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Bangladesh power supply scenarios on renewables and electricity import

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ABSTRACT

Bangladesh, currently a low middle-income economy aspires to become a high middle income country by 2021. To achieve such aspiration, the country will have to ensure adequate power supply for its fast growing economy. Bangladesh lacks energy resources for power generation. This paper explores some of the power supply scenarios with special focus on power imports and higher use of renewables. Using the technology rich, least cost optimization model 'The Integrated MARKAL-EFOM System (TIMES)', the authors developed four possible future power supply scenarios for Bangladesh. These scenarios include an energy security framework (based on the Power System Master Plan (PSMP) 2016 report), a high power import scenario, a scenario with higher use of renewables and a combined high power import - high renewables development scenario. The analysis indicates that the present energy security framework ensures energy security with diversifying fuels used for power generation, however, scenarios with high power imports and a high share of renewables (including the combined scenario) bring down the cost of supplying power along with a reduction in expensive fossil fuel imports while maintaining energy security as fuel sources for power generation still remain diversified.

1. Introduction

Bangladesh is a low middle-income country with a per capita income of US$ 1400 [1] and an estimated GDP growth rate of 7.1% [2] in 2016. Goldman Sachs classified Bangladesh among the 'Next Eleven Economies' [3]. Bangladesh aims to cross the low middle-income threshold by 2021 [4]. Given electricity availability is a prerequisite for sustained economic progress, therefore, to achieve the set economic benchmarks, Bangladesh needs a manifold increase in the power availability from the current level of 281 KWh per capita [5].

Bangladesh faces numerous challenges in its efforts to ramp up electricity supply. Domestic natural gas, which is the chief source of primary energy in the country, is depleting fast. Unless new reserves are discovered and developed, the presently known resources are expected to get exhausted by the year 2023 [6,7]. Despite having large good quality coal reserves, domestic coal supply is facing issues like thick coal seams leading to high cost of extraction, the presence of reserves in densely populated regions, high costs of relocation and rehabilitation and negative public perception towards open cast mining [7]. Bangladesh has no oil reserves and depends on imports to fulfill the demand. It has plenty of water but lacks water flow with required height differences needed for electricity generation.

Awareness on renewables in Bangladesh is low, although, increasing. The Sustainable and Renewable Energy Development Authority Act, 2012 led to the establishment of the SREDA to ensure energy security. Although Bangladesh has a good potential for solar PV, it is a country with large population and small land area. The Government of Bangladesh (GoB) has stipulated that solar parks should only be developed on government-owned non-agricultural land or privately-owned uncultivable land [8]. SREDA study [8] estimated the resource potential for two cases including and excluding the agricultural land. In both cases, two percent of the eligible land was assumed to be suitable for development, in order to take into account potential land obstructions. Utility-scale solar PV potential becomes 1400 MW in Case 1, while 19000 MW is possible in Case 2. Assessment of wind energy potential is being carried out by the United States Agency for International Development (USAID), data are not available.

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Abbreviations

BPDB	Bangladesh Power Development Board
GDP	Gross Domestic Product
HEI	High Electricity Import
HVDC	High Voltage Direct Current
PDP	Power Development Plan
PSMP	Power System Master Plan
PPP	Public-Private Partnership
RES	Reference Energy System
TIMES	The Integrated MARKAL-EFOM System
CAGR	Compound Annual Growth Rate
GoB	Government of Bangladesh
HRE	High Renewable Energy
JICA	Japan International Cooperation Agency
LNG	Liquefied Natural Gas
PGCB	Power Grid Company of Bangladesh
PV	Photovoltaic
SREDA	Sustainable & Renewable Energy Development Authority

Given this domestic resource situation, for the expansion of the future power supply, Bangladesh has to depend on import, either input fuels for electricity production or output product electricity, posing energy security as a key concern. Energy security can be defined as the uninterrupted supply of energy from available sources at an affordable price [9]. Our purpose in this paper is to explore long-term power supply development options for Bangladesh that ensure energy security at cheaper costs. We have analysed the power system development over a 30-year horizon till 2045 by modelling Bangladesh power system using a technology rich multi-period optimization software TIMES.

Given that the country is resource-poor, securing the supply of energy is a straightforward and top priority. However, the methods to secure energy supply are different among different economies. Some countries have put great efforts in the 'diversification of energy supplies' to hedge against price fluctuation and other threats to the reliability of energy supply, particularly supply disruption [10]. Energy independence and self-reliance are the most important policy goals in some countries which include development of new and renewable sources and nuclear power (e.g Japan, Korea) [11]. In our paper, key focus is on electricity import from neighboring countries and extended use of renewables. It is clear, to ensure electricity supply, Bangladesh has no other choice but depending on large scale import, in the form of input fuels or final products (e.g electricity). Electricity import from neighboring countries at certain percentage would introduce diversification in power supply system, relieving country from building capital intensive and challenging fuel import and supply infrastructure (LNG infrastructure, transportation network, coal handling and port facilities) and their maintenance. More importantly, scarce capital could be diverted to other areas with pressing needs such as health, education etc.

2. Literature review

Long-term energy (power) system planning applying computer models is no new subject, is being carried out since the early 1970s [13]. A good review of various models and long-term electricity system planning is given by various authors [13–15]. In general, the available modelling tools can fit in two generic groups: one set is able to analyze the evolution of energy systems in the long-term, while the other set studies the energy balances for a small period of time with a higher resolution [16]. Recently, mostly due to the diversity and increasing amounts of available RE generation technologies, cross-border electricity trade which offers prospects of additional flexibility important to counter intermittency of renewables and reserve management, demand -side response, long-term energy systems planning models need to be more realistic and complex than ever before. The approach needs to account for the short-term dynamics of supply and demand to enable a better match and optimize resources complementarities [14]. The meso-scale gap has been identified by several authors who have brought closer long and short-term approaches using hybrid frameworks, combining more than one model [14]; however, this tends to be more complex and consuming in terms of computational resources. Given that TIMES has a modelling framework that is sufficiently generic to accommodate the features of both types of tools, as stated in Refs. [17,18], building a high time resolution TIMES model (option 1) allows the introduction of supply and demand dynamics while being able to optimize the energy system for a large time period, which is not done if using separate one year (dispatch) models (option 2) [16].

TIMES is a dynamic partial equilibrium optimization model as it finds the minimum cost solution for the exogenously given energy demand evolution through several time periods by making decisions on equipment investment and operation, primary energy supply and energy trade [16] [18]. The main advantage of TIMES, it is possible to sub-divide the year in several time periods with different lengths (defined by the user, allows four levels of time-slices), and this facilitates more detailed studies that need to incorporate higher dynamics in either supply or demand. However, given that the model uses an optimization algorithm and a very large number of technologies, the number of time periods will have a large impact on the computational complexity of the model. So far, no model is capable of optimizing an energy system for many years while looking at every hour of each year [16]. TIMES model is used extensively to analyze long-term scenarios, integration of renewables, trade scenarios, technology roadmap, capacity, and investment planning for the power system [14,16,19–21].

2.1. Modelling and planning of Bangladesh power system

Several studies have analysed issues (energy security, CO_2 reduction) surrounding the expansion of the Bangladesh power system applying different energy system modelling tools and considering various supply options. However, the modelling methodologies used are not adequate to simulate long-term scenarios while considering the hourly dynamics of supply and demand. A paper by Mondal et al. [22] examines the impacts of CO_2 emissions reduction on future technology selection and energy choices in Bangladesh power sector over the period 2005–2035 using the MARKAL (MARKet Allocation) modelling framework. It considered a menu of grid-based renewable technologies (large hydro, biomass, wind and solar PV) as future expansion options for CO_2 reduction. MARKAL is the predecessor of TIMES model, a generic model to represent the evolution of an energy system or sub-system (like electricity system) over a time horizon of usually 40–50 years. Entire time horizon can be further sub-divided into time-periods that are usually of 5 or 10 years long, but also allows some resolution as it recognises three seasons (Winter, Summer and Intermediate) and two diurnal divisions (Day and Night). This limited time resolution cannot capture precisely some of the important features of the modern power systems, e. g. intermittency of renewable sources, power trading. Additionally, electricity import and nuclear option are not included as options for future power supply. Both these options are counted as important candidates in current expansion plan [6]. Bangladesh has already (since 2013 [23]) started importing electricity from India and Ruppur nuclear power project is making progress.[1]

Habib et al. [24] analyzes use of renewable energy and domestic coal in place of imported coal and oil in the expansion of the Bangladesh Power System from 2010 to 2030 as a remedy for energy security and environmental abatement using Long-range Energy Alternatives Planning System (LEAP) model. The main concept of LEAP is the end-use driven scenario based analysis. Its scenarios are based on a comprehensive accounting of how energy is consumed, converted, and produced in a given region or economy under a range of alternative assumptions on population, economic development, technology and so on. LEAP model is not well-suited for power system analyses as it cannot capture many of system characteristics of the operation of the modern power system. Data used in this study are different from the present reality. It assumes that the first two nuclear units come online by 2017 and 2018, while another two nuclear units each of capacity 1000 MW are commissioned in 2024 and 2025 respectively. However, under the current plan [6], commissioning of the first unit of the nuclear power plant is postponed to 2023 and second one to 2024. This has strong implication for the future technology mix and capacity expansion plan. It assumes electricity import of 1750 MW, whereas, much higher amount of import is envisaged in the updated power plan. The capital cost of the nuclear option is taken as 2400 US$/KW which is less than half of the present updated cost. Solar PV cost at 2200 US$/KW, is on the higher side and is assumed to remain same throughout the study horizon ignoring the recent and upcoming rapid cost decline.

Timilsina et al. [25] assessed the potential economic benefits of cross-border electricity trade in South Asia (inclusive of Bangladesh) over the longer-term, i.e., 2015–2040. Using a mixed-integer-programming based optimization approach, the model simulates a base case that considers expansion plan for each country separately, incorporating only existing as well as currently committed transmission interconnections. The results of this base case are compared with the results of an unconstrained trading scenario for the region as a whole. Additionally, it has carried out several other scenarios and sensitivity analyses. As the focus of the analyses is a regional trade, it presents limited information related to the power sector development in an individual country like Bangladesh. Load curve representation is not detailed. The authors obtained data from the 2010 Power System Master Plan (PSMP) prepared by the Japan International Cooperation Agency (JICA), which is old and has been updated by JICA. An updated study [6] is now available and has become reference planning document for the Bangladesh Power Development Board (BPDB) and Ministry of Power. The capital cost of solar PV in the Base case at 2350 US$/kW is high and remains constant, ignoring the recent trend of rapid decline in solar PV cost. Base case projects the total installed capacity of Bangladesh in 2040 as 67.8 GW, with shares of coal, gas and nuclear are respectively 66.8%, 15%, and 0.9%. That is not in line with the current plans of the Bangladesh government with the concern of achieving of energy security through diversification. With 0.9% share, nuclear capacity would be just 618 MW in 2040, whereas, according to the current plan, two units totaling 2400 MW are expected to be online by 2024. It presents the cumulative generation over the period 2015–2041, making it difficult to make any comment.

The focus of the paper by Nikolakakis et al. [26] is robust dispatch optimization model for Bangladesh as they felt a careful scrutiny of power system operations and investment requirements is needed before adopting large-scale variable renewable generation. It also addressed the long term capacity expansion, supply reliability and options issues. These issues were analysed for the year 2014 including a comparison of actual and optimised dispatch and ramifications of different investment options that were being contemplated at the time. The paper applied a basic fuel-constrained dispatch optimization model with a further extension of the model to analyze investment decisions. The paper was critical about the 500 MW Solar Programme of the GoB estimated at $2.76 billion as was proposed in 2012. Comparing of available supply options, the paper concluded that enhancing the power import capacity followed by coal would be the best investment options in the near term.

Shukla and Sharma [27] projected electricity generation/demand of India and its neighboring countries by 2050 to identify the possibility of cross-border electricity trading in the region. To project electricity generation, demand and import/export in Bangladesh until 2050, authors projected electricity generation based on the generation capacity plan of Bangladesh by 2030 and based on the same growth rate of capacity additions thereafter. They projected electricity demand of Bangladesh to increase at a 9% CAGR through 2050 which is significantly higher than the current plan of the government. They found Bangladesh would depend on electricity imports from India and Myanmar to close its electricity shortage. Import amount is around 100 TWh in 2040 and more than 200 TWh in 2050.

Bangladesh has been doing power systems master planning exercise under the aegis of JICA since 2005 using a type of least-cost planning analysis [28]. With the time horizon up to 2030, the Government of Bangladesh formulated the Power System Master Plan 2010 (PSMP 2010) [29] targeting, among others, for a long-term energy diversification due to the foreseen decrease in the production volume of Natural Gas. However, when reviewed in 2015, energy development was not on track compared with the PSMP 2010 plan, because various assumptions about expected sources for base load energy have subsequently changed [30]. Not a single coal power project as identified by the PSMP2010 has seen reaching financial closure as of December 2014 [26]. Need for a review reflecting namely, exponential increasing of oil based rental power plants and development constraints of domestic primary energy was felt. Built upon the PSMP 2010, the PSMP 2016 [30], aims at formulating an extensive energy and power development plan up to the year 2041, covering energy balance, power balance, and tariff strategies. A long-term vision for the power source composition is created by estimating the future peak load demand based on a scenario of macroeconomic growth, simulating a demand/supply operation, and formulating the optimal power development plan (PDP). Two software PDPAT II and WASP IV were used as the tools for the simulation of supply/demand operation in the formulation of PDP [6] [30].

The optimum power source composition is determined by conducting a quantitative evaluation of the economic, environmental and energy security (3E) values of scenarios with different composition ratios for gas and coal power generation capacity. Five scenarios with the share of coal and gas in the total capacity varying from 15% to 55% by 2041 are investigated. The share of nuclear, PI (Power Import)/RE (Renewable Energy) and oil/hydro/others are kept constant at respectively 10%, 15% and 5% in the capacity mix in all these scenarios. The scenario with a share of both gas and coal in power generation capacity in 2041 at 35% has the lowest value for 3E assessment, and therefore is considered to be the optimum power generation mix and is used for the basic future power development plan (referred as Base Case in Ref. [30]). Two more renewable-focused scenarios with a share of renewables

[1] http://www.dhakatribune.com/bangladesh/power-energy/2017/11/30/pm-opens-rooppur-nuclear-power-plant-construction-work/.

respectively at 10% and 20% are developed. However, they increase the unit power generation cost significantly. Presumably, declining cost trend of renewables may not have been considered in these high renewable scenarios, leading to higher power generation cost.

Chattopadhyay et al. [28] carried out a critical review of models used in PSMP. They pointed out some of the basic physical constraints that govern power system operation that should be incorporated, such as, load balance constraints for each time period; generation (maximum) limits; fuel constraints that limit the consumption of different types of fuel etc.

3. Scope and structure of the article

Naturally, PSMP 2016 [30] of the Power Division, Ministry of Power, Energy and Mineral Resources, is the starting point of our paper. The primary objective is to understand the future options of secured electricity supply in Bangladesh to meet the projected requirement at the lowest cost to the economy. It applies TIMES model, which is an advanced modelling tool for power system analysis, capturing variation in load with higher time resolution (e.g. we have captured hourly load curve of a typical day in different months), intermittency of renewables, which are important for current day's power system planning with large presence of variable renewables. Scope of the study is limited to the power system assuming fuels will be delivered to the power plants at assumed prices and remaining part of the energy system, e.g., fuel supply infrastructures are not included.

3.1. Energy security and Bangladesh power system development

As stated earlier, PSMP 2016 has become the central planning document for the expansion plan in Bangladesh [30]. As per the recommendations of the study, the BPDB under the guidance of the Ministry of Energy has decided to adopt an energy security framework for the expansion of the Bangladesh power sector [30]. Under this framework, it is intended that by 2041, capacity from natural gas and coal will contribute 35% each, nuclear will contribute around 12%, electricity import 16%, liquid fuel 1% and hydro combined with renewables shall contribute 1% to meet the demand.[2] With increasing import dependence on fuels, the important feature of this framework is ensuring energy supply security through diversification of the resources used for power generation.

ADB study [7] on Bangladesh energy security concluded that renewables like solar and power trade with neighboring countries as sustainable options for Bangladesh. According to PSMP 2016, much before 2041, Bangladesh will become almost completely dependent on imports for its gas supply. Building and maintaining Liquefied Natural Gas (LNG) infrastructure is expensive and technically challenging. Gas market has remained highly volatile, with LNG price in Asian market touched about US 20/MMBTU not long ago.[3] While Bangladesh with its small demand cannot influence the international gas market, it can manage its relations with its neighbors. In that case, higher electricity import offers a more stable solution for cheap electricity and energy security which Bangladesh could explore. Current politically favorable conditions between India and Bangladesh and rapid increase in power import speaks further in favour of the same. Also, with the dramatic fall in renewable energy costs (solar PV), a higher presence of domestic renewable resources need to be investigated as part of the solution for cheap electricity and energy security, which has been ignored so far as renewable is almost invisible in BPDB's adopted energy mix for 2041.

Current paper uses Bangladesh TIMES model to develop scenarios on a higher share of renewables and electricity import to counter energy security issue. It takes into account the rapidly declining cost trend of renewable technologies and increasing electricity imports in Bangladesh. While indigenous renewable resources improve energy security by reducing fossil fuels import, electricity import not only offers quick and cheaper option (as it does not need the heavy investment needed for building fuel supply infrastructure or both heavy investment as well as long project planning and construction period of nuclear power plant), it can also help in diversifying electricity supply system of the country. It can also offer required system reserve in case of higher renewables. In Bangladesh, with the favorable political situation, electricity import from India is making rapid entry as a power supply source.

In section 4, we describe the existing Bangladesh power sector. TIMES model developed for the study is explained in section 5. Section 6 highlights the different assumptions used to model Bangladesh power system in TIMES and section 7 describes the scenarios. In Section 8, we report model validation and accuracy, while the results in detail are discussed in Section 9. In the last two sections, we conclude by highlighting major outcomes and way forward.

4. Bangladesh power sector

4.1. Electricity supply system

The last ten years have seen more than doubling of the power generation capacity (Fig. 1), which has increased from 5202 MW in 2007–08 to 12180 MW as of August 2016 [5,31]. The generation system of the country is dominated by gas-based capacity, fueled by domestically available natural gas. In order to overcome the shortage of electricity caused by rising demand and dwindling domestic supply of natural gas, the government has promoted installation of oil based plants in the form of 'Quick Rental Power Plants' (QRPP) using furnace oil and diesel in the last five years. Apart from natural gas and oil based plants, Bangladesh has limited hydro and coal based capacity totaling about 412 MW only.

Since 2013–14, Bangladesh has begun importing electricity from India. In 2013, a 500 MW interlink (at the Western side of the country) between Baharampur (India) and Bheramara (Bangladesh) commenced power supply. Another 500 MW of power is expected to be imported using the same line from 2018 [23]. 100 MW power is also being imported from Tripura (India) to Comilla (Bangladesh) (at the Eastern side of the country), since 2016.

The total electricity supply (Fig. 2) in 2014–15 including import was 45.84 TWh, almost double from the 2007-08 supply of 24.95 TWh. The dominance of gas in total power supply has declined from 84% to 64% and taken over by the rapid increase in the use of imported furnace oil. Electricity import was 3.38 TWh in 2014–15 and is growing rapidly.

As reported by the BPDB, the transmission losses have reduced sharply from 6.92% in 2007–08 to 2.77% in 2014–15. The reduction in distribution losses, on the other hand, has been gradual from 14.4% in 2007–08 to 11.2% in 2014–15.

4.2. Renewable energy

The Government of Bangladesh in 2008 came up with the Renewable Energy Policy with a goal to develop renewable energy resources to meet 5% of the total power demand by 2015 and 10% by

[2] Communication with key BPDB professionals.

[3] https://www.wsj.com/articles/asias-liquefied-natural-gas-prices-hit-the-brakes-1461586616.

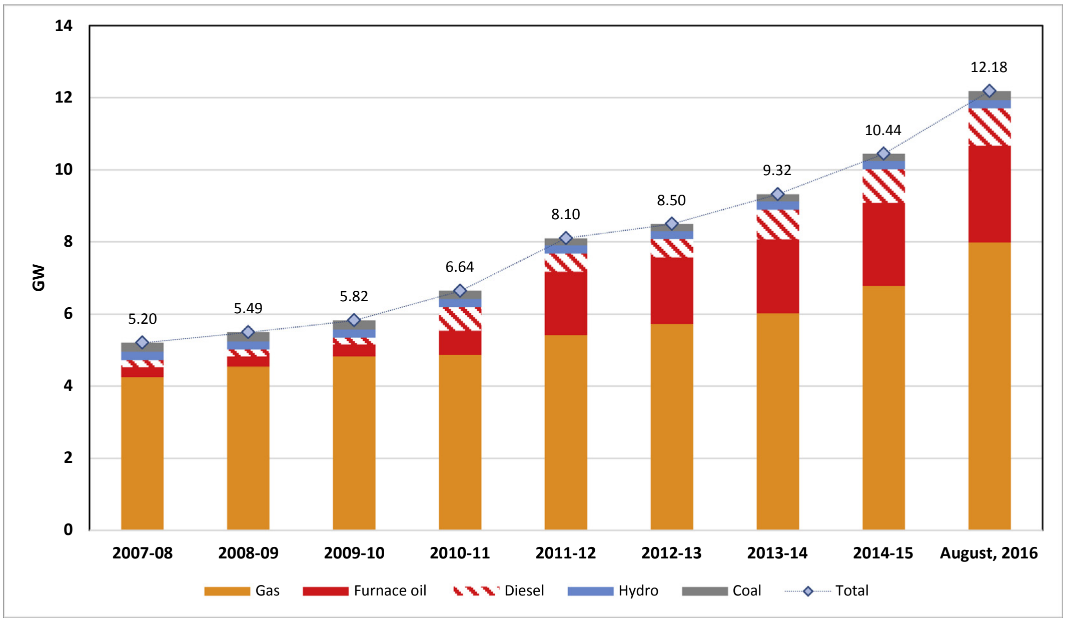

Fig. 1. Total power generation capacity development (by fuel sources) [5].

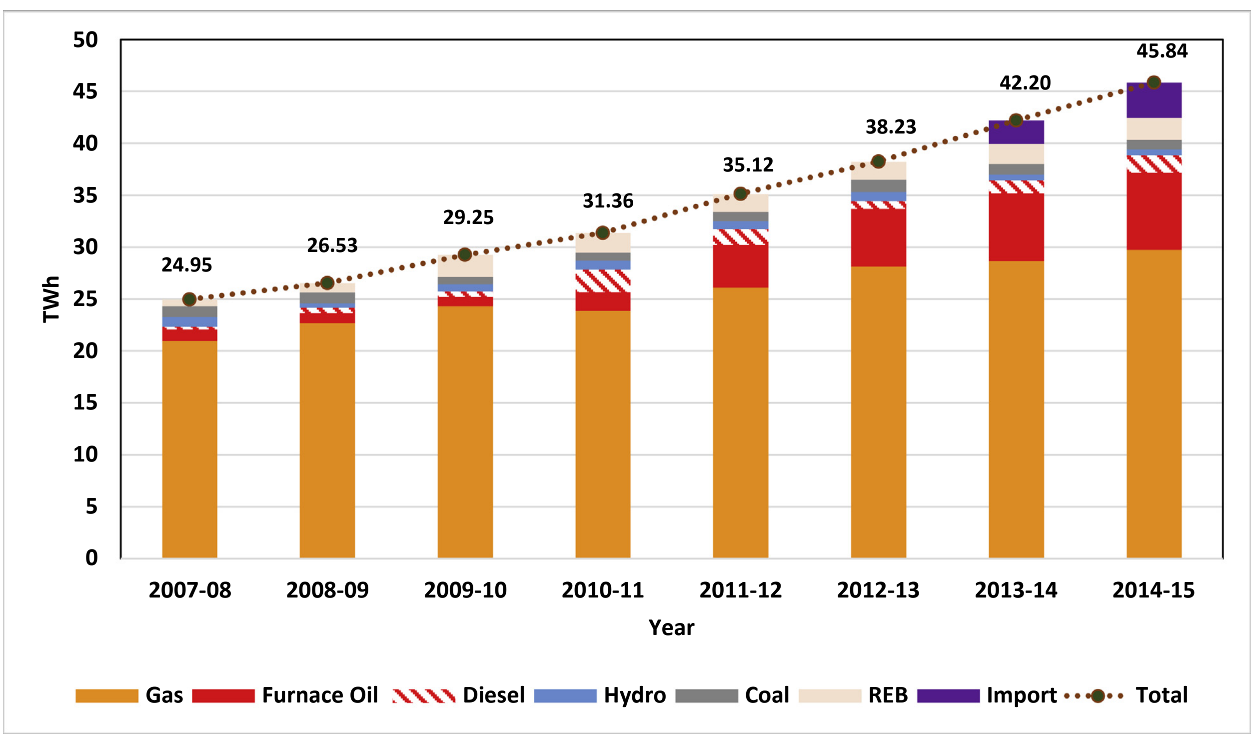

Fig. 2. Past development in electricity supply [5].

2020 [32]. However, progress on renewable energy development is slow. At present, total installed capacity is about 213.1 MW [33], mainly dominated by off-grid solar PV systems. On-grid solar PV and wind capacity is only 10.56 MW and 0.9 MW respectively, which is less than 0.1% of domestic capacity.

Bangladesh has on average 4–11 h sunshine throughout the year except for rainy season from June to August. It indicates that Bangladesh has a good potential for solar PV. As mentioned earlier, Bangladesh government has already stipulated a policy to prohibit farmland use for private solar projects, which limits the solar park potential to 1400 MW.

In October 2015, the SREDA released an investment plan [8] to meet two government directives on renewable energy investment. The first is the 500 MW Solar Program, developed in 2012. The objective of the program is to add 500 MW of solar generation capacity by 2016 through financing and implementing solar powered projects in both the public and private sectors. Other directive calls for an additional 3100 MW of RE capacity to be installed by

2021, of which grid based wind and solar PV capacity to be respectively 1370 MW and 1270 MW. However, first one has not materialized yet. Investment barriers, bureaucratic hassles, land constraint, financing challenges, lack of business models and transaction advisory on the structuring of the Public-Private Partnership (PPP) arrangement are some of the problems listed in SREP and in other published sources,[4,5] [8]. Plan beyond 2021 is not available.

5. Bangladesh TIMES model

A reference energy system (RES) network that links resource supplies, energy conversion, and processing technologies, and end-use demands and the devices that meet them, tracking the flows of energy and associated emissions [20] is the foundation of the TIMES model. RES can include the whole energy system or a sub-system, in our case, it is Bangladesh power system. The physical power system of Bangladesh representing the physical structure (power plants, transmission and distribution infrastructure etc.) and the flows in the power system have been modelled in TIMES. This includes characteristics of the various existing generating stations (vintage, techno-economic performance, rehabilitation schedules, etc.), under construction and committed projects, future power generation options, transmission and distribution, energy flows, demand, load characteristics, energy resources and import/export links. Fig. 3 presents the simplified energy flow network for the Bangladesh electric power system including the existing and expected future alternatives that have been modelled.

The model finds the least-cost path through the RES network to meet user-specified electricity demand, subject to constraints that enforce network integrity as well as any user-imposed (policy) constraints by performing a perfect foresight, perfect information minimization of the net present value of total energy system costs, including the capital and operating costs of all devices, fuel costs built up from stepped resource supply curves, and any taxes and subsidies the user imposes. The electricity demand, time variant load profile and potential supply options variant (resource, technology, various costs, etc.) constitute the model inputs, while new investment requirement in generation capacity, optimal generation and trade schedule, electricity supply cost, emissions etc. are the outputs. It solves for the twin objectives of satisfying power demand at every user-defined time step at the least possible costs. The main advantage that TIMES has regarding its predecessors is its flexibility as it is possible to sub-divide the year in several time periods with different user defined lengths [14].

In Bangladesh TIMES model, the year 2012 is considered as the base year with a modelling horizon of 40 years. The data input years are at a gap of 5 years, i.e., 2012, 2015, 2017, 2022 … 2052 with 2015 being the only exception. The reporting years are also at a gap of 5 years, beginning at 2015 up to 2045.

PSMP 2016 [6] [30] assumed an evolution in load shape over the period 2015–2041. However, available data are not adequate to capture the changes in load shape in our model. Therefore, daily load curve for the year 2015 has been replicated throughout the model horizon. Time resolution is quite detail to capture the seasonal, daily and hourly load pattern as well as the supply of certain resources like hydro, solar and wind. The 8760 hourly load has been arranged into 288-time slices (=12*24, 12 seasons where each month represents a season and 24 hourly load of an average day in each month). The model balances the demand and supply for each time slice (hourly load of a typical day) at minimum cost. This temporal resolution can capture some demand and supply characteristics of the power system, for example, the seasonal variability of renewables, as well as part of the load variability [21]. In the case of a system with high penetration from renewable energy, this fine time resolution enables the analysis of possible advantages of using/building interconnections to import from or to export to the neighboring country in enhancing the technical and economic viability of the grid integration of renewable sources.

All costs in the model are at constant 2015 prices and an inflation[6] free real discount rate of 4% has been considered. A comprehensive list of power generation technologies and fuel options are considered for the future expansion of the Bangladesh power system.

6. Assumptions

6.1. Development of electricity demand

PSMP 2016 reported peak load demand projection for the period 2015–2041 assuming an average GDP growth rate of 6.1% over the period, a constant electricity-GDP elasticity of 1.27 and effect of energy conservation. However, TIMES model demand input is energy and not load. Peak load estimates for the period 2015–2041 is used as input for energy demand analysis. Beyond 2041, peak load is calculated assuming the average growth rate during the period 2036–41. Due to the unavailability of the detailed information how load shape will evolve in future, system load factor of 2014/15 is applied to estimate energy demand for the entire modelling horizon. Energy demand at consumer end is estimated by netting the T & D loss. In recent past, Bangladesh has been able to progressively reduce the T&D loss. However, current T&D loss at 13.5% is still much higher than the industrialised countries like Germany (4%), France (6%)[7] despite having much larger geographic area than Bangladesh. JICA has reported in Bangladesh Power System Master Plan 2016 [6] as T&D loss to decline to 11.5% in future. However, the study recognises this as high as distribution companies will try to reduce social loss component (theft). After discussion with professionals from the BPDB and Power Grid Company of Bangladesh (PGCB), we have assumed T&D loss to decline from 13.5% in 2015 to respectively 9%, 7% and 6% in 2030, 2040 and 2050. Fig. 4 presents the energy demand as assumed in the model. It is to be noted that, despite this high demand growth rate, per capita electricity consumption in 2030 and 2050 would be 749 kWh and 2120 kWh respectively, much lower than the present per capita consumption of the industrialised countries.

6.2. Techno-economic assumptions

Existing power system (as on 2015) is the starting point which includes generation plants by vintage, represented by their technical and economic performance parameters. Typical techno-economic performance parameters are the type of fuel use and fuel costs, thermal conversion efficiency, availability factor, non-fuel operating and maintenance costs, year of initial grid connection and technical service life time, specific emissions, etc. Source of data includes JICA study [6], various BPDB annual report [31] and

[4] http://documents.worldbank.org/curated/en/417631501592121920/pdf/PIDISDS117815-P161869-PUBLIC-Bangladesh-SREP-PDISDS-Concept-Stage-revised-June-2017-Cleared.pdf.

[5] https://scroll.in/article/815806/why-a-power-plant-planned-on-a-bangladesh-island-may-not-be-such-a-bad-thing.

[6] Based on the World Bank data, average inflation rate during 2012–2016 was 6.72%, therefore, nominal discount rate would be 10.72%. https://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG?end=2016&locations=BD&start=1961.

[7] https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS.

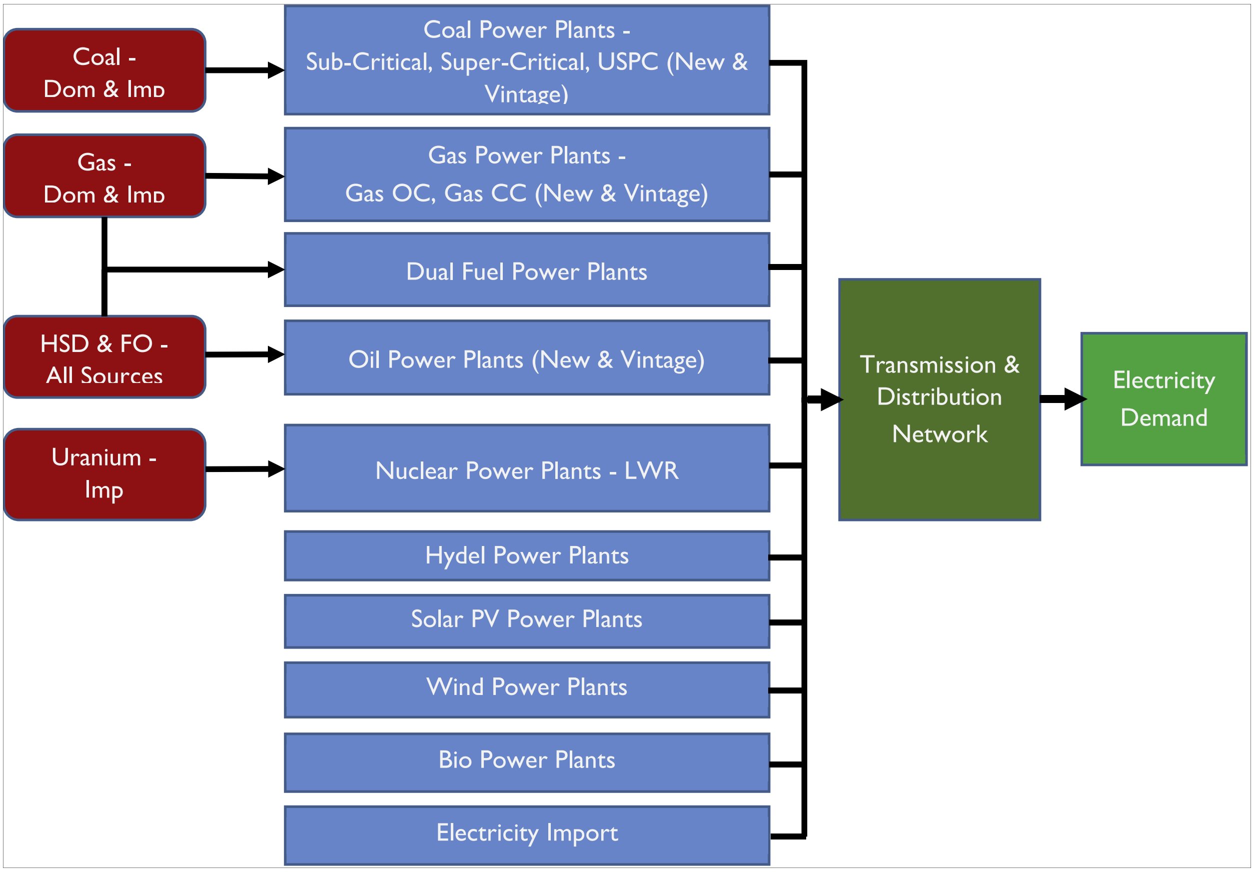

Fig. 3. Simplified Reference Energy System for the Bangladesh power system.

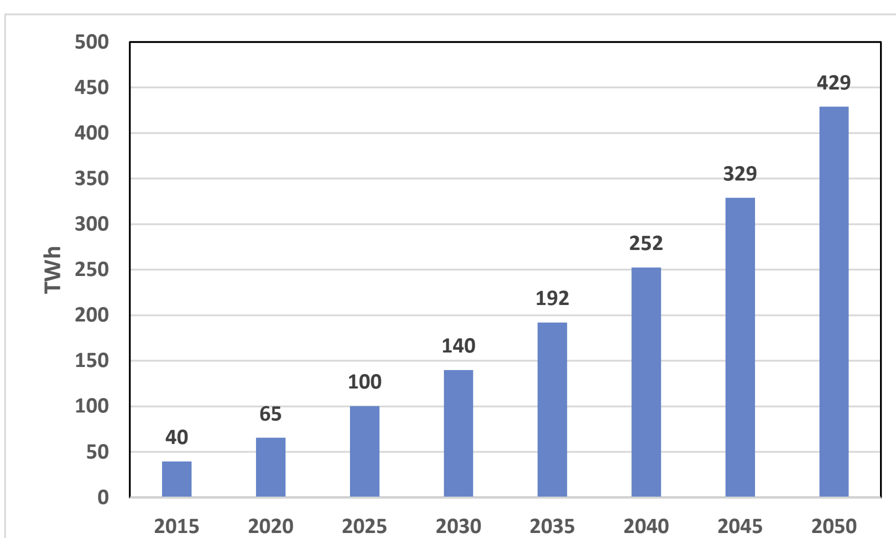

Fig. 4. Electricity demand development.

personal communication with the BPDB officials.

As existing stock retires (calculated by the model based on the inputs on their installation year and assumed life) and demand grows, new capacity needs to be built. The model assumes a menu of technology options for the future expansion of the Bangladesh power system, such as super critical and ultra-super critical coal power plant, combined cycle and open cycle gas power plant, nuclear power plant using light water reactor technology, solar PV, wind, and so on, represented by the technical and economic data. Assumptions on techno-economic data used as model inputs are tabulated in Tables 1 and 2. The data assumed are sourced from published sources or from officials at BPDB and SREDA by personal communication. The capital cost of solar PV and wind for the year 2015 has been taken from SREDA [8]. Reduction in capital cost of

Table 1
Assumptions on technical and economic parameters of power generation technologies.

Parameter/Tech	Gas (CC)	Gas (OC)	Oil	Dual Fuel	Nuclear PP	Coal (Sub) PP	Coal (SC) PP	Coal (USC) PP	Wind PP	Solar PV	Biomass	Hydro
Technology Data												
Thermal Efficiency	0.57	0.38	0.35	Gas - 0.45 Oil - 0.43	–	0.35	0.37	0.43	–	–	0.3	
Fuel Type	Gas	Gas	Oil	Gas and Oil	Uranium	Coal	Coal	Coal	–	–	Rice husk	
Annual Availability Factor	<.85	<.90	<.80	<.85	<.90	<.80	<.80	<.80	<.21	<.18	<.60	<.50
Operational Life Time (Year)	25	20	20	25	60	30	30	30	25	25	20	80
Construction Period (Year)	3	2	2	3	8		5	5	2	2	2	6
Economic Data												
Overnight Cost ($/kW)	667	899	899	667	5000		1038	1400	1812[a]	1551[a]	2059	1861
Fixed O&M Cost ($/kW/year)	30	30	30	30	78	23	25	39	35	26	125	18

[a] Capital costs decline over time and are presented in Table 2. Source: Personal communication with Bangladesh Power Development Board (BPDB) officials; Figures for wind, solar PV and biomass are from SREDA Report [8] and also based on personal communication with SREDA officials.

Table 2
Capital cost (in US$/kW) development in solar PV and wind technology.

	2015	2017	2022	2027	2032	2037	2042	2047	2052
Solar PV	1551	1374	932	667	667	667	667	667	667
Wind	1813	1769	1660	1595	1595	1595	1595	1595	1595

Source [34].

solar and wind power plant over the time horizon, has been modelled. Based on an IRENA study [34] on cost reduction potential to 2025, it is assumed that the cost of solar and wind power plants reduces by 57% and 12% respectively between 2015 and 2025 after which the same stabilises (Table 2).

Under constrution and committed projects are included in the model. The third unit of Barapukuria coal-based power plant in Dinajpur is underway to add 275 MW to the national grid by 2018 which will use domestic coal. All other new coal-fired power plants are assumed to be either super or ultra-supercritical in nature and will be powered by imported coal only. The first reactor of Ruppur nuclear power plant is assumed to be commissioned in 2023 and the second unit in 2024. SREDA targets on the installation of grid based wind capacity of 1370 MW, solar PV of 1270 MW, and biomass power of 54 MW over the period 2015–21 are also modelled. However, beyond 2021, due to the lack of information, no growth in capacity of any of the renewable technology is assumed.

For solar PV, average daily hourly availability factor for each month is input to the TIMES model which is calculated using PVWatts[8] calculator of NREL. Dhaka is used as a representative location for Bangladesh. As stated earlier, wind mapping in Bangladesh is underway. An average annual availability factor of 21.1% is assumed.[9] For hydro power plants, we also consider seasonal availability factors.

6.3. Resource availability and price assumption

Assumptions on annual availability of domestic coal are based on the production data available from JICA study [6]. We have estimated the domestic natural gas availability for the power sector. Data on recoverable reserve of domestic gas is taken from BP statistics. Petro Bangla has a 5-year gas production plan till the year 2021. Balance recoverable reserve in 2022 is calculated by netting cumulative production till 2021 from the recoverable reserve. Annual production in 2021 is then extrapolated until reserve exhausts by 2027. The current share of power sector in total annual gas production is assumed to calculate the future gas availability for the power sector. Table 3 presents the assumptions on annual availability of domestic gas and coal for power generation. No restrictions have been applied to the availability of imported coal, gas, oil and nuclear fuel.

Fig. 5 shows the year-wise fuel price Assumptions at 2015 US$. For the year 2015, actual price has been considered and the price for the future years has been sourced from JICA study [6]. Currently, the domestic gas used for power generation is available at a heavily subsidized price. Gradual removal of subsidy is assumed and the domestic price will converge to the international gas price.

7. Scenarios

Four scenarios have been constructed for this study – (a) PSMP scenario, (b) High Electricity Import (HEI) scenario, (c) High Renewable Energy (HRE) scenario, and (d) High Electricity Import + High Renewables Energy (HEI + HRE) scenario.

7.1. PSMP scenario

Scenarios are developed in consultation with the BPDB officials. Under the guidance of the Ministry of Energy, after examining various scenarios presented in the Power Sector Master Plan 2016, the BPDB has developed a framework for future expansion of the system driven by the energy security concern. A key objective of this framework is achieving energy security through diversifying the energy sources used for power generation. Accordingly, shares of capacity based on coal, natural gas, nuclear, electricity import, liquid, hydro and renewables are fixed respectively at 35%, 35%, 12%, 16%, 1% and 1% of total power generation capacity by 2041. Naturally, our Base or Reference scenario is based on BPDB's expansion framework and we name it as PSMP scenario.

To make the scenario results more stable and meaningful, PSMP scenario, however, follows the same resource mix in the energy as in BPDB expansion framework, instead of capacity as considered by the BPDB. Therefore, the share of coal, natural gas, nuclear, electricity import, liquid, hydro and renewables in total energy supply (generation plus import) would be respectively 35%, 35%, 12%, 16%, 1% and 1% by 2041. Shares for intermediate years are estimated based on linear interpolation. Therefore, for current gas dominated power system, while the share of gas in total supply is expected to decline from current level of 70%–35% by 2040, the share of coal increases from 2% to 35% in 2040. Also, to accommodate the 2015–2021 renewables target of SREDA, the share of the liquid has been reduced. These targeted generation shares of 2041 will continue thereafter. This is also the Reference scenario for our study and other scenario results are compared with this scenario.

In order to take into account the existing power purchase

[8] http://pvwatts.nrel.gov/index.php.

[9] We developed a version of the model that used hourly availability factor by month of on-shore wind calculated using the hourly wind data for the Indian state of Maharashtra for the year 2014 as representative data. However, that model is not used for the current analyses.

Table 3
Annual availability of domestic coal and gas for power generation.

	Unit	2012	2015	2017	2022	2027	2032	2037	2042	2047	2052
Coal	Million tonne	0.86	1	1	1.6	2.6	6.2	10.2	11.2	11.2	11.2
Natural gas	Billion cubic feet	326	392	404	469	469	0	0	0	0	0

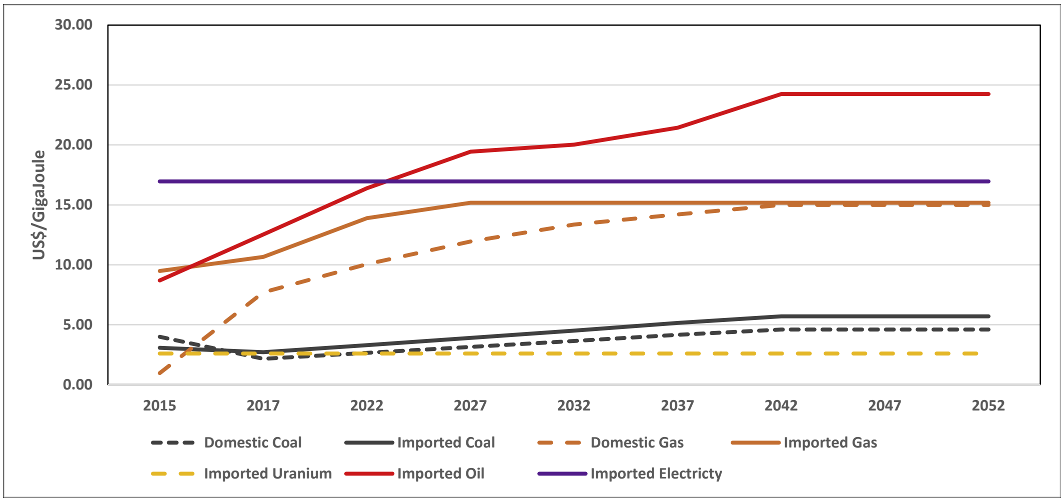

Fig. 5. Fuel price development.

agreements, 50% of 2015's electricity supply from India has been fixed as minimum import level for the technical lifetime of the HVDC link. JICA study [6] also has assessed the potential of the interconnection capacity, which has been used as an upper limit in the model (Table 4).

7.2. Other scenarios

According to PSMP 2016, Bangladesh in 2041 will be completely dependent on import for natural gas. The natural gas market in the past has been highly volatile, and not long ago the price of Liquefied Natural Gas (LNG) in the Asian market touched 20 US$/MMBtu. In contrast, the hydro potential in neighboring South Asian counties is in the range of 350 GW, of which only 14% is exploited so far[10] and is, therefore, waiting for a larger market for further exploitation. Renewables (solar, wind, biomass) are also abundant in the region.

High Electricity Import (HEI) scenario examines the economic implications when electricity import share is raised to 30% (of the total electricity supply) as compared to 16% in the PSMP scenario. The upper limit on interconnection capacity (presented in Table 4) is removed. It is assumed that electricity import will replace domestic electricity generation using imported gas. 35% gas based generation share constraint is also removed.

Table 4
Upper limit on Power Import Capacity (GW).

Year	2025	2030	2035	2040	2045	2050
Capacity	3	5	7	9	9	9

[10] http://www.irade.org/Need%20to%20institutionalize%20cross%20border%20border%20Electricity%20Trade%20in%20South%20Asia%20by%20V.K.Kharbanda%20and%20Rajiv%20Ratna%20Panda-Infraline%20Plus.pdf.

It is described in Section 1, the SREDA study [8] projected utility scale solar PV potential as 1400 MW in Case 1, and 19000 MW in Case 2. The SREDA findings are broadly in line with the RE estimates developed by Mondal and Denich [22] in 2010 which also found a very high (50 GW) potential for solar PV and 4.6 GW of wind potential. Extensive studies were also conducted by Halder et al., in 2014 and 2015 [35] and more or less conclude the same array of RE opportunities in Bangladesh. The common theme across all of the recent studies is that solar is the leading RE resource in the country [26]. The High Renewable Energy (HRE) scenario considers enhanced penetration of renewable energy. Based on the available published information, the potential renewable capacity has been enhanced to 4.6 GW of wind and 10 GW of solar PV and assumed to be completely exploited respectively by 2030 and 2040.

High Electricity Import + High Renewables (HEI + HRE) Scenario combines the measures taken separately in the above-mentioned last two scenarios and explores the economic implications while ensuring energy security through a reduction in fuel import dependence and diversification. Table 5 presents how different scenarios varies from the PSMP scenario.

8. Model validation and accuracy

The model is validated for its accuracy in reproducing the evolution of electricity supply and demand for the years 2012 and 2015. To determine the accuracy, the outputs from TIMES for the years 2012 and 2015 on electricity production, technology mix, capacity were compared to real data provided by BPDB on a yearly basis. It is found that model reproduces the capacity and generation by technology for these two years within acceptable variations.

9. Results

In the long run, the model estimates the electricity generation and capacity required to meet the given energy and load demand at each defined time slice. To meet such demand, the model chooses

Table 5
Variations in various scenarios over the PSMP (Reference) scenario.

Variant	PSMP	HEI	HRE	HEI+HRE
Share of electricity import in total supply	16%	30%	16%	30
Upper limit on interconnection capacity	Yes (according to Table 4)	No	Yes (according to Table 4)	No
Constraint on minimum share of gas as 35%	Yes	No	No	No
Maximum Solar PV capacity (grid) in GW	1.3	1.3	10	10
Maximum Wind capacity in GW	1.4	1.4	4.6	4.6

the cheapest option first and progressively moves to options that are more expensive simultaneously complying all constraints and bounds. Detailed analysis of capacity, generation (by technology, daily/season), fuel demand, CO_2 emissions, and costs are presented in the following sections. Wherever available, the model estimates are compared with the available estimates.

9.1. Capacity

Fig. 6 presents the capacity requirement in four scenarios. Power generation capacity stood at 12.18 GW as on August 2016. In PSMP scenario, to meet the rapidly increasing electricity demand, the total capacity needs to be doubled by 2025 to 24.5 GW. It needs to grow by 42% and 64% in next successive two decades, to reach 39 GW and 65 GW in 2035 and 2045 respectively.

Power System Master Plan (PSMP) 2016 projects annual generation capacity requirement up to the year 2041 [30]. We compare the projections for the years 2030, 2035 and 2040 with our estimates. Given PSMP 2016 is the starting point of our study, as expected, our estimates in these years are close to the PSMP 2016 projections. Our projections are respectively 31.5 GW, 38.9 GW, and 50.7 GW as compared to 31.1 GW, 40.9 GW, and 53.9 GW projected in PSMP 2016. Slightly lower estimates in our case for the future years can be explained by slight variations in assumptions of the values of certain parameters. For example, low T&D loss over time as assumed in our study could be one factor as it reduces the capacity requirement.

Future technology mix in the PSMP scenario is subject to the upper limit on fuel mix imposed in this scenario with the objective of diversifying the power system. It is also influenced by the cost of power generation and availability of fuels. On the whole, as expected, until 2045, evolution in technology mix in this scenario mimics the projection made in the power development plan (Base case) PSMP2016.

Natural gas is domestically available and has long been the fuel of choice for the Bangladesh power system. This trend continues in the 2020s. However, as the domestic gas price is assumed to converge to the international price, coal becomes the cheapest option for power generation in the country. As domestic gas is used up by 2027, additional gas-based capacity is fired by imported gas which is more expensive than all other available options like imported coal, nuclear or electricity import. As structured, future power generation capacity is significantly diversified with a combination of base load plants using coal, nuclear or gas CC and peaking option based on gas open cycle and electricity import. Future gas power plants would be primarily combined cycle type. Gas based capacity is expected to be 12.3 GW in 2025. As existing plants retire and domestic gas becomes expensive and availability declines, gas capacity declines to 10.0 GW in 2030. However, thereafter, driven by diversification concern, gas bounced back and new capacity is added. Gas based capacity is 13.8 GW, 18.7 GW and 24.6 GW in 2035, 2040 and 2045 respectively. While projection in 2035 is slightly lower than the projection of the power system master plan, figures for 2030 and 2040 match quite well.

Government's power development plan (Base case) projects coal capacity in 2020 as more than 5 GW which is clearly will not happen as till today (2018) none of the coal power projects has taken off. The same document projects coal capacity as 7 GW in 2025 [30], while our projection is 2.1 GW. Despite being cheap, committed gas and nuclear capacities restrict the entry of coal till 2025 in our study. However, our projections from 2030 and onwards are quite similar to the Government's Power development plan (Base case) at respectively 8.6 GW, 10.1 GW, 14.3 GW and 18.6 GW in 2030, 2035, 2040 and 2045.

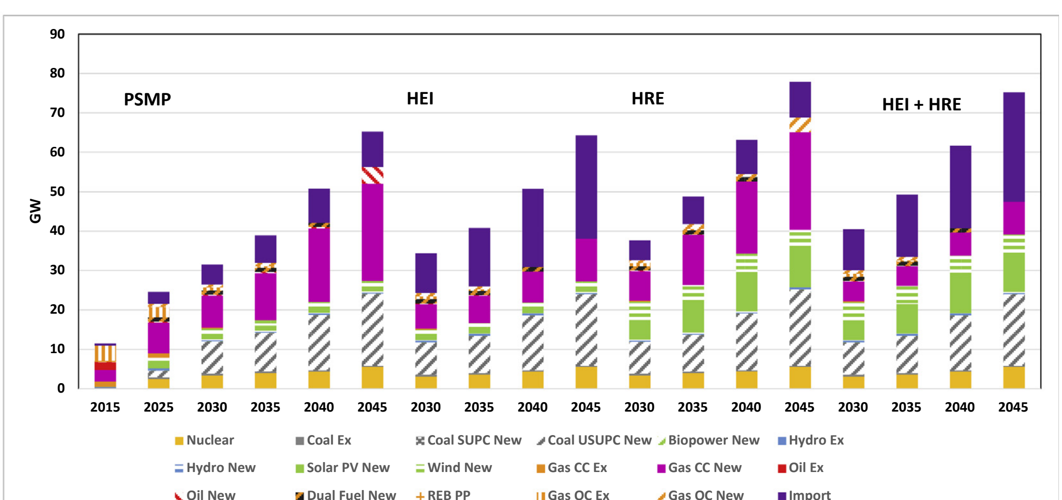

Fig. 6. Scenario wise installed capacity.

The first nuclear unit is assumed to be in operation in 2023 and then the second one in 2024, together totaling 2.4 GW by that year. By 2045, about 5.5 GW of nuclear capacity will be a part of the Bangladesh power system. Although better than the present, from 2021 and onwards, only 1.3 GW of solar PV and 1.4 GW of wind become part of the power system. Despite being cheaper than all options except coal, the upper limit on capacity (following the Government's Power Development Plan) restricts the import capacity at respectively 3 GW, 7 GW and 9 GW by 2025, 2035 and 2045 respectively.

As electricity import is cheaper than all options except coal, therefore, when a higher amount of import is allowed in HEI scenario, higher interconnection capacity is the preferable choice. Import capacity is significantly higher than the PSMP scenario, e. g 14 GW and 26 GW in 2035 and 2045 respectively as compared to 7 GW and 9 GW in PSMP scenario. Bangladesh needs to build less domestic power plant capacity as capacity would be available through import. Gas based capacity would be 8 GW and 10.8 GW in 2035 and 2045 respectively, as compared to 13 GW and 24.6 GW needed respectively in the PSMP scenario. Bangladesh, therefore, can save a substantial amount of investment in power generation capacity which could be flown into other sectors with pressing needs.

Renewable capacity in the PSMP scenario remains constant at 2.7 GW from 2021 and onwards assuming Bangladesh's current reluctance towards grid connected renewables will continue. However, with current rapidly declining capital and other costs, solar PV and wind are already cheaper than most of the available power generation options. HRE scenario demonstrates that the enhanced renewables option is economic despite its intermittency that needs back-up capacity. Entire available potential capacity is absorbed by the system for both solar PV and wind. Renewable capacity is much higher respectively 4.8 GW, 12.1 GW and 14.6 GW in 2025, 2035 and 2045. Availability of renewable capacity (solar 16% and wind 21.5%) is low, so there is a need for back-up capacity. On the whole, the total capacity requirement in this scenario is higher by 9.9 GW and 12.6 GW respectively in 2035 and 2045 that of the PSMP scenario. Both gas combined cycle and open cycle plants which are flexible in operation compared to other options supply the back-up capacity needs, therefore, there is an increase in gas based capacity.

Instead of gas power plants supplying back-up capacity as additional import capacity is not available in the HRE scenario, in high renewable and high electricity import (HEI + HRE) scenario, import capacity supplies the back-up capacity needed for integrating higher renewable capacity in the grid. There is a substantial reduction in gas capacity than HRE scenario which introduces a higher amount of intermittent renewables in absence of higher import availability. Therefore, opting this scenario Bangladesh can reduce dependence on imported gas which has a volatile market.

9.2. Generation and import

Fig. 7 presents the electricity generation mix by scenarios. As demand growth is very high, Bangladesh needs to increase electricity generation by almost two and half times in 2025 from its 2015 generation level. Sharp growth in generation is needed thereafter also. Gross generation in 2025, 2035 and 2045 is respectively 103 TWh, 184 TWh, and 310 TWh as compared to 44 TWh in 2015. Import in these years would be respectively 14 TWh, 34 TWh and 59 TWh.

At present with subsidized gas price, production of electricity using domestic gas is the cheapest among all options. This scenario is constructed following the central expansion plan of the Government of the Bangladesh. Contribution from renewables remains invisible in electricity supply. Future generation mix is driven by the shares imposed on technologies, as well as the cost of generation, fuel availability, and type of load needed, i.e., peak and off-peak.

Current gas dominated power generation system is diversified over time in the PSMP scenario, with coal and gas equally dominating the generation followed by nuclear and import. In 2025, as domestic gas still remains cheaper and available for power generation in sufficient quantity, gas dominates the power generation, followed by nuclear. Entry of two nuclear units totaling 2.4 GW reduces the generation from coal power plants. Import would increase rapidly, contributing about 13.9 TWh, up from 3.8 TWh in 2015. Import is higher in summer months when demand is high and needed throughout the day, whereas during winter months, import is needed primarily in the evening to meet peak. Renewables make a small contribution of 4.6 TWh, less than 5% of the total generation, however, becomes visible in the generation mix.

Thereafter, generation mix is primarily driven by the shares of different fuels as specified in the PSMP scenario. By 2045, both coal and gas contribute an equal amount of 129 TWh, followed by import of 59 TWh. Nuclear contributes 43 TWh and contributions from renewables remain same at 4.6 TWh.

In HEI scenario, the allowance on higher electricity import increases import to 40 TWh in 2030 as compared to 22.8 TWh in 2030 (PSMP scenario). Import in later periods almost doubles as compared to the PSMP scenario. As designed, import replaces gas based electricity generation in this scenario. Gas based electricity production accounts for 28% and 20% respectively in 2030 and 2040 as compared to 39% and 35% in the PSMP scenario. Generation from coal and nuclear remains same.

In the HRE scenario, Bangladesh benefits from the higher generation of renewable energy which replaces the most expensive option-imported gas. Generation from renewables is 15.7 TWh and 22.7 TWh in 2030 and 2040 respectively, whereas in PSMP scenario it remains constant at 4.6 TWh from 2025 onwards. There is about 14% reduction in gas based generation over PSMP scenario. However, higher exploitation of renewables needs a paradigm shift with very aggressive policy efforts discussed in the concluding section.

Higher electricity import and higher use of renewables (HEI + HRE) together substitute generation based on imported natural gas by more than 50% compared to the PSMP scenario. The share of gas in total generation in 2040 would be 14% as compared to 35% in PSMP scenario.

9.3. Seasonal and hourly generation

Figs. 8 and 9 present the hourly electricity supply in a typical day in the winter month of January (low electricity demand) and summer month of June (high electricity demand) by scenarios. As import is limited (up to 30% even in high import scenarios), in all scenarios, use of least-cost import is strategized for the summer season when demand is high. In the winter month, when demand is low, so is the import; and import helps to meet the peak demand that occurs in the evening. In high renewable scenario, that has higher solar PV capacity generating electricity during day, availability of import in the evening is technically and economically favorable option for integration of solar PV to the grid.

Month of June is hot and humid and also monsoon month, hence energy availability from solar PV is low and electricity demand is high. Import is favoured throughout the day to meet the high demand as well as the evening peak. In high renewable scenario, import also helps to compensate the low availability of solar PV during this month, therefore, appropriate option for renewable integration.

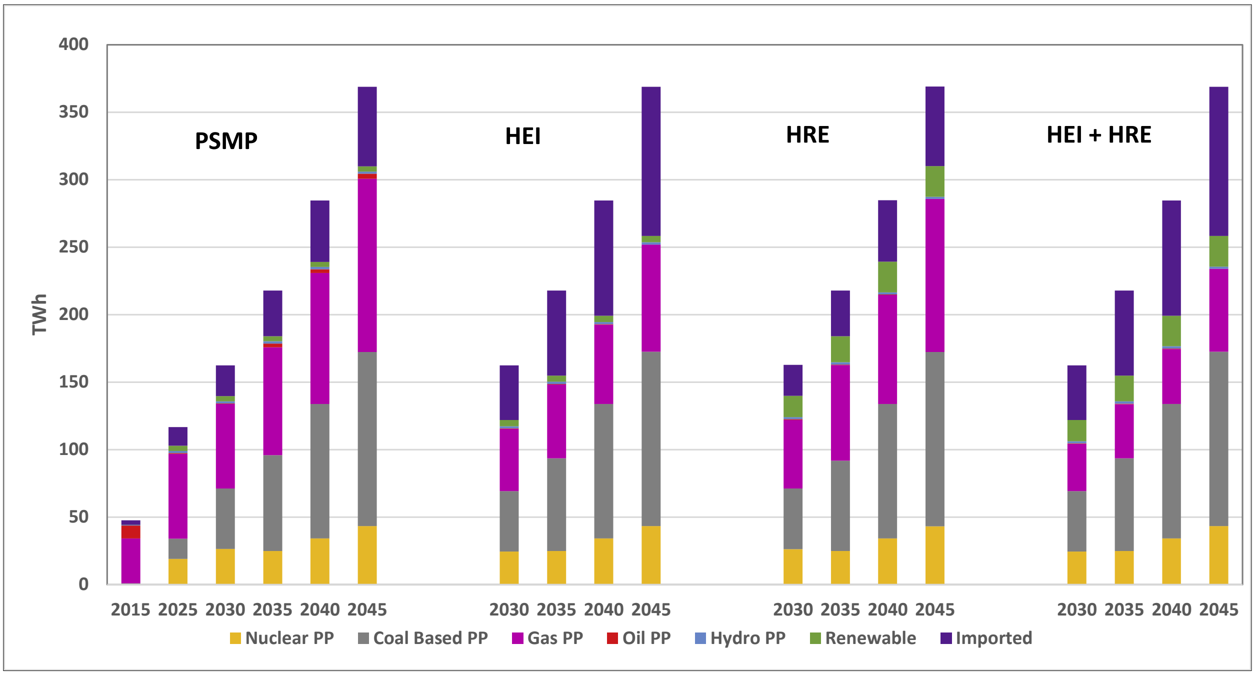

Fig. 7. Scenario wise electricity supply (generation + import).

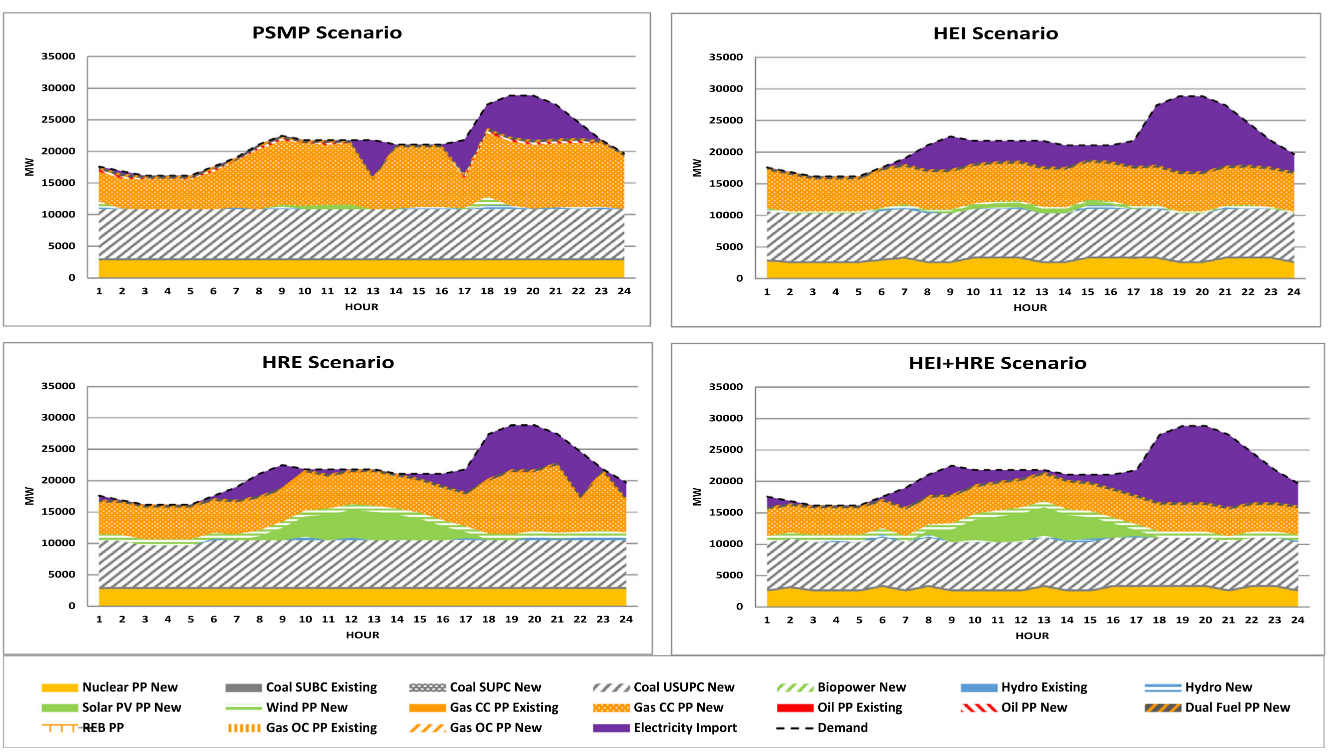

Fig. 8. Hourly generation in a typical day in the Month of January (Winter).

9.4. Fuel demand in power generation

Fig. 10 presents the fossil fuel demand for power generation. Coal and gas, two main fuels for future are presented, while, nuclear fuel is not included. Presently, Bangladesh power system is dominated by domestically produced natural gas with coal playing a marginal role. However, future fuel consumption projected in these scenarios is different. Coal increases its presence from 2020 (not shown here) and by 2035, will have an equal share as gas as a fuel source for power generation. As expected, growth in fuel demand is very high with demand almost doubling every ten years, indicating annual growth is about 7%. In 2025, Bangladesh needs to import 97.7 PJ (3.7 million tonnes (mt)) of coal. After 2025, as domestic gas runs out, fuel for power generation is almost 100% foreign sourced,

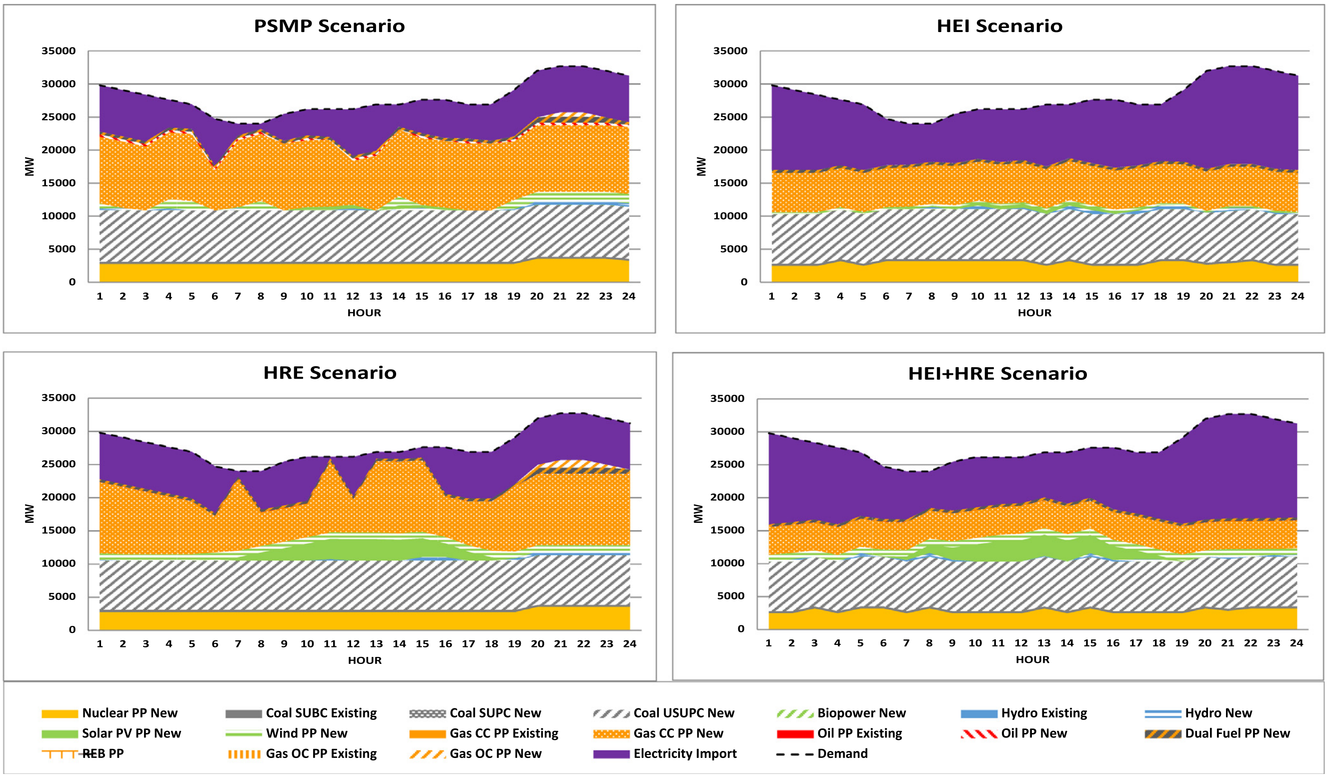

Fig. 9. Hourly generation in a typical day in the Month of June (Summer).

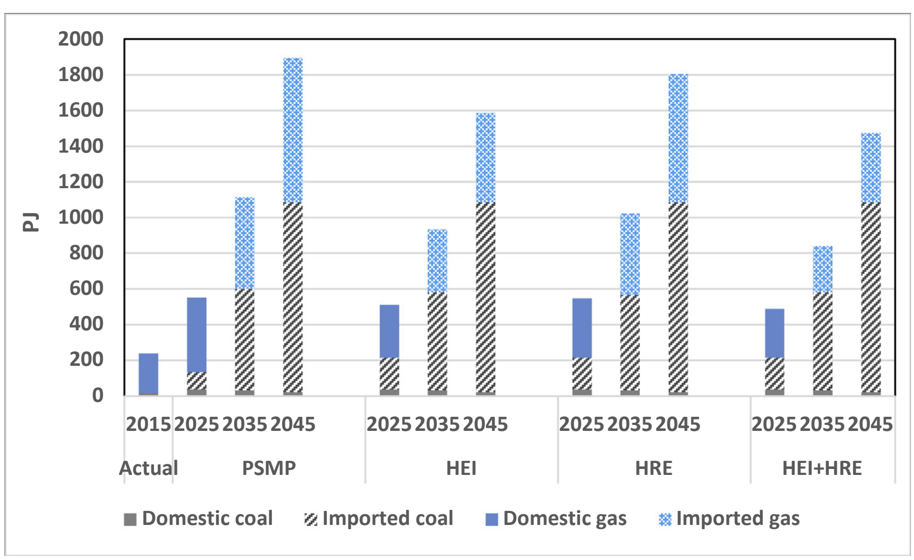

Fig. 10. Fuel demand for power generation.

requiring plenty of foreign currency to buy them. By 2045, Bangladesh needs to import 1065 PJ (40.4 mt) of coal and 810.7 PJ (770 bcft). To mention here, nuclear fuel also needs to be imported. So fuel import involves an outflow of the large volume of foreign currency.

High electricity import scenario reduces fuel demand and hence the fuel import, primarily gas. Gas import is substantially lower by 31% in 2035 and almost 38% in 2045 as compared to the PSMP scenario. However, electricity needs to be imported, therefore, some foreign currency outflow will take place on that account.

Higher use of renewables reduces fuel import for power generation, primarily natural gas. As renewable sources are domestic, promotion of renewables improves energy security, whereas, High Electricity Import scenario shifts the import from fuel to the final product (electricity). Compared to PSMP scenario, natural gas import demand is lower by about 13–14% in 2035 and 2045. Therefore, this scenario saves considerable foreign currency outflow.

Higher electricity import in combination with the higher exploitation of renewables offers the potential of more than 50%

reduction in natural gas demand for power generation when compared to the PSMP scenario. Although some amount of foreign currency outflow will continue for electricity import, it will reduce a substantial amount of investment in gas supply infrastructure, which can be diverted to the other sectors.

9.5. CO_2 emissions

Bangladesh is a highly climate vulnerable country whose emissions are less than 0.35% of global emissions. Electricity production is a dominant contributor to energy related CO_2 emissions in the country. Fig. 11 presents the CO_2 emissions from the power sector, which will increase substantially in future, as power generation currently, dominated by gas, would be increasingly dependent on coal for future power supply along with a manifold increase in power generation. However, the presence of nuclear and electricity import will restrict the growth of domestic CO_2 emissions to some extent. In PSMP scenario, CO_2 emissions from the power system (grid only) are expected to increase from 22 million tonnes (mt) in 2015 to 36 mt in 2025 and thereafter, increase to 88 mt and 152 mt respectively in the years 2035 and 2045.

Both high electricity import and high renewable scenarios offer emissions reduction potentials in the long-run. While HRE scenario with 10 GW of solar PV and 4.6 GW of wind offers respectively 9% and 5% reduction potential over PSMP scenario in 2035 and 2045, the opportunity is larger in HEI scenario (with 30% import), respective numbers were 14% and 13%. HEI + HRE scenario demonstrates that combining electricity import with high renewables exploitation could reduce emissions by 20% and 17% respectively in 2035 and 2045. These scenarios offer the opportunity of earning CO_2 credits to Bangladesh, however, accounting CO_2 emissions from the source of electricity import could be an issue.

9.6. Economics

Total discounted system cost (the value of the objective function which is the sum of all annual costs of the power supply, generation, imports, net of salvage values, discounted to the base year 2012) over the entire time horizon (2012–2050) is an indicator that measures the overall economic performance of a scenario. The lower the cost, economically better the scenario is. Fig. 12 presents the discounted system costs at a real discount rate of 4%.

The optimised total discounted cost of the system differs across the scenarios. The PSMP scenario which mimics the scenario being considered by the Bangladesh government for the future expansion plan has the highest cost, followed by HRE scenario, whereas, HEI + HRE scenario has the lowest cost of all. This demonstrates that HEI + HRE scenario needs to be the preferable option for expanding the power system as it offers electricity supply at cheapest cost while at the same time offering the energy security through diversification and more dependence on domestic resources. Importing electricity from a neighboring country brings higher benefits than building power plants in the country and importing fuel to produce electricity. With rapidly falling costs, expanding domestic renewable energy sector adds further benefits to it in terms of cheap electricity as well as energy security.

Fig. 13 presents the undiscounted power system costs over the study horizon broken into its all components, investment, operating and maintenance, cost of purchasing domestic fuel, costs of imported fuels and cost of importing electricity. Again, PSMP scenario is the most expensive scenario for future electricity supply, whereas, HRE scenario is cheaper than PSMP scenario, and HEI scenario is the cheapest among three. Cost further goes down when measures in HEI and HRE are combined in the HEI + HRE scenario.

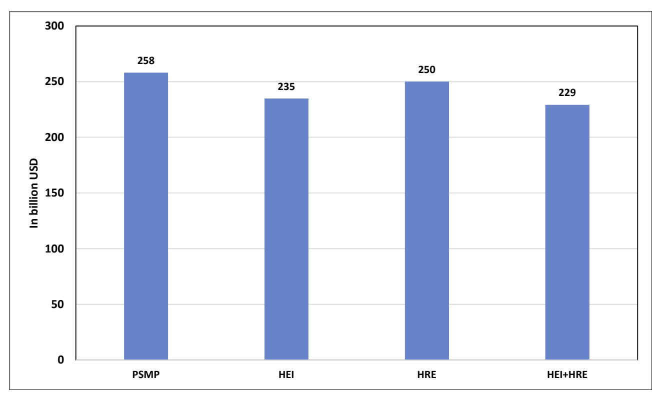

Fig. 12. Discounted power system costs.

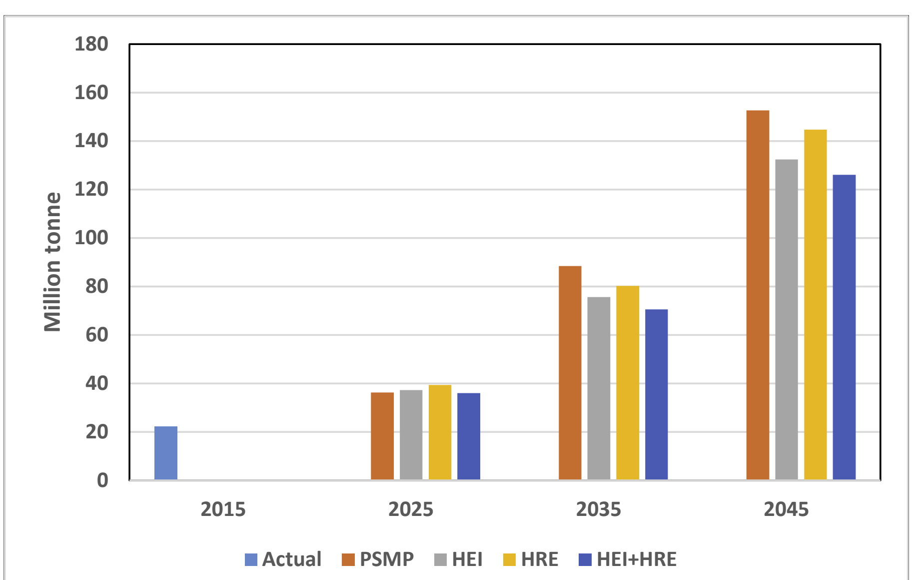

Fig. 11. CO_2 emissions from power generation.

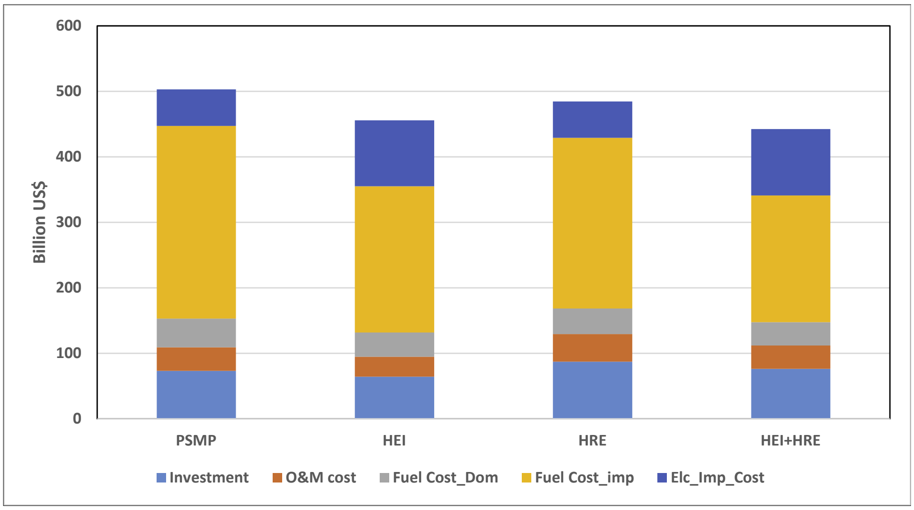

Fig. 13. Undiscounted system costs by components.

Various components of costs vary considerably across scenarios. Although capital costs of renewable technologies are assumed to decline over time, costs are high at the initial periods, which makes HRE Scenario most investment intensive, followed by the PSMP scenario.

HEI scenario, on the other hand, needs less investment in power generation capacity development as it depends on higher electricity import (note: investment cost in building interconnection is not included separately, fixed costs are part of the electricity import price). Fuel import remains the largest cost component in all four scenarios. However, high electricity import (in HEI scenario) reduces fuel import costs by 24%, whereas, high renewable use (HRE scenario) reduces fuel import cost by a modest 11%. However, accelerating of the development of renewables combined with higher electricity import offers a potential reduction in fuel import cost of 34%. This is a significant advantage given that the entire fuel import payment needs to be made in foreign currency. Electricity import cost is obviously higher in HEI and HEI + HRE scenario, however, it still causes a net reduction in fuel import costs. On the whole, HRE scenario offers 4% reduction in total electricity supply costs, whereas, HEI scenario has a potential to reduce overall costs by 9% and HEI + HRE scenario offers 12% lower costs.

10. Concluding remarks

Reliable electricity supply is one of the key ingredients for economic growth, however, reliability comes at a cost. For a low-income country like Bangladesh, such reliability should be accompanied by affordability. With depleting domestic natural gas reserves and limited possibility of economic exploitation of other domestic resources like coal, hydro, Bangladesh faces a mounting challenge of meeting the electricity requirements for its growing economy. Also, volatility of international energy markets implies that Bangladesh cannot rely on a single fuel or technology to meet all of her domestic electricity demand. Diversification is, therefore, key to ensuring stability for Bangladesh while planning the future electricity supply system. This paper attempts to understand the various possibilities and frameworks under which Bangladesh can develop its power system fulfilling twin objectives of affordability and reliability.

For energy resource scarce Bangladesh, the choice for future expansion includes import of fuels, import of final product (electricity) supplemented with the development of domestic renewable resources. Four scenarios, depicting four alternative ways of expanding Bangladesh Power system are explored here. These are PSMP, High Electricity Import (HEI), High Renewable Energy (HRE) and High Import + High Renewables (HEI + HRE) scenarios. The PSMP scenario which is also a Base scenario in our study is built upon the energy security framework based on diversified electricity generation sources (all are to be imported in future) combined with modest electricity import as currently considered by the Bangladesh Power Development Board (BPDB) for future expansion plan. Almost no room is left for renewable energy in this scenario. This scenario is designed to be equally dominated by coal and gas, both of which are to be imported. Price volatility in the international gas market remains a concern.

The paper demonstrates that the HEI scenario that enhances electricity import share in total supply, could supply electricity at cheaper cost. By developing domestic renewable resources combined with higher electricity import, cost of electricity supply could be brought down than what is currently opted by the Government of Bangladesh (examined in PSMP scenario) and insulate the same from the international gas price volatility. Current policies and mindsets do not favour the exploitation of large scale renewable resources in Bangladesh. Our scenarios show that development of these resources not only help the country to enhance its energy security by cutting down fuel imports, it also brings down the electricity supply cost, as the cost of renewable technologies is declining rapidly. The CO_2 reduction is an additional benefit. However, it needs appropriate policies, institutions, and awareness in place. The Sustainable and Renewable Energy Development Authority Act, 2012 led to the establishment of the SREDA to ensure energy security. This young organisation needs to be strengthened fast to enhance its technical, policy formulation and institutional capacity.

World-wide some developing countries are making significant progress in harnessing renewables. Experience of neighboring India could be explored. Core drivers for development and deployment of new and renewable energy in India have been energy security, electricity shortages, energy access, climate change etc. India is the only country in the world to have an exclusive ministry for renewable energy development way back in 1987/88, currently known as The Ministry of New and Renewable Energy (MNRE).[11]

[11] http://mnre.gov.in/information/policies-2/.

MNRE has since developed a range of policy measures and fiscal incentives to encourage the development of renewables (wind farms, solar, biomass) and make them commercially viable. These policy initiatives include:

- fiscal and financial concessions to the renewable energy sector (tax benefits, capital subsidy, accelerated depreciation under the Income Tax Act and also a tax holiday as infrastructure projects).
- preferential feed-in tariffs and minimum quotas for the sourcing of electricity from the renewable sources and market for renewable energy certificates.
- additionally, the Indian Renewable Energy Development Agency Ltd (IREDA), a unique financial organisation, incorporated as a public limited government company under the control of MNRE, provides preferential loans for renewable energy installation and development.

The Ministry is encouraging the setting up of grid-interactive renewable power projects through private investment route. MNRE also provides incentives to carry out detailed survey and investigation and preparation of detailed project reports. The State Nodal Agencies are responsible for promotion and development of private sector projects by way of providing necessary clearances, allotment of land, and facilitating power purchase agreements etc. Solar PV capacity in India jumped from 2.6 GW in 2014 to 20 GW in 2017. Bangladesh Government has good opportunity to learn from the Indian experience.

There is abundant hydro-electric potential in the countries surrounding Bangladesh, namely, Nepal, Bhutan, Myanmar and North-East India [6]. Exploitation of these resources can generate mutual benefits to all these countries. While these resource rich countries could earn export revenue by promoting this resource, import of the same would benefit Bangladesh with stable base load supply, price stability, fuel source diversification and a positive contribution to global climate change mitigation efforts. Bangladesh also benefits from less investment requirement in power sector, which could be diverted, to other sectors of the economy with pressing needs like health, education or non-power infrastructure. However, making this multi-country project reality is a daunting task; policy, institutional and technical infrastructure are needed for electricity trade to materialize. The wider consensus at public and political level is needed. Trust that electricity trade is mutually beneficial (for all the countries involved) needs to be built, and it needs to be conveyed that any delay in implementation of such projects only deprives people of much-needed economic development that they desperately require. Civil society and political establishments need to work together to get swift results. As it involves a huge amount of investment, without a stable, long-term conducive policy and an institutional environment ensuring payment security is in place, it is unlikely that investors will put their money in this risky business.

Of late, significant progress has been achieved. Within a short span of time (2013–2015) import from India has reached 600 MW and soon will expand to 1100 MW. India has also agreed to allow Bangladesh to use its land to import electricity from Bhutan and Nepal. However, lot more work at institutional, policy, market development, regulatory levels is required. Further research is necessitated to strengthen the stakeholders such as policy and decision makers, investors, regulators etc. with adequate and appropriate information. In any case, ensuring electricity import through managing a better relationship with neighbors may be relatively easier than insulating power supply cost from the volatile regional/global gas market.

11. Limitation of our study and future focus of the research

Cautions are warranted when interpreting and using the findings and conclusions of this study. Study is limited to the Bangladesh power system assuming fuel will be supplied to the power plants at assumed price, costs related to the development of fuel supply infrastructure (LNG infrastructure, transportation network, coal handling and port facilities etc.) are not included in the study. Assumptions concerning all input parameters (capital costs, construction time, fuel prices) shape the quantitative scenario results. Sensitivity analyses on these parametric values are recommended as future work.

As stated earlier wind resource assessment is underway. Data on temporal availability of wind when it is available should be included in the model to improve the analyses. Daily load pattern in the current study till 2050 is based on the actual load curve data for the year 2014/15 having a power demand peak in the evening. However, as Bangladesh economy progresses, load shape is expected to reach the daily load curve of advanced countries, where the peak is found in the daytime and evening if the growth of the electrification rate is taken into account. This aspect is included in the Power System Master Plan 2016 [30]. However, the data we got from BPDB was not sufficient to capture this aspect in our model and study. Therefore, work should be carried out to improve data and include the changes in load shape over the study horizon which would have some impacts on capacity, generation, technology mix, and costs etc.

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