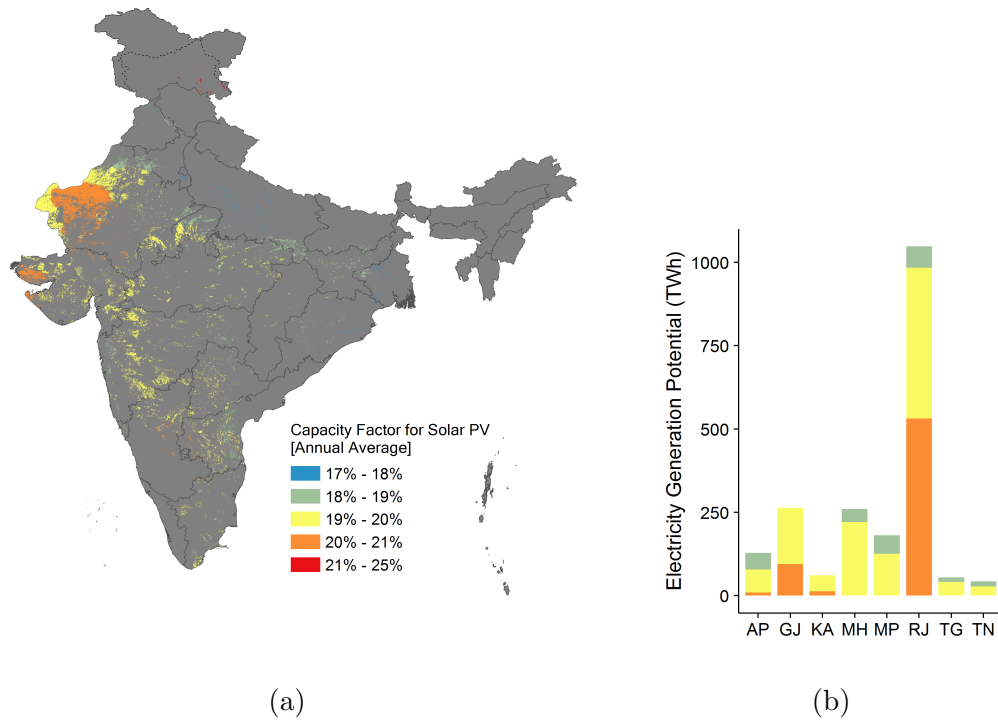


Figure 3: Spatial distribution (a) and state-wise potential (b) of solar PV (fixed tilt) electricity generation for a range of annual capacity factors, estimated for fixed-tilt systems. Global Horizontal Irradiance (GHI) resource threshold is  $4.9 \text{ kWh/m}^2\text{-day}$  and land use factor is  $7.5 \text{ MW/km}^2$ .

328 CSP resources are the most limited amongst the three technologies and  
329 naturally closely follow the pattern of solar PV spatial distribution. Total  
330 energy generation potential for CSP plants with 6-hour storage that have ex-  
331 pected annual capacity factors greater than 36% is about four-fifths of India's  
332 2030 energy demand forecast assuming a land-use factor of 17 MW/km<sup>2</sup> and  
333 only a fifth of this demand forecast if a land-use factor of 4.25 MW/km<sup>2</sup> is  
334 assumed (Table 5, Figure 3).

335 CSP potential is highest in Rajasthan, Gujarat, Maharashtra, Andhra  
336 Pradesh, and Madhya Pradesh (Table 6, Figure 4). More than 60% of CSP  
337 resources lie in Rajasthan. While areas in the Ladakh district of Jammu and  
338 Kashmir have the highest resource quality (i.e., highest DNI), development  
339 potential in this state is limited due to protected areas and hilly topography  
340 considered unsuitable for CSP development.

Table 6: State-wise technical potential for electricity generation and capacity for Concentrated Solar Power with 6-hour storage

State	Area (km <sup>2</sup> )	Land use factor: 17 MW/km <sup>2</sup>		Land use factor: 4.25 MW/km <sup>2</sup>	
		Generation Potential (TWh)	Capacity Potential (GW)	Generation Potential (TWh)	Capacity Potential (GW)
Andhra Pradesh (AP)	1,300	70	22	18	6
Gujarat (GJ)	7,100	400	120	100	30
Jammu & Kashmir (JK)	310	19	5	5	1
Karnataka (KN)	640	35	11	9	3
Madhya Pradesh (MP)	1,200	66	20	16	5
Maharashtra (MH)	1,600	87	27	22	7
Rajasthan (RJ)	24,000	1,400	410	340	100
Tamil Nadu (TN)	140	8	2	2	1
Telangana (TG)	100	6	2	1	1
India Total	36,400	2,100	620	520	160

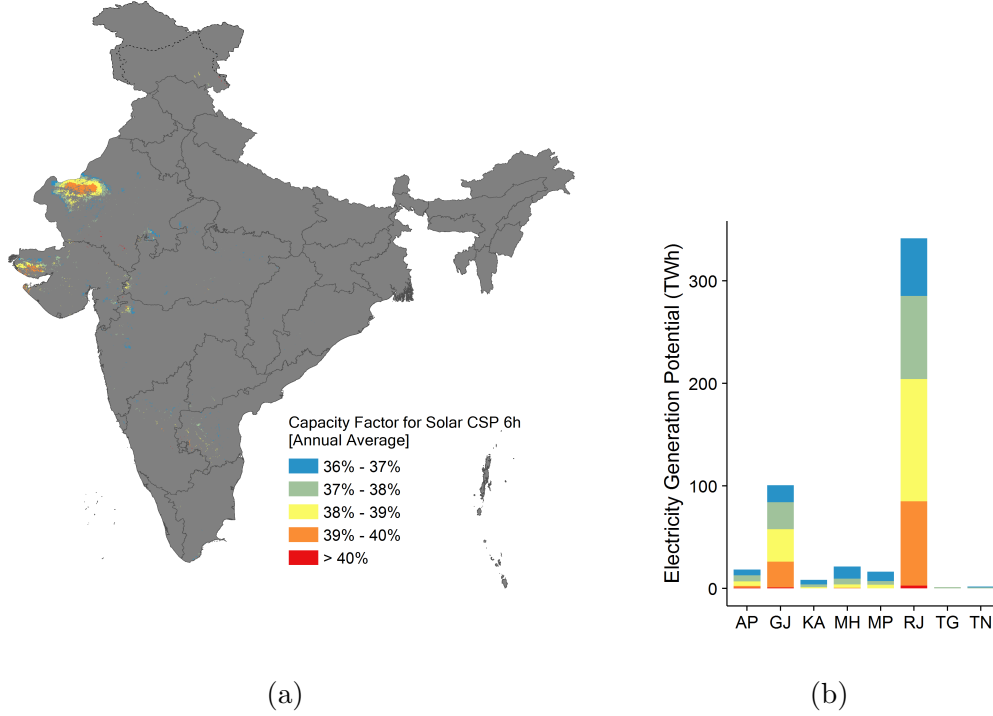


Figure 4: Spatial distribution (a) and state-wise potential (b) of solar CSP (with 6-hour storage) electricity generation for a range of annual capacity factors, estimated for plants with 6-hour storage. DNI resource threshold is 4.9 kWh/m<sup>2</sup>-day and land use factor is 4.25 MW/km<sup>2</sup>.

### 3.2. Costs

Assuming capital costs derived from mean auction prices, the 5th and 95th percentiles of generation LCOE estimates range from USD 47-52 per MWh (INR 3.0-3.4 per kWh) for solar PV (GHI resource quality > 4.9 kWh/m<sup>2</sup>-day) and USD 42-62 per MWh (INR 2.7-4.0 per kWh) for wind (wind speed resource quality > 5.5 m/s). For CSP, assuming capital costs derived from [3], the 5th and 95th percentiles of generation LCOE estimates range from USD 215-234 per MWh (INR 14-15 per kWh) for CSP (DNI resource quality > 4.9 kWh/m<sup>2</sup>-day).

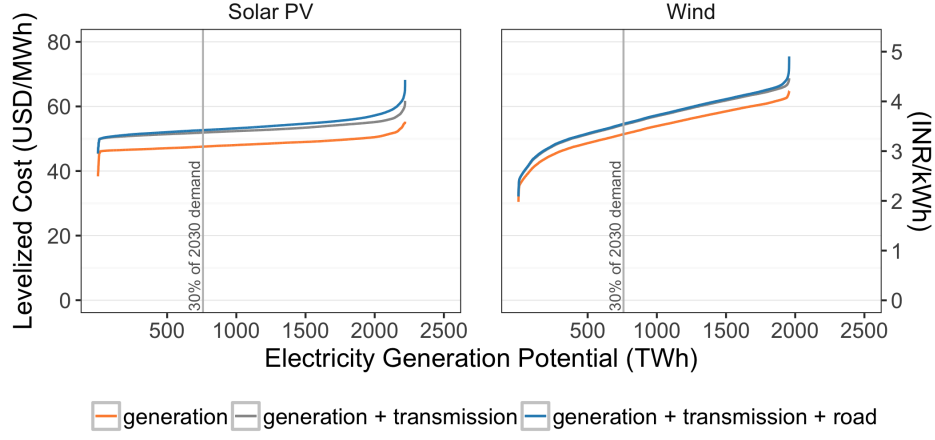
Figure 5a shows that generation LCOEs for solar PV and wind have overlapping distributions. On a levelized cost basis, solar PV and wind are economically competitive with each other. For better clarity of solar PV and wind LCOE supply curves, CSP LCOEs, which are significantly greater,

are shown separately in Figure B.10. CSP is 3 to 5 times more expensive than both solar PV and wind. CSP cost assumptions are likely to have large uncertainties because of limited number of commercial projects and significantly diverse technologies within CSP.

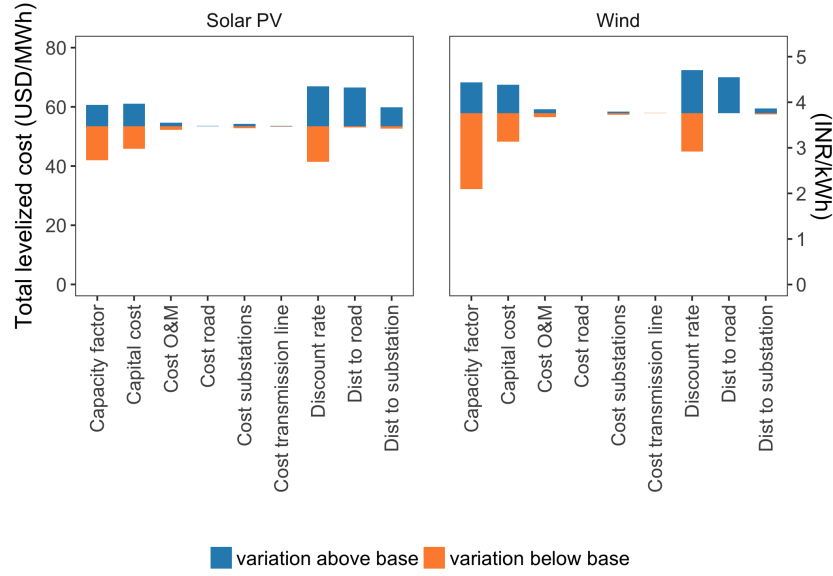
The 5th and 95th percentiles of transmission costs are USD 4-5 per MWh (7-11% of generation LCOE) for solar PV, USD 2-4 per MWh (5-7% of generation LCOE) for wind, and USD 2-3 per MWh (1-2% of generation LCOE) for CSP. Higher transmission costs for solar PV reflect the relatively sparse substation infrastructure in good but remote solar resource areas of Rajasthan and Gujarat. Although CSP sites overlap with and are a subset of solar PV sites, transmission costs on a levelized basis are lower for CSP with storage because of its relatively higher capacity factors compared to solar PV, demonstrating the effect of storage in increasing transmission utilization. High density of roads result in relatively low road costs with median values of less than USD 0.5 per MWh across all technologies.

An important question for scaling up RE is how much its costs will increase as lower resource quality sites are developed with greater deployment of solar PV plants and wind turbines. The greater distribution of wind LCOEs reflects the greater variability in wind quality across the country, whereas lower variation in solar GHI resource quality results in similar LCOEs across solar PV resource areas (See Figure 5a). Therefore, assuming no technology advancement or cost reduction, marginal wind LCOEs are likely to increase much more compared to the rise in marginal solar PV LCOEs as more wind and solar plants are installed.

We conducted sensitivity analysis as outlined in the Methods section. Total LCOE is most sensitive to three parameters: capacity factor, which depends on the resource quality at a project site; capital costs, which evolve through technological advances, economies of scale, and learning by doing; and discount rate, which is a reflection of financing rates available in a region (See Figure 5b). The total LCOE is also sensitive to distances to nearest road and substation, which suggests prioritizing sites close to roads and transmission infrastructure will keep costs low.



(a)



(b)

Figure 5: (a) Electricity generation potential and levelized cost of electricity estimates for generation, transmission, and road for solar PV and wind and (b) total levelized cost of electricity sensitivity to multiple parameters. For sensitivity analysis, maximum, median (base), and minimum values for capacity factors and distances to nearest substation and road are estimates from this analysis; capital cost ranges are derived from lowest and highest 2017-18 auction prices; discount rate is varied from 4% to 10%; other parameters varied by +/- 20% of base values (Table 3).

### 3.3. Access to transmission infrastructure

Project opportunity areas that are farther from the nearest transmission infrastructure will incur higher interconnection costs. Karnataka, Maharashtra, Tamil Nadu, and Telangana are the best states for access to transmission infrastructure in terms of proximity to existing substations. In these states, for both solar PV and wind, between 50-60% of potential capacity is within 25 km and more than 90% of resources are within 50 km of a high-voltage (> 220 kV) substation, indicating high accessibility of renewable resources to transmission infrastructure (Figure 6).

In the states of Gujarat, Rajasthan, Andhra Pradesh, and Madhya Pradesh, strategic investments in transmission infrastructure will enable access to high quality solar and wind resources. While Gujarat's wind resources have high accessibility to transmission networks, for solar resources, only 40-45% are within 25 km and 80% are within 50 km of a high-voltage substation.

In Rajasthan, only 20% of solar and 30% of wind resources are within 25 km distance from the nearest high-voltage substation (Figure 6). For resources within 50 km distance to nearest substation, these shares increase to 60% for solar and 75% for wind. While the total solar PV resources that are near high-voltage substations are abundant, lack of transmission infrastructure may hamper development of wind and CSP resources in Rajasthan. Finally, access to transmission is likely to be a constraint in Andhra Pradesh and Madhya Pradesh, with less than 50% RE resources located within 25 km of a high-voltage substation.

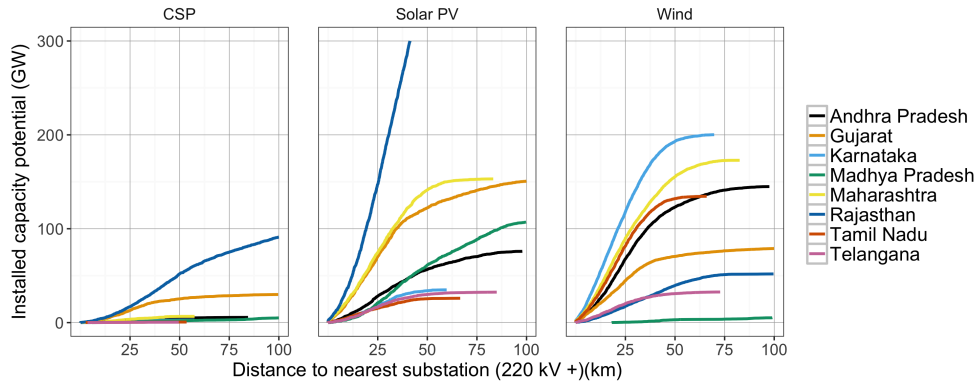


Figure 6: Proximity of concentrated solar power (CSP), solar PV, and wind resources to high-voltage transmission substation infrastructure. Axes are cut off at 100 km and 300 GW

### 3.4. Agriculture and wind power development

In India, 84% of wind resources are located on agricultural lands (Figure 7). As classified by the NRSC land use land cover data, these areas include agricultural lands with single and multiple planting seasons as well as those that are fallow and experience shifting cultivation (Table 1 for land classification). Of all states, Rajasthan and Gujarat have the largest percentage of wind resources on non-agricultural areas. These areas include the Kutch region of Gujarat and desert regions in Rajasthan. More than three-quarters of wind resources in other wind-rich states lie on agricultural lands.

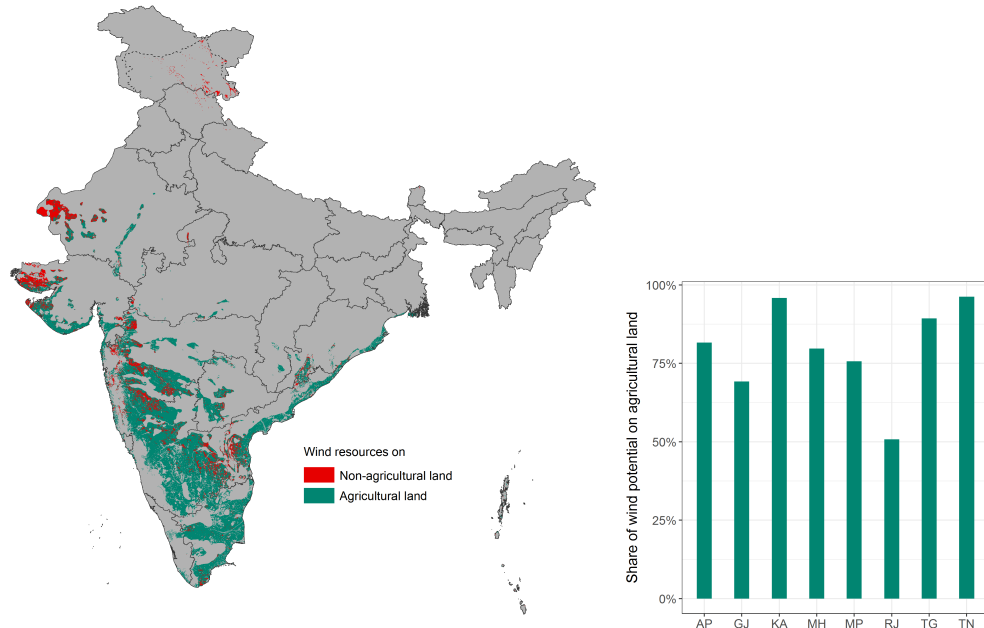


Figure 7: (a) Wind resources on agricultural and non-agricultural lands identified using land use and land cover data from India’s National Remote Sensing Center. (b) Share of wind resources on agricultural land.

### 3.5. Water stress and solar power development

Across India, 71% of CSP resources are in “Extremely High Water Stress” areas and a further 17% are in “High Stress” areas as defined by WRI’s Aqueduct Water Atlas. For solar PV, 57% and 22% of resources are in “Extremely



High Stress” and “High Stress” areas, respectively. In the state of Rajasthan, which contains almost half the country’s identified solar PV potential and more than 60% of CSP potential, almost all the potential project areas are under extremely high water stress (Figure 8). This highlights the severe vulnerability of solar resources to water scarcity in India.

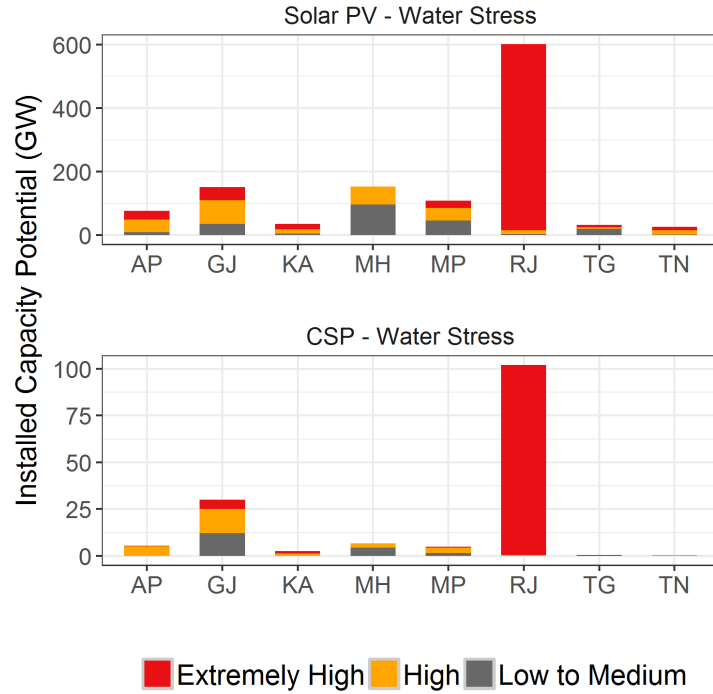


Figure 8: Water stressed resources for solar PV and concentrated solar power (CSP).

### 3.6. Co-locating wind and solar PV plants

We found approximately 48,000 km<sup>2</sup> of area suitable for co-location of wind and solar PV plants (Figure 9a). Assuming lower estimates of land-use factors - 2.25 MW/km<sup>2</sup> for wind and 7.5 MW/km<sup>2</sup> for solar PV, these areas could accommodate 110 GW of wind capacity (or 13% of total wind potential) and 360 GW of utility-scale solar PV capacity (or 28% of total solar PV potential). These co-located wind and solar PV power plants could generate an estimated 25% and 10% of electricity demand in 2030, respectively. Assuming the four times greater (non-discounted) land-use factors for

both wind and solar PV, wind-solar PV hybrid plant potential exceeds the electricity demand in 2030.

Because we excluded croplands from suitable solar resource areas, areas suitable for co-location do not include agricultural areas. Non-agricultural lands with suitable wind resources are almost always suitable for solar PV deployment except when slope is greater than 5%. Andhra Pradesh, Gujarat, Maharashtra, and Rajasthan have greatest potential for co-location.

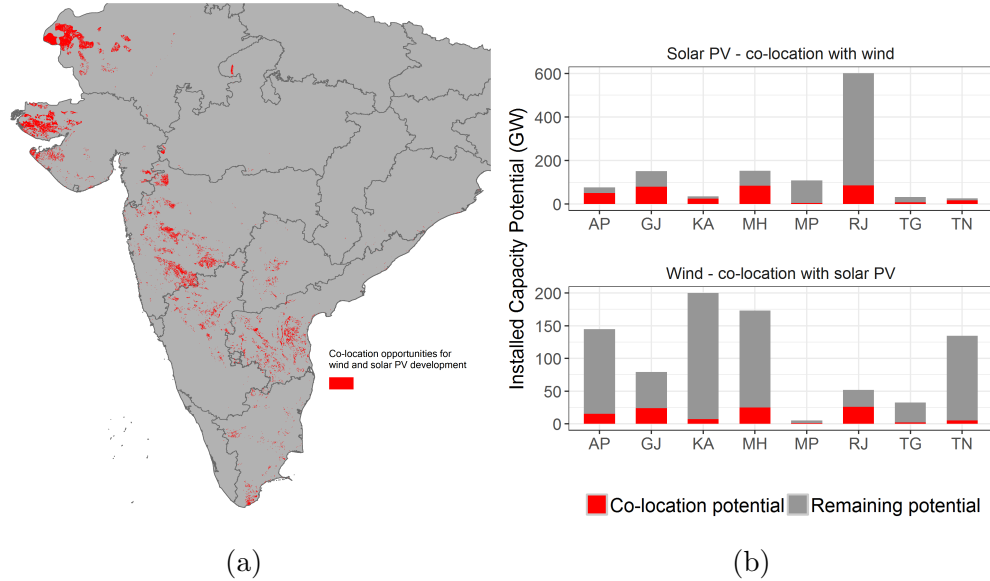


Figure 9: (a) Co-location opportunities for wind and solar PV projects. (b) Wind and solar PV co-location opportunity potential as a share of total potential in major renewable energy states.

## 4. Discussion

### 4.1. Uncertainties in potential estimates

Our estimates of RE resources differ from other studies because of differences in mesoscale resource input data sets, exclusion areas including land-use and land-cover input data and categories, and land-use factors. Assuming the same land-use factor, our wind potential estimate is similar to previous studies [22, 14, 15]. The official Government of India estimate of wind potential is an order of magnitude smaller (102 GW) because of a significantly low

land-use factor assumption compared to this study [19], in addition to different resource input data. For both solar technologies, potential estimates in previous studies [19, 21] are likely exaggerated due to higher land-use factor assumptions, which are not based on empirical estimates unlike this study.

Technology assumptions (e.g. fixed tilt, single or dual axis tracking for solar PV; turbine power curves and hub heights for wind; parabolic trough or central tower with or without storage for CSP) also affect potential estimates [25, 46]. Actual developable potential is limited by ground realities such as land ownership and conflict areas, which are difficult to capture in geospatial analysis. In spite of these uncertainties, RE resources identified and estimated through geospatial analysis are useful for policymaking and understanding the spatial distribution of these resources across regions. Better ground-validated and bias-corrected data sets will improve the accuracy of such analyses.

#### 4.2. Economics of solar and wind

Levelized costs of both wind and solar PV technologies have rapidly declined over the last decade. Cost of solar PV generation fell by almost three-quarters in 2010-2017 due to technological advancements and economies of scale [3]. Costs of wind generation are also declining as wind turbines with higher hub heights allow these machines to harness faster wind speeds, and larger rotor diameters capture more energy at the same sites without incurring a proportional increase in costs [47]. Auction-based energy generation procurements have allowed governments such as India's to capture these cost reductions by encouraging competition [3]. Our estimates of solar PV and wind LCOEs, anchored to India's 2017-18 auction prices, are at the lower end of the 2017 LCOE range estimates by IRENA [3].

On a levelized cost basis, wind and solar PV generation is increasingly cost competitive with coal generation in India [4]. More than 85% of 141 GW coal capacity was more expensive than USD 38 per MWh, the minimum realized auction price for both wind and solar PV in 2017-2018 [48, 49, 50], which is at the lower end of our LCOE estimates.<sup>7</sup>

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<sup>7</sup>Fixed and variable costs for coal generation are from Ministry of Power's Merit Order Despatch of Electricity for Rejuvenation of Income and Transparency website accessed in June 2018. Solar PV auction winning bid of INR 2.47 per kWh ( USD 38 per MWh) is from Solar Energy Corporation of India's (SECI) December 2017 auction in Bhadla, Rajasthan. Wind auction winning bid of INR 2.44 per kWh ( USD 38 per MWh) is from

482 We found that marginal RE resource quality for wind will worsen as more  
483 plants are installed. In contrast, solar resource quality varies relatively less  
484 across India. However, costs and prices of both wind and solar PV will likely  
485 continue to improve with technology advancements, economies of scale, and  
486 market dynamics.

487 Because LCOEs for wind and solar PV are sensitive to multiple factors,  
488 estimates in this study should be interpreted as only indicative. Actual  
489 costs at a site depend on project-specific factors including but not limited  
490 to on-the-ground measurement of resources, capital costs of equipment, and  
491 financing rates.

492 System integration costs or costs incurred due to variability and uncer-  
493 tainty of RE generation are not included in our analysis. Further, an LCOE  
494 does not reflect the economic value of RE generation, which depends on  
495 the timing and location of generation and the marginal avoided costs to the  
496 overall system [51]. The marginal economic value of both wind and solar PV  
497 resources decreases as their share of overall energy generation increases [52]  
498 and is an important area of future research.

#### 499 *4.3. Transmission planning*

500 Lack of high-voltage transmission infrastructure in high quality RE re-  
501 source areas may either deter new RE development or lead to a high number  
502 of low-voltage low-capacity transmission lines from installations to pooling  
503 substations, which would result in greater land fragmentation and environ-  
504 mental impact [53]. Because of their lower capacity to transmit energy,  
505 low-voltage transmission lines are likely to experience more congestion than  
506 high-voltage lines when their transmission limits are violated. During such  
507 congestion events, system operators are forced to curtail RE generation and  
508 project developers may bear the resulting financial losses. Early planning  
509 and expanding high-voltage transmission infrastructure in RE resource areas  
510 or zones will not only lower costs of interconnection for project developers,  
511 but also reduce the probability of transmission congestion. Successful exam-  
512 ples of RE zoning initiatives include Texas' Competitive Renewable Energy  
513 Zones [11, 54] and South Africa's Renewable Energy Development Zones [55].

514 The Government of India's Green Corridors plan has also focused on  
515 building high-voltage transmission infrastructure to evacuate RE generation

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SECI's February 2018 auction all India auction.

516 [35]. However, the study used only near-term siting plans of project devel-  
 517 opers and not spatially-explicit renewable resource and environmental data  
 518 as input to transmission planning studies. Combining spatial data of suit-  
 519 able RE sites with project developer siting plans will enable a more robust,  
 520 stakeholder-driven transmission planning process.

521 We use only proximity to substations as an indicator for access to trans-  
 522 mission. Given data availability, RE resource areas closer to substations that  
 523 have greater margins for evacuating energy should be prioritized. Only phys-  
 524 ical access to the interconnection point may not mean adequate capacity for  
 525 the transmission network to absorb the additional RE generation because  
 526 other parts of the electricity network may experience congestion. Compre-  
 527 hensive power flow analyses and transmission planning studies are essential  
 528 to plan new RE plants.

#### 529 *4.4. Multiple criteria for planning*

530 Incorporating multiple criteria including social and environmental crite-  
 531 ria in addition to economic criteria would enable economically competitive,  
 532 low-environmental-impact, and socially beneficial renewable resources to con-  
 533 tribute toward meeting India’s future electricity demand. This study focused  
 534 on minimizing conflict with agriculture and encouraging dual use for wind  
 535 power development, avoiding solar power deployments in water stressed areas  
 536 and employing strategies to minimize water usage, and pursuing opportuni-  
 537 ties for co-locating wind and solar power plants.

538 Understanding constraints to RE development would prompt mitigation  
 539 actions. For example, robotic dry cleaning systems [56] and emerging tech-  
 540 nologies such as hydrophobic nanocoatings and electrostatic curtains for solar  
 541 PV panels [57] could limit water usage in water-stressed regions. Dry-cooling  
 542 in CSP plants have the potential to reduce water consumption by more than  
 543 90% [44], although greater efficiency losses would affect the economics of  
 544 the plant. Because the direct land footprint of a wind turbine is small (5-  
 545 10%) relative to the entire area of a wind farm [58], dual use of the land  
 546 for farming and wind generation is not only possible, but preferable to in-  
 547 crease land-use efficiency and avoid environmental impacts from greenfield  
 548 development projects. The large wind potential in agricultural areas offers  
 549 the opportunity for the agricultural community to earn revenues from energy  
 550 generation, which could be facilitated through socially-equitable policies that  
 551 encourage cooperative-ownership, land leasing, and revenue-sharing.

Additional criteria that may improve planning of RE resources include socio-economic parameters like local gross domestic product, employment rate, and basic infrastructure; economic parameters such as capacity value, which depends on the coincidence of RE generation with peak electricity prices; and environmental indicators such as biodiversity value, bird and bat habitats, and human footprint. Multi-criteria planning of RE resources will avoid conflict, increase co-benefits, and accelerate deployment of RE [26, 59].

## 5. Conclusions

We identify abundant renewable resources in India – 850-3,400 GW for wind, 1,300-5,200 GW for solar PV, 160-620 GW for CSP. Just the lower estimates of wind and solar PV resources could each generate energy almost equivalent to India’s expected 2030 demand. But these resources are geographically unevenly distributed, and are concentrated in western and southern states—Tamil Nadu, Maharashtra, Gujarat, Rajasthan, Andhra Pradesh, Telangana, Karnataka, and Madhya Pradesh—which collectively will have a share of 55 percent of India’s expected electricity demand in 2030 [8]. The spatial unevenness of RE resources underscores the importance of inter-regional transmission lines and sharing of balancing resources across the entire grid to ensure cost-effective and reliable integration of high shares of variable RE generation.

Deriving capital costs from 2017-18 auction prices in India, we estimate the 5th and 95th percentiles of generation LCOE ranging from USD 47-52 per MWh for solar PV and USD 42-62 per MWh for wind, similar to the lower end of IRENA’s 2017 global cost estimates. Assuming capital costs from [3] for CSP, the 5th and 95th percentiles of our estimates of generation LCOE range from USD 215-234 per MWh, which are 3-5 times greater than those for wind and solar PV. Levelized costs of generation for wind and solar PV overlap significantly but they vary much more across wind resource areas than those across solar areas because of greater heterogeneity in the quality of wind resources compared to that of solar. LCOE estimates are most sensitive to capital cost, capacity factor, and discount rate.

Karnataka, Maharashtra, Tamil Nadu, and Telangana are the best states in terms of proximity of RE resources to existing high-voltage substations. Transmission investments in Gujarat, Rajasthan, Andhra Pradesh, and Madhya Pradesh are needed to help harness significant renewable resources. Identifying high quality resource areas for pre-planning of high-voltage transmis-

588 sion infrastructure will encourage RE development and avoid long-distance  
589 low-voltage transmission interconnections that often result in congestion and  
590 land fragmentation.

591 More than 80% of India’s wind resources lie on agricultural lands where  
592 dual land use strategies could encourage wind development, avoid loss of agri-  
593 culturally productive land, and increase land use efficiency. Approximately  
594 90% of CSP resources and 80% of solar PV resources are in areas experienc-  
595 ing high water stress, severely restricting development of solar plants, unless  
596 their water requirements are minimized. We find co-location potential of at  
597 least 110 GW of wind and 360 GW of solar PV, which together could meet  
598 35% of India’s electricity demand in 2030. Incorporating multiple criteria in  
599 spatial planning will help identify constraints and harness opportunities to  
600 rapidly scale up wind and solar development.

#### 601 **Declaration of Interest**

602 None

#### 603 **Acknowledgements**

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610 for data on substations.

611 **A. Supplementary Information: Data sources and resource assess-**  
612 **ment thresholds**

Table A.7: Data sources and resource assessment thresholds

Stage of analysis	Cate-gory	Source	Description	Year	Default exclu-sion thresh-olds
Resource assess-ment	Bound-aries	Global Ad-ministrative Database (GADM) v2	GADM is a spatial database of the location of the world's administra-tive areas (or administrative bound-aries) including countries and lower level subdivisions.	2012	
Resource assess-ment	Bound-aries	Ministry of New and Renewable Energy	The Ministry of New and Renewable Energy of India published a map of the state and district boundaries of India as part of its solar resource assessment.	Un-known	
Resource assess-ment	Elevation	Shuttle Radar To-pographic Mission (SRTM) CGIAR-CGI Digital Elevation dataset v4.1	Originally produced by NASA, the SRTM is a high quality digital eleva-tion dataset for large portions of the tropics and other areas of the devel-oping world, and has a resolution of 3 arc seconds (approx. 90 m).	2000	>5000 m (all tech-nologies)
Resource assess-ment	Slope	SRTM - CGIAR	Created from elevation dataset using ArcGIS Spatial Analyst.	2000	>5% (solar); >20% (wind)
Estima-tion of Project oppor-tunity area at-tributes	Tempera-ture	WorldClim	WorldClim is a set of global climate layers (climate grids) with a spatial resolution of about 1 square kilome-ter (Hijmans et al. 2005).	1950 - 2000	
Resource assess-ment	Land use/land cover (LULC)	NRSC of India	<a href="http://www.worldclim.org/formats">http://www.worldclim.org/formats</a> Developed by the National Remote Sensing Centre of the Indian Space Research Organisation, this land use-land cover dataset is provided at a scale of 1:50,000. Overall accuracy of different LULC classes can vary from 79% (agro-horticulture) to 97% (waterbodies).	2010-11	See Table 1



Stage of analysis	Category	Source	Description	Year	Default exclusion thresholds
Resource assessment and Project opportunity area attributes	Water bodies	World Wildlife Federation Global lakes and wetlands database	Comprises lakes, reservoirs, rivers and different wetland types in the form of a global raster map at 30-second resolution. Exclusion categories in this analysis include: lake, reservoir, river, freshwater marsh, floodplain, swamp forest, flooded forest, coastal wetland, brackish/saline wetland, and intermittent wetland/lakes.  <a href="http://www.worldwildlife.org/pages/global-lakes-and-wetlands-database">http://www.worldwildlife.org/pages/global-lakes-and-wetlands-database</a>	2004	<500 m buffer
Project opportunity area attributes	Rivers	Natural Earth	Natural Earth is a public domain map dataset featuring both cultural and physical vector data themes. The rivers datasets are originally from the World Data Bank 2. <a href="http://www.naturalearthdata.com/downloads/">http://www.naturalearthdata.com/downloads/</a>	Unknown (version 3.0.0)	
Project opportunity area attributes	Population density	LandScan (ORNL)	Oak Ridge National Laboratory's LandScanTM is the community standard for global population distribution. At approximately 1 km resolution (30" X 30"), it is one of the finest resolution global population distribution data available and represents an ambient population (average over 24 hours).	2012	
Resource assessment	Wind	Vaisala (formerly 3Tier)	Data were created from computer simulations using a meso-scale numerical weather prediction model and validated using publicly available wind speed observations. Annual average wind speed, wind power density, and wind power output were provided at 80 m hub height and 3.6 km resolution for a typical meteorological year.	10-year model run	<5.5 m/sec
Resource assessment	Solar DNI	NREL	Annual average direct normal irradiance data with a resolution of 10 km were provided by the National Renewable Energy Laboratory.	2014	<4.9 kWh/m <sup>2</sup> -day
Resource assessment	Solar GHI	NREL	Annual average global horizontal irradiance data with a resolution of 10 km were provided by the National Renewable Energy Laboratory.	2014	<4.9 kWh/m <sup>2</sup> -day

Stage of analysis	Category	Source	Description	Year	Default exclusion thresholds
Resource assessment	Protected Areas	World Database of Protected Areas (WDPA)	The World Database on Protected Areas (WDPA) is a comprehensive global spatial dataset on marine and terrestrial protected areas available. The WDPA is a joint project of UNEP and IUCN, produced by UNEP-WCMC and the IUCN World Commission on Protected Areas working with governments and collaborating NGOs.	2014	<500 m buffer
Resource assessment	Protected Areas	Protected Planet	Open source database that includes most WDPA locations, but also includes polygon representations of the WDPA point locations (those with unknown extents/boundaries)	2014	<500 m buffer
Project opportunity area attributes	Roads	gROADSv1-Columbia University	Global Roads Open Access Data Set, Version 1 was developed under the auspices of the CODATA Global Roads Data Development Task Group at Columbia University. The dataset combines the best available roads data by country into a global roads coverage, using the UN Spatial Data Infrastructure Transport (UNSDI-T) version 2 as a common data model.	Variable; compiled 2010 (1980-2010)	
Project opportunity area attributes	Transmission substations	POSOCO	Transmission substation location data was provided by the Power Systems Operation Corporation of India, and various internet sources.	2016	

613 **B. Supplementary Information: Estimates of electricity generation**  
614 **potential and levelized cost of electricity for concentrated solar**  
615 **power, solar PV and wind**

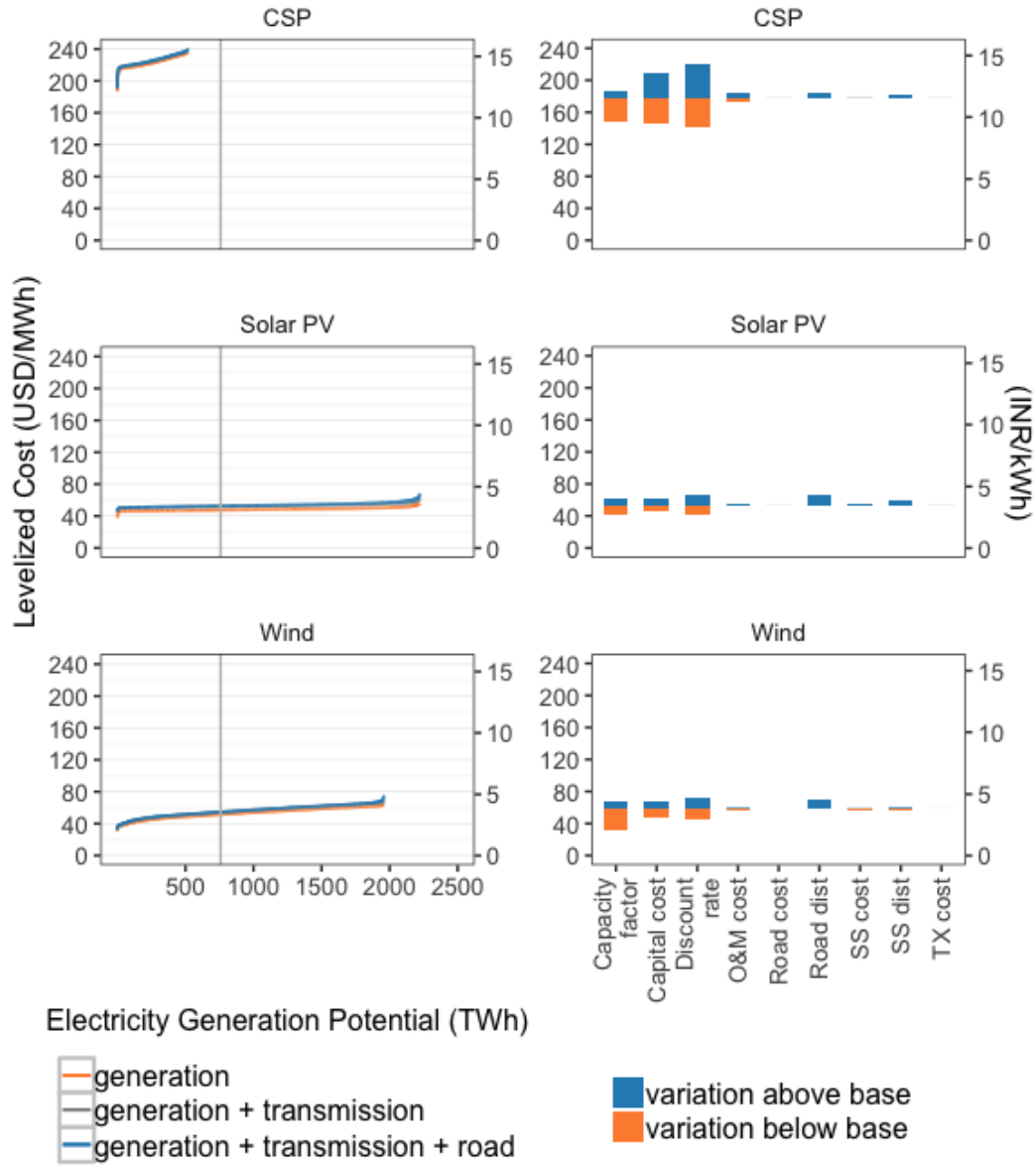


Figure B.10: (a) Electricity generation potential and levelized cost of electricity estimates for generation, transmission, and road for concentrated solar power (CSP), solar PV, and wind, and (b) total levelized cost of electricity sensitivity to multiple parameters. For sensitivity analysis, maximum, median (base), and minimum values for capacity factors and distances to nearest substation and road are estimates from this analysis; capital cost ranges are derived from lowest and highest 2017-18 auction prices for solar PV and wind, and from IRENA [3] for CSP; discount rate is varied from 4% to 10%; other parameters varied by +/- 20% of base values (Table 3). SS-substation. TX-Transmission.

616 C. Supplementary Information: Relationship between direct nor-  
617 mal irradiance and concentrated solar power capacity factors

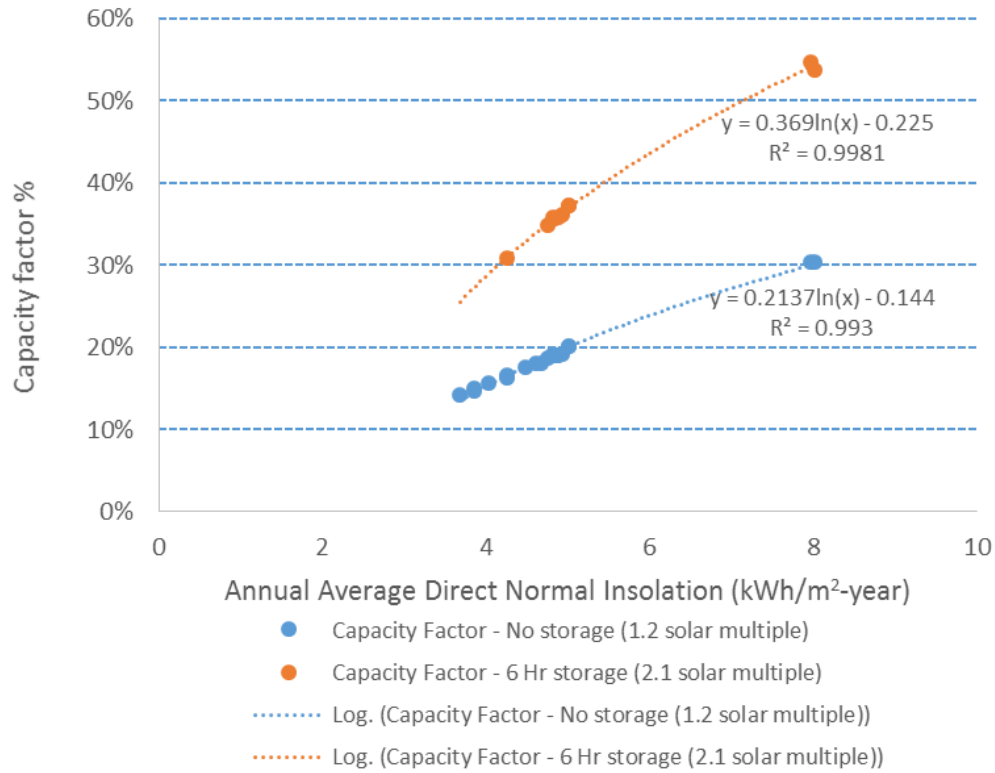


Figure C.11: **Relationship between capacity factor and Direct Normal Irradiance (DNI).** Capacity factors were simulated using the generic CSP plant in NRELs System Advisor Model for 19 locations across high quality resource areas in India. Logarithmic equations were fit to the simulated capacity factor data to statistically model the relationship between capacity factor and annual average DNI.

- 618 [1] WRI, Climate Analysis Indicators Tool: WRI's Climate Data Explorer,  
619 Technical Report, World Resources Institute, Washington, DC, 2018.
- 620 [2] IEA, Renewables 2017: Analysis and Forecasts to 2022, Technical Re-  
621 port, International Energy Agency, 2017.
- 622 [3] IRENA, Renewable Power Generation Costs in 2017, Technical Report,  
623 International Renewable Energy Agency, 2018.
- 624 [4] Greenpeace, Uncompetitive: Coal's cost disadvantage grows as renew-  
625 able tariffs plummet., Technical Report, Greenpeace, 2017.
- 626 [5] IRENA, Renewable Energy Capacity Statistics 2018, Technical Report,  
627 International Renewable Energy Agency, Abu Dhabi, 2018.
- 628 [6] GoI, India's Intended Nationally Determined Contribution, as submit-  
629 ted to the United Nations Framework Convention on Climate Change,  
630 Technical Report, Government of India, 2016.
- 631 [7] World Bank, The World Bank Data, 2018.
- 632 [8] CEA, 19th Electric Power Survey, Technical Report, Central Electricity  
633 Authority, 2017.
- 634 [9] TISS, Land conflicts in India - An interim analysis, Technical Report,  
635 Tata Institute of Social Sciences, 2016.
- 636 [10] A. Mohan, Whose land is it anyway? Energy futures & land use in  
637 India, Energy Policy 110 (2017) 257–262.
- 638 [11] Electricity Reliability Council of Texas, Competitive Renewable Energy  
639 Zones Transmission Optimization Study, Technical Report, ERCOT  
640 System Planning, 2008.
- 641 [12] F. Gassert, M. Landis, M. Luck, M. Reig, T. Shiao, Aqueduct Global  
642 Maps 2.1, Technical Report, World Resources Institute, Washington,  
643 D.C., 2014.
- 644 [13] T. V. Ramachandra, B. V. Shruthi, Wind energy potential mapping in  
645 Karnataka, India, using GIS, Energy Conversion and Management 46  
646 (2005) 1561–1578.

- 647 [14] J. Hossain, V. Sinha, V. V. N. Kishore, A GIS based assessment of  
648 potential for windfarms in India, *Renewable Energy* 36 (2011) 3257–  
649 3267.
- 650 [15] A. Phadke, Reassessing Wind Potential Estimates for India: Economic  
651 and Policy Implications, eScholarship (2012).
- 652 [16] TERI, Integrated Renewable Energy Resource Assessment for Gujarat,  
653 Technical Report, The Energy and Resources Institute, 2012.
- 654 [17] WISE, Action Plan for Comprehensive Renewable Energy Development  
655 in Tamil Nadu, Technical Report, World Institute of Sustainable Energy,  
656 2012.
- 657 [18] CSTEP, Wind Power in Karnataka and Anhra Pradesh: Potential As-  
658 sessment, Costs, and Grid Implications, Technical Report, Center for  
659 Study of Science, Technology, and Policy, 2013.
- 660 [19] CSTEP, WFMS, SSEF, Reassessment of India’s onshore wind potential,  
661 Technical Report, Center for Study of Science, Technology, and Policy,  
662 WinDForce Management Services, and Shakti Sustainable Energy Foun-  
663 dation, 2016.
- 664 [20] T. V. Ramachandra, R. Jain, G. Krishnadas, Hotspots of solar potential  
665 in India, *Renewable and Sustainable Energy Reviews* 15 (2011) 3178–  
666 3186.
- 667 [21] R. Mahtta, P. K. Joshi, A. K. Jindal, Solar power potential mapping  
668 in India using remote sensing inputs and environmental parameters,  
669 *Renewable Energy* 71 (2014) 255–262.
- 670 [22] X. Lu, M. B. McElroy, J. Kiviluoma, Global potential for wind-  
671 generated electricity, *Proceedings of the National Academy of Sciences*  
672 106 (2009) 10933–10938.
- 673 [23] G. He, D. M. Kammen, Where, when and how much wind is available?  
674 A provincial-scale wind resource assessment for China, *Energy Policy*  
675 74 (2014) 116–122.
- 676 [24] G. He, D. M. Kammen, Where, when and how much solar is available? A  
677 provincial-scale solar resource assessment for China, *Renewable Energy*  
678 85 (2016) 74–82.

- 679 [25] A. Lopez, B. Roberts, D. Heimiller, N. Blair, G. Porro, U.S. Renew-  
680 able Energy Technical Potentials: A GIS-Based Analysis, Technical Re-  
681 port NREL/TP-6A20-51946, National Renewable Energy Laboratory,  
682 Golden, CO, 2012.
- 683 [26] G. C. Wu, R. Deshmukh, K. Ndhluukula, T. Radojicic, J. Reilly-Moman,  
684 A. Phadke, D. M. Kammen, D. S. Callaway, Strategic siting and regional  
685 grid interconnections key to low-carbon futures in African countries,  
686 Proceedings of the National Academy of Sciences 114 (2017) E3004–  
687 E3012.
- 688 [27] CPUC, Renewable Energy Transmission Initiative (RETI) Phase 1B,  
689 Technical Report, California Public Utilities Commission, 2009.
- 690 [28] Black & Veatch Corp., NREL, Western Renewable Energy Zones, Phase  
691 1: QRA Identification Technical Report, Technical Report NREL/SR-  
692 6A2-46877, Western Governor’s Association, 2009.
- 693 [29] S. Ong, C. Campbell, P. Denholm, R. Margolis, G. Heath, Land-Use Re-  
694 quirements for Solar Power Plants in the United States, Technical Re-  
695 port NREL/TP-6A20-56290, National Renewable Energy Laboratory,  
696 Golden, CO, 2013.
- 697 [30] M. Bolinger, J. Seel, Utility-Scale Solar 2015: An Empirical Analysis  
698 of Project Cost, Performance, and Pricing Trends in the United States,  
699 Technical Report LBNL-1006037, Lawrence Berkeley National Labora-  
700 tory, 2016.
- 701 [31] NREL, National Solar Radiation Database, Technical Report, National  
702 Renewable Energy Laboratory, 2016.
- 703 [32] NREL, System Advisor Model (SAM), Technical Report, National Re-  
704 newable Energy Laboratory, 2016.
- 705 [33] Black & Veatch Corp., RETI Coordinating Committee, Renewable En-  
706 ergy Transmission Initiative (RETI) Phase 1B Final Report, Technical  
707 Report RETI-1000-2008-003-F, 2009.
- 708 [34] S. Tegen, E. Lantz, M. Hand, B. Maples, A. Smith, P. Schwabe, 2011  
709 Cost of Wind Energy Review, Technical Report NREL/TP-5000-56266,  
710 National Renewable Energy Laboratory, 2013.



- 711 [35] PGCIL, Report on Green Energy Corridors, Technical Report Volume  
712 1, Power Grid Corporation of India Ltd, 2012.
- 713 [36] P. Collier, M. Kirchberger, M. Sderbom, The Cost of Road Infrastruc-  
714 ture in Low and Middle Income Countries, The World Bank Economic  
715 Review (2015).
- 716 [37] CERC, Terms and conditions of tariff determination from renewable  
717 energy sources (Fifth Amendment) Regulations 2016, Technical Report,  
718 Central Electricity Regulatory Commission, 2016.
- 719 [38] R. Sioshansi, P. Denholm, The Value of Concentrating Solar Power and  
720 Thermal Energy Storage, IEEE Transactions on Sustainable Energy 1  
721 (2010) 173–183.
- 722 [39] J. King, A. Clifton, B.-M. Hodge, Validation of Power Output for the  
723 WIND Toolkit, Technical Report NREL/TP-5D00-61714, National Re-  
724 newable Energy Laboratory, 2014.
- 725 [40] IEC, International Standard IEC 61400-12- Wind Turbine Generator  
726 Systems - Part 12: Wind turbine power performance testing, 1998.
- 727 [41] L. Svenningsen, Power Curves Air Density Correction and Other Power  
728 Curve Options in WindPRO, 2010.
- 729 [42] R. Wiser, E. Lantz, M. Bolinger, M. Hand, Recent Developments in the  
730 Levelized Cost of Energy from U.S. Wind Power Projects, 2012.
- 731 [43] K. Sreenivas, N. S. Sekhar, M. Saxena, R. Paliwal, S. Pathak, M. C. Por-  
732 wal, M. A. Fyzee, S. V. C. K. Rao, M. Wadodkar, T. Anasuya, M. S. R.  
733 Murthy, T. Ravisankar, V. K. Dadhwal, Estimating inter-annual diver-  
734 sity of seasonal agricultural area using multi-temporal resourcesat data,  
735 Journal of Environmental Management 161 (2015) 433–442.
- 736 [44] J. Macknick, R. Newmark, G. Heath, K. C. Hallett, Operational water  
737 consumption and withdrawal factors for electricity generating technolo-  
738 gies: a review of existing literature, Environmental Research Letters 7  
739 (2012) 045802.

- [45] T. Sarver, A. Al-Qaraghuli, L. L. Kazmerski, A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches, *Renewable and Sustainable Energy Reviews* 22 (2013) 698–733.
- [46] E. Rinne, H. Holttinen, J. Kiviluoma, S. Rissanen, Effects of turbine technology and land use on wind power resource potential, *Nature Energy* 3 (2018) 494–500.
- [47] R. Wiser, M. Bolinger, 2016 Wind Technologies Market Report, Technical Report, Lawrence Berkeley National Laboratory and U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, 2016.
- [48] Ministry of Power, Government of India, MERIT: Merit Order Despatch of Electricity for Rejuvenation of Income and Transparency, 2018.
- [49] SECI, Results of e-RA for 500 MW projects in Bhadla Phase-III solar park, Rajasthan under NSM Ph-II, BIV, Technical Report, Solar Energy Corporation of India, 2017.
- [50] IEA, Renewable Energy: Renewable Policy Update, Technical Report Issue 19, International Energy Agency, 2018.
- [51] P. L. Joskow, Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies, *The American Economic Review* 101 (2011) 238–241.
- [52] A. Mills, R. Wiser, Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California, Technical Report LBNL-5445E, Lawrence Berkeley National Laboratory, 2012.
- [53] G. C. Wu, M. S. Torn, J. H. Williams, Incorporating Land-Use Requirements and Environmental Constraints in Low-Carbon Electricity Planning for California, *Environmental Science & Technology* 49 (2015) 2013–2021.
- [54] N. Lee, F. Flores-Espino, D. Hurlbut, Renewable Energy Zone (REZ) Transmission Planning Process: A Guidebook For Practitioners, Technical Report NREL/TP-7A40-69043, United States Agency for International Development and National Renewable Energy Laboratory, Golden, CO, 2017.

- 773 [55] Department of Environmental Affairs, Council for Scientific and Indus-  
774 trial Research, Renewable Energy Development Zones, Technical Re-  
775 port, 2014.
- 776 [56] A. Al Shehri, B. Parrott, P. Carrasco, H. Al Saiari, I. Taie, Accelerated  
777 testbed for studying the wear, optical and electrical characteristics of  
778 dry cleaned PV solar panels, *Solar Energy* 146 (2017) 8–19.
- 779 [57] A. Alshehri, B. Parrott, A. Outa, A. Amer, F. Abdellatif, H. Trigui,  
780 P. Carrasco, S. Patel, I. Taie, Dust mitigation in the desert: Cleaning  
781 mechanisms for solar panels in arid regions, in: 2014 Saudi Arabia Smart  
782 Grid Conference (SASG), pp. 1–6.
- 783 [58] P. Denholm, M. Hand, M. Jackson, S. Ong, Land-use requirements of  
784 modern wind power plants in the United States, Technical Report, Na-  
785 tional Renewable Energy Laboratory Golden, CO, 2009.
- 786 [59] R. Deshmukh, G. Wu, A. Phadke, Renewable Energy Zones for Bal-  
787 ancing Siting Trade-offs in India, Technical Report 1007272, Lawrence  
788 Berkeley National Laboratory, 2017.