WPS8517

Policy Research Working Paper 8517

Integrating Variable Renewable Energy in the Bangladesh Power System

A Planning Analysis

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WORLD BANK GROUP
Energy and Extractives Global Practice
July 2018

Policy Research Working Paper 8517

Abstract

Integration of large-scale variable renewable energy (VRE) generation resources—wind and solar—into national grids has been gaining importance as costs of these technologies, especially that of solar, continues to fall rapidly. However, there continues to be a lack of a framework to systematically analyze the role played by large-scale VRE integration for most developing countries. This study develops such a framework and applies it to analyze VRE policies in Bangladesh. The study uses a least-cost planning approach to assess the volume of solar and wind that can technically and economically be integrated in the power system, accounting for spinning reserve generation capacity requirements and adequacy of transmission capacity. The study shows that solar and wind can provide a significant share of the 13 to 21 GW of new capacity needed by 2025 to meet rapidly growing electricity demand, although most of it does not pass the cost/benefit test in the near term till 2022. Efforts are also required to cope with what otherwise would be a large and costly increase in on-demand ("spinning") reserve capacity. The analysis demonstrates how an investment strategy to cover peak demand, and prudent changes in system operational practices, allow for the system to provide the needed reserve capacity without a prohibitive increase in system costs. In addition, the study examines the adequacy of transmission capacity for the first large-scale solar and wind project in Bangladesh.

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Integrating Variable Renewable Energy in the Bangladesh Power System: A Planning Analysis [1]

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JEL classification numbers: **C61,Q41, Q47**

Key words: Electricity system. Renewable energy. Power system planning. Bangladesh.

[1] The authors acknowledge with gratitude support for the project from the Korea Green Growth Trust Fund and the NDC Partnership. The authors acknowledge the review of the paper by Silvia Martinez Romero (ESMAP VRE Integration) and Professor Jong-bae Park (Konkuk University, South Korea). Responsibility for the content of the paper is the authors' alone.

Introduction

Integration of large-scale "variable" renewable energy (VRE) generation resources – wind and solar – into national grids has become an interest in many developing countries. A significant drop in investment costs of these technologies, their ability to reduce reliance on imported fuels, and the lack of emissions of either local air pollutants of carbon dioxide – all contribute to their continued uptake. A significant volume of work on renewables has been carried out over the last 20 years, especially since 2012 when large-scale grid-connected solar and wind began to ramp up quickly in many countries around the world. NREL's *Renewables Future Study* (NREL, 2012) was one the first studies in this recent body of work, and it laid the foundation for much of the analysis done subsequently. Mills and Wiser (2012) and Madrigal and Stoft (2012) focused in more specific detail on generation and transmission planning aspects, respectively.

A large number of studies that have been done over the past 20 years may be categorized as follows:

1. Simple "back-of-the-envelope" approaches that rely on comparison of levelized cost of electricity (LCOE) or auction prices more recently, of VRE and non-renewables. Ueckerdt et al (2013) discusses a number of these studies and the pitfalls of such an approach in failing to capture the variable nature of renewable resources;

2. Highly detailed production costing (e.g., Olsen et al, 2013) and load flow studies (e.g., O'Sullivan et al, 2014) that look at generation and transmission system operational aspects, respectively; and

3. Planning models of various vintages from WASP-IV that had its beginning in the seventies (e.g., Botswana Study, 2009) to modern tools like PLEXOS (e.g., IRENA 2016 presentation in Namibia and ECA 2017 study for South African Power Pool).

Many LCOE studies have been undertaken to assess various policies and investment decisions. While the LCOE approach focuses on the economics of renewables, it ignores practically all the technical aspects that are important in power system planning. The second category of more technically focused studies, on the other hand, are completely devoid of economics and are essentially a "feasibility check" on a given power system plan, including those with a high share of VRE.[2] These studies do not provide insight as to how much renewables *should be* in the mix.

Studies in the third category consider economic and technical issues jointly. Least-cost planning studies, for example, consider VRE resources as part of the portfolio of generation resources (Blanford and Niemeyer, 2011). Key issues to address in these models are: (a) the level of detail that can realistically be modeled; and (b) coordination among a hierarchy of long- and short-term models. IRENA (2017) is an excellent review of these issues and the capabilities of existing models. There has also been a limited effort to link among these models. For instance, Diakov et al (2015) includes some features of dispatch in a capacity planning model. De Sisternes et al (2016) also make an effort to approximate hourly representation of load in a capacity planning model.

[2] Load/power flow and stability studies, for instance, check the ability of the transmission network to accommodate the generation from all sources including VRE without violating line flow and voltage limits, and the ability of the system to restore normal operation following loss of a major generator/line.

As indicated above, integration of renewables using a collection of planning and operational models is still incompletely understood, with efforts to address the challenge being made only in recent years. Applications of such an approach to examine capacity and operational decisions specifically focusing on VRE are even more limited. This is a major issue especially for developing countries where planning is generally weak. The technical challenges of VRE can be significant in developing country systems that typically have no mechanism to provide spinning (on-demand) reserve, and a weak transmission network.

In this study we build on previous dispatch and network analyses to assess the role that may be played by solar power in Bangladesh.[3] The emphasis in the analysis is to bring together the economics of solar and technical issues (namely variability of the resource, spinning reserve, transmission constraints), in both the long term and the short term. To illustrate the challenge for power sector planning in Bangladesh, there was a proposal to undertake a 500 MW solar project back in 2011, at a cost of $2.76 billion. Apart from being an expensive proposition for a country that was struggling to find good baseload generation options, analysis of past dispatch and spinning reserve practices showed that the lack of economic considerations in dispatch and shortage of spinning reserve during most peak hours pose a great challenge to accommodate large-scale grid-connected solar generation (Nikolakakis et al, 2016). A DIGSIELNT Australia (2016) study conducted for the World Bank also showed there are significant transmission constraints in the existing network. It is imperative that system planning incorporating renewables takes into consideration these constraints in a consistent way.

Context: Bangladesh's Power Sector

Generation

Electricity generation in Bangladesh reached 50 Tera Watt-hour (TWh) in 2016, with natural gas accounting for nearly 70% of the power supplied followed by oil (15%), coal (5%) and hydro (3%). Demand for power grew by 8% on average per year in the years between 2005 and 2015 (BPDB, 2016). Power demand growth mirrored a robust economic growth as real GDP (in constant US$) increased on average by 6.7% year-on-year over the same period (World Bank, 2017). To meet demand, the power generation capacity increased from 5 GW to nearly 11.5 GW over this period, mostly through investments in gas and oil-fired generation by the private sector. Bangladesh liberalized power generation in 2005, while the government-owned Bangladesh Power Development Board (BPDB) retained its dominance over transmission (76.25% ownership). The growth in generation came largely from investments by independent power producers who now provide 46% of the electricity generated (BPDB, 2017).

[3] The focus is on solar since wind resource quality is quite poor in the country.

Figure 1. Power generation capacity by fuel type

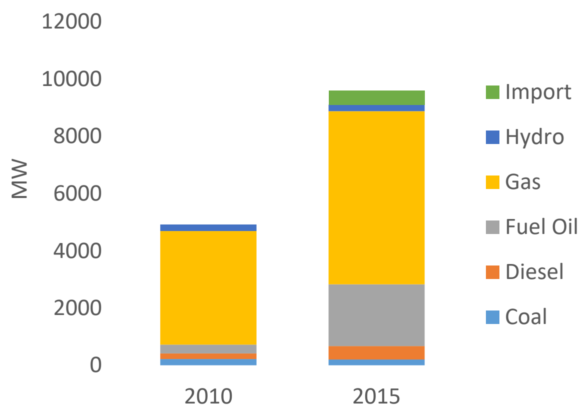
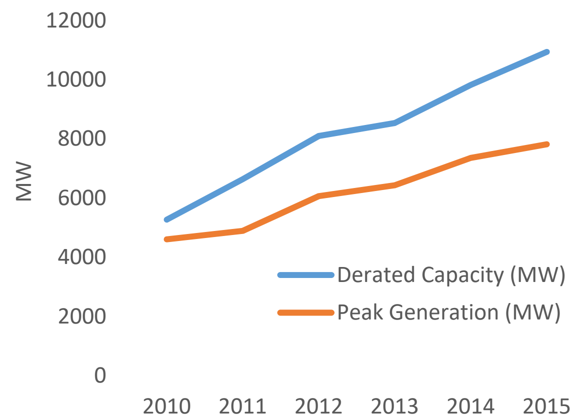


Figure 2. Capacity and hourly peak generation



Source: BPDB (2016)

Power policies now face a significant challenge in securing primary fuels for generation. The domestic gas sector has supplied all of the gas used by power plants from onshore gas fields. In the Gas Master Plan (Wood Mackenzie, 2006), combined production from these fields was projected to decline beginning in 2018 as new discoveries failed to meet growth in demand for gas and existing reserves were reaching production capacity. As a result, government policy now targets the import of coal, natural gas in the form of LNG, and power coming mainly from India. Bangladesh has no experience with importing coal or LNG as of 2017 and will have to develop the infrastructure needed to import these energy sources. Power imports from India began in 2013 with 500 MW capacity and has increased to 660 MW. Power import is poised to increase significantly over the coming years to potentially reach up to 3,000 MW in the medium term.

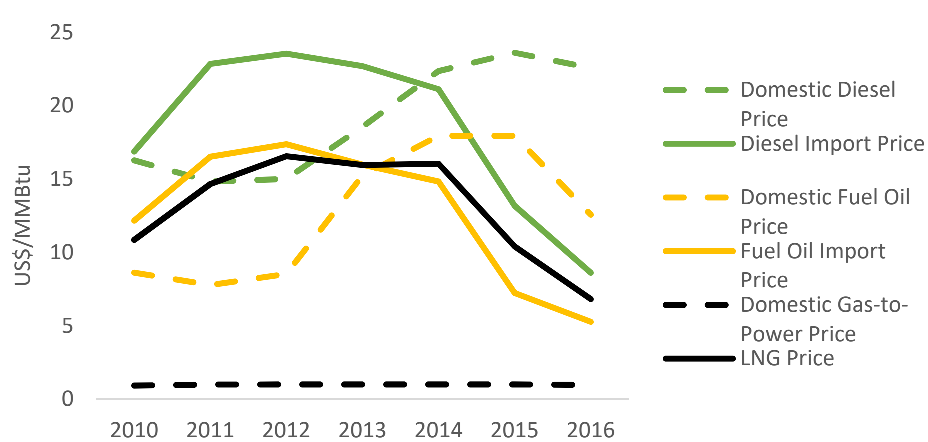
The Government of Bangladesh (GoB) envisages a dramatic increase in coal-fired generation to meet demand for base-load power. The latest projections by the Power System Master Plan (JICA, 2017) forecast coal generation capacity to reach 20 GW by 2041. A number of coal-fired projects are currently in different stages of planning. The Government agreed with India on a joint venture to build a 1,320 MW coal plant along with a coal import facility near Rampal, in the South-West of Bangladesh (Sharda and Buckley, 2016). Construction of the facility began in 2016 with concessional finance from the Export Import Bank of India. Further coal project developments are underway for the South-East and South-West regions with plans for three more coal plants each with capacity in excess of 1,200 MW. To address demand growth in the immediate future, the Government tendered 700 MW of fuel oil generation capacity to meet near-term demand growth for power, with plans to add a total of 1,000 MW of fuel oil generation capacity.[4]

The limited supply of gas forced the power sector to invest in oil-fired generation capacity and increase the imports of fuel oil. Fuel oil generation capacity grew from 300 MW in 2010 to 2,100 MW in 2015 (BPDB, 2016). The government regulates oil prices in Bangladesh, including the price of fuel oil, which largely reflected international prices as the country imports all of its oil from abroad. Between 2014 and

[4] The Financial Express. "BPDB selects sponsors for seven more IPPs", 2016. Source: http://www.thefinancialexpress-bd.com/2016/12/01/54877/BPDB-selects-sponsors-for-seven-more-IPPs

2016, the price of fuel oil significantly exceeded the import price as domestic oil prices were not adjusted to reflect the drop in international prices. However, the government recently allowed independent power producers to procure oil from abroad at international prices. This led to a dramatic decline in oil imports by the state-owned Bangladesh Oil and Gas Corporation (BOGC which also goes by the name of *Petrobangla*) and an effective reduction in the price of oil paid by the power sector. Bangladesh regulates the prices of all forms of energy, including power prices. The prices of electricity are set based on a cost-plus basis but regulation continues to factor in a government subsidy for electricity use. This subsidy has implied below-cost pricing for consumers and direct transfers to the state-owned company involved in power purchase and distribution.

Figure 3. Fuel prices [5]



Our model's assumptions reflect the above features of the power sector in Bangladesh in a number of important ways. First, we account for the transition from a predominantly gas-based generation fleet to an increasing reliance on coal, LNG and direct import of power in the supply mix. We also incorporate near-term plans for expanding the fuel-based power generation. Second, we incorporate the changes in fuel oil price policies and use the international power prices as an input to the model.

Transmission network

Despite having a population of 163 million (in 2016), Bangladesh's land area is only 147,000 square km, which is roughly the size of Iowa or Tunisia. The country's grid correspondingly does not require the wheeling of power over large distances. The longest distance between two points within the nation is 630 km and, yet, 50% of power demand is concentrated in the Dhaka and Chittagong metropolitan areas. As of 2016, the existing network has a total of 9,909 circuit km of transmission lines (400 kV, 230 kV, and 132 kV) connecting 139 substations.[6] One 400 kV line is currently in operation between the Dhaka suburbs of Aminbazar and Meghnaghat with 400 kV substations at each end. The existing grid relies on an extensive network of 230kV lines to transport power over longer distances. The East and West grids, which are

[5] Domestic prices: Petrobangla. "Annual Report 2014-15", 2017; International Prices: IEA. "Energy Prices and Taxes" 2017.

[6] Power Grid Company of Bangladesh. Source: https://www.pgcb.org.bd/PGCB/?a=pages/substations.php

separated by the Brahmaputra river in the North and the Padma river in the south, are connected by two 230 kV lines. Four additional 230 kV lines connect the four corner regions of the country to the Dhaka region. The existing 230 kV grid totals 3,185 circuit km in length between 23 substations. The 132 kV network has a total length of 6,504 circuit km and 115 substations and spans the entire Bangladesh. Despite the extent of the network, we note that approximately 30% of the population still lack access to the grid.

The network will need to be expanded to meet the anticipated growth in future demand and supply and the shift in the source of supply. Nearly 40% of power generation is concentrated in the Dhaka region which relies heavily on gas supplied from the main gas fields in the North-Eastern part of Bangladesh. An additional 18% of generation capacity is in the areas East and North-East of Dhaka and most of these also rely on gas for generation. As domestic gas production begins to decline in 2018, government policy now targets the import of power from India and the import of coal and gas. While Dhaka will continue to account for a significant share of power demand in the future, power supply will shift to the East, due to plans for increasing power imports from India, and the South, where planned coal and LNG imports facilitate the construction of new coal and gas plants.

The geographic shift in the source of supply has two key implications for the grid. First, the network will have to be upgraded to from the West to Dhaka and from the South to Dhaka to enable an increase in imports and coal-fired generation. Currently, one High Voltage Direct Current (HVDC) line connects India and Western Bangladesh. This line has a capacity on 500 MW and will be expanded by another 500 MW, which is expected to begin operation in 2018/19. Bangladesh has plans to import another 1,000 MW from India through the Rangpur region, which will require the construction of new capacity between the North-West of the country and the Dhaka region. Given that three new coal plants of 1.3 GW capacity each and several new gas plants are planned for the Khulna and Chittagong regions, the network will need to be expanded with a number of new 400 kV lines to supply power to Dhaka. Second, the shift in the supply of power away from Dhaka implies a challenge to maintain voltage stability and reduce losses through reactive power support. Current plans for expanding the grid include a 400 kV ring around Dhaka, which helps the voltage stability issue but additional reactive power support around Dhaka including dynamic sources such as Static VAR Compensators (SVCs) will be needed.

Renewable energy policy targets

The Sustainable Development Goals and Targets (SDGs) set a target for increasing "access to affordable, reliable, sustainable and modern energy for all." Goal 7 of the SDGs specified the objective to increasing the share of renewable energy in the global energy mix and "*expand[ing] infrastructure and upgrade[ing] technology to supply modern and sustainable energy services*." The Government of Bangladesh integrated the SDGs in its 7th Five Year Plan (2016-2020), which was prepared by the Bangladesh Planning Commission. The 7th Five Year Plan outlined a range of targets for renewable energy generation with the aim of realizing Goal 7 of the SDG. Most notably, the Plan called for a total of 800 MW of renewable generation capacity, including the addition of 500 MW of solar generation, by 2017 and a 10% share of renewables in the generation mix by 2020.

The Government of Bangladesh reinforced the above plans for expanding renewable energy generation in its commitment to the UNFCCC's 21st Conference of Parties in Paris. In its Nationally Determined Contribution (NDC), the Government proposed to develop 1,000 MW of utility-scale solar and 400 MW of grid-connected wind generation capacity in the short to medium term. These targets may fall short of the plans outlined in the 7th Five Year Plan but still imply a substantial expansion of renewable generation capacity over the coming years.

The 10% target implies a substantial increase in renewable energy generation. Given the recent growth rates of 8% per annum in electricity demand, we expect that power generation will need to grow to 73.5 TWh by 2020 of which renewables will have to account for 7.3 TWh to meet the 10% target. Achieving the 7.3 TWh target, will require the installation of approximately 5 GW of variable renewable generation capacity. The Scaling Up Renewable Energy Program (SREP) study conducted in late 2015 concluded the long term potential of solar covering all technologies to be around 3.7 GW and that for wind to be 624 MW (excluding flood prone areas but allowing for low quality wind sites that yields capacity factor as low as 20%).[7] Given that the cost of solar in particularly has significantly improved since then, we have considered the possibility of a higher volume of 4.2 GW of solar and 0.5 GW of wind to be potentially built by 2025, consistent with the 10% target. We have also explored factors that would determine economic merit of these projects as part of the least-cost analysis.

Methodology

The centerpiece of the analytical framework that we use is a least-cost optimization model to determine the investment and dispatch plan over 2017-2025. Using this model, we identify the best portfolio of generation (including renewable generation) and associated dispatch to meet future demand growth in power. Demand growth is exogenous to modeling and the projection we have used relies on recent load growth in Bangladesh. The inputs to the model comprise economic data concerning the existing generation fleet, planned capacity expansions, and fuel prices along with solar and wind resource data, and key financing assumptions.

There are three major components of the analytical model that are performed in sequence:

1. A **long-term investment optimization** that uses a mixed integer programming (MIP) model to optimize investment decisions and performs a high-level dispatch analysis around a load duration curve that represents demand for each year using 30 load conditions from peak to off-peak for each of the years 2017-2025. The long-term model also considers some of the operational features including the spinning reserve allocation among generators for each load condition that may often be critical because of limited availability of it exacerbated by the need to manage variability of solar (and wind);

2. A **short-term dispatch optimization model** that uses a linear programming model to minimize the short-term cost of supply given a capacity plan. Dispatch planning differs from investment planning in that dispatch optimizes plant utilization within a select, short timeframe. We model dispatch over a representative four-week period in 2017, the base year, and 2025 the last year of the forecast period. Dispatch modeling takes the results from the investment planning model and optimizes generation based on marginal costs of each generator. Hence, dispatch modeling ignores fixed costs or investment costs. The result is a generation scenario where the power output from plants with the lowest marginal cost is maximized to meet demand over the select period. In the investment planning

[7] Sustainable Renewable Energy and Development Authority (SREDA), *Scaling Up Renewable Energy in Low Income Countries (SREP)*, Ministry of Power Energy and Mineral Resource, October 2015.

model, the generation technologies with the lowest cost, including fixed and variable costs, will be built; and

3. A **static transmission system load flow** model that takes the dispatch for a specific load condition (e.g., annual peak) and calculates the flows along the lines and voltages at each (high voltage) node/substation of the transmission network. The objective of the load flow analysis is mainly to ensure that the generation investment plan and dispatch produced in the preceding two steps can be accommodated in the transmission system, i.e., power flows on all lines remain within limit, voltage at all sub-stations remain within limits, including contingency events when one of the large generator or line is on outage.

Investment optimization in the first step takes into account fixed costs including annualized capital cost of new entrant projects as well as variable fuel and variable O&M costs. In addition, the cost of power import and any cost of unserved energy are also considered. The model takes into account depleting domestic gas availability in Bangladesh, which in turn means the option of either importing expensive LNG and using the available infrastructure needs to be compared with building new coal plants and using imported coal, and/or renewables.

Dispatch modeling takes into account plant flexibility to meet additional power requirements for a system where output from renewables can change unexpectedly and substantially. In general coal plants have lower ramp-up and ramp-down rates due to higher technical constraints. Gas and oil-fired plants are more flexible and are better suited to provide back-up power to renewables. The model constrained the changes in power output from each plant from one hour to the next to account for these differences in flexibility.

The transmission analysis takes into account existing and planned substations, transmission lines and the current and projected loads at each 132kV substation. The inputs consist of 132kV, 230kV and 400kV substations and the transmission lines connecting them. Each transmission line's capacity mirrors the existing grid and the projects for increasing capacity. The system will need to balance supply and demand with nearly uniform voltage levels in order to maintain voltage stability and reduce losses. For this analysis, we targeted substation voltage levels to be within stipulated voltage level (e.g., ±5%). Voltage levels could be narrowed further with the addition of shunts in the system, though fine-tuning the grid to set voltage levels within a narrower band adds little value to long-term analysis. Substation load is scaled by the overall growth rate in demand. For the grid analysis, we used Siemens' PSS/E system analysis tool.

The modeling framework is the first application of a full suite of capacity, dispatch and load flow models to address VRE policy in the country. As discussed above, comprehensive analyses that fully considers all three levels of analysis on a consistent basis, with due consideration of spinning reserve and transmission, is also of recent origin. The need for spinning reserve to manage variability, for instance, is often ignored in analysis of VRE although it can prove to be a critical consideration.

For the optimization, we use Electricity Planning Model (EPM) developed at the World Bank (Chattopadhyay et al, 2018) using the General Algebraic Modeling System (GAMS, 2017) language.[8] The

[8] GAMS is a popular mathematical programming language that consists of a compiler and a range of integrated high-performance solvers including CPLEX from IBM that we have used for this analysis. GAMS, originally developed by the World Bank, permits the modeling of complex, large-scale problems. Excel provides the framework for data input to modeling and analysis of outputs. Full details of the model is available:

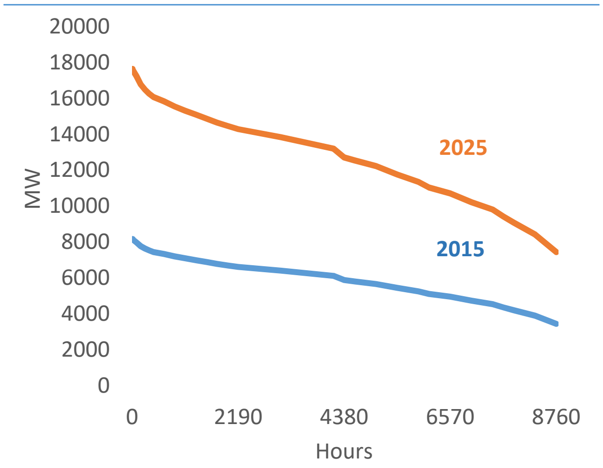
model is capable of seamlessly optimizing the capacity plan, passing the optimal plan into a dispatch module, which in turn produces the input files for PSS/E. The implementation of the model for Bangladesh to comprehensibly analyze VRE policies for Bangladesh is also noteworthy. It demonstrates that good quality analysis of this type can be produced using a customized model in a short space of time for developing countries that often do not have the ability to procure commercially available tools. The model developed for Bangladesh has been delivered to the Bangladesh Power Development Board (BPDB) in late 2017, which is now in the process of using the model to update the Power Systems Master Plan (PSMP) including renewable resources.

Inputs and Assumptions

Demand assumptions in generation and dispatch planning

As noted above we assume power demand to be exogenous to the modeling even though changes in generation costs and power prices have an impact on demand. The basic assumption is that power demand will grow by 8% per annum. The power demand in 2015, the base year for modeling, reached 48 TWh. The 8% growth in demand implies that power use will rise to 100 TWh by 2025. To account for variability in demand over the course of a year, we construct a load duration curve (LDC) from 8760 hours of the day and divide this curve into 30 unequal time blocks to model capacity expansion. For dispatch modeling, we selected four representative weeks that best approximate the overall demand and solar profile in the country.

Figure 4. Load duration curves (MW)[9]



New generation options and costs

Generation and dispatch planning take into account *inter alia* technical characteristics of existing plants, committed and new plants, and assumptions on coal/gas prices. When modeling capacity expansion, some assumptions had to be made about the system's ability to add new capacity. The development of

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https://www.researchgate.net/publication/325534590_World_Bank_Electricity_Planning_Model_EPM_Mathematical_Formulation_World_Bank_Electricity_Planning_Model

[9] Power Grid Company of Bangladesh. "Operational Daily" Source: https://www.pgcb.org.bd/PGCB/?a=pages/operational_daily.php

coal-fired generation capacity has been delayed for years and this trend seems to continue. The Rampal power plant has been in development since 2010 and construction only recently began. The Matarbari coal plant project has seen a similar slow development to date. Beyond these known coal projects, we have also allowed for generic coal projects at $1,800/kW for an additional 1,200 MW that can be commissioned from 2023.

The addition of new gas and oil generation capacity has been more seamless due, in part to experience and to private sector participation. The Siddirganj Power Plant, a 335 MW CCGT, recently began operation and several new CCGT plans are set to start this year and next. Summit Energy developed two new 335 MW power plants near the Bibiyana gas field in the North and an additional 225 MW will come online on the island of Bhola this year. In addition to these known projects, the model allows for generic open cycle and efficient combined cycle gas turbines at a cost of $940/kW and $1,250/kW, respectively.

To meet growth in power demand, the government has opened up the generation sector in 2005 for private companies and, since then the sector added 2 GW of fuel oil generation. A recent tender called for an additional 10 - 100 MW each - fuel oil generators set to be located around the country. The decline in oil prices also eased the fiscal burden on BPDB as the single buyer of all power, including fuel oil based power. As noted above, private generators can now import fuel oil at essentially international prices. Given the delays in coal generation, the development of more fuel oil capacity remains likely. The model allows for up to 900 MW of additional HFO based generation capacity.

The data for existing generators uses reported fixed costs, variable operating and maintenance costs, heat rates, retirement dates, and international fuel prices. Plant level data comes from the Bangladesh Power Development Board’s System Planning division. For state-owned generating units, the dataset provides fixed and variable costs. For private generators, the data available pertains to the fixed and variable costs as defined in the power purchase agreements. The two sets of costs differ as the latter includes economic costs and rate of returns for each generator. Given that economic data is unavailable for private generators, the reported contractual terms serve as a proxy.

New build capacity costs are based on industry assumptions for capital and operating and maintenance (O&M covering both fixed and variable) costs. Such capital costs are amortized over the life of the plant and appear as annualized capital costs. A weighted average cost of capital (WACC) was used to calculate annualized capital costs. The power sector in Bangladesh relies increasingly on new generation capacity by private companies. The cost of capital varies across the projects depending on the source of financing and underlying interests. The Rampal coal power plant project, for instance, is a joint venture between state-owned power companies from India and Bangladesh. The project received a concessional finance from the Government of India and hence its amortized annual fixed costs take into account the (lower) interest rate reported on the loan.

Hourly solar resource data, an input into the model, comes from Solargis. Global Horizontal Irradiance (GHI) data aggregates direct and diffuse solar irradiation on an hourly basis for South Asia, including Bangladesh. This solar resources data is available with a 1km by 1 km resolution. A comparative analysis of GHI data for different parts of Bangladesh shows little variation of irradiation across the country. We, therefore, assumed a single point reference for the entire system, an assumption that is also supported by minimal prior work on site selection. Given Bangladesh’ high population density, high flood risk, and extensive reliance on agriculture, site selection for utility-scale projects will indeed be a critical issue.

Using the System Advisory Module (SAM) developed by National Renewable Energy Laboratory (NREL) in the US, we generated an hourly generation profile assuming a standard module and inverter. The NREL SAM model has a range of modules and inverters, and using the NREL reported solar irradiance data, we considered a number of technologies. In general, the average capacity factor is estimated at around 16% across Bangladesh.

Figure 5. Average monthly power generation (LHS) and average monthly solar global horizontal irradiance (RHS)[10]

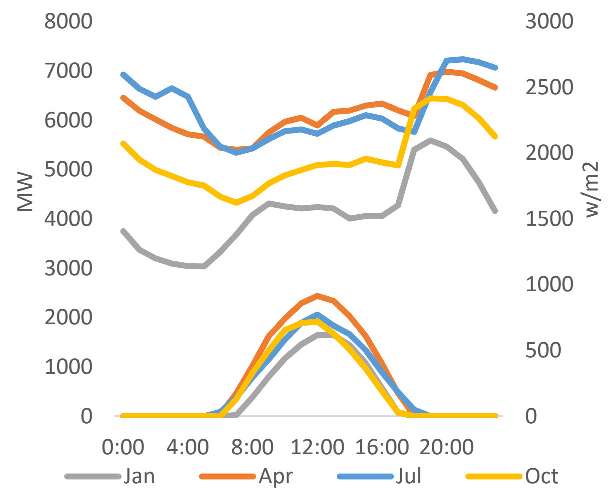
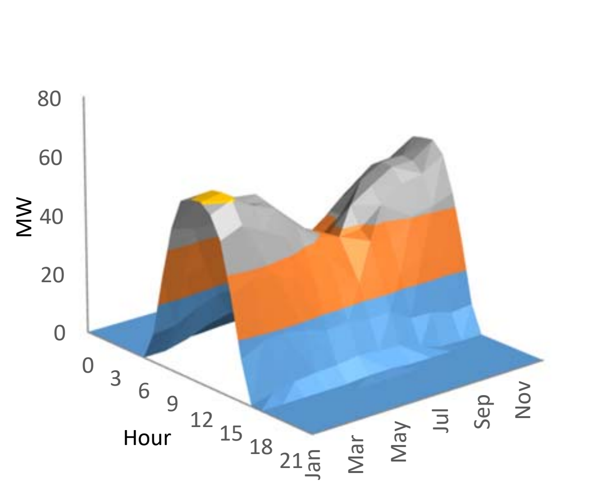


Figure 6. Monthly average power generated at each hour of a day from a 100MW solar PV plant



Transmission analysis builds on the existing the 132 kV, 230 kV, and 400 kV network in Bangladesh and configures the network in the future as needed to meet demand in Bangladesh' different regions. The analysis here considers system requirements on maintaining voltage levels, frequency, and providing sufficient capacity for transmission using the PSS/E transmission planning software. Projected network configurations take into account reactive power needs and shunt requirements. The timeframe for modelling capacity and generation spans the period between 2015 and 2025. For transmission, this analysis uses the existing (2015) network data provided by the Power Grid Company of Bangladesh (PGCB). and projections for the grid in 2025, prepared by Tokyo Electric Power Company for the Power System Master Plan (PSMP), as the basis and, subsequently, expands on the projections to analyze whether those will fulfill system requirements for transmission capacity. The investment and dispatch planning for renewables looks at a few policy scenarios that have different outcomes on the power generation mix and, correspondingly, on the transmission network. The transmission analysis takes into account the key policy scenarios as well.

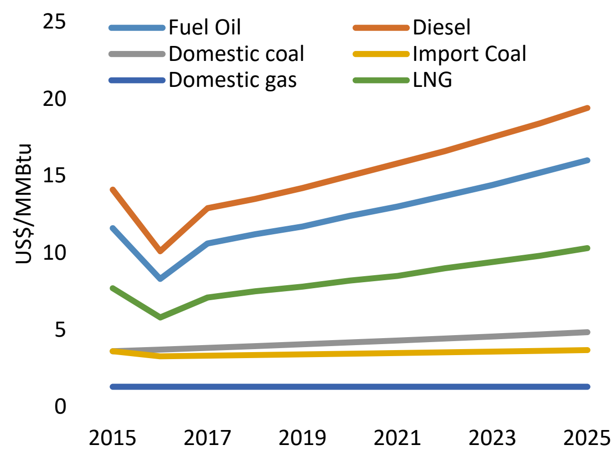
Our modeling bases fuel prices on the World Bank's commodity price forecasts for oil, coal and LNG. For the domestic gas, we assume that the current prices will persist, although we model a scenario where gas prices reach parity with import LNG prices.

Our model takes into account the limits on domestic gas supplied imposed by the lack of resources. Bangladesh has limited onshore gas reserves and will soon have to import natural gas to meet demand

[10] Solar irradiation data: Solargis, 2017.Demand data: PGCB. Daily Reports, 2017.

for power generation. Domestic gas fields produce nearly 1 trillion cubic feet (TCF) of natural gas but known reserves hold only 11TCF of gas. Production will peak in 2018 and begin to decline thereafter, dropping to less than 10% of current output by 2030. Natural gas accounts for 57% of countries Total Primary Energy Supply and power sector consumes roughly 40% of gas supplied. In all scenarios, we assumed that domestic gas availability for power generation will decline at the rate projected for overall gas supply.

Figure 7. Fuel price assumptions[11]



Transmission

The power network in the transmission analysis is based on the existing grid and plans for additional substations and transmission lines. The input dataset consists of information on each 132 kV, 230 kV, and 400 kV substation and transmission lines connecting them. Each line's rating is taken into account. The transmission network is analyzed using PSS/E, which permits the assessment of system operation under different generation, transmission and load scenarios and the system's viability under different configurations. The results from the generation and dispatch model provides the input on generation, while substation loads were scaled uniformly according to the projected growth in overall demand.

Spinning reserves

Spinning reserve management in Bangladesh faces a fundamental issue due to the absence of participation by most plants in frequency support. Until recently, frequency fluctuations of ±2 Hertz (Hz) had regularly occurred in recent years due to the lack of automatic (load) frequency control mechanism. The system operator now limits frequency variations to within -1.5 Hz and +1 Hz. A group of six plants provide frequency response jointly. However, when frequency drops below 48.5 Hz, the operator relies on large-scale load shedding to maintain stability.

When considering solar and wind deployment, we introduce a spinning reserve requirement to cover 7% of potential solar and wind generation. This means that up to 7% of potential solar generated needs to be covered by fast reacting power generation capacity to account for unexpected changes. Spinning reserve

[11] World Bank. "World Bank Commodities Price Forecasts (January 2017)" 2017. Source: http://pubdocs.worldbank.org/en/926111485188873241/CMO-January-2017-Forecasts.pdf

capacity has to be available and ready to provide power almost instantaneously to make up for unexpected changes in the supply of renewables. Baseload plants, like coal and nuclear, have limited ability to provide spinning reserves. On the other hand, open cycle gas turbines can ramp up and down power output more quickly and can provide spinning reserves. Combined-cycle gas turbines are increasingly able to provide ancillary services. Ramp-up rates of the latest technologies can achieve up to 4-5% of nameplate capacity per minute. When the steam cycle is decoupled the increase in generation can be even faster.

Table 1. Spinning Ramp Rate Assumptions (% of capacity/min)[12]

Plant and fuel type	Existing	New Build	Existing (MW/Min)
Reciprocating Engines			
Gas	10%	10%	151
Fuel Oil	5%	5%	128
Diesel	5%	5%	13
Combustion Turbines (Gas)	10%	10%	
Combined Cycle Gas Turbine (Gas)	5%	5%	140
Steam Turbines			
Gas	2%	5%	64
Fuel Oil	2%	5%	1
Diesel	2%	5%	0
Coal	2%	5%	4
Total			501

The key question on variation in solar output concerns the changes in solar radiation. The impact of weather can change radiation significantly. As of now there has been no study done on solar irradiance in Bangladesh on a sub-hour timeframe but studies from other regions indicate that variations in output can be significant within minutes even seconds, which requires the minute-by-minute and second-by-second control mechanism from generators or other new technologies such as battery energy storage system (BESS). Minute-by-minute data on GHI from other countries including USA shows that during peak solar hours GHI can drop by up to 80%, due to changes in cloud cover. We note that some studies show that within minute variations could mean ramp rate needs of up to 50% of a solar plant's output. However, as spinning reserves need only to cover unexpected and unforeseen changes in solar, which means spinning reserve requirements can be reduced with improved accuracy in forecasting.

In general, many power markets have spinning reserve assumptions that go beyond renewable generation. The California Independent System operator requires that spinning reserves cover 5% of demand and all power imports at any given time. In the Bangladesh context, this would require covering up to 9.5 GW of peak demand and 600 MW of imports (in 2017). The current generation, however, has an estimated 501 MW of spinning reserve so implementing a system-wide requirement similar to the one California remains infeasible in the current system without significant changes to the grid operation practices.

[12] The assumptions here reflect a review of existing literature on spinning ramp-up rates. We note that these rates differ significantly depending on technology of the plant and operational practice.

Model Results

Economics of solar

The SREP (2015) study projected costs of large-scale solar parks at $1,551/kW (excluding cost of land). Given the low cost of domestic gas and relatively low resource quality of solar in Bangladesh (that yields average capacity factor around 16%), it is not economic at those costs. Smaller scale solar technologies have been shown to be even more expensive (Chattopadhyay et al, 2016). In light of the significant drop in cost that has taken place over the last few years and the potential for further decline, we have considered a capital cost of $1,000-1,200 per kW (including land and connection costs) for projects in 2020 further declining at a rate of 5%-10% pa through to 2025. We have also considered pessimistic scenarios in which (a) LNG prices increase at a lower pace than we have considered in the base case to reach $8.7/MMBTU instead of $10.5/MMBTU by 2025; and (b) spinning reserve requirement of 5% is imposed commensurate with international standard, but spinning reserve availability remains restricted to an absolute maximum of 800 MW (reached by 2025) that would effectively limit the amount of variable renewable energy resources that can economically be added. In **Table 1**, below we discuss the summary outcomes for the following alternative sets of conditions:

1. **$1,200 (5%):** Solar cost of $1,200/kW declining at 5% pa;
2. **$1,000 (10%):** Solar cost of $1,000/kW declining at 10% pa;
3. **$1,200 (5%) LOWLNG:** Sensitivity 1 with lower LNG price of $8.7/MMBTU in 2025; and
4. **$1,200 (5%) LOWSPIN:** Sensitivity 1 with lower spinning reserve availability of 800 MW.

Table 1 Comparison of solar sensitivities

Scenario	NPV of System Cost ($m)*	Solar entry (MW)					
		2020	2021	2022	2023	2024	2025
$1,200 (5%)**	47,061	0	0	2400	2400	2400	2900
$1,000 (10%)	46,587	1200	2650	4200	4200	4200	4200
$1,200 (5%) LOWLNG	45,728	0	0	1000	1000	1000	1000
$1,200 (5%) LOWSPIN	49,061	0	0	1000	1000	1800	2710

* Discounted system cost at 6% over 2017-2025 including annualized cost of capital, all operating expenses and penalties for unserved energy and reserve.

** Scenario name represents base capex $1200/kW and rate of decline 5% in parenthesis.

The salient aspects of these results include:

1. Large-scale grid-connected solar in Bangladesh is not economic until 2022 in three out of four of these scenarios. The only circumstance when solar entry occurs in 2020 assumes solar costs starting at $1000/kW and falling rapidly at 10% pa. The results provide a context for understanding the current realities of no large-scale grid-connected solar project yet getting off the ground in Bangladesh, despite concessional financing and substantial amounts of interest from donor agencies. The results demonstrate the value of using a systems approach to understand the economics of large-scale solar relative to other options.

2. Economic entry of solar by 2025 varies from 1 GW to full potential of 4.2 GW, with the latter achieved using relatively aggressive cost assumptions such that all-in cost of solar parks drops below $500/kW in 2025.

3. In fact, solar is not economic at $1,200/kW (5%) until 2022 when domestic gas production falls significantly. This and the results in (2) together again relate to the first observation we made – it would actually take a sharp price reduction in solar projects before solar could compete with current low prices of domestic gas and even LNG. Although solar prices on a levelized basis has been compared to gas, coal and power import, a systems approach is useful to establish that such comparisons are meaningless. Solar availability is variable across the seasons, limited to the day hours when the peak in Bangladesh occurs in the evening, and requires spinning reserve which is a scarce commodity. When we do a proper valuation of solar is done taking these issues into consideration, solar is less attractive than what a LCOE or auction price on a levelized cents/kWh basis might suggest.
4. A lower solar capex $1,000 (10%) scenario reduces discounted system cost by $474 million term over 2017-2025.
5. On the other hand, if we assumed a more realistic $1,200(5%) capex, lower LNG price would significantly diminish entry from 2,900 MW to just 1,000 MW. While we do not assume that a low LNG price would continue, it is useful to note that solar entry competes directly with LNG as the marginal resource from a long-term planning perspective.
6. Tighter availability of spinning reserve has a very significant impact on system cost increasing it to be $3.3 billion over 2017-2025 as economic generation needs to be withheld to provide reserve. A large part of this increase in system cost does not relate to solar. However, since all forms of variable renewable energy including solar has the impact of increasing the requirement for spinning reserve, this sensitivity results show that solar entry is reduced to 1,000 MW till 2023 (as opposed to 2,400 MW without any binding limit on spinning reserve availability).

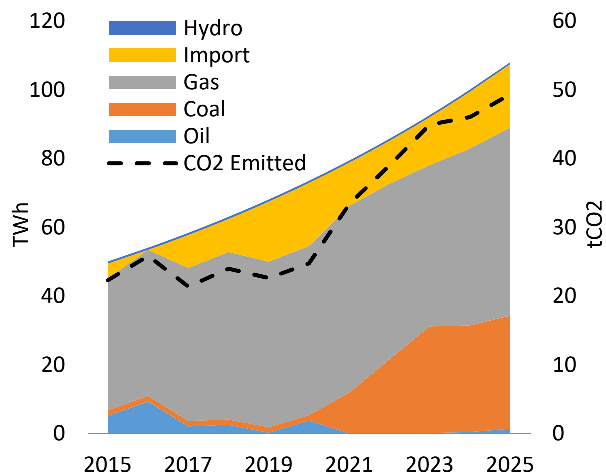
These results underline the significance of undertaking a proper cost-benefit analysis for solar projects. Moreover, as a more expensive source of generation from a system perspective, solar is quite sensitive to not only the cost of the project, but also alternative sources of generation and other technical issues such as spinning reserve.

Model Results – Reference Case

A reference case was developed to benchmark the analysis of all other scenarios. Under the reference case, three new large, 1.3GW coal plants will be added to the mix. Imports from India increase from the current 600 MW[13] to 2.1 GW by 2025. An additional 1.7 GW of fuel oil generation will be added as well. These expansion assumptions reflect ongoing government policies to increase near-term and long-term peak load and baseload generation capacity from coal and oil in light of the shortage in gas. To meet the 8% demand growth, the assumption in the base, an additional 3 GW of combined cycle capacity will need to be added by 2025.

[13] As of 2017, two transmission lines connected India and Bangladesh. One HVDC line connects Western Bangladesh and India with a capacity of 500MW and one AC line connects Easter Bangladesh with India with a capacity of 100MW.

Figure 8. Reference case forecasts of power generation (LHS) and CO2 emissions from power generation (RHS)



In the Reference Case, gas will continue to dominate the generation mix until 2023 when imports of power and imported coal will become the major source of power. Gas generation will drop from 75% of total generation in 2015 to 51% by 2025. Imported coal based power will account for 31% of generation and the share of imports will rise from 9% to 17% of generation. Due to the projected increase in coal based generation, CO_2 emissions will rise from 24 mt CO_2 in 2015 to 65 $MTCO_2$ by 2025.

The reference case scenario reflects the fact that coal generation remains the cheapest source of power even as Bangladesh will need to import almost of its additional coal demand. The reference case assumption implies that levelized generation costs will rise from 3.1USc/kWh to 7.7USc/kWh by 2025. While this is a steep increase in costs, the current system costs observed in Bangladesh is actually even higher at 7 Tk/kWh than the 2025 estimate. The reason for the difference between the estimate and observed costs has to do with the absence of merit order dispatch in Bangladesh. Least-cost optimization maximizes generation at the lowest cost. This inherently assumes merit order dispatch – an issue that has been analyzed by Nikolakakis et al (2016).

Figure 9. Hourly dispatch during peak demand in 2015

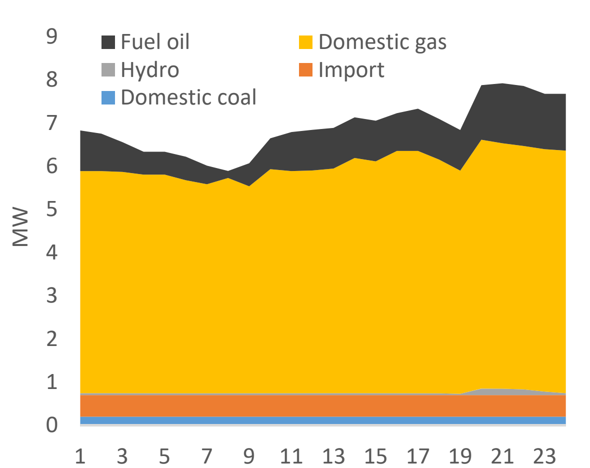
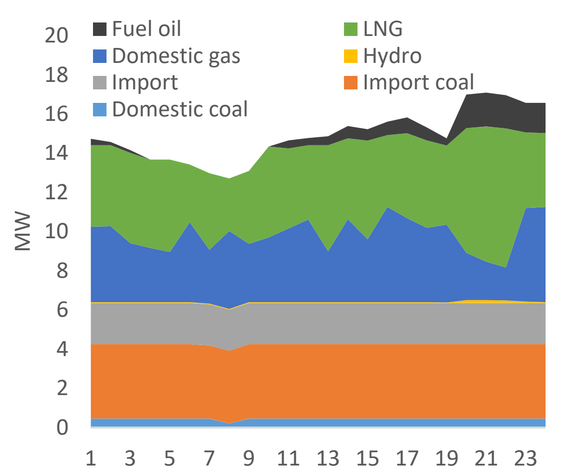


Figure 10. Hourly dispatch during peak demand in 2025 (MW)



The hourly dispatch data for Bangladesh show that the system will still use fuel oil during evening hours when demand is at its maximum. During peak demand hours fuel oil output reaches up to 80% of fuel-oil based generation capacity, providing up to 2.5 GW of energy. In the base 2025 scenario, fuel generation will decline during daytime hours. The reference case assumes that no renewable energy sources of energy, other than the existing hydro plant, will be added to the generation mix. As we discuss later, solar will replace daytime fuel oil generation, contributing to the reduction of carbon emissions.

The modeling of spinning reserve costs becomes complex when other reserve requirements are considered, as we have noted previously. The reference case and all other cases assume that there will be 15% capacity reserve margin over and above peak demand. Without any renewable generation capacity, available spinning reserves are projected to grow from 501 MW in 2015 to 880 MW in 2025. Making this maximum spinning reserve capacity available in the system means that all generators will have to run below full capacity to enable some flexibility. This implies a slight deviation from merit-order dispatch, which is the key driver in short-run spinning reserve costs. Between now and 2025, providing the full projected spinning reserve will cost between US$22 million (in 2017) and US$95 million (in 2024).

Table 2. Potential spinning reserve (MW)[14]

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Generation costs (USc/kWh)	3.35	3.26	3.49	3.81	4.01	4.28	4.58	4.96	5.28	5.93	6.59
In-built, full spinning reserve potential (MW)	501	576	622	598	550	558	643	706	738	815	880
Annual cost of providing full spinning reserve potential (US$mln)	13	9	22	22	31	15	27	31	43	95	69

Model Results –10% Renewable Target Policy Scenario

The Reference Case considered that solar and wind generation costs will far exceed projected system costs, and hence, none of these technologies would be deployed within the forecast period. For the high renewable scenario, renewable energy generation costs were reduced below USc6.5/kWh by 2025, which enables the deployment of solar up to a capacity limit. For this scenario, the maximum generation capacity was limited to 4.2 GW for solar and 500 MW for wind.

[14] Source: World Bank calculation.

Figure 12. High renewable case forecasts of power generation (LHS) and CO2 emissions (RHS)

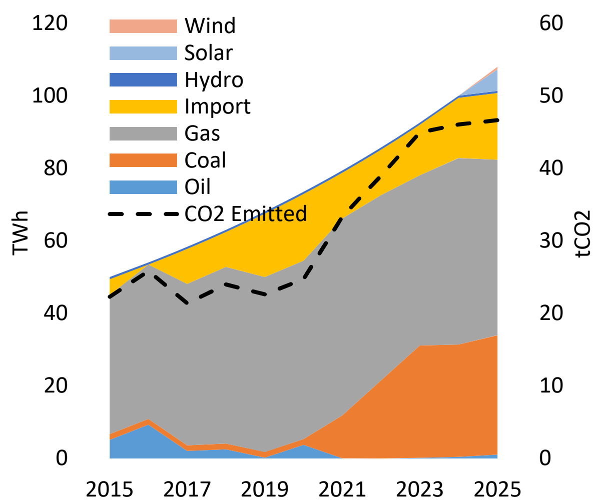
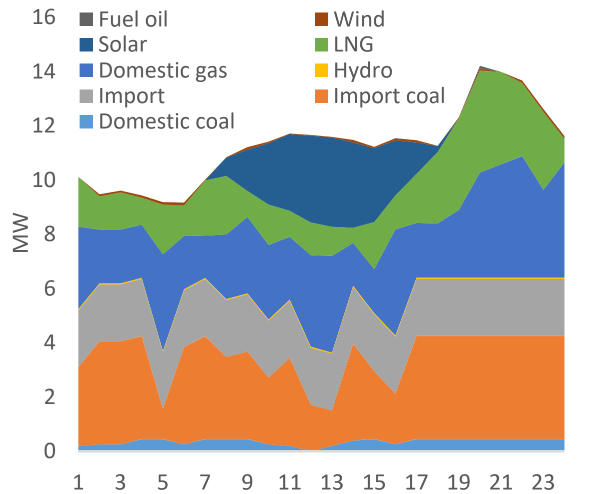


Figure 13. Hourly power dispatch (MW) during peak solar generation in 2025 under the high renewable case



The addition of solar and wind will reduce carbon emissions by 2 million tons per year by 2025, as compared to the reference case scenario. The reduction comes mainly from the displacement of fuel oil and some gas generation. Solar and wind deployment avoid 300 MW in fuel oil generation, compared to the reference case. Coal, power imports and to a large extent gas will continue to provide baseload energy in 2025 under all scenarios. Generation from natural gas will rise from 38 TWh in 2015 to 54 TWh in 2025. This increase can be met with a modest 100 MMCF/d increase in gas use by the power sector given that a number of new gas plants with high efficiency will displace some existing units that are due to retire.

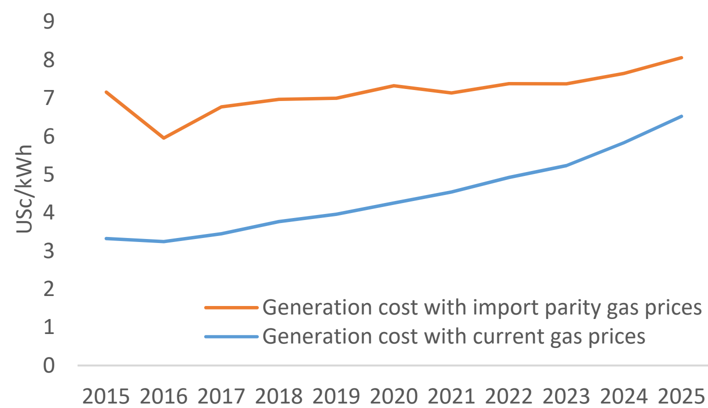
Electricity and solar cost analysis

The above scenario assumes that solar and wind costs will drop to below grid parity costs. More specifically, the cost of solar and wind generation need to be below the cost of available generation at the time and resource is scheduled to provide energy. For example, solar generation occurs during daytime hours in Bangladesh which coincides with low demand. During this period, solar effectively competes with baseload generation.

The average cost of power generated is projected to rise from USc3.35/kWh in 2015 to USc6.59/kWh in 2025 with current domestic gas prices. However, gas pricing policies pose a difficulty in assessing the cost of generation in Bangladesh. As the power sector pays only US$1/MMBtu for natural gas, average generation costs are far below the costs projected when gas is priced at import parity. The benchmark generation costs rise significantly when gas sold for power generation is priced at import LNG parity.

Due to a declining domestic gas production, the supply of low-cost domestic gas will need to be supplemented with imports of LNG. The expected rise in imported gas accounts for much of the increase in the forecast for power prices in the Reference Case. Modeling the Reference case is based on a projected decline of domestic gas used by the power sector from 950 MMcf/d in 2015 to 480 MMcf/d in 2025 and an increase in LNG from 120 MMcf/d in 2018 (the year imports are expected to begin) to 454 MMcf/d in 2025. This translates into an increase in the average gas price for power generation to US$5.8/MMBtu.

Figure 11. Generation costs (USc/kWh)



Given that renewables have close to zero short-run marginal costs, investment and financing costs become the most crucial factors in defining generation costs. Correspondingly, the most important assumptions for least-cost optimization planning concern the assumptions on capital and financing costs for solar generation. Table 3 allows for a comparison of potential solar generation costs with generation costs. The uptake of solar is highly sensitive to solar prices. We estimate that solar costs have to decline to around 6.5USc/kWh for solar to economic in the Bangladesh context given regional capacity factors, reserve requirements, and grid generation costs. This will essentially require the capital cost of solar to drop below $1,000/kW for a weighted average cost of capital of 5%. Given the paucity of land and the need to import vast majority of the capital, realistic chance of doing projects at GW scale is likely to be limited at least in the near term. This certainly aligns well with the lack of sufficient degree of interest on the ground to mobilize projects during 2016/2017.

Table 3. Cost of solar power generation under different assumptions (USc/kWh)

	Cost of financing solar (%)							
Capital Cost of Solar (US$/W)	9%	8%	7%	6%	5%	4%	3%	2%
1.5	13.0	12.2	11.4	10.7	9.9	9.2	8.5	7.9
1.4	12.3	11.5	10.8	10.0	9.3	8.7	8.0	7.4
1.3	11.5	10.8	10.1	9.4	8.8	8.2	7.6	7.0
1.2	10.7	10.0	9.4	8.8	8.2	7.6	7.1	6.6
1.1	9.9	9.3	8.7	8.2	7.6	7.1	6.6	6.1
1.0	9.1	8.6	8.1	7.5	7.1	6.6	6.1	5.7
0.9	8.4	7.9	7.4	6.9	6.5	6.1	5.6	5.3
0.8	7.6	7.1	6.7	6.3	5.9	5.5	5.2	4.8
0.7	6.8	6.4	6.0	5.7	5.3	5.0	4.7	4.4
0.6	6.0	5.7	5.4	5.1	4.8	4.5	4.2	3.9
0.5	5.2	5.0	4.7	4.4	4.2	4.0	3.7	3.5

Transmission analysis

The transmission network will need to be upgraded and re-designed to some extent to enable the delivery of power from the four corners of the country to the Dhaka region in an efficient manner. In 2015, roughly 40% of power was generated and consumed in the Dhaka region. By 2025, peak demand in Dhaka is projected to grow from 3.4 GW to 8.1 GW, whereas local supply will remain essentially the same as in

2015 at 3.3 GW. New sources of power will come from the addition of HVDC lines to import power via the South-West and North-West of Bangladesh, new coal-fired generation in the South-West and South-East regions, and gas fired-generation plans in the North-East and South-East regions.

The current system relies heavily on 230 kV lines for transmission over longer distances and around Dhaka. However, the system at present is not particularly well designed and some of these lines do not achieve adequate utilization. For instance, two lines that connect the Western and Eastern grids operate at around 21% to 23% capacity even during peak demand hours and the 230 kV line on the Meghnaghat-Comilla-Hathazari route operates at just 11% during peak hours. In comparison, utilization on the line between Ghorashal and Tongi reaches 72% during peak hours, reflecting the importance of power delivery from the two largest plants Ashuganj and Ghorashal to Dhaka. The system lacks a proper higher voltage backbone network to have a more balanced allocation of flows over the existing lines, and to ensure that the changing demand-supply balance across the sub-zones (including Dhaka that will be less self-reliant going forward) can be addressed through this enhanced network.

A 400kV network has therefore been proposed to connect Dhaka to the four corners of Bangladesh. These lines will add significant transmission capacity in the next five years. The North-East will be connected with the Bibiyana-Kaliakoir line to Dhaka. The South-East region will connect Chittagong and Dhaka with a 400 kV line, set to be built between Meghnaghat and Maduaghat. The North-West region, which imports power from India via a 500 MW HVDC line, will be connected to Dhaka with two additional 400 kV lines and another 230 kV line. Imports from India via this region are expected to grow to 2.5 GW by 2025. The South-West region, where plans for two new coal-fired plants will increase capacity by 2.6 GW, will be connected via Gopanganj to Dhaka with a 400 kV. Further plans will create a 400 kV ring around Dhaka. The first phase of this ring, a line between Meghnaghat and Aminbazar, has already been in operation since 2016. All proposed 400 kV lines will be double-circuit with projected capacities of roughly 3 GW. [*See appendix for a regional demand and supply analysis]*

Table 4. Projected changes in regional generation, demand and inter-regional transport capacity (MW)

	Peak Generation		Peak Demand		Line capacity between region and Dhaka	
Regions	**2015**	**2025**	**2015**	**2025**	**2015**	**2025**
Dhaka	3666	4031	3347	8091	0	0
North/NorthEast	1545	2684	731	1180	1200	7200
North-West	595	2805	1219	2075	1200	7800
South-West	929	4268	812	1607	900	3900
Central	361	321	583	1047	900	900
South-East	551	2738	744	2321	900	4500
Total	**7647**	**16846**	**7437**	**16321**		

The existing plans for the transmission network will create a grid that can indeed accommodate the 4.2 GW of solar and 550 MW of wind. For this modeling, solar plants are assumed to be connected to the proposed Feni 230kV substation and the existing Khulna and Bogra 230 kV substations. At peak, generation output from these plants reaches 3.2 GW. Feni is currently connected to the grid via a 132 kV substations on a route between Comilla and Hathazari. An existing 230 kV line between Comilla and the Chittagong region passes by Feni. Government plans included the addition of a substation on this line to connect Feni's 132 kV substation. Bogra and Khulna both have 230 kV substations already. The Bogra to Sirajganj double circuit 230 kV line, which delivers power from Bogra to Dhaka, has ratings of 597 MVA. At peak hours the lines operate at 21% utilization which leaves space for another 400 MW of energy. Khulna-to-Bheramara 230 kV has similar capacities and its utilization at peak is 10%, which also leaves space for connecting solar plants in the short-term. These 230 kV substations that evacuate the solar power will be located on routes with 400 kV line reinforcements which carry the bulk of inter-regional power transfer.

Grid-integration modeling assumed that the planned grid expansions will be realized that is needed for large-scale deployment of renewables. The Feni site's grid integration was modeled with the proposed 750 MW of solar and another 100 MW of wind. For Bogra, the assumption was that up to 1000 MW of solar and 100 MW of wind would be connected to the grid. Another 2.4 GW of solar capacity was linked to the grid via the Khulna region. Modeling shows that both Feni and Bogra are ideal locations for the integration of large-scale solar energy. With the proposed grid-expansions both sides would comfortably accommodate the modeled solar generation. Khulna's 230 kV substation will need to be connected to the 400 kV line proposed to link the Rampal power plant with Gopalganj and Dhaka. Without this connection the site will not be able to accommodate the 2.4 GW capacity. Connecting the region directly with Dhaka via a 400 kV line will be critical for large-scale deployment of solar.

Near-term deployment of grid connected solar – the case of Feni

The Government of Bangladesh reportedly committed three sites near the town of Feni for the development of solar parks. [15] The total capacity envisaged could reach up to 750 MW of solar on 2,500 acres of public land and additional wind capacity of 100 MW. Feni is currently connected to the grid via a 132kV substation along the route of Hathazari-Comilla-Meghnaghat 230 kV power line. That power line does not yet have a substation and so near-term projects may need to feed into the 132 kV line. The Government is in the process of developing an additional 230 kV line from which would connect the Chittagong area to the Comilla-Meghnaghat 230 kV line via Chowmuhani and the Chandpur region. This line would have a substation in Chowmuhani, which is a few kilometers West of Feni.

Our analysis shows that at least 300 MW of solar and wind generation can be connected to the Feni 132 kV substation with limited consequences for the overall grid. The first solar park would be located near the Songazi Municipality just South of Feni. The project would connect a 50 MW solar park and, subsequently, a 50 MW wind farm to the grid. Three 132 kV lines connect Feni to the power grid of Bangladesh. These are each double circuit, each rated 148 MVA. At peak demand hours the three routes to Feni have an average utilization between 20% and 25% on a total of 900 MW. Both lines going West and North connect Feni with Comilla. The line heading West goes to Comilla via Chowmuhani and Chandpur while the line to the North links Feni directly to Comilla. These two lines have a total capacity of 600 MW and during peak hours carry around 150 MW. The 132 kV lines are used to serve local area

[15] Feni is a district in South-Eastern part of Bangladesh in between two major load centers of Dhaka and Chittagong. Location of Feni on the Bangladesh power grid is shown in: Power Grid Company of Bangladesh. "GEO Map [for the transmission network]", 2017. Source: https://pgcb.org.bd/PGCB/?a=pages/geo-map.php

demand and not constitute main routes for transporting power from the South to Dhaka. As such these lines do have the capacity to absorb near-term projects including a 50 MW solar park and a 50 MW windfarm.

The 132 kV substation in Feni currently has a 60 MW load at peak hours. This could grow to be a 100 MW by 2025, given 8% annual average growth rates. That means the station and the adjacent lines will need to guarantee the delivery of 100 MW of power in the future and reduce the reliance on existing/planned expensive power plants in the area. Two small power stations operate near Feni, each with 20 MW capacity and another 100 MW fuel oil based capacity has been tendered for construction near Feni. The city is therefore expected to be a net supplier of power to the region, making the evacuation of solar energy to higher demand regions the challenge.

Concluding Remarks

Bangladesh is undergoing a major change in its fuel mix as it runs out if its cheap domestic gas to rely on imported power and increased imports for primary fuels. Solar, in particular, has an opportunity to contribute to the impending crisis for domestic energy, especially as its cost drops at a time when Bangladesh's supply costs are on the rise – we find that economic potential of solar can be somewhere between 1 GW and 4.2 GW by 2025, depending on the cost of solar, gas price and cost of financing. High solar uptake can be achieved with a reduction in solar prices which can occur due to changing market fundamentals, further declines in solar investment costs, and reductions in financing costs. There are also more technical issues around variability of solar (and wind), need for spinning reserve and transmission capacity.

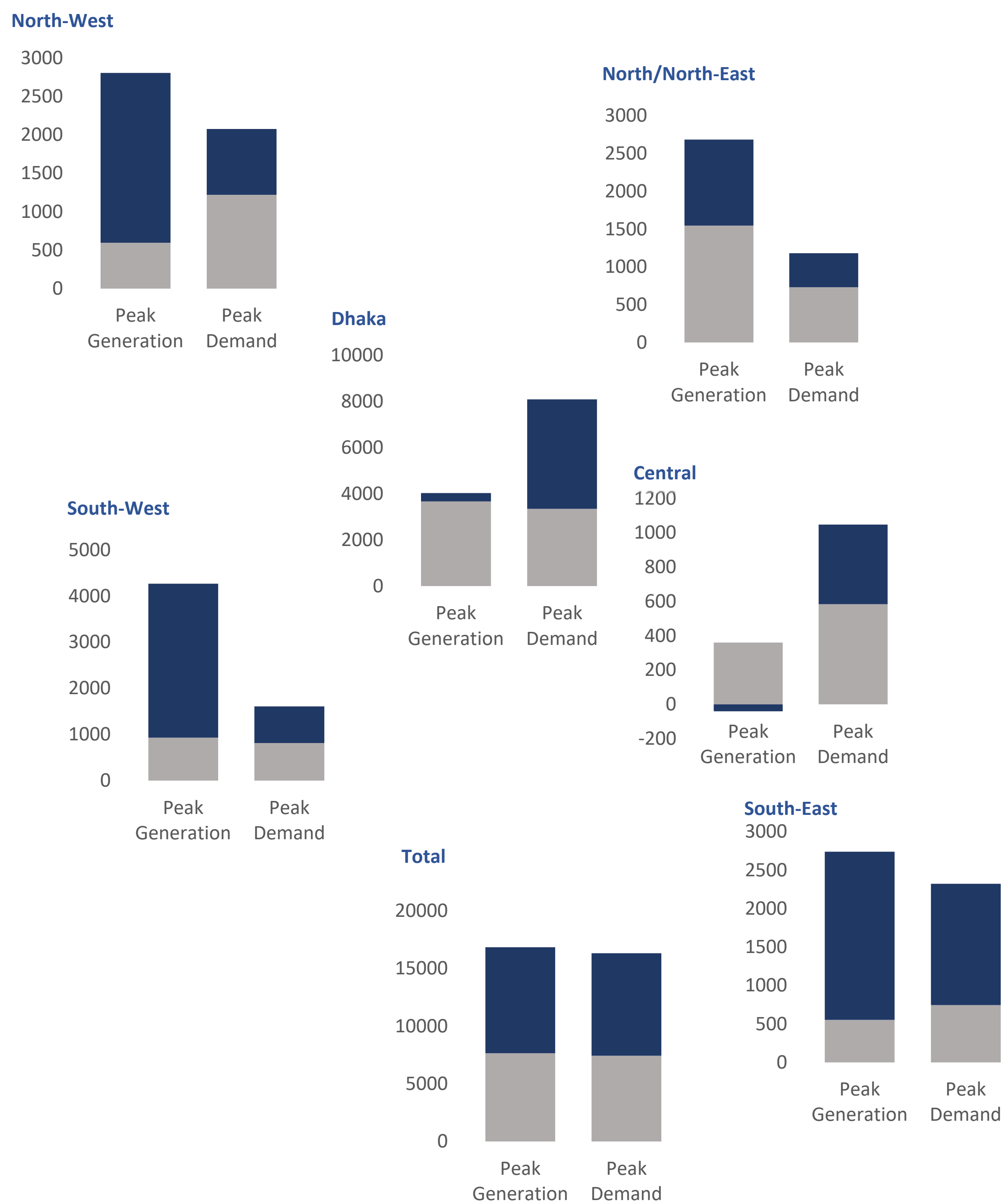
These issues require a comprehensive analysis starting with a long-term planning optimization, down to dispatch simulation and load flow. We found that although there is a more recent effort to foster a systems approach to analyze these issues, it is a relatively fresh beginning to implement such a methodology in practice, and the present work certainly is a new application of it for Bangladesh. There are also technical modeling issues around incorporating spinning reserve in a long-term planning model that are important in a country like Bangladesh.

Bringing together the economic and technical issues pertaining to solar and wind using a systems approach, reveals that these VRE resources would remain a relatively limited choice in the short to medium term till at least 2022, if not 2025. If renewable generation costs decline below USc6.5/kWh then solar and wind generation can attain up 4.2 GW of generation capacity. This, however, would require the availability of sufficient spinning reserve capacity. Indeed, spinning reserve needs to be rise from 501 MW to 880 MW by 2025 to support the deployment of 4.2 GW of intermittent renewable generation capacity. A more realistic target is in the range of 2,400-2,900 MW. Limited spinning reserve and/or continued low LNG price through the next few years might also restrict the potential to 1,000 MW. This is at a first glance a surprising conclusion for a country that is so devoid primary energy resources with rapidly expanding demand from a population of 160 million plus. This however does align better with observed reality that no major solar or wind projects have been implemented yet despite the talk around these since 2011.

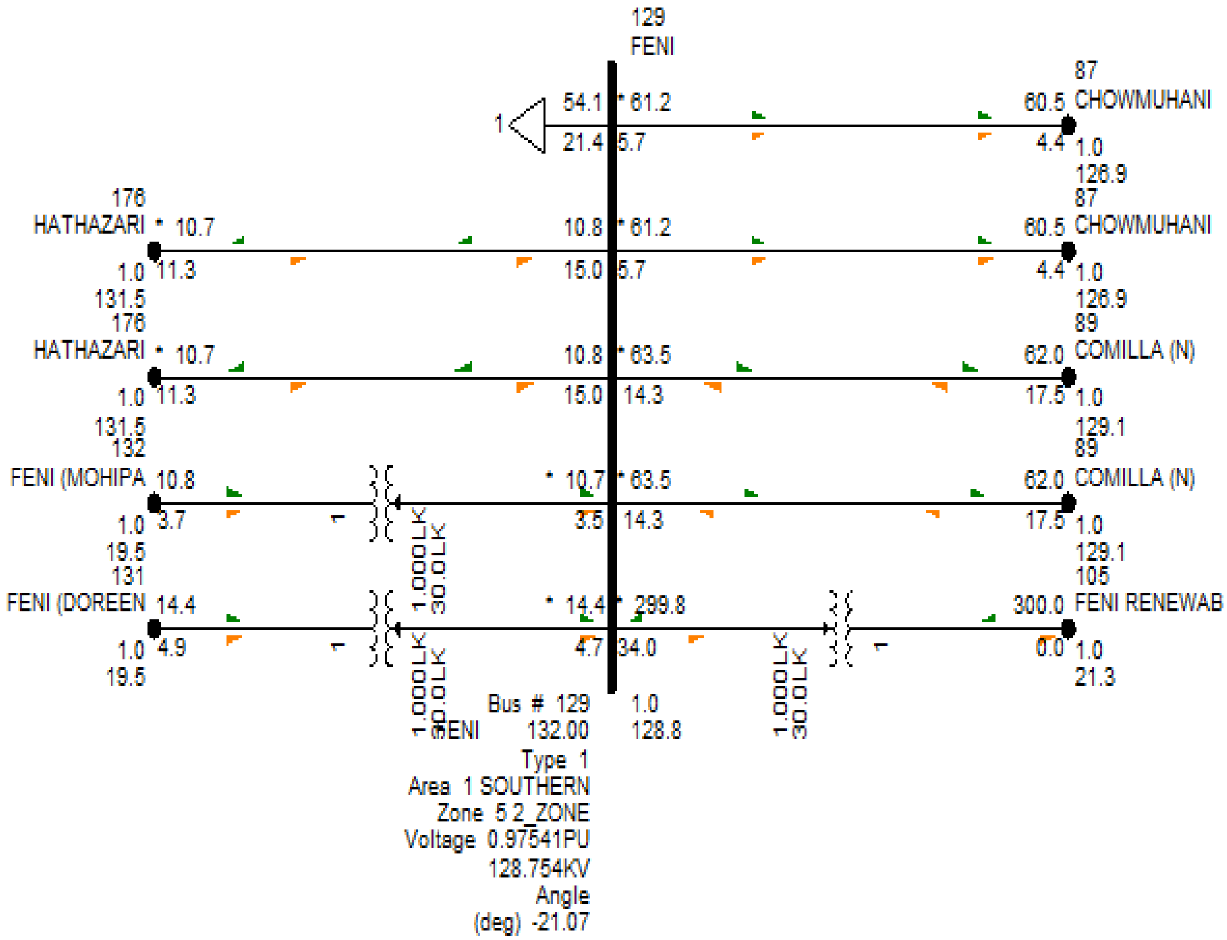
The planned transmission investments need to be realized to accommodate the additional generation capacity. Bangladesh faces the prospect of sustained, strong electricity demand growth. Given the geographic realignment in supply and demand, this necessitates the planned investments in 230 kV and 400 kV power lines to deliver the power to the Dhaka region, the main demand center. The good news, however, is that the projects in the order of several hundred MWs may be accommodated in the near term. For the immediate future, the Feni site does have the potential including adequate transmission evacuation capacity to accommodate the energy from the planned solar and wind park.

Appendix 1. Changes in regional peak generation and demand between 2015 and 2025 (MW)

Note: The grey areas of the chart show the 2015 value for peak generation and demand. The dark blue area shows the forecast changes between 2015 and 2025.



Appendix 3. PSS/E results showing the grid impact of connecting 300 MW of renewable energy generated to Feni's existing 132 kV substation



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