

Identifying High Priority Clean Energy Investment Opportunities for Bangladesh

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February 18, 2018



Summary for Policymakers

Bangladesh has committed to provide electricity for all by 2021, to reduce its greenhouse gas emissions by 5% from power and other sectors by 2030, and to develop 100% domestic renewable energy as rapidly as possible. This study is the first of its kind to examine potential areas for solar and wind energy projects in Bangladesh that can help to meet those goals. To do this, we excluded all areas likely to be environmentally or socially unacceptable for solar or wind projects (low-lying areas, steep slopes, dense settlements, protected areas and their buffer zones, etc.), and then estimated the leveled cost of electricity for each $5km^2$ “project opportunity area”.

We found that there is far more utility-scale solar PV potential than previously estimated, at costs lower than coal power, and conversion of cropland can likely be avoided. In 2016, electricity demand in Bangladesh was 11.4 GW. By 2021, the Government plans to develop 13.3 GW from new coal plants, and less than 2 GW of solar energy. But Bangladesh could replace large portion of 13.3 GW of planned coal projects with utility-scale solar for an average LCOE of \$91/MWh, compared to \$110/MWh for coal, given the identified 53GW potential from solar PV. This would prevent widespread toxic contamination of air, water and soil, spare tens of thousands of Bangladeshis from premature death and disease, and protect critical ecological resources like the Sundarbans World Heritage Area, which protect millions from storm surges and deadly floods. Furthermore, unlike coal, utility-scale solar PV can be rapidly deployed—usually less than a year—and easily scaled to meet the required load of the end user with low maintenance costs. 7.8 GW of utility-scale solar, which is the Bangladeshi Government’s renewable target in 2030, would use only 0.17% of Bangladesh’s total land area, and would require converting a maximum of 1.4% of land—ideally non cropland—within any $5km^2$ project opportunity area. New designs for utility solar farms are also allowing crops to be grown within them, further reducing impacts on farmers and food security.

Concentrated solar power (CSP) with thermal storage could provide 29 GW—more than the total electricity demand projected for 2021 (24 GW). CSP without storage could provide 53 GW, far more than projected energy needs through 2030 (39 GW). While costs of CSP without storage is nearing cost competitiveness (range: \$127-160/Mwh), CSP with storage is currently expensive (USD\$237-\$300/MWh). Innovations in storage will reduce these costs over time.

Rooftop solar PV systems on commercial/residential buildings could provide 17% of current peak demand (2 GW) at dozens of urban locations across the country. While rooftop solar costs averaged USD\$244/Mwh, it can provide important sources of clean energy without displacement of communities, conversion of cropland, air or water pollution, premature deaths, public health costs, or inflationary fuel prices.

Wind energy could generate 5% of current peak demand (0.57 GW), at costs of \$99-108/MWh. Identified project areas include parts of Rangpur, Sylhet and coastal Chittagong. While slightly more expensive than solar PV, wind energy is still more economically, environmentally and socially preferable to new coal-fired power projects.

Contents

1	Introduction	6
2	Data and Methodology	7
3	The Bangladesh Case Study	13
4	Results	15
4.1	Resource Quality and Generation Potential in Project Opportunity Areas (POAs)	15
4.2	Distribution of Generation Potential and Levelized Cost of Electricity	20
5	Discussion	26
5.1	Avoidance of cropland conversion in clean energy development	26
5.2	Trade-offs between elevation threshold for exclusion and renewable energy potential	27
5.3	Trade-offs between population density thresholds and renewable energy potential	28
5.4	Falling cost of renewable energy and its uncertainty	29
5.5	Necessary measurements to accommodate high penetration of solar PV	30
6	Limitations	33
7	Conclusions	34

List of Tables

1	Data Type and Source	10
2	Exclusion thresholds	11
3	Classification and exclusion of particular land use types (IGBP classification). Land use discount factor for wind and solar PV/CSP are 25% and 10%, respectively, except for that of cropland for solar PV/CSP. The land use discount factor of cropland for solar PV/CSP is set from 1 to 10%.	11
4	Clean energy potential estimates and their weighted-average LCOE in Bangladesh compared with installed/projected electricity capacity in 2016/2030	18
5	Clean energy targets and potential estimates in Bangladesh	19
6	Generation potential and LCOE of solar PV, wind, and CSP in Bangladesh assuming that a maximum of 10% of any primarily cropland Project Opportunity Area (POA) would be used for solar PV and CSP projects, while a maximum of 25% of a POA could be used for wind projects.	24

List of Figures

1	Existing power system infrastructure in Bangladesh (PGCB, 2016)	12
2	Installed capacity by fuel type in MW as of November 2017 (SREDA 2017) . .	14
3	Generation by fuel type in GWh in FY2015-2016 (BPDB 2017)	14
4	Global horizontal irradiance (GHI) of solar PV resource areas (project opportunity areas) in Bangladesh. Low quality resource area and environmentally/socially unsuitable areas are already excluded applying exclusion thresholds listed in Tables 2 and 3.	15
5	Direct normal irradiance (DNI) of solar CSP resource areas (project opportunity areas) in Bangladesh. Low quality resource area and environmentally/socially unsuitable areas are already excluded applying exclusion thresholds listed in Tables 2 and 3.	16
6	Wind power resources of resource areas (project opportunity areas) in Bangladesh. Low quality resource area and environmentally/socially unsuitable areas are already excluded applying exclusion thresholds listed in Tables 2 and 3.	16
7	Global horizontal irradiance (GHI) of urban and built-up areas in Bangladesh	20
8	Average total leveled cost of electricity (LCOE) of solar PV estimated using resource quality, distance to nearest transmission line or substation, and the nearest road.	21
9	Average total leveled cost of electricity (LCOE) of CSP without storage, estimated using resource quality, distance to nearest transmission line or substation, and the nearest road.	22

10	Average total leveled cost of electricity (LCOE) of CSP with 6-hour storage (C) estimated using resource quality, distance to nearest transmission line or substation, and the nearest road.	23
11	Average total leveled cost of electricity (LCOE) of wind zones estimated using resource quality, distance to nearest transmission line or substation, and the nearest road.	24
12	Supply curve (LCOE curve) of renewable energy generation. Supply curves show the cumulative potential of all solar PV, wind, and CSP. Project opportunity areas are sorted by generation LCOE	26
13	Relationship between elevation thresholds and generation potential of solar PV, CSP, and wind	28
14	Relationship between population thresholds and generation potential of solar PV, CSP, and wind	29
15	Relationship between weighted mean LCOE and reduction in capital costs of solar PV, CSP, and wind	30
16	Hourly demand histogram for the top 3 hours of demand hours per day in Bangladesh in 2016 (calculated from the hourly demand data from PGCB website)	32
17	Annual load duration curve of Bangladesh in 2016 (BPDB 2016)	33

1 Introduction

Bangladesh is an important emerging economy widely acknowledged to be making strides in human development and economic growth. With a growth rate of over 7%, Bangladesh's economy was the second fastest major growing economy of 2016 (World Bank 2013). However, inadequate infrastructure and unreliable power supply remains a constraint on growth and affordable and reliable social services. Not only does poor power supply create significant commercial losses that dampen national revenue earnings, but more than a third of the population remains without access to electricity.

Bangladesh is one of the world's most vulnerable countries to the effects of climate change, including extreme temperatures, erratic rainfall, floods, drought, tropical cyclones, rising sea levels, tidal surges, salinity intrusion and ocean acidification. It has an unconditional contribution in its Intended Nationally Determined Contribution (INDC) to reduce its greenhouse gas emissions from Business as Usual by 5% by 2030 from the power, transport and industry sectors, and a conditional contribution to reduce this by 15%, pending appropriate international support (Bangladesh Government 2015). In 2016, Bangladesh joined the Climate Vulnerable Forum in striving to meet 100% domestic renewable energy needs as rapidly as possible (Climate Vulnerable Forum 2016).

The Bangladeshi Infrastructure Development Company Limited (IDCOL) is a government owned financial institution that began implementing a Solar Home System (SHS) program in 2003 (Newcome and Ackom 2017). With support from local NGOs and private companies and an innovative model for partnership, finance and system ownership, the IDCOL SHS program quickly spun a local clean energy industry, making it the largest and fastest growing off grid program in the world. As of July 2017, about 4.5 million are installed, generating over 200 MW of electricity (SREDA 2017). Many experts are calling Bangladesh the worlds first solar nation (ARC Finance 2017). In sharp contrast to this remarkable success in domestic off-grid Solar Home Systems, Bangladesh's development and operation of utility-scale renewable energy is very limited. Instead, the Bangladeshi government through the Bangladesh Power Development Board (BPDB) plans to add substantial coal-fired and natural gas fired power plant capacity to the current generation mix to catch up with rapidly growing electricity demand, resulting in increased reliance on foreign resources. As it is an industry-recognized example of distributed renewable energy competing successfully in a free market economy, Bangladesh is an ideal case for studying the potential of utility-scale, low-carbon, clean energy alternatives, which together with Bangladesh's proven distributed energy solutions can support the country's goals for sustainable economic development. Inadequate geospatial and economic information on alternative energy resources is often a significant barrier to policy makers considering socially equitable, environmentally friendly and cost effective energy development. A review of the literature shows that Bangladesh lacks even a basic publicly available renewable energy resource assessment. In addition to

the appropriate economic valuation of high quality renewable resources, other criteria such as grid operability, transmission and road infrastructure cost, proximity or overlap with environmentally sensitive areas, and population density are also crucial to making balanced decisions on large scale grid connected energy development. Publicly available literature on the costs, benefits and tradeoffs of various energy capacity expansion options is thus critical to supporting informed public engagement and discourse.

Our study analyzes the cost and availability of different potential alternative energy generation technology mixes in Bangladesh by building a robust, integrated, spatial energy system model populated with locally specific data, laying the foundation to replicate such models for other countries in the future. We first identify and comprehensively value high quality solar photovoltaic (PV), concentrating solar power (CSP), and wind resources across Bangladesh through a multi criteria planning approach to spatial analysis. These results then support the prioritization of areas for energy development. The model outputs values for different siting criteria estimated for each cell by technology type. These criteria include the levelized cost of electricity (LCOE) of generation by technology, cost of transmission connection and ease of road access. Finally, we group like cells together into potential suitable project areas so that we obtain aggregate estimates of alternative energy technology potential for Bangladesh along with cost and impact estimates. Through spatial cellular aggregation, our model comprehensively identifies high quality resources for grid integration based on techno economic criteria, generation profiles and socio economic impacts.

2 Data and Methodology

This study builds on methods of a preceding study on renewable energy potential in African countries (Wu et al. 2016, Wu et al. 2017). The Multicriteria Analysis for Planning Renewable Energy (MapRE) was developed as a tool to estimate grid-connected renewable resources and spatially specific criteria for project site selection using ArcGIS, Python and R programming languages and the arcpy spatial analysis modules of ArcGIS. We used a combination of global and country-specific datasets, which can be categorized into 1) physical (elevation and slope), socio-economic (population density, built-areas, roadways and railways), technical (resource quality, utility infrastructure), and environmental (land use and land cover, protected areas). The sources of datasets are summarized in Table 1.

First, we applied exclusion thresholds and buffer distances (see Table 2 and Table 3) used in previous studies with necessary adjustments to identify suitable areas for renewable energy development (stage 1). Next, we divided the identified suitable areas into 5 x 5 km spatial grids, which we call “Project Opportunity Areas (POAs)” (stage 2). Finally, we estimated site selection criteria values for each project opportunity area (stage 3). The site selection

criteria are elevation; population density; resource quality; distance to nearest transmission line, substation, road, and surface water body; land cover type; and total land area. Then, these criteria are used to calculate annual electricity generation and various levelized cost of electricity (*LCOE*) values for each project opportunity area. *LCOE* is a metric that describes the average cost of electricity for every unit of electricity generated over the lifetime of a project at the point of interconnection. Transmission or substation *LCOE*, generation *LCOE*, road *LCOE*, and total *LCOE* for each project opportunity area are estimated with the following equations, using the size (km^2) of the project opportunity area (a); associated land use factor (*LF*); land use discount factor (*LDF*); distance to nearest substation (or transmission line: d_s) and road (d_r). Land use factor is installable capacity of power generation per unit of land [MW/km^2].

Land use discount factor is the percentage of total potential land (or energy projects) developed given additional socio-economic, cultural, or physical constraints identifiable only with higher resolution data or through on-the-ground surveys.

$$LCOE_{generation} = \frac{a * LF * (1 - LDF) * (C_g * CRF + OM_{f,g})}{a * LF * (1 - LDF) * cf * 8760} + OM_{v,g} \quad (1)$$

$$LCOE_{interconnection} = \frac{a * LF * (1 - LDF) * (d_s * (C_t * CRF + OM_{f,t}) + C_s * CRF)}{a * LF * (1 - LDF) * cf * 8760} \quad (2)$$

$$LCOE_{road} = \frac{d_r * (C_r * CRF + OM_{f,r})}{cf * 50MW * 8760} \quad (3)$$

$$LCOE_{total} = LCOE_{generation} + LCOE_{interconnection} + LCOE_{road} \quad (4)$$

The capital recovery factor (*CRF*) converts a present value to a uniform stream of annualized values given a discount rate (i) and the interest period (N).

$$CRF = \frac{i * (1 + i)^N}{(1 + i)^N - 1} \quad (5)$$

Cost estimates relied on assumptions about fixed and variable costs from various studies specific to the technology and subtechnology. Since the capital cost for solar PV is rapidly falling, we used an Indian Government's Benchmark capital cost for utility-scale solar PV in fiscal year 2016-2017 as a latest estimate, which is approximately 760,000 [USD/MW] (CERC 2016) is used, instead of cost data from an IRENA's cost study (IRENA 2012).

We then conducted sensitivity analysis to examine the robustness of results by comparing the results with set of different assumptions for elevation, population density, capital costs, and land use discount factors in areas that are primarily cropland.

Although utility-scale clean energy projects are the scope of this study, we also roughly estimated the magnitude of rooftop solar PV potential as a basis for comparison. After identifying solar resource in urban and built-up area in Bangladesh, generation potential of rooftop solar PV and its generation LCOE are estimated assuming 1% to 10% of the urban and built-up areas are used for commercial and residential rooftop PV.

Table 1: Data Type and Source

Data Type	Description	Data Source
Land Use Land Cover	500m grid of land cover categories and class in 2013, e.g. forest, cropland, wetlands, degraded forest, urban, bare, water bodies etc. (IGBP classification).	MODIS-MCD12Q1 (NASA, Moderate Resolution Imaging Spectroradiometer)
Protected Areas	Shapefile of legally recognized protected areas	IUCN (World Database on Protected Areas)
Resource Quality: Wind	Wind speed and wind power density GIS data at 50m above ground and 5km resolution for Bangladesh from RisoeDTU from the KAMM/WASP studies for Bangladesh in 2004. Using the wind profile power law, the wind speed values are modified at 80m	Technical University of Denmark (RisoeDTU)
Resource Quality: Solar PV	Solar: monthly global horizontal (GHI) at 10km resolution for Bangladesh from DLR in 2000, 2002, and 2003	German Aerospace Center (DLR)
Resource Quality: CSP	Solar: monthly direct normal (DNI) GIS data at 10km resolution for Bangladesh from DLR in 2000, 2002, and 2003	German Aerospace Center (DLR)
Population Density	Population density estimate in 2015	NASA, SEDAC (Socio Economic Data and Application Center)
Elevation	Digital elevation SRTM raster	CGIAR-SRTM
Slope	Percentage slope raster file is calculated from the elevation data	Calculated from elevation data
Roadways and railways	Line shapefiles of major roadways and railways	Digital Chart of the World
Utility infrastructure	Existing transmission lines, substations, power plants with length, voltage, installed capacity in CSV and jpeg map (Figure 1 is georeferenced)	Georeferenced from utility infrastructure map of PGCB (Figure 1)
Hourly national demand data	Hourly generation and demand data in aggregate for country from January 2016 to December 2016	PGCB (Power Grid Company of Bangladesh Ltd.)

Table 2: Exclusion thresholds

Category	Exclusion threshold
Elevation	>1,500m
Slope	>5% for solar, >20% for wind
Water bodies	< 500 m buffer
Population density	> 800 persons/ km^2
Wind	< 180 W/m ²
Solar DNI	< 180 W/m ²
Solar GHI	< 180 W/m ²
Protected areas	< 500 m buffer (10 km buffer is applied only for the Sundarbans Reserve Forest)
Rail	<500m buffer
Land Use Land Cover (LULC)	See Table 3

Table 3: Classification and exclusion of particular land use types (IGBP classification). Land use discount factor for wind and solar PV/CSP are 25% and 10%, respectively, except for that of cropland for solar PV/CSP. The land use discount factor of cropland for solar PV/CSP is set from 1 to 10%.

Class	Class Name	In/Ex Categories
1	Evergreen Needleleaf Forests	EX
2	Evergreen Broadleaf Forests	EX
3	Deciduous Needleleaf Forests	EX
4	Deciduous Broadleaf Forests	EX
5	Mixed Forests	EX
6	Closed Shrublands	IN
7	Open Shrublands	IN
8	Woody Savannas	EX
9	Savannas	IN
10	Grasslands	IN
11	Permanent Wetlands	EX
12	Cropland	IN
13	Urban and Builtup	EX
14	Cropland/National Vegetation Mosaics	EX
15	Snow and Ice	EX
16	Barren	IN
0	Water Bodies	EX

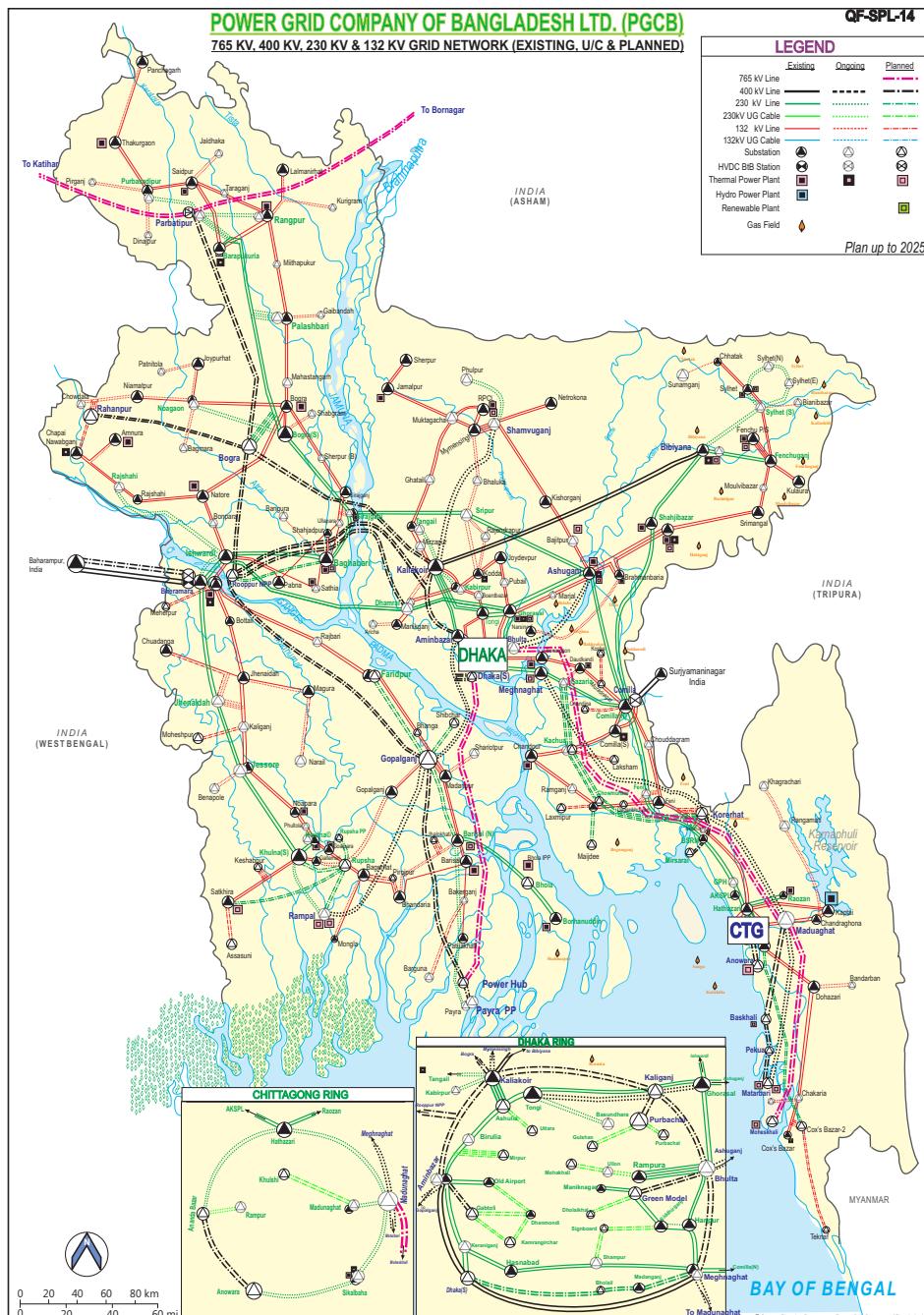


Figure 1: Existing power system infrastructure in Bangladesh (PGCB, 2016)

3 The Bangladesh Case Study

Electricity is considered one of the most crucial inputs for development on various fronts. Bangladesh has experienced substantial demand growth in the past decade with an average annual growth rate of 13% (BPDB 2016). To address its rapidly growing demand, the Bangladesh Government expanded the country's total installed capacity from 5,166 MW in 2008-2009 to 16,070 MW as of November 2017 including off-grid renewable energy (SREDA 2017). The annual demand in 2015-2016 was 52,193 GWh and maximum demand was 11,405 MW, with per capita consumption of 281 kWh. The Bangladeshi Government in its Vision 2021 document set the target 'Electricity for all by 2021'. The target to provide reliable and affordable electricity to all citizens by 2021 has also been recognized in the recent 7th Five-year plan, recognizing that the electrification rate is 77% as of December 2015, primarily through the national grid (BPDB 2016).

The current generation mix is heavily dependent on fossil fuels as shown in Figure 2 and 3; natural gas accounts for 53.1% (8,530 MW) of total capacity, followed by furnace oil (17.4%: 2,629 MW), diesel (7.0%: 1,028 MW), and power import (4.1%: 660 MW). Coal currently accounts for only 1.6% of total capacity.

In terms of generation, natural gas generates 35,822 GWh (68.6%). The rest is generated by furnace oil (8,673 GWh. 16.6%), power import (3,822 GWh. 7.3%), diesel (2,067 GWh. 4.0%), hydropower (962 GWh. 1.9%) and coal (847 GWh. 1.6%).

Renewable energy generation capacity in Bangladesh is 478.50 MW as of November 2017, with 245.85 MW on-grid and 232.65 MW off-grid. In addition to 230 MW on-grid hydropower, the on-grid capacity of solar PV and wind are 14.95 MW and 0.90MW, respectively. The off-grid capacity of solar PV, wind, biogas to electricity, and biomass to electricity are 229.57 MW, 2 MW, 0.68 MW, and 0.40 MW (SREDA 2017).

The average cost of electricity from grid ("average bulk electricity supply cost") is 5.55 Tk/kWh, equivalent to approximately 68 USD/MWh, assuming 1 Tk is equivalent to 12.3 cents. On the other hand, per unit generation cost in public and private generators is 5.10 Tk/kWh, equivalent to approximately 63 USD/MWh.

The Bangladesh Government plans to increase its generation capacity from 12,365 MW in 2015-2016 to 24,000 MW in 2021 to 39,000 MW in 2030 (BPDB 2016). According to its Electric System Master Plan in 2016, coal-fired power plant plays critical role in generation capacity expansion. Although coal-fired power plants currently contribute to a fraction of total generation and capacity, the Bangladesh Government plans to drastically increase the capacity of coal from 1.6% (250 MW) as of November 2017 to 35% (13,300 MW) by 2030 and reduce its reliance on natural gas from 53.1% (8,530 MW) as of November 2017 to 35%

(13,300 MW) in 2030, according to the Power System Master Plan 2016. As for renewable energy, Renewable Energy Policy of 2008 obligates the renewable energy share to be 10% by 2020 (Bangladesh Government 2008). In response to the obligation, the Bangladesh Government set a year-wise renewable plan in 2015 (SREDA 2017).

Transmission and distribution have also been steadily expanded to deliver electricity to more residential, commercial, and industrial end users. In fiscal year 2015-2016, a total of 9,893 circuit km transmission lines and 357,000 km distribution lines have been connected to the power system network. Figure 1 shows Bangladesh's current transmission, distribution, and substation map. The Bangladesh Government plans to construct 10,000 circuit km transmission lines and 481,000 km distribution lines and related grid and distribution substations by 2021.

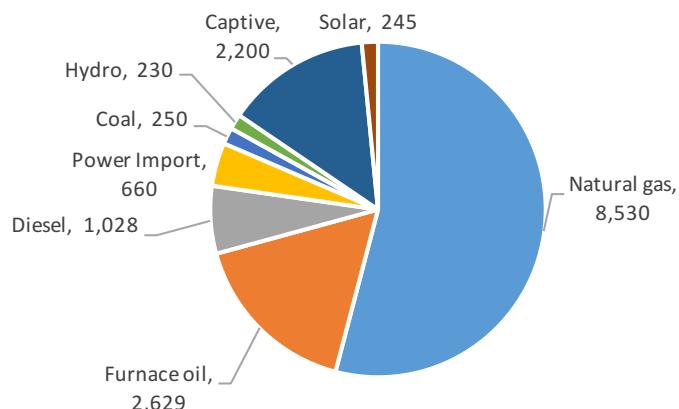


Figure 2: Installed capacity by fuel type in MW as of November 2017 (SREDA 2017)

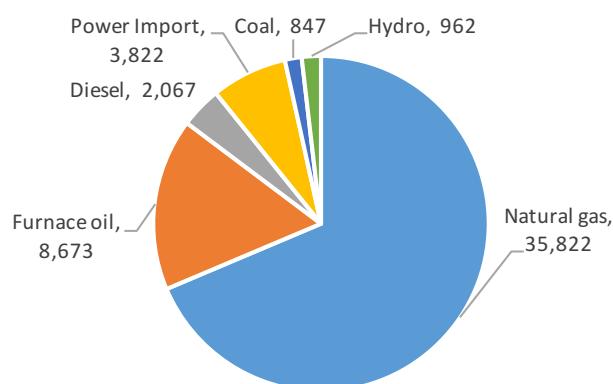


Figure 3: Generation by fuel type in GWh in FY2015-2016 (BPDB 2017)

4 Results

4.1 Resource Quality and Generation Potential in Project Opportunity Areas (POAs)

Project opportunity areas (POAs) are identified and summarized in Figure 4, 5, and 6. As shown in Figure 4 and 5, Solar PV and CSP resources are widely available across the country. Particularly high quality solar resources are located in the northern part of the country in Rangpur, Rajshani, Mymensingh, and Sylhet. These solar resources are available in distant, less populated areas, which enable rural electrification much faster than fossil fuel projects and help to achieve the government's 'Electricity for All' target by 2021. On the other hand, as shown in Figure 6, wind resource is available only in Sylhet and Chittagong. More than 99% of the resource area of solar PV and CSP and 100% of wind resource area are located in areas that are primarily cropland according to MODIS classification (NASA). For large scale clean energy integration in Bangladesh, targeting of non-cropland areas within POAs that are primarily cropland will be critical, as discussed in Section 5.

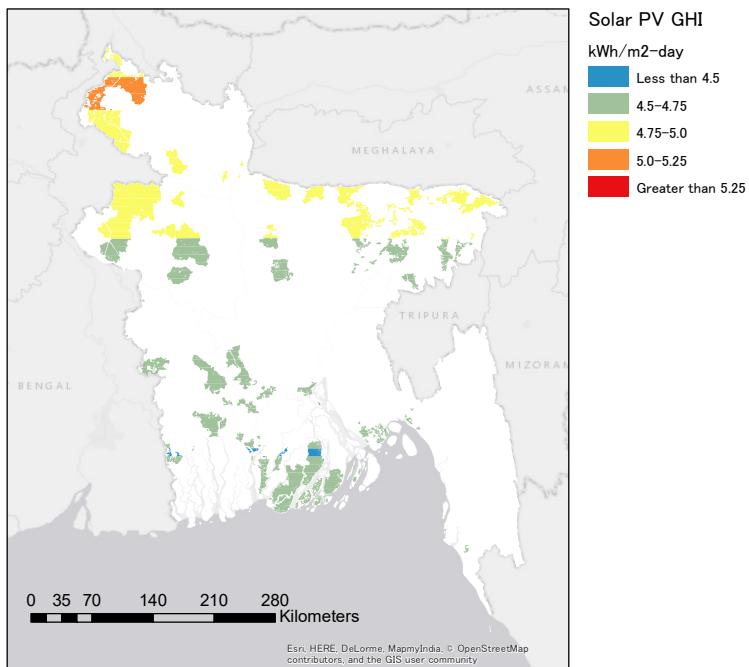


Figure 4: Global horizontal irradiance (GHI) of solar PV resource areas (project opportunity areas) in Bangladesh. Low quality resource area and environmentally/socially unsuitable areas are already excluded applying exclusion thresholds listed in Tables 2 and 3.

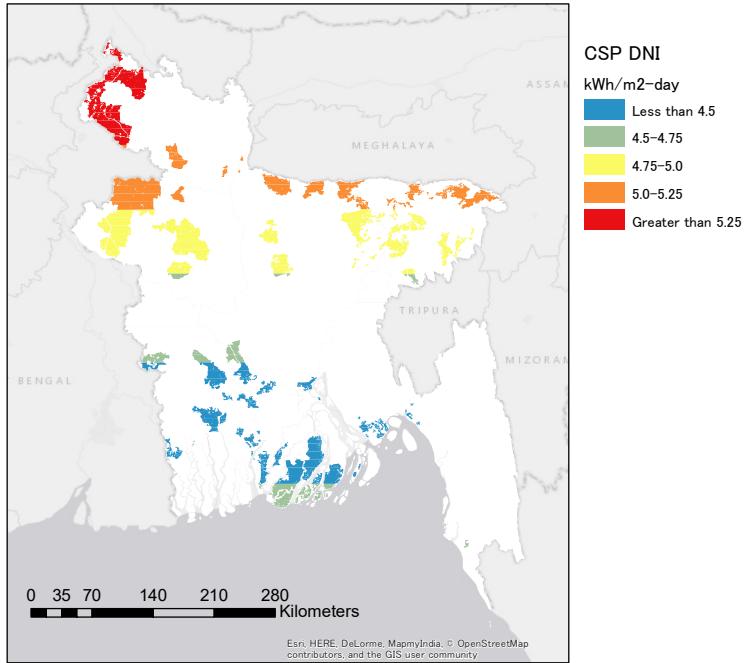


Figure 5: Direct normal irradiance (DNI) of solar CSP resource areas (project opportunity areas) in Bangladesh. Low quality resource area and environmentally/socially unsuitable areas are already excluded applying exclusion thresholds listed in Tables 2 and 3.

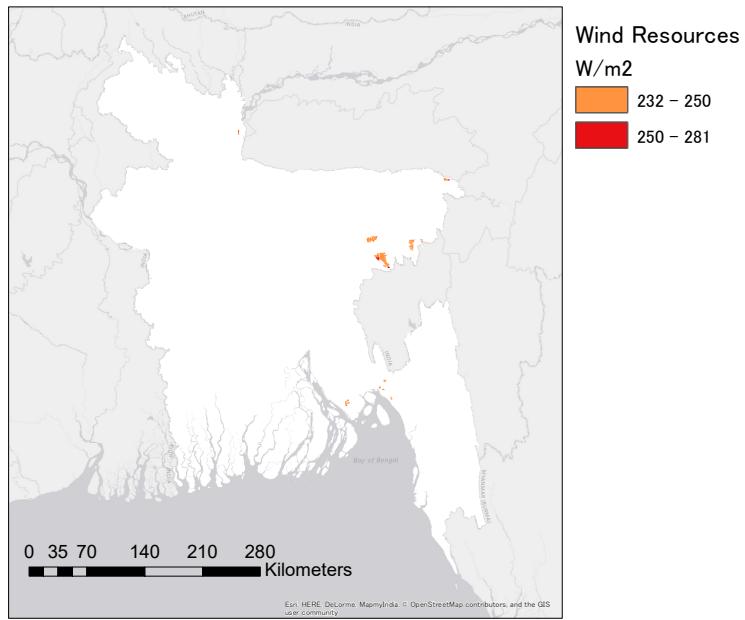


Figure 6: Wind power resources of resource areas (project opportunity areas) in Bangladesh. Low quality resource area and environmentally/socially unsuitable areas are already excluded applying exclusion thresholds listed in Tables 2 and 3.

Annual generation potential and capacity of solar PV, CSP, and wind are summarized in Table 4. The annual generation potential in project opportunity areas for solar PV, CSP with and without 6-hour storage, and wind are approximately 8.4-84 TWh/year, 9.8-98 TWh/year, 17.3-173 TWh/year, and 1.7 TWh/year, while the current national demand in FY 2015-2016 was 52.2 TWh/year. Likewise, the generation capacity in project opportunity areas for solar PV, CSP with and without 6-hour storage, and wind are approximately 5.3-53GW, 3.0-30GW, 5.3-53GW, and 0.57GW, while the current generation capacity was 12.3 GW in 2016. These estimates are dependent on the land-use discount factor of cropland, as explained below. Because the project opportunity areas of solar PV and CSP completely overlap, the potential generation and capacity of solar PV and CSP are mutually exclusive; only one of them could be selected and developed in each project opportunity area.

To estimate generation potential, only a fraction of each suitable land area (project opportunity area) is considered by applying a land use discount factor. The land use discount factor represents the uncertainty in the development of the resource on project opportunity areas due to additional constraints not captured by the input data. For solar PV and CSP, it was assumed that from 1% to 10% of POAs that are primarily cropland could be developable in project opportunity areas, while 10% of POAs that are primarily non-cropland could be developable. Given the lack of industry experience and empirical data on the potential solar projects, this was chosen somewhat arbitrarily. (In previous studies in Africa, a 10% land use discount factor was used for non-cropland project opportunity areas, and a 0% land use discount factor was used for cropland POAs (NREL 2009).) We assumed that 25% of the screened area could be developable for wind, based on industry experience from other regional wind studies, and because wind power has essentially no conflict with crops.

Table 4: Clean energy potential estimates and their weighted-average LCOE in Bangladesh compared with installed/projected electricity capacity in 2016/2030

	Land use discount factor in POAs that are primarily cropland	Percentage of area in urban and built-up area used for rooftop PV	Generation [TWh/yr]	Capacity [GW]	Necessary cropland area [km ² ; relative to national land in parenthesis]	Weighted average LCOE [USD/MWh]
Solar PV	1%	-	9.4	5.3	169 (0.1%)	91
	5%		42	26	864 (0.6%)	
	10%		84	53	1,690 (1.2%)	
CSP without storage	1%	-	17.3	5.3	169 (0.1%)	143
	5%		86.7	26.4	864 (0.6%)	
	10%		173	53	1,690 (1.2%)	
	1%	-	9.8	3.0	169 (0.1%)	267
CSP with 6 hour storage	5%		49	14.3	864 (0.6%)	
	10%		98	30	1,690 (1.2%)	
	-	-	1.65	0.57	-	106
Rooftop solar PV	-	1%	0.32	0.20		244
		5%	1.6	1.0		(generation)
		10%	13	2.0		
Peak demand& capacity installed in 2016	-	-	61.7	9.0	-	Total: 68
					(demand)	Hydro: 14
					12.3	Gas: 28
					(capacity)	Coal: 110
						HFO: 237
						Diesel: 472
Projected demand& planned capacity in 2016	-	-	-	34		
					(demand)	
				39		
					(capacity)	

Table 5: Clean energy targets and potential estimates in Bangladesh

	Generation [TWh/yr]	Capacity [GW]
Government target in 2021 (BPDB)	-	1.7 (solar PV) 1.3 (wind)
Government target in 2021 and 2030 by Renewable Energy Policy of 2008	-	10% in 2021 (i.e. 2.4GW) 20% in 2030 (i.e. 7.8GW)
Power System Master Plan 2016 Final Report	2 (solar PV) 1.25 (wind)	-
IEEFA (2016) estimate for 2024-2025	17.52 (utility-scale solar) 0.48 (wind)	10GW by solar PV 0.30 GW by wind
Mondal & Islam (2011)	-	50GW by solar PV
Noor & Muneer (2010)	-	0.1GW by CSP
Expected participation by public sector (Govern- ment estimation)	-	0.235 GW by wind

As a comparison to the utility-scale renewable energy potential, rooftop solar PV potential in urban and built-up areas was roughly estimated. Although urban and built-up areas are excluded in identifying project opportunity areas for utility-scale projects, rooftop solar PV can be deployed in those areas. Figure 7 shows solar PV resources in urban and built-up areas in Bangladesh. Urban and built-up areas are defined as lands covered by buildings and other man-made structures in MODIS. Assuming 1-10 % of urban area is used for rooftop solar PV, its potential is 0.32-3.2 TWh and 0.20-2.0 GW. With the same level of capital costs of rooftop PV in the U.S., which is 2.93 USD/Watt DC in Q1 2016 (NREL 2016a), weighted average generation LCOE is calculated as 244 USD/MWh. While rooftop PV could play a critical role in swift electrification of distant, rural areas, Table 4 shows that the size of generation potential by rooftop PV is relatively smaller and more costly than those of utility-scale solar PV. However, rooftop solar PV could serve a different purpose than utility-scale PV system; it can be a point of use energy source as in the Solar Home System in Bangladesh. Rooftop solar PV can be quickly installed in less than one week; can flexibly meet the required load of the end user due to its modular design; and with batteries and a backup generator can be used to implement a 'micro-grid'. For rural areas with no current electrical infrastructure, the costs of developing and maintaining a distribution grid needs to be taken into account when comparing the costs of the rooftop solar PV and utility-scale solar or other energy options. For accurate estimation of rooftop solar PV potential, image recognition techniques are necessary, which was beyond the scope

of this study.

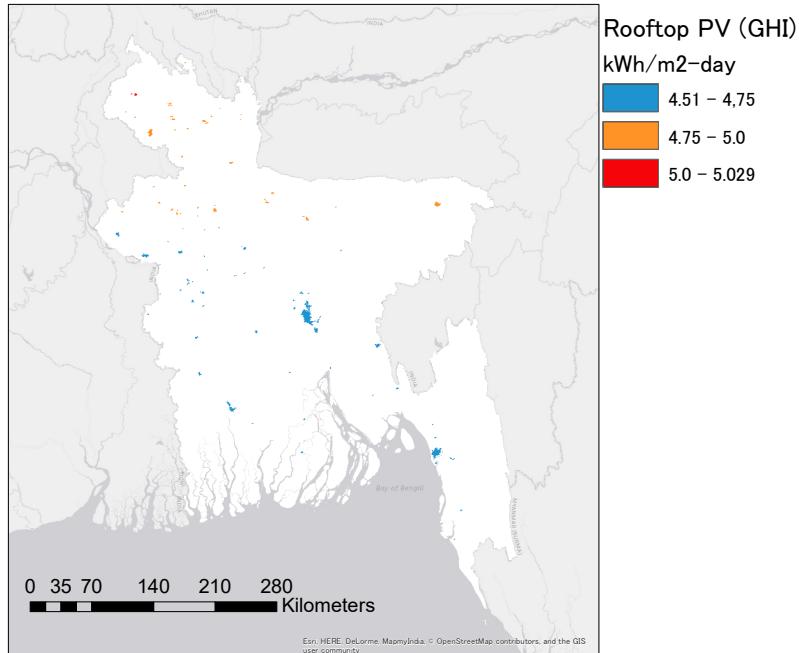


Figure 7: Global horizontal irradiance (GHI) of urban and built-up areas in Bangladesh

4.2 Distribution of Generation Potential and Levelized Cost of Electricity

Figure 8, 9, 10, and 11 summarize the map of LCOE of solar PV, CSP with and without 6-hour storage and wind using resource quality in project opportunity areas, distance to nearest transmission line or substation, and the nearest road. Table 6 summarizes the distribution of LCOE. The LCOE of solar PV is the lowest among these technologies, ranging from 84 USD/MWh to 107 USD/MWh. More than 99% of the generation potential is below 100 USD/MWh. LCOE of CSP without storage and wind power are 127-160 USD/MWh and 99-108 USD/MWh range. LCOE of CSP with 6-hour thermal storage is 237-300 USD/MWh, the most expensive among all options. As a reference, average electricity cost from grid is currently 5.55 Tk/kWh, or 68 USD/MWh. Total LCOEs are largely determined by the generation costs. The average contribution to total LCOE for solar PV, CSP, and wind of transmission and road construction are 8.5 %, 2.8% and 7.0% respectively.

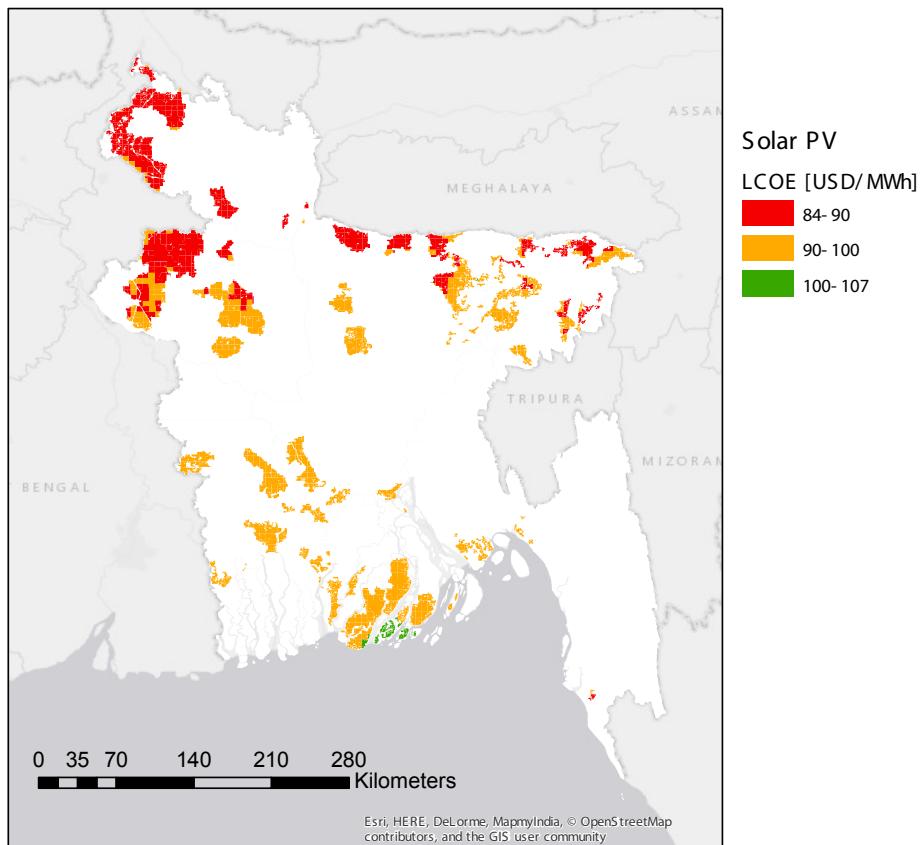


Figure 8: Average total levelized cost of electricity (LCOE) of solar PV estimated using resource quality, distance to nearest transmission line or substation, and the nearest road.

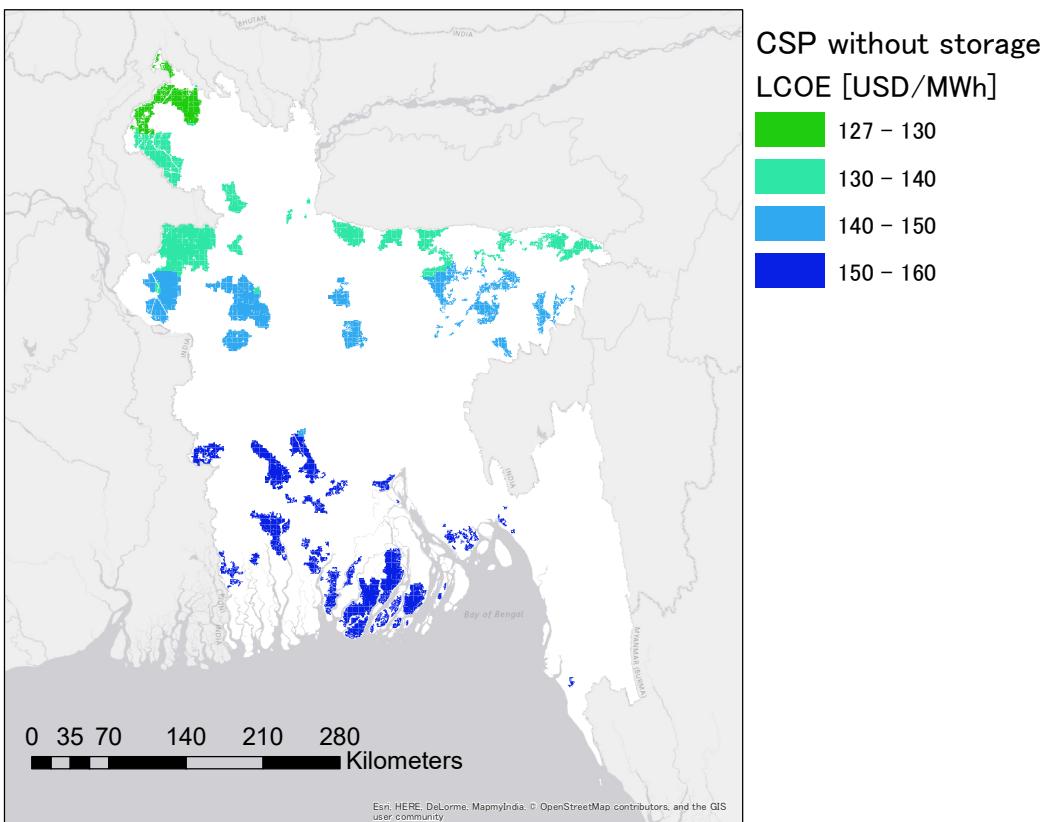


Figure 9: Average total levelized cost of electricity (LCOE) of CSP without storage, estimated using resource quality, distance to nearest transmission line or substation, and the nearest road.

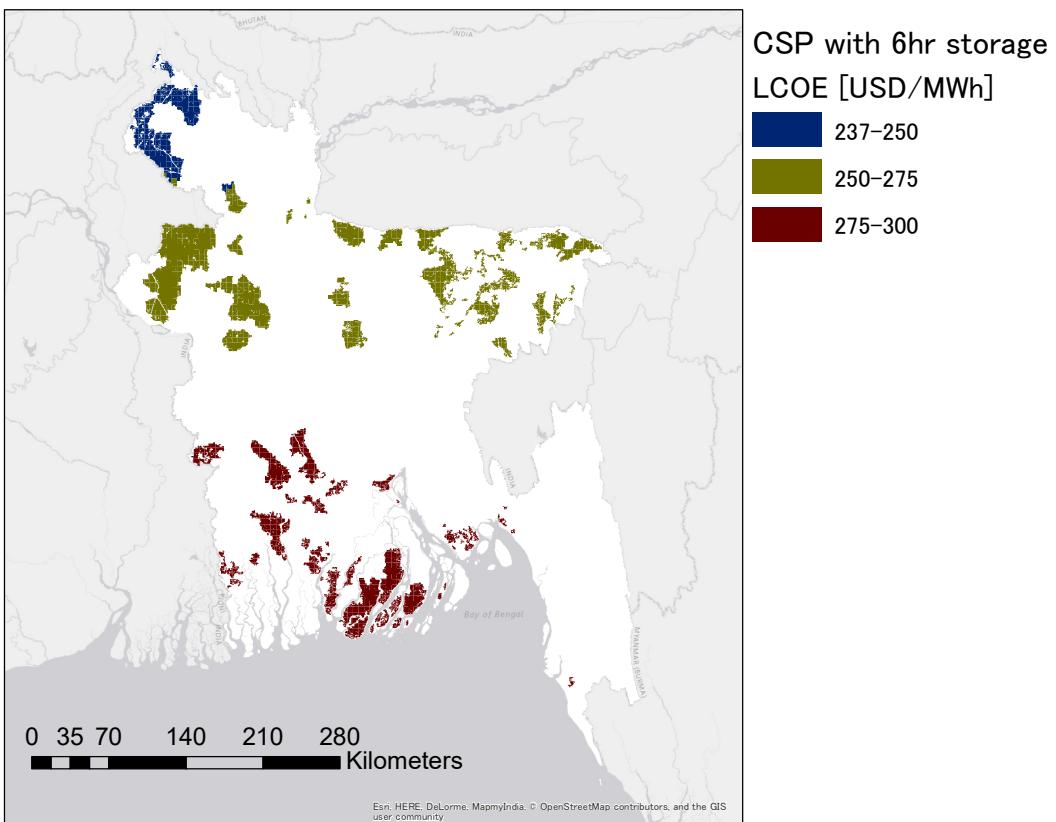


Figure 10: Average total levelized cost of electricity (LCOE) of CSP with 6-hour storage (C) estimated using resource quality, distance to nearest transmission line or substation, and the nearest road.

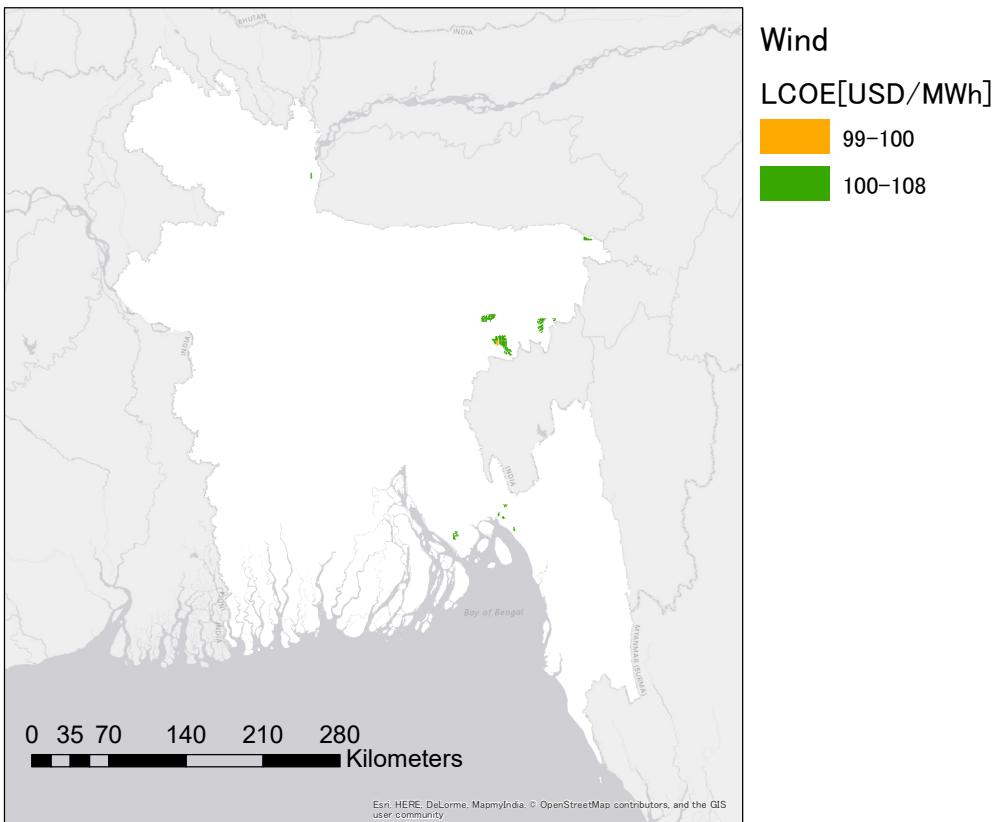


Figure 11: Average total levelized cost of electricity (LCOE) of wind zones estimated using resource quality, distance to nearest transmission line or substation, and the nearest road.

Table 6: Generation potential and LCOE of solar PV, wind, and CSP in Bangladesh assuming that a maximum of 10% of any primarily cropland Project Opportunity Area (POA) would be used for solar PV and CSP projects, while a maximum of 25% of a POA could be used for wind projects.

LCOE [USD/MWh]	Solar [TWh]	PV	Wind [TWh]	CSP without storage [TWh]	CSP with storage [TWh]
<100	84		0.05	-	-
100-150	0		1.6	120	-
150-200	-		-	53	-
200-300	-		-	-	98
Total	84		1.65	173	98

Figure 12 summarizes the levelized cost of electricity (LCOE) curve. The LCOE curve represents a supply curve of renewable energy in Bangladesh. The X-axis shows cumulative generation [TWh/year], and Y-axis shows LCOE. The area under the LCOE curve represents total cost of electricity. Solar PV has the cheapest LCOE across all technologies. Weighted average LCOE of solar PV is 91 USD/MWh with a low standard deviation of 3.7 USD/MWh. In addition to the lowest LCOE, solar PV has other benefits: due to its simple and modular design and low requirements of maintenance, solar PV can rapidly deploy to meet the load. Installation takes usually 6-12 months and can be managed by a small crew (IFC 2015). CSP without storage has the largest generation potential, 17.3 TWh/year, but its weighted average LCOE, 143 USD/MWh, is approximately 40-50% higher than that of solar PV and its potential locations completely overlap with that of solar PV. The weighted average LCOE of CSP with 6-hour thermal storage is 267 USD/MWh, the most expensive option, with a generation potential of only 9.8 TWh/year. Its land use factor is by necessity lower than that of CSP without storage due to additional land needed for storage facilities. There are jumps in LCOE of CSP that are caused mainly because resource quality, DNI, is low in the southern part of the country (see Figure 5). As a result, LCOEs of CSP are more heterogeneous than that of solar PV, with standard deviations of 9.2 USD/MWh without storage and 17.0 USD/MWh with storage. Finally, in contrast to solar PV, CSP requires high maintenance costs and a large trained workforce to manage the plant. The wind resource potential is limited. The weighted mean of wind LCOE is 106 USD/MWh with a standard deviation of 1.9 USD/MWh. In sum, solar PV is the most important option in terms of both generation potential and costs.

This result suggests substantially larger solar PV and CSP energy potential in the country than those shown in the current Power System Master Plan 2016 Final Report as summarized in Table 5. According to the report, renewable energy potential in Bangladesh was as follows: PV 2 TWh/year, Wind 1.25 TWh/year, and no CSP potential (Bangladesh Government 2016). The largest difference between that report and ours is the availability of land for renewable resources. IEEFA (2016) also found the Government's study to have overly conservative assumptions about land availability).

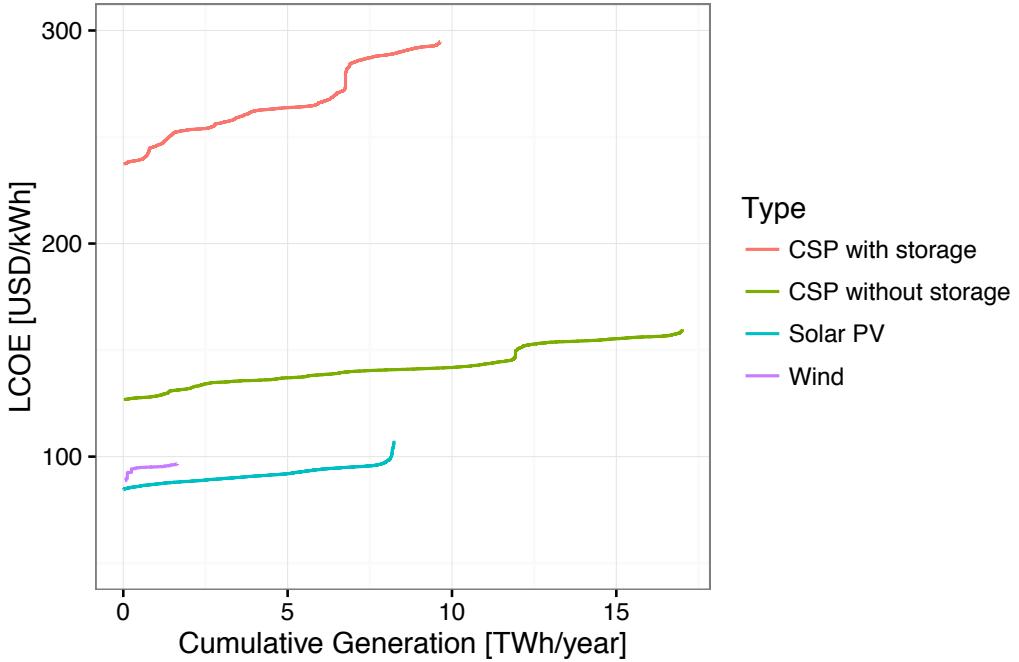


Figure 12: Supply curve (LCOE curve) of renewable energy generation. Supply curves show the cumulative potential of all solar PV, wind, and CSP. Project opportunity areas are sorted by generation LCOE

5 Discussion

5.1 Avoidance of cropland conversion in clean energy development

Because most POAs are over primarily cropland, research at the local scale is needed to identify non-cropland areas within these POAs for possible renewable energy development. As shown in Table 4, if a maximum of 1% of land in POAs (172 km^2) is converted to solar PV farm, it could provide 5.5 GW capacity. (Only 0.3% of these POAs (53 km^2 , or 0.036% of total Bangladesh land area ($147,610 \text{ km}^2$), is necessary to meet a 1.7 GW solar PV target in 2021.) Likewise, only 1.4% of land within POAs (244 km^2 , or 0.17% of total Bangladesh land), is needed to meet the Government's 7.8 GW renewable energy target in 2030.

The required annual conversion rates of land for solar PV farm to reach 244 km^2 in 2030, are $19 \text{ km}^2/\text{year}$ from 2017 to 2030. These annual conversion rates are less than 3 percent of the average annual decrease in cropland area in Bangladesh, which was 688 km^2 per year between 2000 and 2010 (Quasem 2011). Croplands has been steadily converted to non-agricultural land such as industrial land, degraded land, and rural and urban settlements. Cropland accounted for 67.38% ($94,395 \text{ km}^2$) of total land in 1976 and decreased to 60.04% ($87,519 \text{ km}^2$) in 2010 at annual reduction rate of 0.75% between 2000-2010. On the other hand, rural settlement and urban and industrial area increased from $14,580 \text{ km}^2$ and 475

km^2 in 2000 to $17,661\ km^2$ and $876\ km^2$ in 2010 with annual growth rate of 1.9% and 6.3%, respectively.

Appropriate planning and public participation are crucial to select and convert only land with little to no agricultural productivity within the identified suitable project areas in this study. Because agricultural productivity of land is heterogeneous across the country (e.g. Gumma et al., 2014), selecting land with low agricultural productivity for renewable energy projects reduces impacts on farmers and food security.

Solar PV farms can take up a lot of area, but new designs can avoid conversion of cropland by allowing crops underneath and between solar panels. The mounting structures are raised so that there is sufficient space below the modules for crops and tractors (NREL 2013, NREL 2016b). Large solar PV farms are also now being installed over fish farms, avoiding conflicts with land use altogether (e.g. Civil Engineer 2017).

When compared with coal fired power plants, it is important to remember that coal facilities also require ports, terminals, fuel storage areas, and ash yards. Those take up a lot of land and inevitably pollute surface water, groundwater, and local soils for many kilometers in all directions due to fugitive coal particles, fugitive coal ash dust, emissions of sulfur dioxide, mercury and other heavy metals, and coal ash leachate interacting with surface and groundwater (Lemly 2017). For example, the proposed Maitree Power Plant near Rampal, with 1.32 GW capacity, will use 1,834 acres of land, which is equal to $7.4\ km^2$. While utility solar PV needs about 5.6 times more land per GW than the coal-fired power plant, the environmental impacts of soil and water pollution of utility solar PV are negligible compared to those that the Maitree plant poses to the downstream mangroves and fisheries of the Sundarbans Reserve Forest and World Heritage Site (UNESCO 2016).

Moreover, renewable energy development could help electrification of rural areas and economic development of the country, resulting in mitigation of land degradation, as both croplands and forests in Bangladesh are under severe stress from resource exploitation to meet energy needs. Degraded land area was $68,422\ km^2$ (47.52 % of total land) between 1981 and 2003 (Hasan et al. 2017). Renewable energy development could lessen deforestation for biomass and other agricultural outputs, whose various services could be substituted by rural electrification by renewable electricity (Tanner and Johnson, 2017).

5.2 Trade-offs between elevation threshold for exclusion and renewable energy potential

With 25% of its land lower than 1m above the sea level, Bangladesh is considered to be one of the most vulnerable countries to sea level rise, subsidence, storm tides, and flood

(e.g. Ali 1999). In this analysis, land lower than 1m above the sea level was excluded from suitable areas (project opportunity areas) to be conservative. Figure 13 shows the relationship between elevation thresholds for exclusion in identifying project opportunity areas and generation potential of solar PV, CSP, and wind. About 20% of project opportunity areas for solar PV and CSP are located between 1m and 2m elevation, mostly in southern Bangladesh. Therefore, to be conservative about the risk of flooding and sea level rise, the potential of solar PV and CSP could be discounted by 20%. On the other hand, generation potential of wind is less sensitive to elevation-related risks than those of solar PV and CSP. With appropriate system design, however, the effects of flooding can be mitigated by raising the panels and inverters above the flood plain (e.g. Solar Builder Magazine 2016).

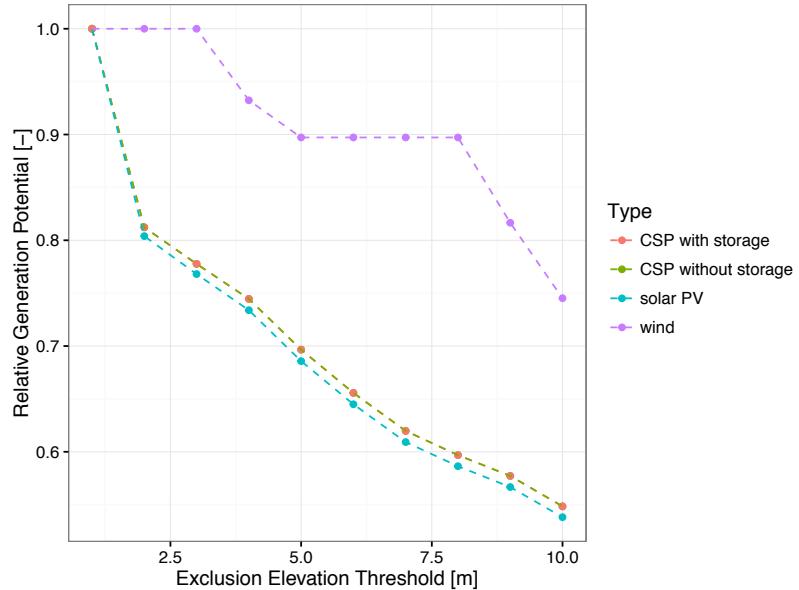


Figure 13: Relationship between elevation thresholds and generation potential of solar PV, CSP, and wind

5.3 Trade-offs between population density thresholds and renewable energy potential

Bangladesh has the highest population density among large countries, with 1,237 person/ km^2 in 2012. Renewable energy potential is sensitive to the exclusion threshold for population density. In this analysis, 800 person/ km^2 is used as an exclusion criterion because thresholds below the value greatly reduce the renewable energy potential of solar PV and CSP. Figure 14 shows the relationship between population thresholds and renewable generation potential.

Because urban and built-up areas are already excluded in identifying project opportunity areas and renewable energy potential in this analysis, there is no direct competition between

dense settlement and renewable energy project sites. One potential benefit of renewable energy projects being located close to dense settlements (load centers) is the relatively low institutional, financial, and time barriers for development of renewable energy projects. Construction of long transmission lines and roads are not necessary, so energy projects can be quickly developed and efficiently used in or near the load center.

Renewable energy project sites will need to coexist within relatively close distances to some settlements. Therefore, renewable energy projects need to be carefully planned with public participation and transparency to minimize displacement of communities. Indigenous communities in particular must not be displaced from their traditional lands and resources without their free, prior and informed consent.

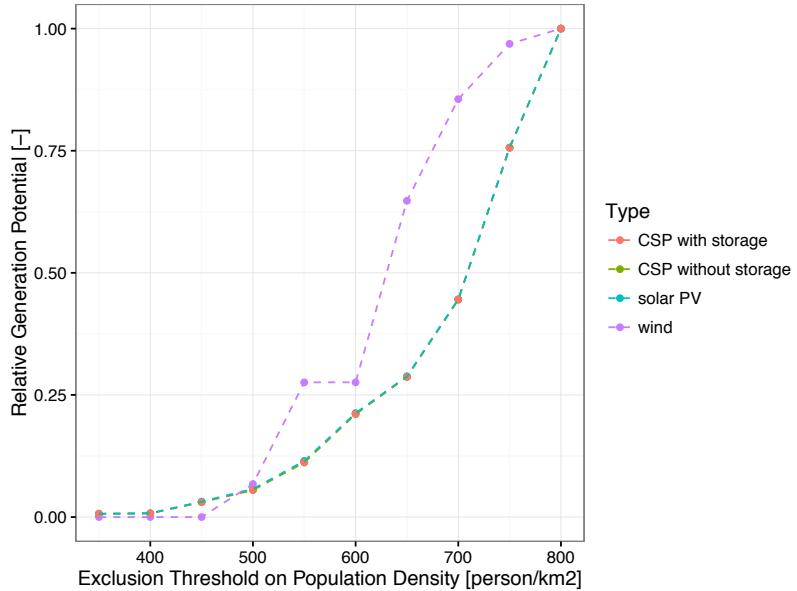


Figure 14: Relationship between population thresholds and generation potential of solar PV, CSP, and wind

5.4 Falling cost of renewable energy and its uncertainty

As shown in Table 4 and Figure 12, solar PV is the cheapest electricity source among all renewable energy technologies in this study, given our set of assumptions. Because the costs of those technologies have been rapidly falling globally (e.g. IRENA 2014), those costs are expected to decrease in Bangladesh as more renewable energy projects are developed. When planning the long-term electricity generation mix, it is important to consider the substantial reductions of capital costs of solar PV, CSP, and wind by innovation, learning-by-doing, and economies of scale (e.g. Painuly 2001).

Therefore, sensitivity analysis of capital costs on weighted average of LCOE was conducted and is summarized in Figure 15. Initial (capital) costs of solar PV, CSP, and wind changed +20% and -40% from the default value. As shown in Figure 15, solar PV is consistently the cheapest technology within the capital cost ranges.

Average grid electricity cost is 5.55 Tk/kWh, or 68 USD/MWh. Considering potential cost reduction in capital costs of solar PV, although the LCOE of solar PV is nearing competitiveness with the retail electricity prices now, it is still not comparable to the grid electricity costs. Innovation and economies of scale will reduce the costs to a comparable level with the grid electricity costs in the 2020 and 2030 horizon, given falling LCOE of utility-scale solar PV around the world. As the module prices of solar PV have fallen 80% since 2010 (IRENA 2017) and US Department of Energy set new targets to reduce the costs of module price, balance of system hardware, and soft costs of utility solar PV by 43% (USDOE 2017), 40% reduction of capital costs of utility solar PV is well within reach.

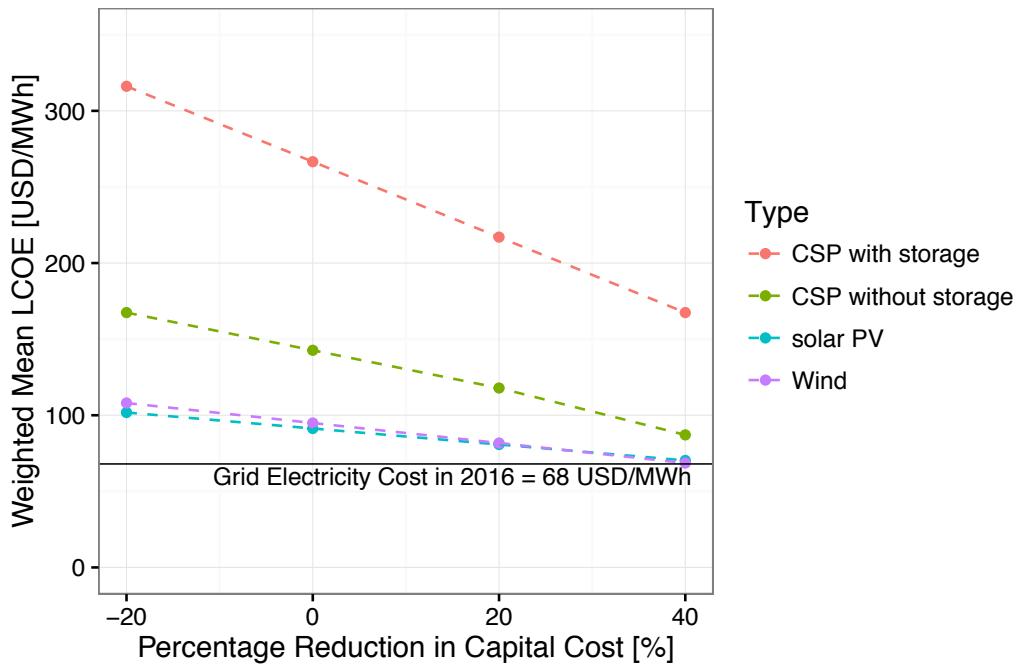


Figure 15: Relationship between weighted mean LCOE and reduction in capital costs of solar PV, CSP, and wind

5.5 Necessary measurements to accommodate high penetration of solar PV

Peak generation from solar PV does not coincide with the peak demand hours in Bangladesh. As shown in Figure 16, the top 3 hours of demand concentrate between 5pm and 11pm

(BPDB 2016). A significant gap exists between peak solar PV generation (around noon) and peak demand. As shown in Figure 17, the current load duration curve of Bangladesh in 2016 is relatively steep; the highest 1 percentile demand is around 8.1 GW and the lowest 1 percentile demand is around 3.8 GW. Therefore, it is necessary to invest in the flexibility of the grid to fully utilize the vast solar energy potential while avoiding substantial curtailment¹.

Importantly, storage is not necessarily required within the level of the Government's 2030 renewable energy target of 7.8GW. Previous studies showed that flexible conventional generation, interconnected transmission network, load-shift, and other sources of grid flexibility enable accommodation of 15-20% of variable renewable energy (VRE) generation in energy basis. For example, energy storage capacity is not necessary in California and other western states in the United States (CAISO 2011). Therefore, the Bangladeshi Government's renewable target in 2030 of 20% in capacity, which is far less than 10% in energy with 15% capacity factor for solar PV, does not require energy storage installation. On the other hand, beyond this level of penetration of solar PV, a significant rise of curtailment occurs and energy storage becomes necessary to utilize the vast solar PV potential (NREL, 2016). Fortunately, the cost of lithium-ion batteries is rapidly decreasing and cost reductions are expected to continue up to 2030 (Kittner et al, 2017).

Lastly, CSP with thermal storage enables greater penetration of solar PV (NREL 2011). CSP is relatively new technology to Asia and still expensive, as shown in Table 6 and Figure 12. However, CSP projects have been rapidly developed in the past five years in China and India. That of China has exceeded 1GW. Figure 15 shows that even a 40% decrease in capital costs of CSP with 6-hour storage is not sufficient to compete with conventional energy sources and solar PV. Therefore, substantial cost reductions are necessary for large-scale, cost effective deployment of CSP with thermal storage.

¹Curtailment is defined as "a reduction in the output of a generator from what it could otherwise produce given available resources (e.g., wind or sunlight), typically on an involuntary basis." (NREL, 2014)

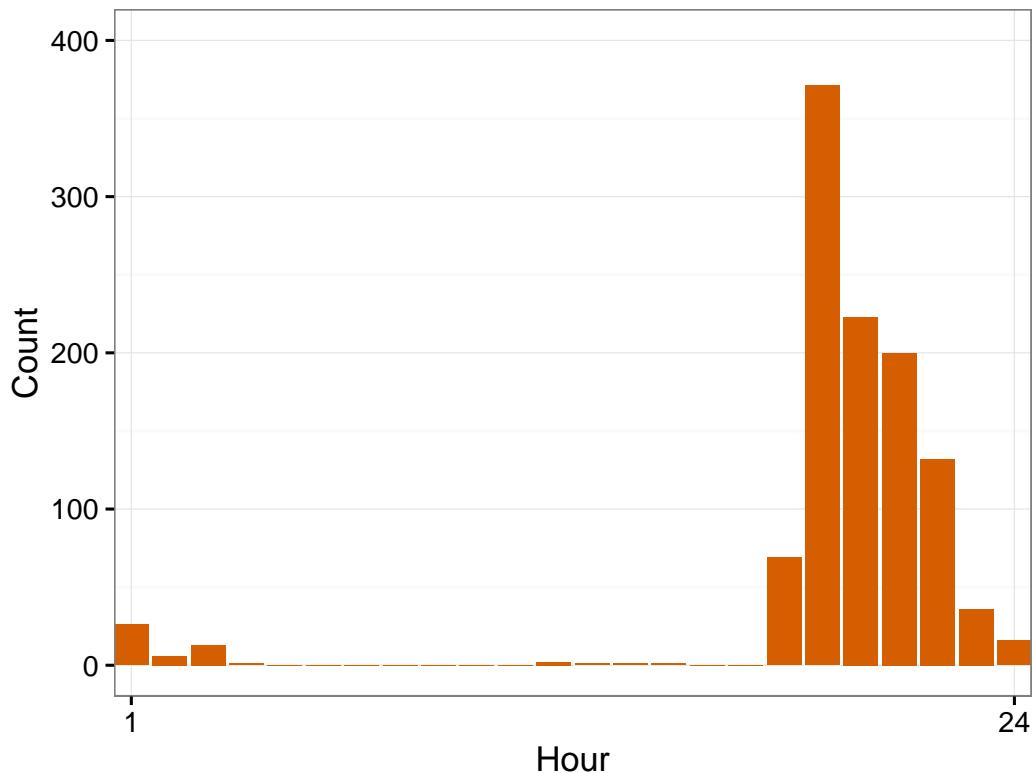


Figure 16: Hourly demand histogram for the top 3 hours of demand hours per day in Bangladesh in 2016 (calculated from the hourly demand data from PGCB website)

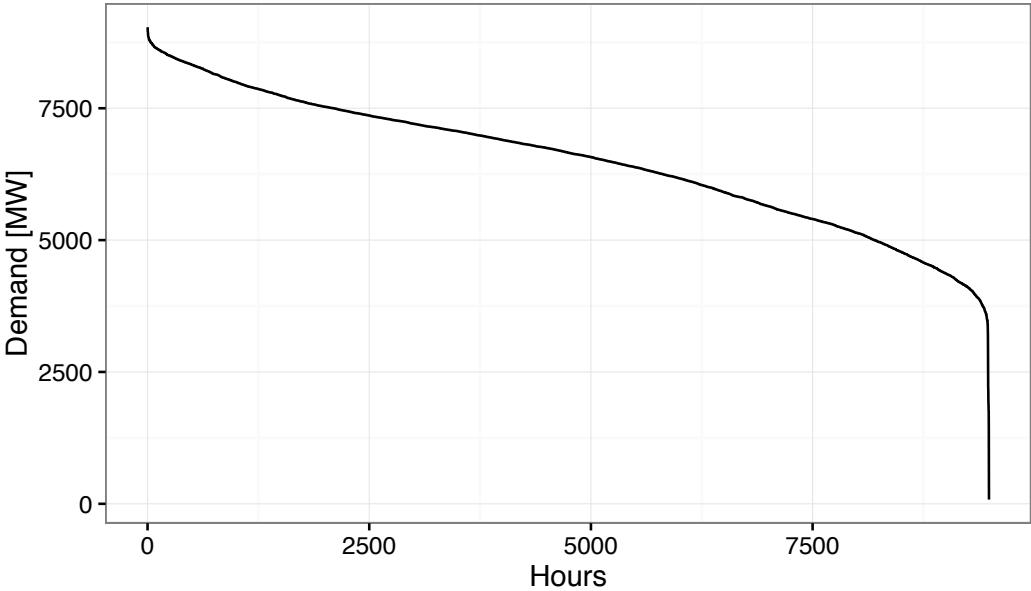


Figure 17: Annual load duration curve of Bangladesh in 2016 (BPDB 2016)

6 Limitations

There are several limitations on data and methodologies of this study. First, estimation of LCOEs, generation potential and identification of project opportunity areas rely on various assumptions. For example, because of data availability, we used Africa's construction costs of transmission, substation, and roads. As stated in section 4.2, the sum of transmission, substation, and road LCOEs are less than 10% of total LCOE for all four technologies. Therefore, underestimation of these values would not change overall results. Capital costs and operations and maintenance (O&M) costs are taken from IRENA 2012, except for solar PV. These values may be outdated or not accurate for Bangladesh, particularly due to its high land cost. We therefore conducted sensitivity analysis for capital costs, which are known to have major impact on total LCOE, to see the uncertainty in LCOE estimation because of the uncertainties in capital costs and O&M costs.

Second, although representative, mean, or simulated values of parameters such as capacity factor, resource quality, and various costs are used to estimate renewable generation potential and LCOE, these parameters themselves have their own (random) distribution. No physical site reconnaissance has been done to verify the results of this study. This study is intended to broadly identify opportunity areas for solar and wind project development. Appropriate long term ground-level data measurements are essential for project development. Third, LCOE does not account for differences in the value of electricity generated by different technologies in a particular location or system integration costs or balancing

costs. Fourth, we considered only utility-scale projects in this study, but the Bangladeshi Government could utilize rooftop PV and SHS to meet those targets in addition to these utility-scale renewable energy options.

7 Conclusions

We identified and comprehensively valued high quality solar PV, CSP, and wind resources across Bangladesh and estimated the levelized cost of electricity (LCOE) of generation by technology, cost of transmission connection and road access. We found that there is vast solar energy potential with costs competitive with the current retail electricity price. The annual generation potential and capacity are approximately 8.4-84 TWh/year and 5.3 to 53 GW for solar PV; 9.8 to 98 TWh/year and 3.0 to 30 GW for CSP with 6-hour storage; 17.3 to 173 TWh/year and 5.3 to 53 GW for CSP without storage; and 1.65 TWh/year and 0.57 GW for wind. Because the project opportunity areas of solar PV and CSP completely overlap, only one of them could be selected in a given project opportunity area. Solar PV is the most important option in terms of both costs and generation potential among these options. Furthermore, utility solar PV is modular and can be deployed in various sizes to meet space and/or load requirements. It is also quite rapid to deploy: a 100 MW plant can be built in under 12 months. We also conducted sensitivity analysis with various assumptions on capital costs and exclusion thresholds for elevation and population density to see the robustness of the results. The potential of solar PV and CSP are sensitive to the exclusion criteria of elevation and population density. Though low elevation area is excluded for the risk of flooding, the effects of flooding can be mitigated with the appropriate system design of solar PV. The sensitivity analysis of capital costs does not change the conclusion of this study. Because practically all project opportunity areas are primarily cropland, research at the local scale is needed to identify non-cropland areas (such as degraded areas) within these POAs for possible renewable energy development. This study found that the necessary land area to convert is just a fraction of the country's total land and can be developed. If 1% of land in project opportunity areas is converted to solar PV farm, it could provide 5.3 GW of solar PV. 0.3% of project opportunity areas, which is 0.036% of total Bangladesh land, is necessary to meet a 1.7 GW solar PV target in 2021. Likewise, 1.1% of project opportunity areas, which is 0.17% of total Bangladesh land, is needed to meet a 7.8 GW solar PV target in 2030. By overlaying finer-scale agricultural productivity information with the project opportunity areas and avoiding high agricultural productivity land for conversion, planners can minimize the negative impacts on farmers and food security. Public participation in project planning and free, prior and informed consent of indigenous communities are also key components of socially and environmentally responsible project planning.

Solar PV energy resources are widely available in distant, less populated areas, can be

rapidly deployed due to its simple modular structure, and does not require trained workforce for operation and maintenance. These features enable rural electrification much faster than fossil fuel projects and grid extension. Therefore, utility-scale renewable energy projects, particularly utility-scale solar PV, could play a crucial role in achieving the 'Electricity for All' target by 2021. To enable sustainable development in Bangladesh through electrification, investment planning in energy generation, transmission, and distribution should be strategically designed to make the best use of the large, well-distributed potential in solar PV and CSP.

Recommended next steps include collection and analysis of high resolution data and on-the-ground surveys to identify non-croplands within potential project areas; minimize displacement of communities; and plan for appropriate energy generation and storage relative to the grid. There is currently an intense debate taking place over the energy future of Bangladesh and its ramifications for social, ecological and environmental spheres of life – both locally and for the global commons. Our study (i) provides much needed statistics on the potential for renewable energy resources in country; (ii) demonstrates the cost effectiveness of these socially and environmentally preferable clean energy solutions for Bangladesh; and (iii) specifically identifies high-priority zones for alternative energy investment to support data needs for government planners, communities and potential investors.

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