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Geospatial multi-criteria analysis for identifying high priority clean energy investment opportunities: A case study on land-use conflict in Bangladesh

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HIGHLIGHTS

- We estimate renewable energy (RE) potential in Bangladesh considering land-use conflicts.
- We find 53 GW of low-cost utility-scale PV potential, far more than previously estimated.
- Though more expensive, rooftop solar PV could provide 17% of current peak demand (2 GW).
- Meeting Bangladeshi 2030 RE targets requires only 0.17% of total land area.
- Even with a conservative land use program there is enough RE capacity to support growth.

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ABSTRACT

Bangladesh is a globally important emerging economy with rapidly increasing energy demand. The Bangladeshi government's primary capacity expansion plan is to install 13.3 GW of new coal by 2021, including the 1.3 GW Rampal coal power plant to be developed in the Sundarbans. Inadequate geospatial and economic information on clean energy investment opportunities are often a significant barrier for policy makers. Our study helps fill this gap by applying a new method to assess energy investment opportunities, with focus on understanding land-use conflicts, particularly important in this context as Bangladesh is constrained on land for agriculture, human settlements, and ecological preservation. By extending a geospatial multi-criteria analysis model (MapRE) we analyze the cost of various renewable energy generation technologies based on resource availability and key siting criteria such as proximity to transmission and exclusion from steep slopes, dense settlements or ecologically sensitive areas. We find there is more utility-scale solar potential than previously estimated, which can be developed at lower costs than coal power and with minimal cropland tradeoff. We also find significant potential for decentralized roof-top solar in commercial and residential areas. Even with a conservative land use program that reserves maximum land for agriculture and human settlement, there is more renewable energy capacity than needed to support Bangladeshi growth. This study provides critical and timely information for capacity expansion planning in South Asia and demonstrates the use of geospatial models to support decision-making in data-limited contexts.

1. Introduction

Bangladesh is an important emerging economy widely acknowledged to be making strides in human development and economy. With a population of over 50 million and an economic growth rate of over 7%, Bangladesh's economy was the third fastest growing of 2017 [1]. However, inadequate infrastructure and unreliable power supply constrain growth and access to affordable energy services. Not only does poor power supply create commercial losses that dampen national revenue earnings, but about a third of the population remains without electricity access [2]. Bangladesh has relied on its vast domestic natural gas reserve as a predominant energy source since the 1970s but the rapidly depleting supply is proving insufficient to meet growing energy demand (World Bank, 2011).

In 2016, Bangladesh joined the Climate Vulnerable Forum in striving to meet 100% domestic renewable energy needs as rapidly as possible [3]. But in sharp contrast to the remarkable success of its domestic off-grid Solar Home System (SHS) program, with about 4.5

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million SHS installations generating over 200 MW of electricity [4], Bangladesh's development and operation of utility-scale renewable energy is actually very limited. In fact, to address its depleting domestic natural gas reserve (World Bank, 2011), 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, which will result in increased reliance on imported coal and liquified natural gas. The Rampal Power Plant for instance – a 1.3 GW coal power plant scheduled to begin operations by 2021 – is a partnership between the Bangladesh Power Development Board and the Indian state-owned National Thermal Power Corporation. The plant is facing fierce local and international opposition, with calls from UN experts to halt development [5].

Although clean and decentralized energy resources could be promising options for meeting growing electricity demand given their recent steep reductions in costs (e.g. [6]), Bangladesh and other developing countries in Asia such as India, Indonesia, Malaysia, Thailand, and Vietnam are expanding coal- and gas-fired generation, due to relatively low costs and stable supply of fossil fuels [7,2,8]. Energy choices have significant impact on environmental and energy justice, public health, and food security [5]. Inadequate geospatial and economic information on clean energy resources is one of the significant barriers to policy makers in developing countries considering socially equitable, environmentally friendly and cost-effective energy planning and development.

Alongside assessments of theoretical or technical renewable energy potential, data on other criteria needed to assess viability of energy projects are lacking – such as the economic valuation of high-quality renewable resources or transmission and road infrastructure costs. Equally critical but less commonly included in long-term energy planning frameworks is the role on land-use conflicts, such as proximity to or overlap with environmentally sensitive areas, population density and competition for land for food production. Land-use impact data is often lacking, as is the case in Bangladesh, presenting a major challenge to balanced decisions on large-scale grid-connected energy development.

An essential effort to assess renewable energy potential in Bangladesh was conducted by Mondal and Denich [9]. They conducted the first GIS-based assessment of technological potential of renewable energy resources in Bangladesh. They estimated the technical potential of grid-connected solar PV, wind, biomass, and small hydroelectric power as approximately 50 GW and 4.6 GW, 0.57 GW, 0.13 GW, respectively (we present further relevant literature below). However, an economic assessment of renewable energy potential has not been conducted in Bangladesh, especially one that considers critical land-use conflicts such as competition with food production, or the encroachment on ecological sensitive areas such as the Sunderbans.

Our study fills this gap, using new methods to analyze the cost and availability of potential alternative energy generation technology mixes in Bangladesh. We develop a method to apply and refine filters on land-use conflict. We take a detailed look at conflicts with food production in a particularly people-dense nation and explore opportunities for decentralization of generation to minimize the conflicts. We explore both domestic and international energy supply options given the close Bangladesh-India energy cooperation. To do this we employ and extend the MapRE spatial model designed by Wu et al. [10] using locally specific data to first identify and value high quality solar photovoltaic (PV), concentrating solar power (CSP), and wind resources across Bangladesh through a geospatial multi-criteria planning approach. We also assess potential for decentralized generation – specifically rooftop solar PV potential in urban and built-up areas. These results then support the prioritization of areas for energy development according to siting factors such as the levelized cost of electricity (LCOE), cost of transmission and ease of road access. Like-cells are aggregated into potential suitable project areas providing economic estimates of alternative energy technology potential for Bangladesh and identifying high-priority investment areas. We apply land-use discount factors to these areas, identifying those lands that present the least conflict and explore the trade-offs between them across key decision-making factors.

Thus, this work provides an interdisciplinary but quantitative assessment of high-quality renewable energy resources for grid integration, based on techno-economic criteria and generation profiles as well as social, environmental and economic impacts. Given its industry-recognized experience with distributed renewable energy, 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.

More broadly, however, this study opens a new intellectual line of inquiry to explore the impacts on emerging power systems of large-scale shifts to clean energy with high-resolution data and modeling tools. This is a surprisingly under-explored area of research, often because poor and emerging economies are rarely studied with high-resolution data or advanced energy planning tools. Our recent work on the Bornean, Kenyan and Nicaraguan energy systems [11,12,13] raised important issues about the roles of carbon pricing, demand-side energy management, and the role of energy storage as surprisingly important elements of power-sector management in emerging economies. In keeping with these recent studies, this work on Bangladesh raises important and largely unexplored issues of high penetration of renewable energy in areas with both high population densities and pressure to preserve farm land for agricultural sustainability. With the 2018 publication of the IPCC 1.5 degree report [14] the challenges of climate and local sustainability are becoming increasingly central to both academic and practical studies of decarbonized economies. This paper advances that dialog. We offer an effective yet user-friendly method for directly exploring land-use impacts of energy infrastructure development and the opportunities for minimizing or mitigating impacts. This is relevant given the lack of such data and analysis available for public consumption especially in emerging markets, and it is timely given the current discussion around alternatives to coal power in Bangladesh specifically. We advance a publicly available geospatial tool and use only publicly available data to directly address the need for more accessible information and to ensure a reproducible and transferable method that is useful even in data-limited contexts.

2. Relevant literature

South Asian countries, including Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka, have extremely high population densities and limited land resources. South Asia has approximately one-fourth of the world population in 3% of the world's land [1], resulting in one of the lowest cultivated land to person ratios in the world, estimated at 0.12 ha per capita [15]. With its rapid economic development and electrification, the energy demand in the South Asia will grow at more than doubled the world average rate over the coming decades [2]. As a result, there is an escalating competition for land resources to supply sufficient energy, food, and water in the region (e.g. [16]). Because water, energy, and food (WEF) resources are interconnected, integrated policy and planning is critical [16].

Increasing electricity demand inevitably requires more land inputs for mining, transportation, storage, processing, and distribution regardless of the energy type, and the distributional politics of developing energy infrastructure needs to be examined [5]. As such, there is a rapidly growing body of energy justice literature, exploring the politics of energy infrastructures and energy poverty [17,18]. More regionally, new literature explores the impacts of solar power projects in India [19] and the relationship between coal-fired power plants and climate change adaptation in Bangladesh [5,20]. Exclusionary capture of lands is a major concern in Bangladesh, where the inequality in land ownership and land grabbing have been a long-term issue with significant impact on decision-making [21,20]. Informed, representative and participatory energy planning and decision-making processes grounded in publicly available information are therefore critical.

However, publicly available literature on the costs, benefits and trade-offs of energy capacity expansion options is often quite limited, especially for emerging markets outside of India and China. In recent years, Geographic Information Systems (GIS) has been widely applied to the assessment of renewable energy potential, because of the spatial distribution of renewable resources and the dependence of costs and other important criteria on spatial attributes. There is no single classification of renewable energy potential but commonly used classifications are theoretical, technological (or technical), and economic potential (e.g. [22,23,24]). These are based on the restrictions being applied. For instance, theoretical potential is the highest potential that considers natural and climatic restrictions; technical potential further incorporates technical limitations such as conversion efficiency; and economic potential limits the technical potential with cost information of the technology and competitors. In addition, the GIS- based approach is often combined with multi-criteria decision methods (MCDM) to further rank the identified potential of each renewable energy technology based on additional criteria, such as using the Analytic Hierarchy Process (AHP) method (e.g. [25]).

Most studies on renewable energy potential focus on single technologies at local scale in developed countries [24,26,27,28,29,30,31]. Some economic potential renewable energy studies have emerged, including assessments of offshore wind potential in UK [32], onshore wind power potential in India [33], and small-scale solar power in western China [34]. Except for the study on the UK's offshore wind, however, economic analyses do not usually include costs associated with transmission and road construction, which could be significant when constructing remote solar or wind farms. GIS-based spatial assessments of renewable energy potential are particularly limited in South Asia and primarily focus on technical potential. Some examples of studies of technical potential in South and South-East Asia include assessments of solar energy and biomass residues in ASEAN countries [35,36], onshore wind power potential in India [37], PV, onshore wind and offshore wind in India [33,37,38], utility scale solar power in Pakistan [39], Vietnam [40], and Malaysia Penninsla [41], residential solar PV potential in Sri Lanka [42], residential solar power and wind power potential in Thailand [43,44].

Therefore, although literature on economic renewable energy potential with cost information is growing as explained above, economic RE potential studies for emerging markets are still limited. Considering that more than half of the investment in electricity generation capacity until 2035 is expected to occur in non-OECD countries with electricity demand increasing and most of them are fossil fuel generation (IEA, 2014), information on economic RE potential for national power systems planning is critical to avoid unnecessary "lock-in" to fossil-fuel based electric power systems. Some of the few examples of economic potential studies for developing countries are Wu et al. [10,45] and [33] which evaluated the economic potential of solar and wind energy in African countries and that of wind energy in India, respectively. However Bangladesh still lacks publicly available renewable energy assessments due to data availability [46]. Bangladesh Government's SREDA and World Bank estimated the technical potential of utility scale solar and wind power in Bangladesh as 2.0 GW and 1.25 GW, considerably smaller than its demand increase, due to land availability and metrological conditions [47,48].

3. Data and methodology

The Multicriteria Analysis for Planning Renewable Energy (MapRE) tool was developed by Wu et al. [10] 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 employ this model, using a combination of global and country-specific datasets, which can be categorized into 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). Data sources are detailed in the supplemental information.

Using MapRE we first apply exclusion thresholds and buffer distances cited in previous studies to map data for Bangladesh, thereby identifying suitable areas for renewable energy development (stage 1). We adapt the method to also include an assessment of rooftop solar PV potential in urban and built-up areas by relaxing exclusion thresholds under certain scenarios. MapRE then divides the identified suitable areas into 5×5 km spatial grids, called "Project Opportunity Areas (POAs)" (stage 2). We estimate site selection criteria values for each project opportunity area (stage 3), where site selection criteria include elevation; population density; resource quality; distance to nearest transmission line, substation, road, and surface water body; land cover type; and total land area. These criteria are used to calculate annual electricity generation and levelized cost of electricity (LCOE) values for each project opportunity area. LCOE describes the average cost of electricity for every unit of electricity generated over the lifetime of a project at the point of interconnection.

We then further extend the method by adding key selection criteria to explore land-use conflicts, and by comparing the influence of key investment criteria though testing robustness of fit. More specifically, we apply land-use discount factors to each project opportunity area. 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. Land-use discount factors are determined from high resolution data or through on-the-ground surveys. In the absence of such data for Bangladesh we analyze and report on sensitivity to a range of factors. Based on previous studies (e.g. [49,45,10]) it was assumed that for solar PV and CSP 10% of POAs that are primarily non-cropland could be developed and for wind 25% of the screened area could be developable. On the other hand, we assumed 1% to 10% of POAs that are primarily cropland could be developed in project opportunity areas and examined the trade-off between land-use for clean energy and agricultural production.

We also conduct extensive sensitivity analysis to examine the robustness of results across key parameters, including technological parameters like fixed and variable costs, which can be specific to local markets. We use available literature where available (see supplemental information) and compare the results on technology potential and cost across a spectrum of assumptions for key parameters: elevation, population density, and capital costs, in addition to land-use discount factors in areas that are primarily cropland. All parameters used and tested in this study are summarized in the supplemental data. Finally, we also extend the method to explore investment opportunities beyond utility-scale clean energy projects – as a point of comparison we estimated the magnitude of rooftop solar PV generation potential and LCOE by assuming 1% to 10% of the urban and built-up areas can be developed for residential roof-top PV.

4. The Bangladesh case study

Bangladesh's economy has dramatically expanded in the past decade with an average annual growth rate of 13% [48]. Electricity is considered one of the most crucial inputs for development, so to address its rapidly growing demand, the Bangladesh Government expanded the country's total installed capacity from 5166 MW in 2008–2009 to 16,070 MW as of November 2017 including off-grid renewable energy [4]. 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 Bangladesh 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 [48].

The current electricity market of Bangladesh is unbundled after major market reforms since 1990s. Approximately half of electricity is supplied by Independent Power Producers (IPPs) [50]. Although generation and retail sectors are deregulated, the Bangladesh Government subsidize both IPPs and retail companies to make electricity price affordable [51]. On the other hand, Power Grid Company of Bangladesh (PGCB) owns and operate 100% of national grid under the supervision of the Bangladesh Government.

The current generation mix is heavily dependent on natural gas due to the abundant local reserve and affordable costs of domestic natural gas. However, the formerly vast reserve is depleting at a rapid rate [52]. Natural gas accounts for 53.1% (8530 MW) of total capacity, followed by furnace oil (17.4%: 2629 MW), diesel (7.0%: 1028 MW), and power import (4.1%: 660 MW). In terms of generation, natural gas generates 35,822 GWh (68.6%). The rest is generated by furnace oil (8673 GWh. 16.6%), power imports (3822 GWh. 7.3%), diesel (2067 GWh. 4.0%), hydropower (962 GWh. 1.9%) and coal (847 GWh. 1.6%).

Renewable energy generation capacity in Bangladesh is 478.50 MW (3.0% of total installed capacity) as of November 2017, with 245.85 MW on-grid (1.5%) and 232.65 MW off-grid (1.5%). In addition to 230 MW on-grid hydropower, the on-grid capacity of solar PV and wind are 14.95 MW (0.1%) and 0.90 MW (0.006%), respectively. The off-grid capacity of solar PV, wind, biogas to electricity, and biomass to electricity are 229.57 MW (1.4%), 2 MW (0.1%), 0.68 MW (0.004%), and 0.40 MW (0.002%) [4]. The average cost of electricity from grid ("average bulk electricity supply cost"), which is the In the generation cost of BPDB's own plant and Electricity purchase from other sources, is 5.66 Tk/kWh (6.7 cents/kWh, or 67 USD/MWh) in the FY2016-2017 [50]. Transmission and distribution have also been steadily expanded to deliver electricity to more residential, commercial, and industrial end users. 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 (ibid).

The Bangladesh Government plans to further increase its generation capacity from 12,365 MW in 2015–2016 to 24,000 MW in 2021 to 39,000 MW in 2030 [48] with imported coal and natural gas playing a critical role. Although coal-fired power plants currently contribute to a fraction of total generation and capacity as stated above, 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 to address the surge of electricity demand and reduce its reliance on natural gas from 53.1% in 2017 to 35% in 2030 (Power System Master Plan 2016). The Bangladesh Power Development Board is in fact currently in a joint venture partnership with India's state owned National Thermal Power Corporation to build a proposed 1320 MW coal-fired power station over 1800 acres of land situated 14 km north of the Sundarbans – the world's largest mangrove forest, globally critical biodiversity hotspot and UNESCO world heritage site [53]. This comes even though the Renewable Energy Policy of 2008 obligates the renewable energy share to be 10% by 2020 [54]. Our study thus explores physically and technically feasible renewable energy investment opportunities in Bangladesh, contributing critical yet missing information to discussions on alternatives for energy planning.

5. Results

5.1. Resource quality and generation potential in project opportunity areas (POAs)

Here we present on results of our analysis. Project opportunity areas (POAs) are identified and summarized in Fig. 1a–c. As shown in Fig. 1a and b, Solar PV and CSP resources are widely available across the country. Particularly high-quality solar resources are located in the rural, less populated northern part of the country in Rangpur, Rajshani, Mymensingh, and Sylhet. On the other hand, as shown in Fig. 1c, wind resource is available only in Sylhet and Chittagong. Our analysis finds that more than 99% of the resource area of solar PV and CSP and 100% of wind resource area are in areas that are primarily cropland according to MODIS classification (NASA). This suggests that for large scale clean energy integration in Bangladesh, careful targeting of non-cropland areas within POAs will be critical – especially those POAs that are primarily cropland. We discuss implications in Section 5.

Annual generation potential and capacity of solar PV, CSP, and wind are summarized in Table 1. The annual generation potential in project opportunity areas for solar PV, CSP with and without 6-h 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-h storage, and wind are approximately 5.3–53 GW, 3.0–30 GW, 5.3–53 GW, and 0.57 GW, 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 can be developed in each POA.

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. Fig. 2 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 India, which is 1.56 USD/Wp in 2016 [55], weighted average generation LCOE is calculated as 130 USD/MWh.

While rooftop PV could play a critical role in swift electrification of distant, rural areas, Table 1 shows that the size of generation potential by rooftop PV is relatively small and costlier than utility-scale solar PV. However, rooftop solar PV could serve a different purpose than utility-scale PV: it can be a point-of-use energy source. Rooftop solar PV can be quickly installed (in less than one week); can flexibly meet the required demand 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 multiple consumers. For rural areas with no current electrical infrastructure, the costs of developing and maintaining a distribution grid needs to be considered when comparing the costs of the rooftop solar PV and utility-scale solar or other energy options. For more accurate estimation of rooftop solar PV potential, image recognition techniques are necessary, which was beyond the scope of this study.

5.2. Distribution of generation potential and levelized cost of electricity

Fig. 3 summarizes the results of LCOE of solar PV, CSP with and without 6-h storage and wind using resource quality in project opportunity areas, distance to nearest transmission line or substation, and the nearest road. Table 3 summarizes the distribution of LCOE. The LCOE of solar PV is 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 respectively. LCOE of CSP with 6-h thermal storage is 237–300 USD/MWh, the most expensive among all the options. As a reference, average electricity cost from grid is currently 5.55 Tk/kWh (68 USD/MWh). Total LCOE is largely determined by the generation costs. The average contribution of transmission and road construction to total LCOE for solar PV, CSP, and wind is 8.5%, 2.8% and 7.0% respectively.

Fig. 4 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

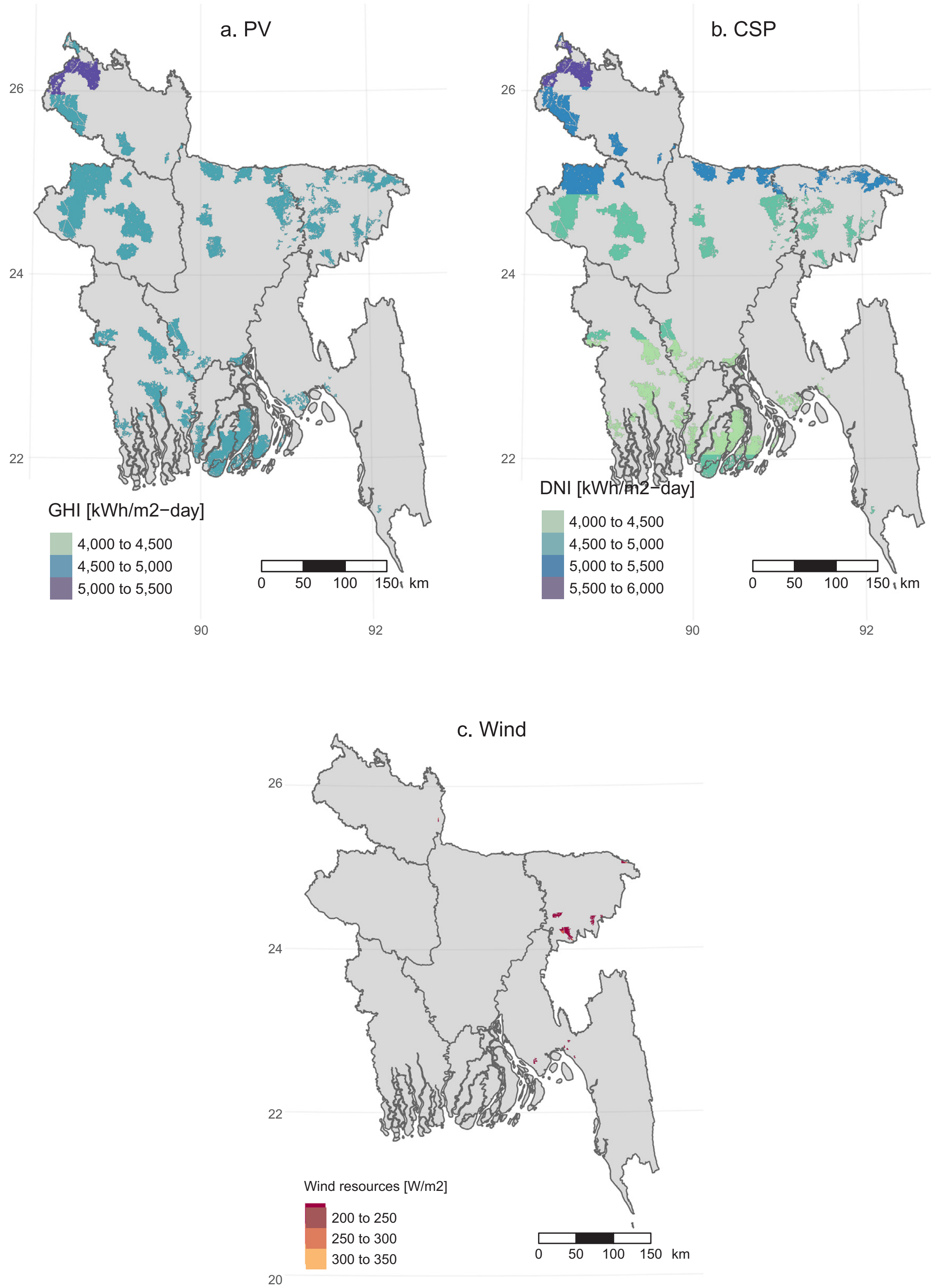

Fig. 1. Global horizontal irradiance (GHI) of solar PV resource areas (project opportunity areas) in Bangladesh. Low quality resource areas and environmentally/socially unsuitable areas are already excluded by applying exclusion thresholds listed in supplemental information.

shows LCOE. The area under the LCOE curve represents total cost of electricity. Solar PV has the cheapest LCOE across all technologies. The 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 be rapidly deployed to closely match load. Installation takes 6–12 months and is not labor intensive [56]. 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 over- lap with that of solar PV.

The weighted average LCOE of CSP with 6-h thermal storage is 267

Table 1
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% 5% 10%	–	9.4 42 84	5.3 26 53	169 (0.1%) 864 (0.6%) 1,690 (1.2%)	91
CSP without storage	1% 5% 10%	–	17.3 86.7 173	5.3 26.4 53	169 (0.1%) 864 (0.6%) 1,690 (1.2%)	143
CSP with 6-h storage	1% 5% 10%	–	9.8 49 98	3.0 14.3 30	169 (0.1%) 864 (0.6%) 1,690 (1.2%)	267
Wind	–	–	1.65	0.57	–	106
Rooftop solar PV	–	1% 5% 10%	0.32 1.6 13	0.20 1.0 2.0		244 (generation)
Peak demand & capacity installed in 2016	–	–	61.7	9.0 (demand) 12.3 (capacity)	–	Total: 68 Hydro: 14 Gas: 28 Coal: 110 HFO: 237 Diesel: 472
Projected demand & planned capacity in 2016	–	–	–	34 (demand) 39 (capacity)		

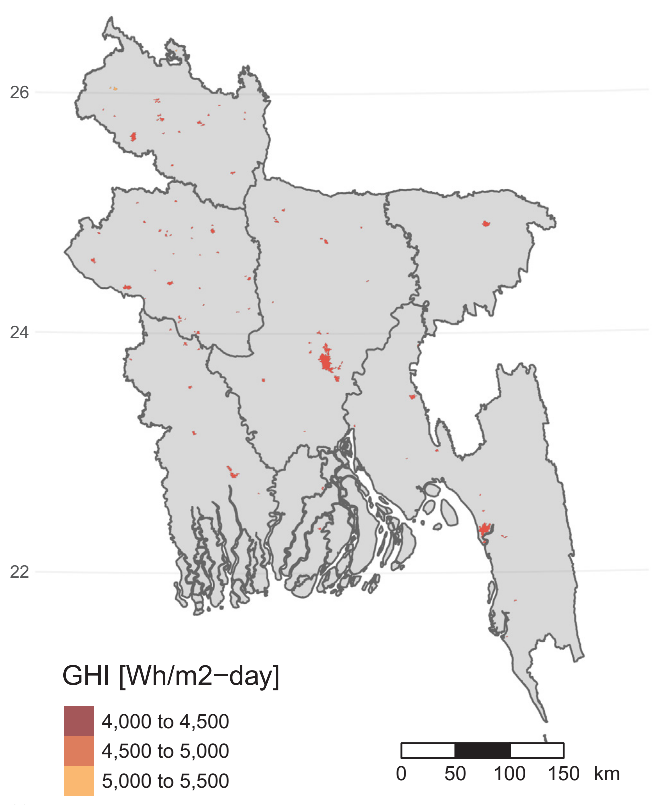

Fig. 2. Global horizontal irradiance (GHI) of urban and built-up areas in Bangladesh.

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 spikes in CSP's LCOE that are mainly due to resource quality, DNI, being low in the southern part of the country (see Fig. 1b). As a result, the LCOE of CSP is 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 involves high maintenance costs and a large trained workforce to manage the plant. 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 feasible and therefore important option, in terms of both generation potential and costs.

In addition, we also conducted sensitivity analysis on these results, testing the impact of assumptions and exclusion thresholds related to elevation and population density to understand the robustness of results (see supplemental information). We find that solar PV and CSP potential are sensitive to elevation and population density as exclusion criteria. Though low elevation areas are excluded for the risk of flooding, the effects of flooding can be mitigated with the appropriate system design of solar PV.

These results suggest 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 2. According to the report, renewable energy potential in Bangladesh was as follows: PV 2 TWh/year (2.4% of this study's estimate), Wind 1.25 TWh/year (76% of this study's estimate), and no CSP potential (this study's estimate is 98 TWh/year with 6-h storage) [48], under assumption that 10% of cropland POAs of PV/CSP and 25% of POAs of wind are developed. The largest difference between that report and ours is the availability of land for renewable resources. IEEFA [57] also found the Government's study to have overly conservative assumptions about land availability.

6. Discussion

6.1. Implications of crop-land conversion

For Bangladesh, because most POAs are in primarily cropland area, research at the local scale is needed to identify non-cropland areas within these POAs for possible renewable energy development. As shown in Table 1, if a maximum of 1% of land in POAs (169 km^2) is

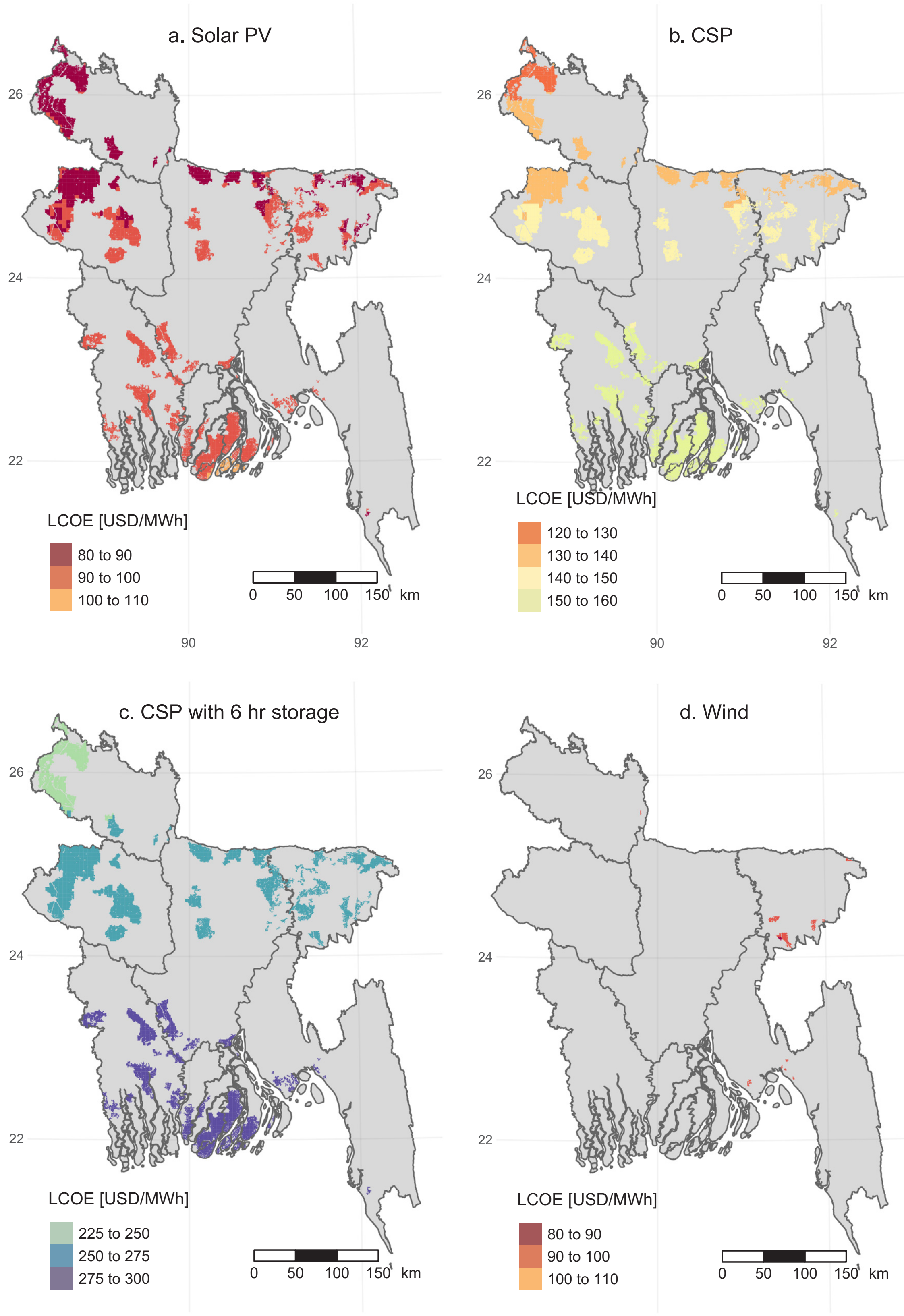

Fig. 3. Average total levelized cost of electricity (LCOE) estimated using resource quality, distance to nearest transmission line or substation, and the nearest road.

converted to solar PV farms, it could provide as much as 5.3 GW additional generation capacity. In fact, only 0.3% of these POAs (53 km^2, or 0.036% of total Bangladesh land area (147,610 km^2), is necessary to meet its 1.7 GW solar PV target for 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 by 2030.

The required annual conversion rates of land for solar PV farm to reach 244 km^2 in 2030, are 19 km^2/year from 2017 to 2030. This

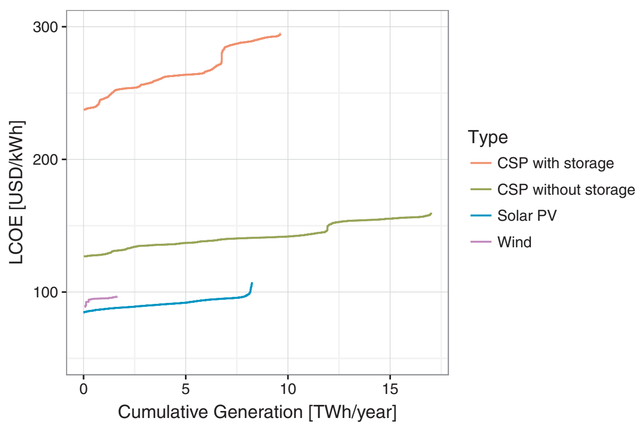

Fig. 4. Supply curve (LCOE curve) of renewable energy generation. Supply curves show the cumulative potential of all solar PV, wind, and CSP. Project opportunity areas are sorted by LCOE.

annual conversion rate is equivalent to 3% of the current average annual decrease in cropland area in Bangladesh, which was 688 km^2 per year between 2000 and 2010 [58]. Cropland in Bangladesh has been steadily been degraded or converted to non-agricultural land for industrial use and for rural and urban settlements. Croplands accounted for 67.38% (94,395 km^2) of total land in 1976 and decreased to 60.04% (87,519 km^2) in 2010 at annual reduction rate of 0.75% between 2000 and 2010. On the other hand, rural settlement and urban and industrial area increased from 14,580 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 those lands with little to no agricultural productivity within the identified suitable project areas. Because agriculture is ubiquitous across the country (e.g. [59], selecting land with low agricultural productivity for renewable energy projects is therefore important to reduce impacts on farmers and food security. Furthermore, while conventional solar PV farms can occupy sizable area, 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 [60,61]. Large solar PV farms are also now being installed over fish farms, avoiding land-use conflicts altogether (e.g. [62]). Assessing locally appropriate PV system designs is another area for further local research.

When considering the land areas that would be required for renewable energy development, it is important to remember that thermal power plants land footprint also comprises other land areas for ports, terminals, fuel storage areas, mining and ash yards. These require substantial additional land and place environmental stress on surface water, groundwater, local soils, and air pollution 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 [63]. For example, the proposed Maitree Power Plant near Rampal, with 1.32 GW capacity, will use 1834 acres of land, which is equal to 7.4 km^2. Furthermore, depending on the mine location, type of coal, and mining technology, the 30 year life time land use requirements for coal have been shown to exceed that of solar PV [64].

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 from 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 [65]. Moreover, as mentioned, renewable energy development could support electrification of rural areas and economic development of the country, further mitigating land degradation. Bangladesh's degraded land area was 68,422 km^2 (47.52% of total land) between 1981 and 2003 [52]. Studies suggest that renewable energy development and rural electrification could curb deforestation for cooking fuel biomass [66], however further local study is needed to understand adoption behavior and substitution effects.

6.2. Implications of the falling costs of renewable energy

As shown in Table 3 and Fig. 4, solar PV is the cheapest electricity source among all the renewable energy technologies assessed in this study given our set of assumptions. Due to lack of experience with utility-scale renewable energy projects in Bangladesh, the capital costs may be higher than the referenced capital costs (i.e. negative reduction percentage in Fig. 5) at early stages of deployment. However, because the costs of those technologies have been rapidly falling globally (e.g. [6], costs are still 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. [67]).

Sensitivity analysis of the weighted average LCOE to capital costs was conducted (see Fig. 5). Initial capital costs of solar PV, CSP, and wind changed +20% and −40% from the default value. As shown in Fig. 5, solar PV is consistently the cheapest technology within the capital cost ranges. The current per unit generation cost in Bangladesh is currently 5.66 Tk/kWh (67 USD/MWh) in 2016–2017 [50] and thus the LCOE of solar PV is still not comparable. Nevertheless, the average

Table 2
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. 2.4 GW) 20% in 2030 (i.e. 7.8 GW)
Power System Master Plan 2016 Final Report	2 (solar PV) 1.25 (wind)	1.4 (solar PV) 0.637 (wind)
IEEFA [57] estimate for 2024–2025	17.52 (utility-scale solar) 0.48 (wind)	10 (solar PV) 0.30 (wind)
Mondal & Islam [74]	–	50 (solar PV) 4.6 (wind) 0.57 (biomass) 0.13 (small hydro)
Noor & Muneer [75]	–	0.1 GW by CSP
Expected participation by public sector (Government estimation)	–	0.235 GW by wind

Table 3
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 PV [TWh]	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

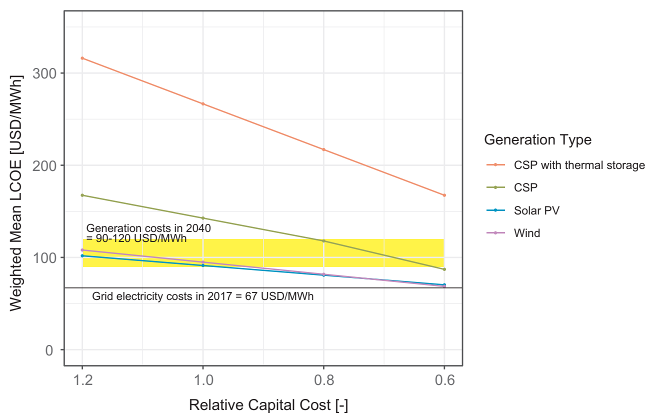

Fig. 5. Relationship between weighted average LCOE and reduction in capital costs of solar PV, CSP, and wind.

generation cost for Bangladesh is expected to rise to 90–120 USD/MWh range by 2040 due to increasing fuel costs of foreign coal and gas [68].

Innovation and economies of scale will reduce the costs of renewable technologies to levels comparable with grid electricity costs in the 2020 and 2030 horizon, given falling LCOE of utility- scale solar PV globally and given the long-term trend of increasing fuel costs. The module price for solar PV has fallen 80% since 2010 [6] and the US Department of Energy set new targets to further reduce the costs of module price, balance of system hardware, and soft costs of utility solar PV by 43% [69]. Thus a 40% reduction of capital costs for utility solar PV is well within reach.

6.3. Implications of high solar PV penetration

We compute daily load profiles and load duration curves for Bangladesh and find that peak generation from solar PV does not coincide with the peak demand hours. As shown in Fig. 6, the top 3 h of demand concentrate between 5 pm and 11 pm [48]. A significant gap exists between peak solar PV generation (around noon) and peak demand. As shown in Fig. 7, 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 grid flexibility to fully utilize the vast solar energy potential while avoiding substantial curtailment.

Experience in California and other western states in the United States show that mechanisms such as flexible conventional generation, interconnected transmission network, load-shifting, and other sources of grid flexibility can be deployed to accommodate as much as 15–20% of variable renewable energy (VRE) generation [70]. Furthermore, the cost of lithium-ion batteries is rapidly decreasing and cost reductions are expected to continue up to 2030 [71]. Though not explicitly required in the Government's 2030 renewable energy target of 7.8 GW, flexibility services and energy storage may be an important

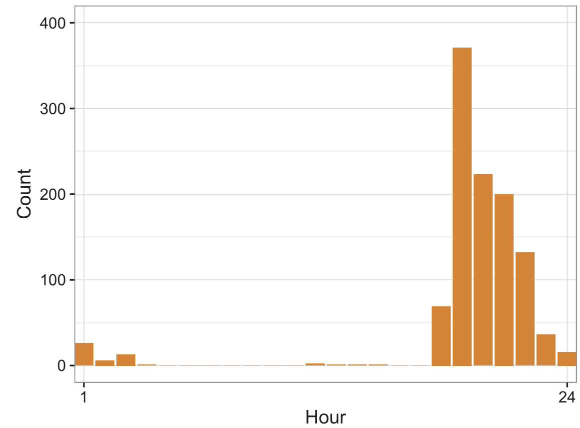

Fig. 6. Hourly demand histogram for the top 3 h of demand hours per day in Bangladesh in 2016 (calculated from hourly demand data from PGCB website).

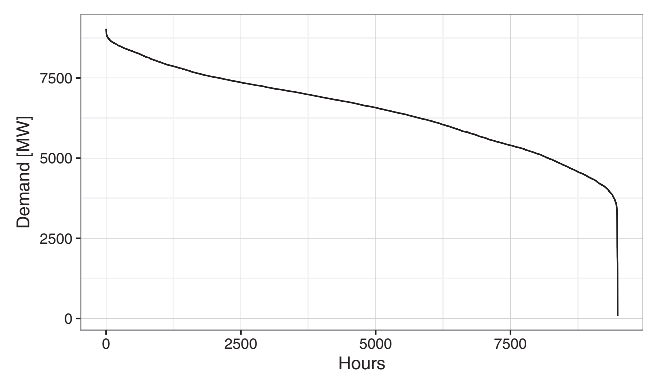

Fig. 7. Annual load duration curve of Bangladesh in 2016 [48].

consideration for further study.

Lastly, CSP with thermal storage enables greater penetration of solar PV [72]. CSP is relatively new technology to Asia and still expensive, as shown in Table 3 and Fig. 4. However, development of CSP projects are planned in the coming years in China and India. China plans to install 5 GW CSP capacity by 2020, some of which is already under construction [73]. However Fig. 5 shows that even a 40% decrease in capital costs of CSP with 6-h storage is not sufficient to compete with conventional energy sources and solar PV. CSP with thermal storage will not be cost effective for Bangladesh without very dramatic cost reductions.

7. Conclusions

There is an intense debate currently taking place regarding the energy future in Bangladesh and its social, ecological and environmental implications – both locally and for the global commons. The 1.3 GW Rampal Power Plant scheduled to begin operations by 2021 is facing fierce local and international opposition, with calls from UN experts to halt development. Despite the global ramifications of such development there are less than a handful of studies on the potential for utility scale energy alternatives in Bangladesh. Our study provides much needed statistics on the potential for renewable energy resources in country; demonstrates the cost effectiveness and land- use trade-offs of these clean energy solutions for Bangladesh; and specifically identifies high-priority zones for alternative energy investment to fill data gaps for government planners, communities and potential investors.

We have identified and 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 trans- mission connection and road access. We find that there is vast solar energy potential with costs competitive with the electricity generation costs in the 2020 and 2030 horizon, given falling LCOE of solar PV and the increasing long-term trend of fuel costs. The annual generation potential and capacity are approximately 8.4–84 TWh/year and 5.3–53 GW for solar PV; 9.8–98 TWh/year and 3.0–30 GW for CSP with 6-h storage; 17.3–173 TWh/year and 5.3–53 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 can be developed in each POA. Solar PV is the most important option in terms of costs and generation potential among all options studied.

Because of the widespread nature of agricultural activity in Bangladesh, further research at the local scale is needed to identify non-cropland areas (such as degraded areas) within these POAs for possible renewable energy development. Our study finds the necessary land for PV is just a fraction of the country's total land, and a small fraction of ongoing agricultural land conversion rates. If 1% of land in POAs is converted to utility solar PV, it would equate 5.3 GW of generation potential. Put another way, only 0.3% of POAs, or 0.036% of total Bangladesh land, is necessary to meet a 1.7 GW solar PV target by 2021. Likewise, 1.1% of POAs, which is 0.17% of total Bangladesh land, is needed to meet a 7.8 GW solar PV target in 2030.

Our extension of geospatial methods shows that by overlaying finer scale agricultural productivity data with opportunity layer maps, such as those produced by our study, planners can minimize impacts of energy infrastructure development on farming and food security. Public participation in project planning is key, along with free, prior and informed consent of indigenous communities. Furthermore, we find that solar PV generation does not align with Bangladesh's average daily load profile, and as such options for increased grid flexibility and storage should be explored. Our study employs and advances geospatial planning methods providing key results which can help stakeholders understand, weight and compare the trade-offs of various energy development paths for Bangladesh. This demonstrates a simple yet effective method to support decision-making in the face of competing factors and limited data availability that is reproducible and highly transferable to other contexts of energy planning and development.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2018.10.123.

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