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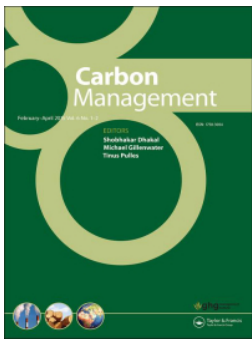
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Why is Bangladesh's electricity generation heading towards a GHG emissions-intensive future?

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ABSTRACT

Bangladesh—recently graduated to developing nation category from a least developed country with an emerging economy also is one of the severely affected countries by climate change—is heading towards a coal-intensive electricity generation mix contrary to global decarbonisation efforts. It is facing formidable challenges in achieving universal access to affordable, reliable, and sustainable electricity, decarbonising the energy mix by 2030 to achieve the objective of Sustainable Development Goal (SDG) 7, despite a 285% increase of installed capacity between 2008–09 and 2020–21 and aiming at achieving 40 GW and 60 GW by 2030 and 2041 with planned expansions, respectively. This study reviewed Bangladesh's electricity sector developments—demand, generation, transmission, and distribution (T&D)—to identify progress in policies, drivers, and challenges behind the Greenhouse gas (GHG) emissions-intensive future direction. The rapid population and economic growth and shift towards industry-based economy drove the exponential growth in energy demand, eventually influencing the rapid generation capacity and T&D infrastructure development. However, Bangladesh has targeted transitioning from natural gas to coal dominating fuel mix due to the lower renewable potential, energy, and food security challenges, because of the anticipated substantial future electricity demand for becoming an Upper Middle and a High-income country by 2031 and 2041, respectively. We also recommended nuclear energy, (renewable) electricity import and floating solar plants to decarbonise the current trajectory.

KEYWORDS

Electricity generation; supply sector; demand sector; Bangladesh

Introduction

Electricity consumption in Bangladesh increased 206% in 2000–14 (526% in 2000–2021 [1]), which was significantly higher than countries with similar economic development during this period, such as Nigeria (94%), Sri Lanka (79%), Malaysia (67%), Philippines (40%) and Indonesia (108%) [2]. Despite the massive increase, about 92.2% of the total population—88.85% of rural and 97.8% of the urban population—had access to grid electricity by 2019, which was 62.4% in 2014 [2]. Also, Bangladesh has the world's eighth-largest population (164 million)—approximately 1265 people living per square kilometres in 2020 [2]—and is projected to reach about 210 million by 2050 [3]. Historical data showed that electricity consumption per capita has increased exponentially in Bangladesh and is projected to be 22 times by 2050 than in 2014 (Figure 1A). Therefore, Bangladesh will cross Nigeria, Sri Lanka, the

Philippines, and Indonesia by 2050 (Figure 1A). It targets to become an Upper Middle and a High economic country by 2031 and 2041, respectively [4].

GHG and CO₂ emissions intensity in developing contexts such as Nigeria, Bangladesh, Sri Lanka, the Philippines, and Indonesia were lower than the world average [2, 5]. However, the projected emissions per capita in developing contexts will rise quickly. By 2050, countries such as Bangladesh, whose emissions intensity was as low as 0.46 tCO₂e/capita in 2014 [2], will cross two tCO₂e/capita (Figure 1B). With the UN projected population (considering Medium Variant) [3], the total CO₂ emissions can reach up to 201 and 402 million tonnes (Mt) by 2030 and 2050, respectively. That rough estimate contradicts Bangladesh's Intended Nationally Determined Contributions (INDC) [6] on reducing future GHG emissions.

The electricity generation sector in Bangladesh has been fossil fuel dominating since 1971. In

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2015–16, the total installed capacity was 12.5 GW with 91% fossil fuel dominating —natural gas-based— energy mix [1]. The future master plan of energy sector development up to 2041 suggests that Bangladesh will retain its fossil fuel dominating energy mix [7]; however, transitioning into a coal-dominated fuel mix from a natural gas-based one. Bangladesh will have to decarbonise the energy sector to reduce emissions that depend on emerging energy sources and technologies to shift towards renewable dominating energy mix. As demand will be one of the highest globally by 2050, a 2°C scenario would require that developing countries such as Bangladesh are already on a decarbonising path [8].

In the previous studies, there were attempts at investigating the energy scenarios in Bangladesh. However, they were predominantly aimed at renewable energy. Baten et al. [9] reviewed the renewable energy scenario in Bangladesh, including distribution, research, and infrastructural development [9]. However, the scope of the study did not analyse the entire electricity generation sector concerning the policies and challenges. Islam et al. [10] studied the contemporary energy mix, energy crisis, and prospect of overcoming the crisis using alternative renewable energy sources in Bangladesh [10]. Similarly, other studies [11–14] also focused on renewable resource potential and GHG emissions. The focus of the previous studies was not necessarily on the drivers behind the policies and fast development of coal dominating electricity generation mix —especially not during the development period of 2014–21— which encouraged the current study on the rapidly expanding electricity sector in Bangladesh, particularly a GHG emissions-intensive one. The electricity sector is investment intensive and has higher inertia, which means their capacity will determine what they will have in the future, making it imperative to study the sector's evolution and policies, especially in developing countries like Bangladesh. In this study, the objective was to review the energy policies, electricity generation and demand sector, including the T&D infrastructures, to find the drivers, challenges for the emissions-intensive growth of the electricity sector of Bangladesh, and recommend potential resources for decarbonisation from the current trajectory.

Energy and electricity sector acts, policies, and master plans

The electricity sector in Bangladesh underwent several significant restructurings since its humble

beginning at the turn of the twentieth century. Electricity accessibility was limited, predominantly to the wealthy residents in the capital with small power plants [15], but gradually shifted its focus towards serving essential businesses and industries by 1947 [16]. When the Indian subcontinent was divided into India and Pakistan in 1947, East Pakistan (now Bangladesh) had an installed capacity of 21 MW, predominantly serving private companies and the industry sector [16]. Bangladesh Power Development Board (BPDB)¹ was created on 01 May 1972 [1] after the liberation from Pakistan on 16 December 1971, with a total installed capacity of 200 MW [1]. With limited generation, BPDB supplied urban centres and their peripheries only. For providing electricity service to rural areas, the Rural Electrification Board (REB) was constructed in 1977 [17]. The electricity generation was divided into East and West zones, connected by a 230 kV transmission line in 1982 [16]. The power sector deregulation was initiated in 1994 with the National Energy Policy [16]. A publicly owned company, Rural Power Company Limited (RPCL), began its journey as the first independent power producer (IPP) in 1994 [18], paving the path for eventual private investments in electricity generation sector. Entirely private-sector owned IPPs started in 1997, under the build-own-operate (BOO) model of public-private partnership (PPP), which began to operate under rental agreements lasting between three and fifteen years after further deregulation [19]. The first rental power plant (RPP) became operational in 2008 and augmented rapidly in number, contributing to the total electricity generation of Bangladesh.

At present, the Power Division of the Ministry of Power, Energy and Mineral resources [20] acts as the apex governmental organisation for developing the sector [20]. However, a separate entity, Bangladesh Energy Regulatory Commission (BERC), regulates the power sector. There were seven public electricity generation companies involved in 2021—Bangladesh Power Development Board (BPDB); Ashuganj Power Station Company Limited (APSCL); North-West Power Generation Company Limited (NWPGL); Electricity Generation Company of Bangladesh (EGCB); Rural Power Company Limited (RPCL); B-R Powergen Ltd. (BRPL) and Joint Venture (Bangladesh-China Power Company (Pvt) Limited (BCPCL)) [1]. Also, there were private sector generation/rental: Independent Power Producers (IPPs)/Small Independent Power Producers (SIPPs), and rental. The transmission of

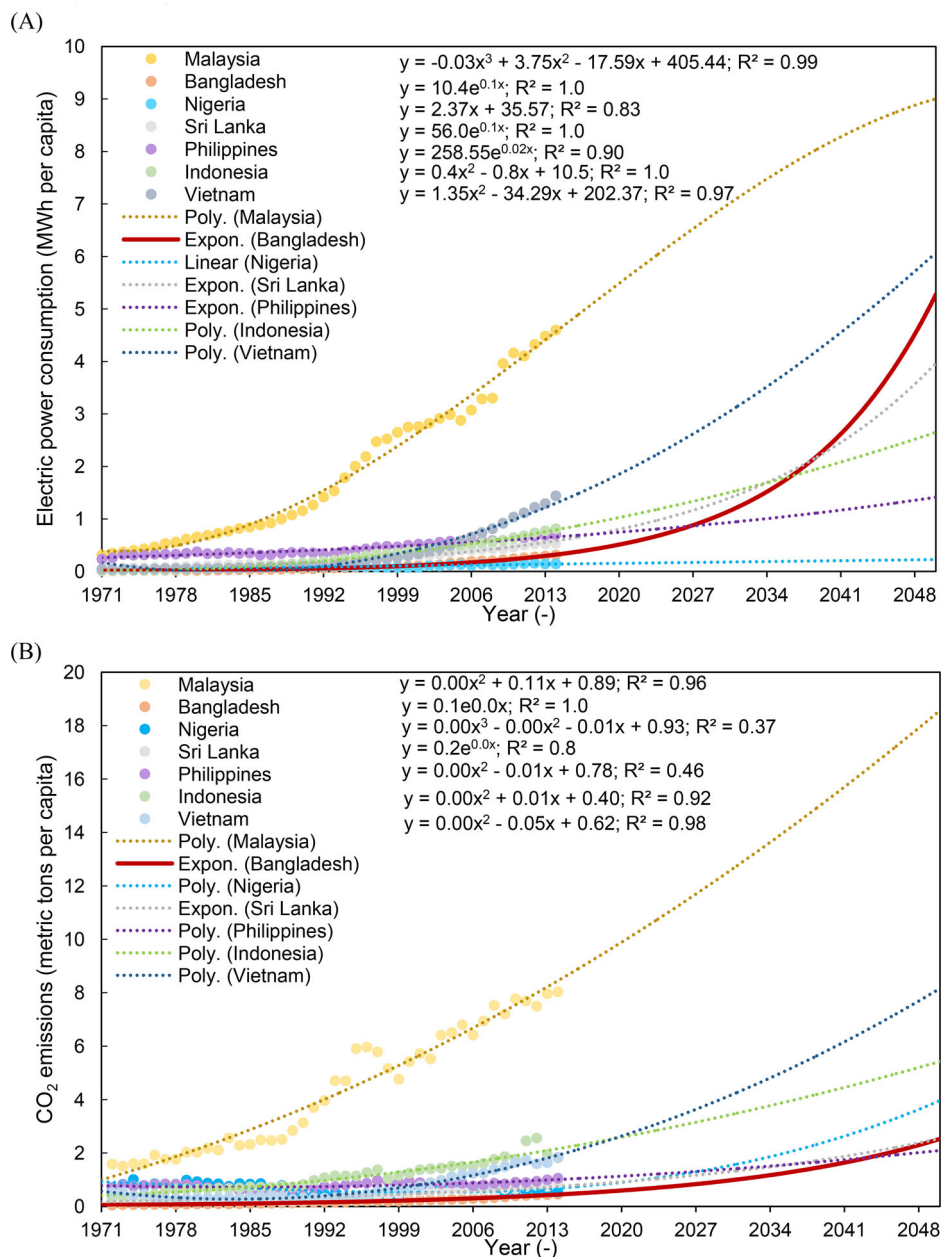


Figure 1. (A) Electricity consumption per capita in different countries (1971–2014) and forecasting the trend up to 2051; (B) CO₂ emissions per capita in different countries (1972–2014) and forecasted trend up to 2051; data source [2].

the power sector was operated and maintained by the Power Grid Company of Bangladesh Limited (PGCB). On the distribution side, there were six organisations currently operational in Bangladesh: Bangladesh Power Development Board (BPDB), Dhaka Power Distribution Company (DPDC), Dhaka Electric Supply Company Limited (DESCO), West Zone Power Distribution Company Limited (WZPDCL), Northern Electrical Supply Company Limited (NESCO) and Rural Electrification Board (REB) through Rural Co-operatives [1].

The first record of an electricity act for the region was published in 1910 [1]. After that, until 1972, there was no significant change in the energy sector policies. The BPDB order was active from 1972 with the objective of urban electrification. The rural electrification was kept in blindside

until 1977 when the rural electrification board ordinance came into action [21], and the REB was established. After 1977, there was no significant energy sector policy development for almost 25 years (Figure 2). In 2003, Bangladesh energy regulatory commission act was passed [22], and the Bangladesh Energy Regulatory Commission (BERC) became functional to regulate the energy market in Bangladesh. The following primary energy sector policy was the Sustainable Energy Development Authority (SREDA) act 2012 [23]. The first policy directly targeted sustainable energy development in energy generation and demand sectors. SREDA was a significant progression towards occupancy and public awareness development towards sustainable energy use. SREDA is also involved in national research and

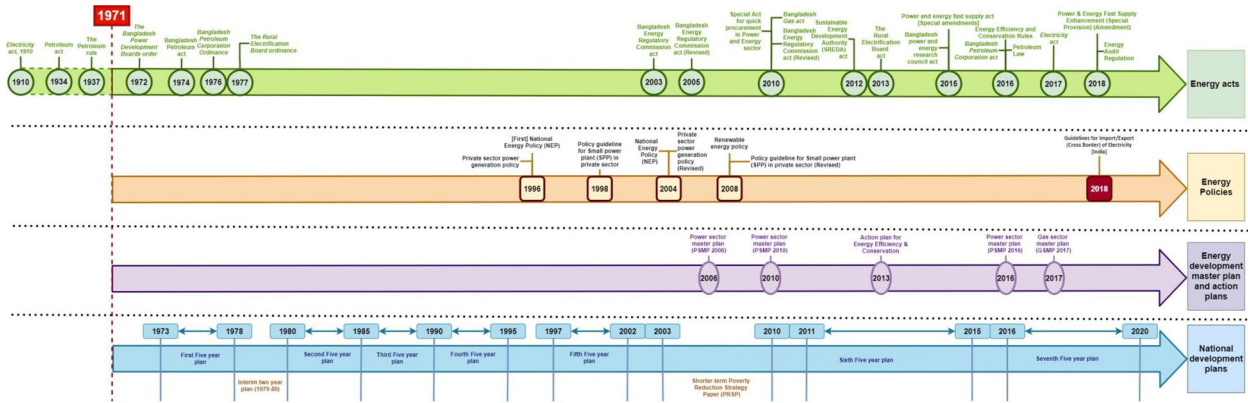


Figure 2. Timeline of energy-related policies, acts, master plans and action plans in Bangladesh.

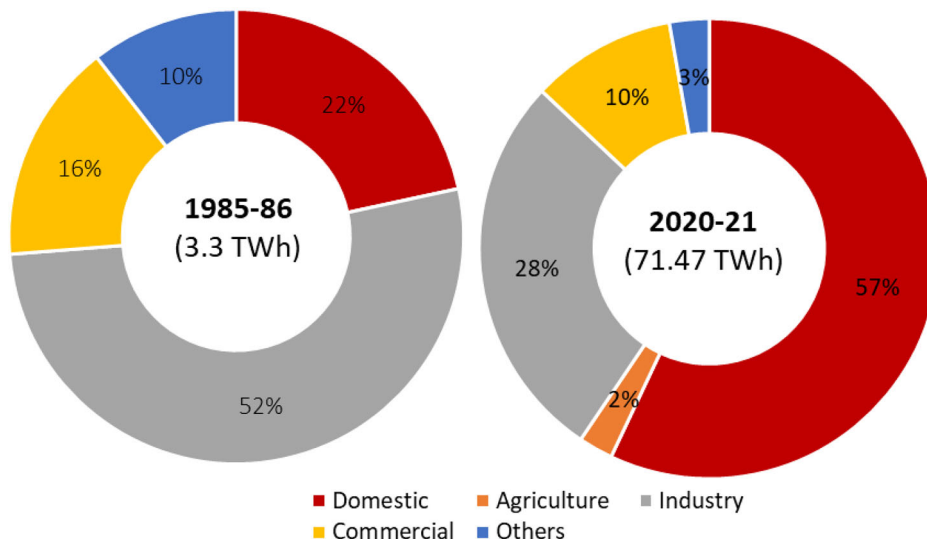


Figure 3. Electricity demand profile in 1985–86 and 2020–21; data source [1].

development for sustainable technology development within Bangladesh, collaborating with industry and academia. Figure 2 showed Bangladesh’s rapid energy policy development since 2003 due to the high need for energy due to accelerated economic growth.

Electricity demand

In 1985–86, 52% of the electricity demand came from the industry sector for Bangladesh. Moreover, 22%, 16%, and 10% of electricity demand were domestic, others, and commercial. By 2020–21, domestic electricity demand (57%) became the largest of all the sectors. The industry had the second most significant demand (28%) for electricity in 2020–21 (Figure 3). Historical trends demonstrated exponential growth in domestic, industrial and commercial sector electricity demands (Figure 4). The total electricity demand was 3,307 GWh in 1985–86 —11,409 GWh by 2000–01— which reached 71,471 GWh by 2020–21. Therefore, approximately 21.6 times aggregated demand

increase between 1985–86 and 2020–21. Although, the domestic electricity demand reduced by 46% in 1996–97 than 1995–96 because of two cyclones in 1994 and 1995. Also, there was a sudden drop (153% reduction) in industry sector electricity demand in 1997–98 because of political instability in 1996 —localised frequent and extended load-shedding/power cut and destruction of T&D infrastructure in parts of the country due to a military coup, and the sixth & seventh national elections (due to associated protests and conflicts)— which resembled the finding on the impact of political instability on electricity demand in [5,24]. Other than the two incidents, the electricity demand elevated exponentially in Bangladesh. Also, a study on rural household demand demonstrated a significant increase in electricity demand by 2050 [25].

Despite the growing electricity demand, 76% of the population had access to grid electricity in 2016, rapidly increasing to 92.2% by 2019 [2]. Moreover, the generation sector cannot meet the demand resulting in load shedding (Figure 5B).

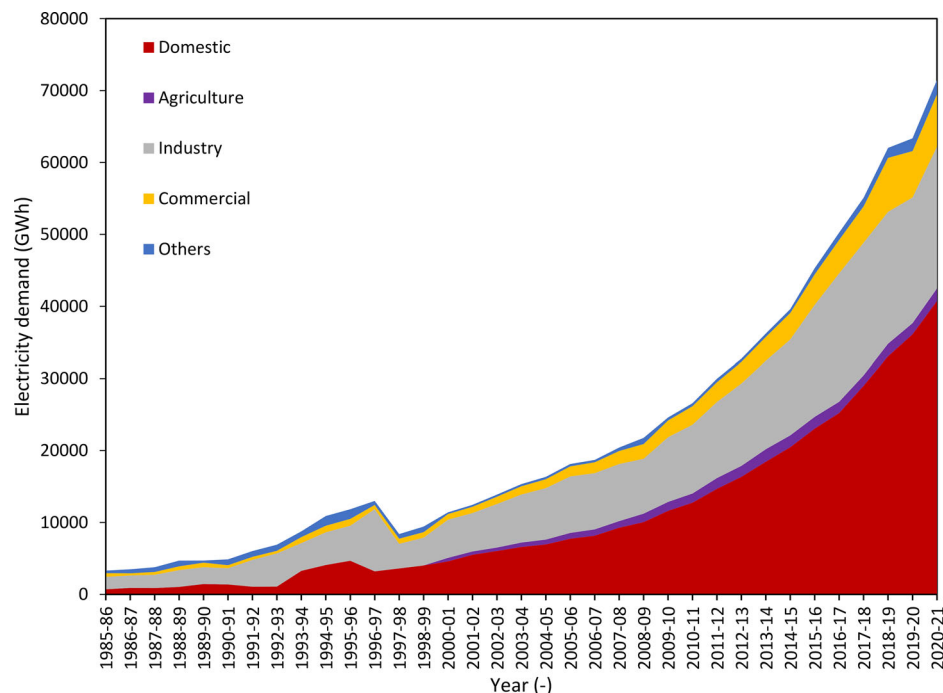


Figure 4. Electricity demand in different sectors from 1985–86 to 2020–21; data source [1].

Despite the maximum generation of 7.4 GW in history (1974–75 to 2013–14), 932 MW maximum load shedding in 2013–14. In 2005–06, the load shedding was highest at 1.3 GW, while the maximum was 3.7 GW. In eight years (2005–2013), the maximum generation elevated 1.9 times with a 29% reduction in load shedding. Thus, the load shedding is reducing in Bangladesh. However, a suppressed demand can rise faster with more access to grid electricity and higher buying capacity in developing contexts such as Bangladesh [26], rapidly increasing Bangladesh's electricity demand.

Electricity generation

The installed capacity has been elevating exponentially to meet the demand (Figure 5A). The derated installed capacity improved since 2009–10 because most of the newly built power plants became operational after 2009, and they are still in an early stage of their lifespan (Figure 7). However, the present installed capacity is insufficient, and the result is load shedding. Public sector generation capacity has increased exponentially between 1970 and 1997 (Figure 6). However, the growth in the public sector slowed down in 1997 when the private sector began generation (Figure 6). Most of the growth since 1997 came from the private sector, and the trend is projected to continue. By 2020–21, the private sector generated 25% more electricity than the public sector (Figure 6). However, government master plans for the energy sector also increase public investments. The total

installed capacity will be 60 GW in 2041 [27] from 12.5 GW in 2017 [1], a 380% increase in 24 years. The public and private generation sector's installed capacity was 5.8 and 4.4 GW in 2015, respectively, with an additional 500 MW imported from India (Table 1). The total generation capacity of Bangladesh was 10.7 GW in 2015, which increased only 0.1% in 2016. However, the total installed capacity elevated to 12.5 GW in 2017, a 17.1% increase in a year. In 2017, the public and private sector installed capacity were 6.6 and 5.3 GW, respectively, with 600 MW imported from India (Table 1). The imported electricity raised to 1160 MW in 2020–21, when the total installed capacity was 22 GW [1]. The public sector installed capacity increased by 13% between 2015 and 2017 and 73% between 2017 and 2020–21. APSC and NWPGL achieved 74.77%, and 19.6% increased installed capacity in two years (2015–17). On the other hand, the private sector had a 22% increased installed capacity in 2017 than in 2015, whereas 80% between 2017 and 2020–21. The IPP and Quick Rental Power Plant (QRPP) installed capacity increased by 60.6% and 26.9% in two years (2015–17). However, the total installed capacity of RPPs was reduced by 48% by 2017.

There were 74 public and 85 private owned power plant units operational in 2015. Among the public plants, 6% are older than 40 years. However, 23% and 25% of the plants are in the 30–40- and 20–30-years old range. Moreover, 30% of power plants are less than ten years old. On the other hand, 85% of private power plants are less than

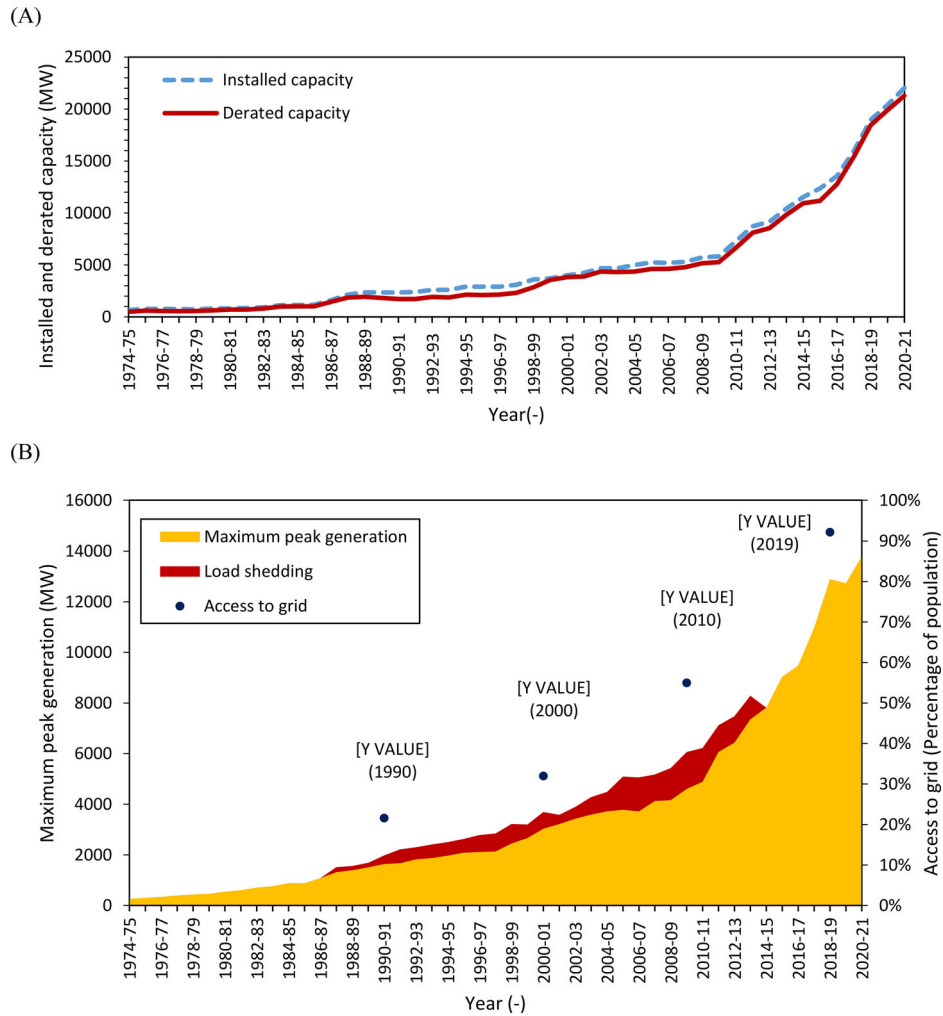


Figure 5. (A) Installed and derated capacity in Bangladesh (1974–75 to 2020–21), (B) Maximum peak generation (1974–75 to 2020–21) and load shedding (1974–75 to 2014–15 [No data after 2014–15]) in Bangladesh; data source [1,2].

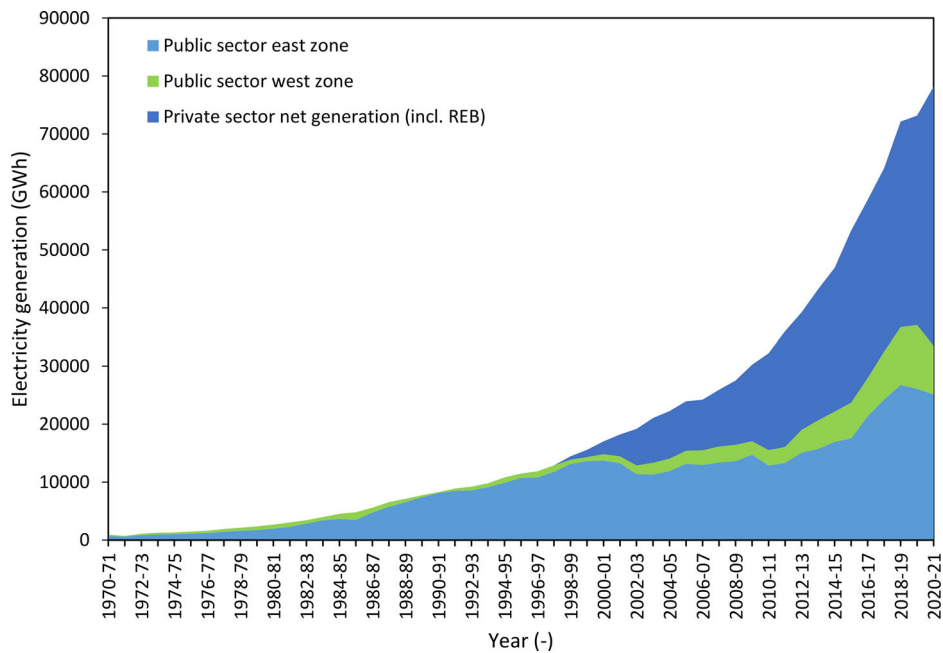


Figure 6. Public and private sector net generation from 1970–71 to 2020–21; data source [1].

ten years old (Figure 7). Altogether, 58% of the total power plant units are less than ten years old.

Most of the existing thermal power plants are situated in the country’s north, north-west, east

and middle east parts (Figure 8). Among the existing power plants, the east zone had 9.7GW installed capacity, of which 4.3GW (44% of the east zone) was situated in the Dhaka zone in 2017.

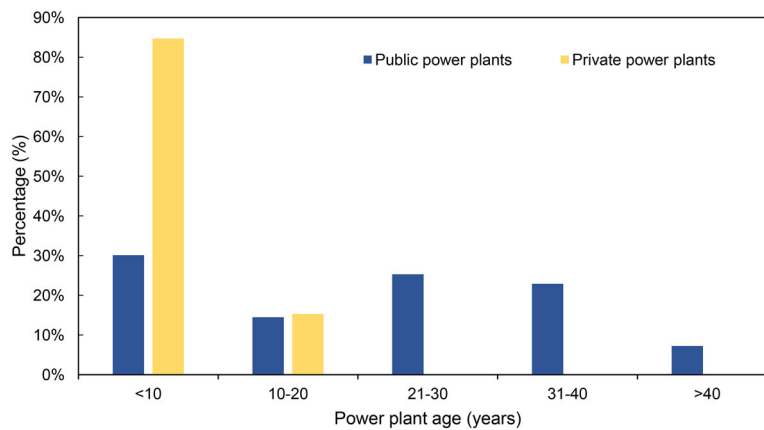


Figure 7. Age of public and private power plants; data source [1].

Table 1. Electricity generation installed capacity; data source [1]. Total public generation of 10146MW was generated by BPDB, APSC, EGCB, NWPGL, RPCL, and PDB-RPCL in 2020-21. For private generation, 1188MW was (collectively) generated by SIPP-PDB, CIPP-REB, QRPP and RPP in 2020-21.

Generation authority	Installed capacity (MW)			
	2015	2016	2017	2020-21
Public				
BPDB	4126	3758	4088	10146
APSC	687	840	1200	
EGCB	622	210	622	
NWPGL	368	368	440	
RPCL	0	77	77	
PDB-RPCL	0	149	149	
Joint venture	0	0	0	1244
Private				
IPP	1883	2485	3025	8042
SIPP-PDB	99	99	99	1188
CIPP-REB	25	25	25	
QRPP	1114	1414	1414	
RPP	998	506	519	
SIPP-REB	226	226	226	251
IMP (import)	500	500	600	1160
Total	10648	10657	12484	22031

However, the west zone had only 2.8 GW installed capacity in 2017. Therefore, the east zone had 3.5 times more installed capacity than the west zone. The positions were mainly close to the fuel source such as gas, coal, or liquid hydrocarbons. Close to a river is another requirement for thermal power plants due to the high-water demand for cooling. The rivers act as the fuel transport medium in the plants fuelled with imported liquid hydrocarbons. A significant number of fossil fuel-based thermal power plants are under construction and planned by 2030 (Figure 8). However, there will be eight new thermal power plants built in the southern coastal areas of Bangladesh by 2030. Five of them will be near the southeast corner of the country, close to the port city of Chittagong. The other three will be constructed on the south-western side of the country, which will come very close to the world's largest mangrove forest Sundarbans (dashed circle in Figure 8). The proposed 1320 MW

imported coal-fuelled Rampal power plants would be constructed 14 km north of Sundarbans. There has been significant conflict between the government and local people, and environmental activists due to GHG emissions on the forest [31].

Moreover, land acquisition and deforestation are also of significant concern as 742 hectares would be built for the power plant by cleaning forest and adjacent lands. There were more conflicts regarding coal mining in Phulbari, Bangladesh, in 2005. An open-pit coal mine project was proposed by Asia Energy Corporation, which displaced 220000 local people and destroyed agricultural land. Due to the large protest from the local people and environmental authority, the government had to stop this project. These conflicts around the only proven coal deposit in Bangladesh's north and geographical characteristic may have influenced the future energy planning master plan PSMP 2010 and 2016. In PSMP 2010 and 2016, the government was suggested by JICA to move towards imported coal-based ultra-supercritical power plants. Due to the dependency on imports, the future power plants were positioned in the coastal areas. However, constructing a coal power plant close to Sundarbans is still questionable from an environmental perspective. Domestic coal mining was suggested in PSMP 2016 by JICA [7] despite the environmental and social issues.

In 1975, 78% of public electricity generation utilised natural gas. By 2013, natural gas fuel use increased 21 times. Moreover, liquid hydrocarbon-based fuel use elevated to 7.26 times that of 1975. Thus, there has been rapid fuel use in public power plants between 1975 and 2013 (Figure 9).

In 2015, 68% of the power plants were natural gas-fuelled (Figure 10). Moreover, 24% of power plants were liquid hydrocarbon fuelled. Only 2% generation was from a renewable source (Hydro). Imported electricity accounts for 4% of the

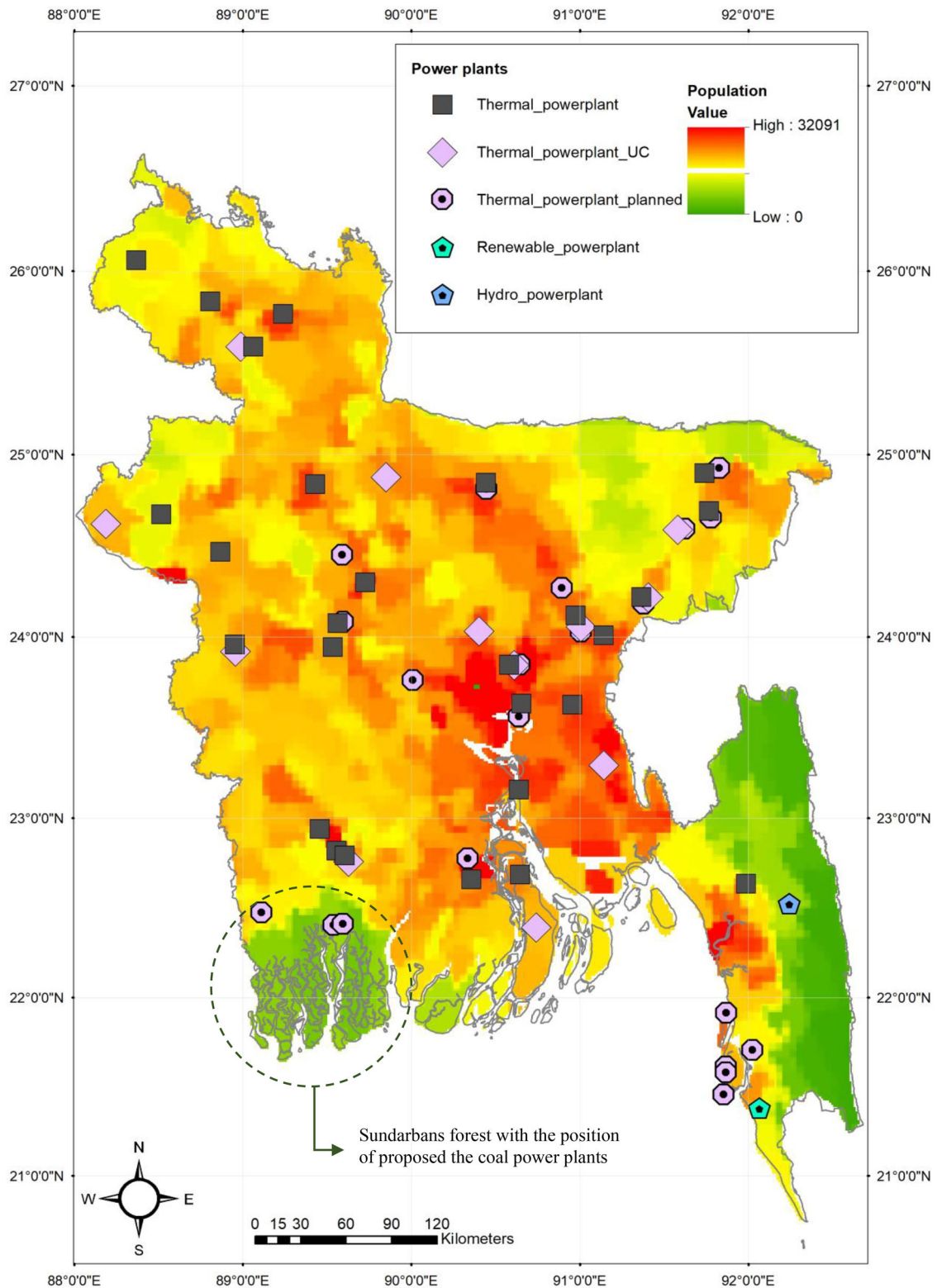


Figure 8. Power plants in Bangladesh, including under construction and planned (2015–2021). Map drawn by authors using data from [28–30]. The dotted circle at the southwest corner denotes the proposed Rampal and other coal power plants.

electricity. PSMP 2010 proposed shifting from natural gas-based electricity generation to coal-based (50%) one by 2030 [32]. However, the coal dependency was updated to 15–55% under different scenarios by 2041 under PSMP 2016 [7]. Under PSMP 2016, most generation capacity shifts among gas, oil and coal-based plants; e.g. if coal is only 20% of the energy mix, the 25% and 38% share

would depend on petroleum and gas, respectively. Therefore, the energy mix would always be fossil fuel dominating Bangladesh, at least up to 2041. After that, most fossil fuels would be imported liquefied natural gas (LNG), petroleum and coal [7].

Most RPPs are oil-based and rely on imported petroleum, as Bangladesh has insufficient oil reserves. By increasing oil dependency [33], the

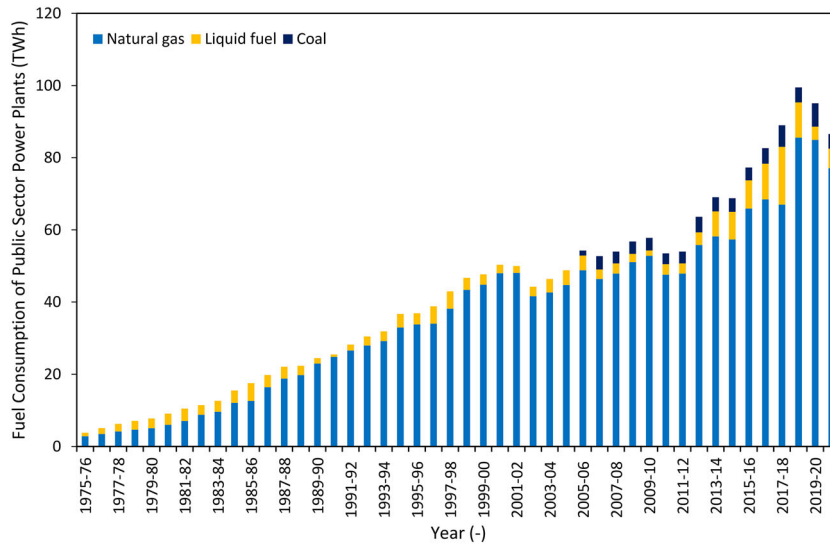


Figure 9. Fuel for the public energy sector from 1975–76 to 2020–21; data source [1].

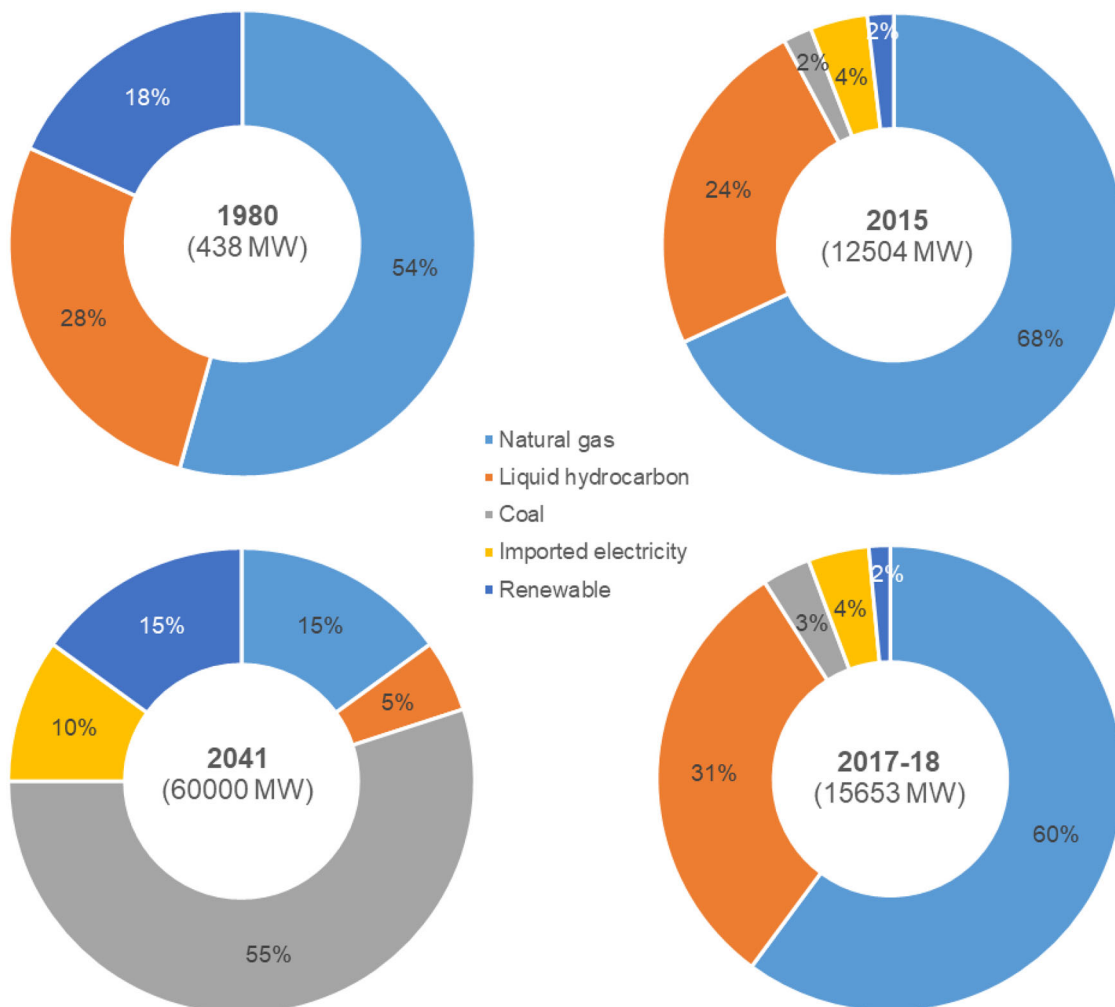


Figure 10. Installed Capacity (MW) and fuel types; data source [1].

energy sector was exposed to the volatile international oil market [18]. Energy sector subsidies have escalated because of growing import prices for fuels to meet accelerated energy demand [33]. Moreover, the lack of transparency in the public procurement process acted as an incentive for corruption to increase in the energy sector of

Bangladesh [8,34–36]. There were no data on how much fuel is used in private power plants separately.

The high dependency on fossil fuels in generating electricity also elevates CO₂ emissions gradually. Only 27.8% of CO₂ emissions from total fuel combustion in Bangladesh came from electricity

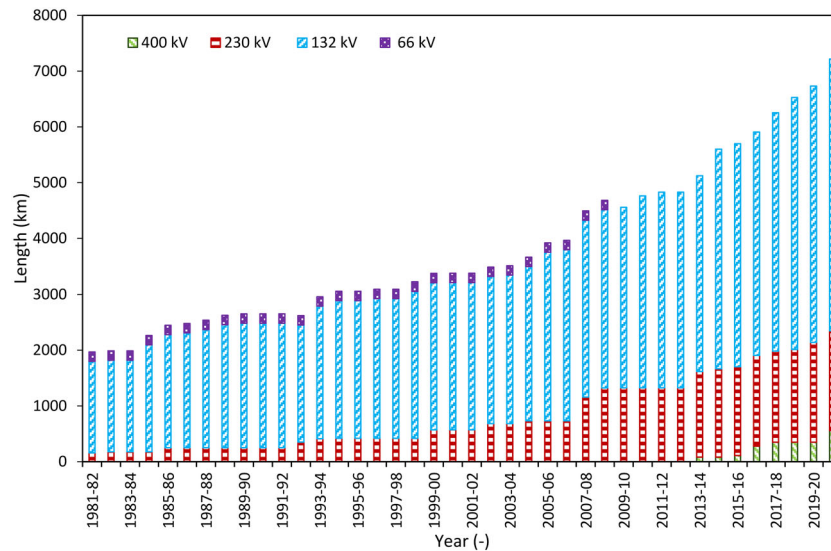


Figure 11. Transmission lines in Bangladesh from 1981–82 to 2020–21 [No data for 66 kV after 2008–09]; data source [1].

and heat production in 1971, while 83% of generation was from oil and gas sources [2]. The total electricity generation was 0.68 TWh in 1971 [1]. The generation increased 56 times in 41 years and reached 38.23 TWh in 2012 [1], of which 98.4% was from oil and gas sources [2]. As a result, the CO₂ emissions from total fuel combustion from electricity and heat production reached 49.3% in 2012 [2], 1.7 times higher than in 1971.

Transmission and distribution

In 1981–82, 1967 km of transmission line (66 kV, 132 kV and 230 kV) increased to 2652 km by 1990–91. However, only 22% of the population had grid electricity in 1981–82. By 2012–13, the length of the transmission line² (132 kV and 230 kV) elevated to 4829 km (Figure 11), 1.8 times increase to supply electricity to 60% of the population. Total transmission line length reached 7217 km —3.66 times than that of 1981–82— by 2020–21 in addition to 400 kV³ (556.84 km) with 132 kV (4869.10 km) and 230 kV (1791.01 km) lines (Figure 11). The transmission line length will elevate because a substantial number of lines are under construction and planned (Figure 12). Although areas with higher population density have access to grid electricity, a significant number of rural and suburban regions does not have access to electricity (Figure 12).

There are three types of transmissions substations in Bangladesh, such as 230/132 kV, 132/33 kV, and 66 kV. Distribution substations are 33/11 kV type. In the case of distribution transformers, two types of 33/0.4 kV and 11/0.4 kV are present in Bangladesh. These substations will also

increase significantly by 2021 to supply most countries (Figure 13). Moreover, HVDC stations work in the interconnection between India and Bangladesh in Bheramara, Kushtia. Another one is under planning in the northern part of Bangladesh (Figure 13).

Bangladesh's distribution lines are of three capacities- 33 kV, 11 kV and 0.4 kV. In 1981–82, the total length of the distribution line was 24156 km, which elevated two times to reach 49460 km by 2013–14. Customer number and GDP per capita showed a positive linear relationship in Bangladesh, which can interpret as the higher buying capacity among the people elevates the number of electricity consumers (Figure 14), which resonates with the studies by [37]. However, the customer number increases exponentially with the growth in distribution line length (Figure 14), resulting from suppressed demand in a country with high energy poverty. Moreover, distribution system loss in Bangladesh was 35.79% in 1991–92, reduced to 11.89% by 2013–14 with efficient maintenance and planning [1].

Drivers behind the emissions-intensive electricity sector development

The previous sections demonstrate rapid and substantial progress in Bangladesh's electricity generation, supply, and T&D sector, mainly in the past two decades, driven by the rapid population and economic growth, energy security need, and transition from agriculture to the industry-led economy. But the limited land for solar energy generation while competing with food security and lower (other) renewable potential to supply the energy demand from the rapidly growing

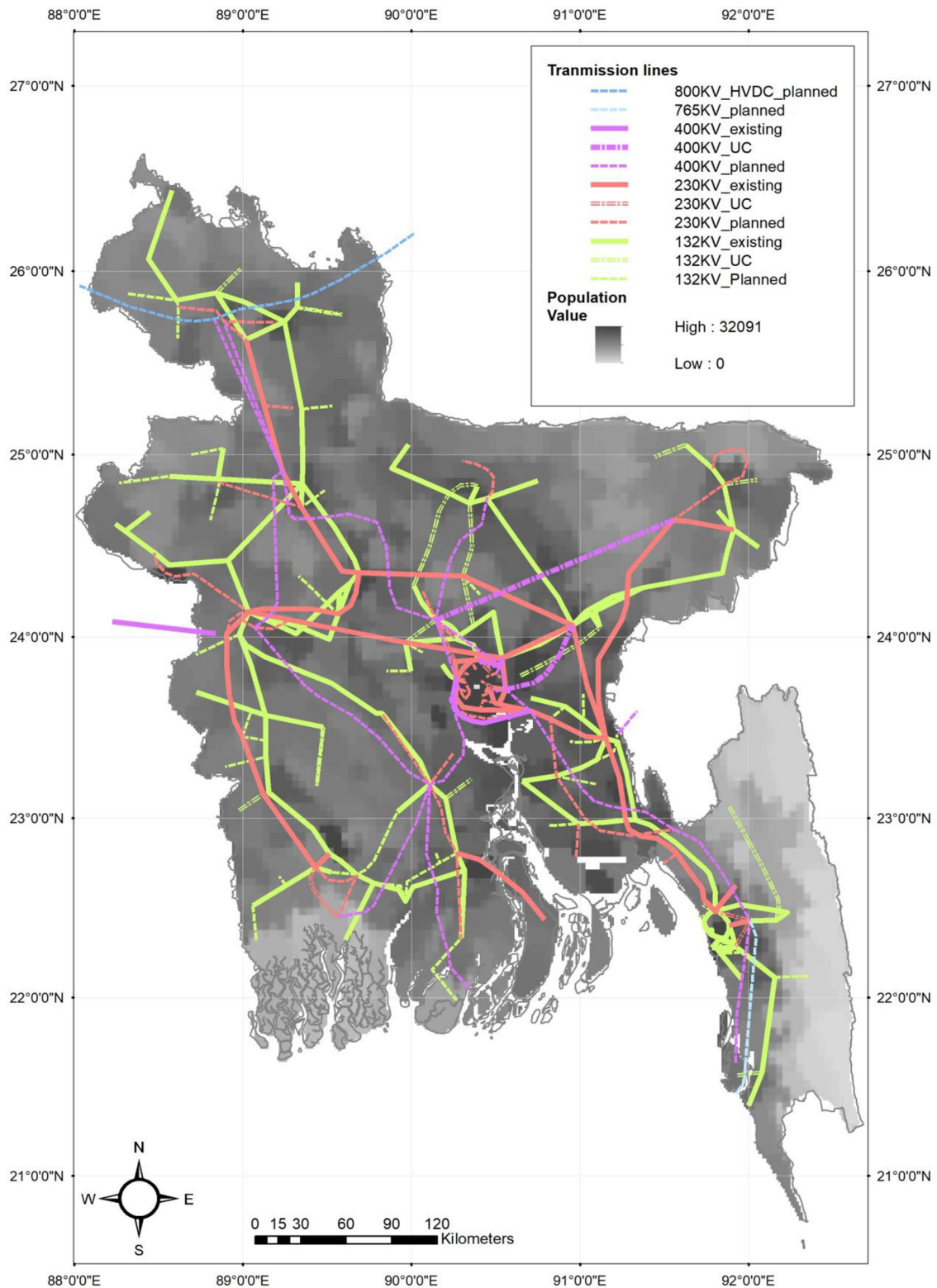


Figure 12. Existing, under construction and planned electricity transmission network in Bangladesh (2015–2021). Map drawn by authors using data from [28–30].

industry-led economy drove the development of the emissions-intensive electricity sector, which was discussed here.

Economic and population growth: Rise of the Middle class

In 2020, Bangladesh was the world's eighth-most populous country, with approximately 164

million with an annual 1% growth rate [2] (Figure 15A). With a total area of 0.148 million square kilometres (km^2), the population density was $1265.2/\text{km}^2$ in 2020, making Bangladesh one of the world's highest densely populated countries. Therefore, Bangladesh outnumbered larger populous nations such as India and China, where population density was 464.1 and $149.7/\text{km}^2$ in 2020 [2].

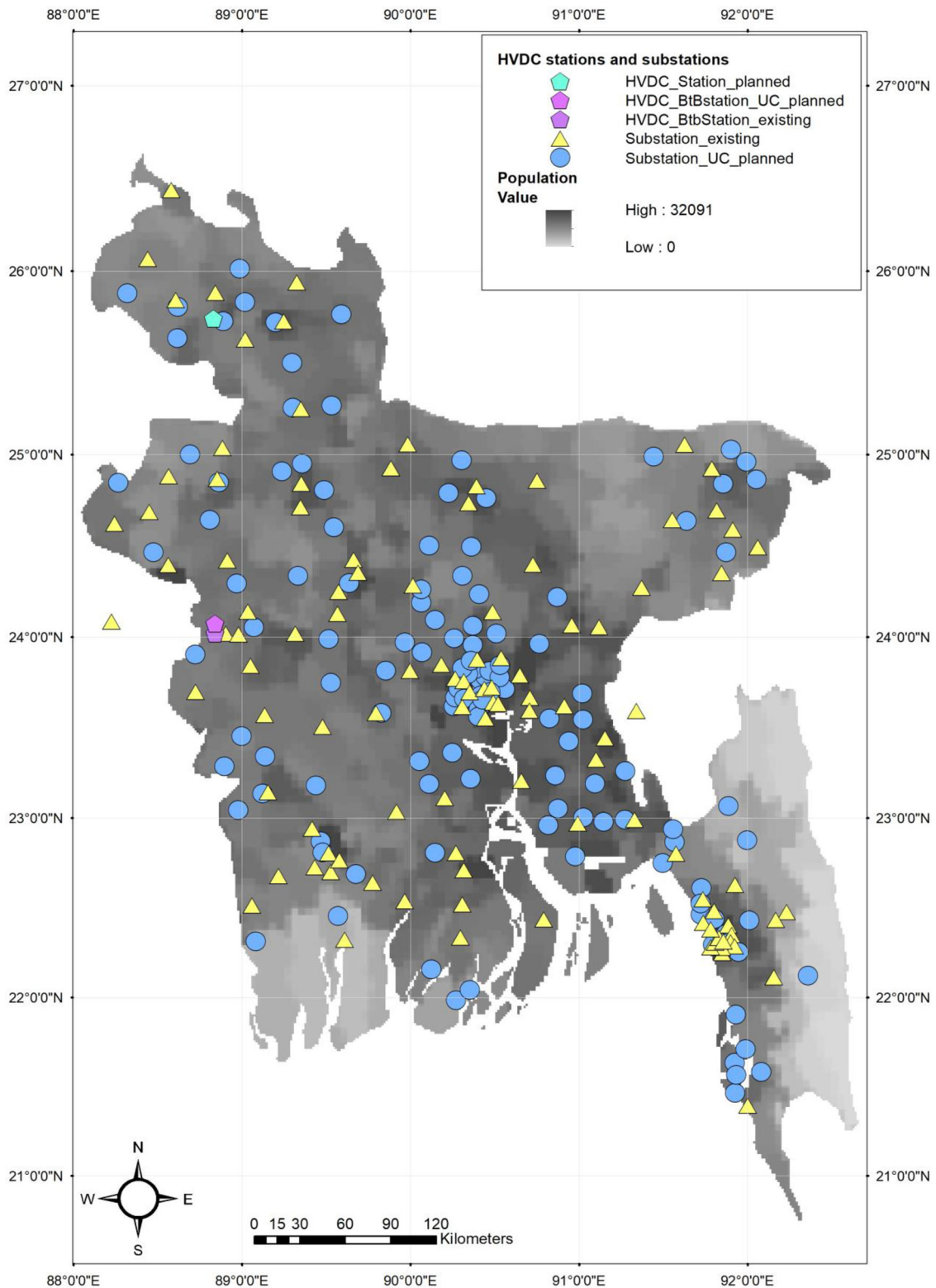


Figure 13. Substations and HVDC stations in Bangladesh (2015–2021). Map drawn by authors using data from [28–30].

Also, Figure 15A illustrated the exponential growth in GDP since the liberation war of 1971. Before 1971, GDP growth was uneven and unpredictable (Figure 15B). After the war, the uneven growth continued. However, in the early 1990s, the GDP growth started to stabilise, and from there, it increased to 8.15% in 2019 before plummeting to 3.5% in 2020 due to COVID-19 induced constraints. In the past 50 years, the highest GDP

growth was recorded at 10.95% in 1964 [2]. In 2020, Bangladesh's GDP was 12.16 times (\$270.7 Billion (constant 2015 US\$)) that of 1960 [2]. Bangladesh's GDP per capita was \$1248.45 (constant 2015 US\$) in 2015, which increased to \$1625.65 in 2020 [2]. In addition, the geographical position made Bangladesh vulnerable to natural disasters. Since 1971, severe natural disasters such as floods, cyclones, and hurricanes negatively

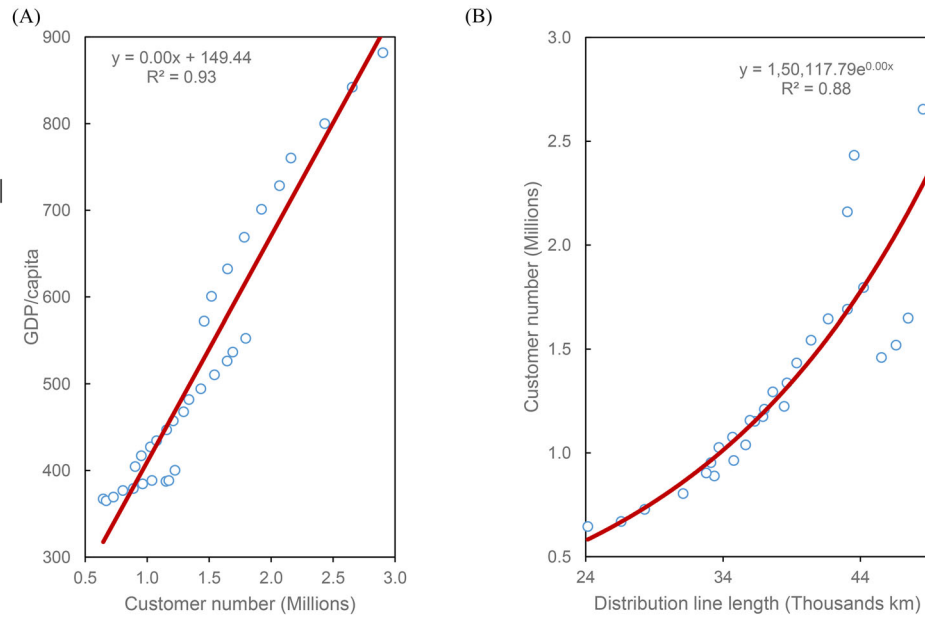


Figure 14. (A) Relation of electricity customer numbers with GDP per capita and (B) distribution line length in Bangladesh; data source [1, 2].

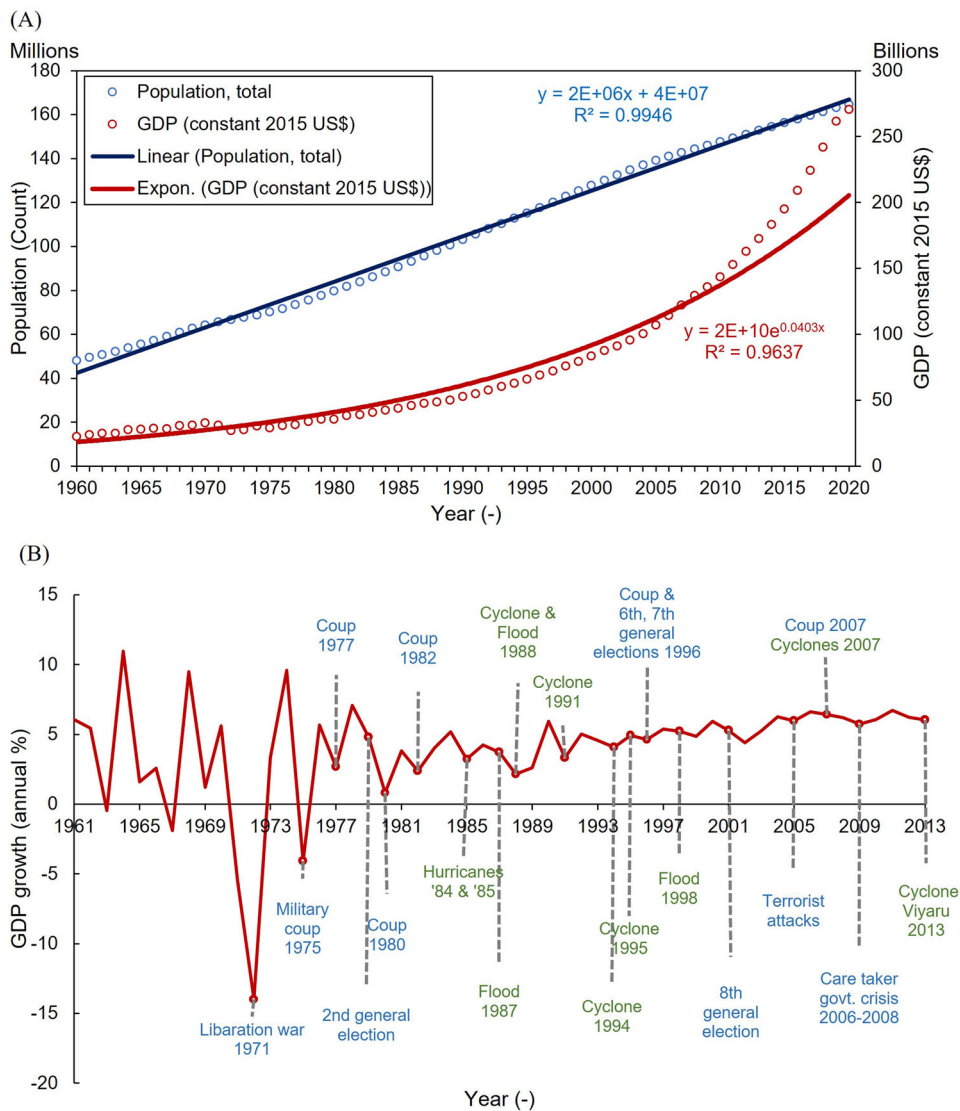


Figure 15. (A) Population and GDP in Bangladesh from 1960–2020 (Data source [2]). The population has been rising at a positively linear trend. However, GDP is demonstrating an exponential trend. (B) The historical GDP growth rate of Bangladesh (Data source [2]) and plausible reasons (the blue coloured reasons are political and green ones are natural disasters).

affected the country's economy in 1984, 1985, 1987, 1988, 1991, 1994, 1995, 1998, 2007 and 2013 (Figure 4). Moreover, political instabilities such as the 1971 liberation war, a military coup (1975, 1977, 1980, 1982, 1996, and 2007), general election time protest and activities (1979, 1996, and 2001), caretaker government crisis (2006–2008), and terrorist attack (2005) also contributed to reducing GDP growth in different times (Figure 15B). According to the World Bank, the country's poverty has decreased by 26% between 2000 and 2010 [38]. Despite an annual 7.1% GDP growth, 4.07% of the total labour force was unemployed in 2016, from 2.2% in 1991 [2]. The cause behind this higher unemployment rate may be the transition from the agriculture-based economy to a manufacturing industry based one, as agriculture is a more labour-intensive job sector than that of the manufacturing industry in Bangladesh.

The household final consumption expenditure and the Purchasing Power Parity (PPP) trend in Bangladesh demonstrated exponential growth in 1990–2016 (Figure 16A). Moreover, the household final consumption expenditure, PPP and per capita electricity consumption of Bangladesh demonstrated a positive linear relationship with $R^2=0.98$ (Figure 16B). The combined effect of the population growth and rapid economic development rendered the increased buying capacity of the people, especially the middle class, which may have influenced the electricity consumption towards rapid growth, also evident in the past studies. For example, Lee & Chang [39] examined the economic growth in Taiwan (1955–2003) and concluded that the relationship between energy consumption and economic growth in Taiwan was characterised by an inverse U-shape, where there was lower energy consumption, energy consumption promoted economic growth [39]. In another study, analysis of 16 Asian countries during 1971–2002 also demonstrated a positive long-run co-integrated relationship between real GDP and energy consumption [40]. Bangladesh was included in the least developed country category in 1975 [41]; became a lower-middle-income country from a lower-income country in 2015 [42] and graduated to the developing nation's category in 2021 [43]. Energy use per capita (kg of oil equivalent) and GDP per capita demonstrated a positive exponential correlation with $R^2=0.98$ (Figure 16C). Only 76% of the total population had access to electricity in 2016 [2]; therefore, 24% of people in Bangladesh lived

without electricity in 2016, which reduced to only 7.8% in 2019 (92.2% of the total population had access to grid electricity). Increased energy consumption per capita had shown a high economic output in Bangladesh with massive energy poverty—electricity consumption of only 422.13 kWh per capita in 2020–21 [1]—among the population, resonating with the study's findings in the Taiwanese context [39].

Historical data on electricity demand indicated an exponential growth ($R^2=0.99$) in the last 42 years since 1971 (Figure 16D). No data before 1971 was found. Electricity consumption in Bangladesh elevated to 293 kWh per capita in 2013 from only 11 kWh in 1971 [2], which means a 27 times increase in 42 years. The GDP-electricity elasticity of the country exhibits a robust linear relationship ($R^2=0.99$); for one kWh/capita electricity consumption augmentation, GDP/capita increased US\$1.8 on average between 1971 and 2013 (Figure 16E). The correlation from Figure 16D also resonates with another study conducted by Mozumder & Marathe [44], where a unidirectional causality from per capita GDP to per capita electricity consumption in Bangladesh was concluded [44].

Energy security

Uninterrupted energy availability at an affordable cost is defined as energy security [45]. In the case of Bangladesh, the energy generation is continuously unable to meet the demand resulting in load shedding (Figure 5B). Therefore, the Bangladesh government targeted achieving a constant electricity supply to all the households by 2021 to ensure better energy security [46]. Among the N-11⁴ countries, Bangladesh had the second-lowest—after Nigeria—population (75.9%) with access to electricity in 2016 (Figure 17) which rapidly increased to 92.2% in 2019. Although Bangladesh had the lowest access to electricity until 2008 [2], it elevated rapidly since 2008—a 50% and 11% increase by 2016 compared to 2008 and 2015, respectively—evidencing the progression towards 100% grid-connected household 2021 as per government target. The elevated access to electricity and household buying capacity collectively may be a significant driver in rapidly elevating electricity demand in the domestic sector, accounting for 57% of the total demand in 2020–21 for Bangladesh [1].

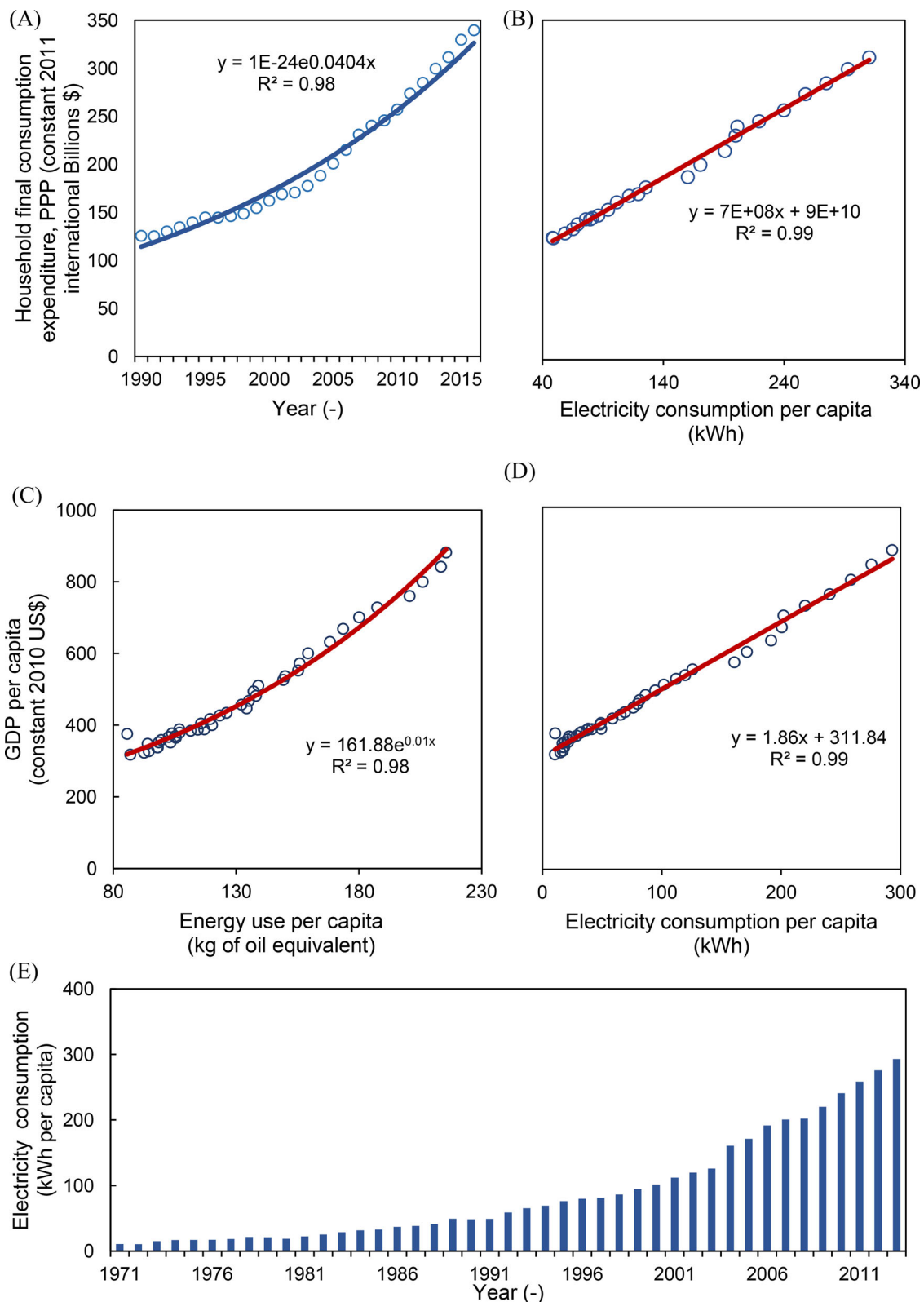


Figure 16. (A) Household final consumption expenditure, PPP (constant 2011 international billion US\$) in Bangladesh 1991–2016. (B) Relationship between household final consumption expenditure, PPP (constant 2011 international billion US\$) and per capita electricity consumption of Bangladesh. (C) GDP elasticity with energy use. (D) GDP elasticity with electricity consumption per capita of Bangladesh. (E) Historical electricity consumption in Bangladesh (1971–2013); data source [2].

Rapid service and manufacturing industry growth

The service⁵ and manufacturing industry sector has been increasing in Bangladesh since 1985, and

the value-added in GDP has been increasing. On the other hand, the value-added GDP from the agriculture sector has continuously been reducing (Figure 18A). In 1960, the agriculture and service sectors contributed 57.5% and 35.6% of the GDP,

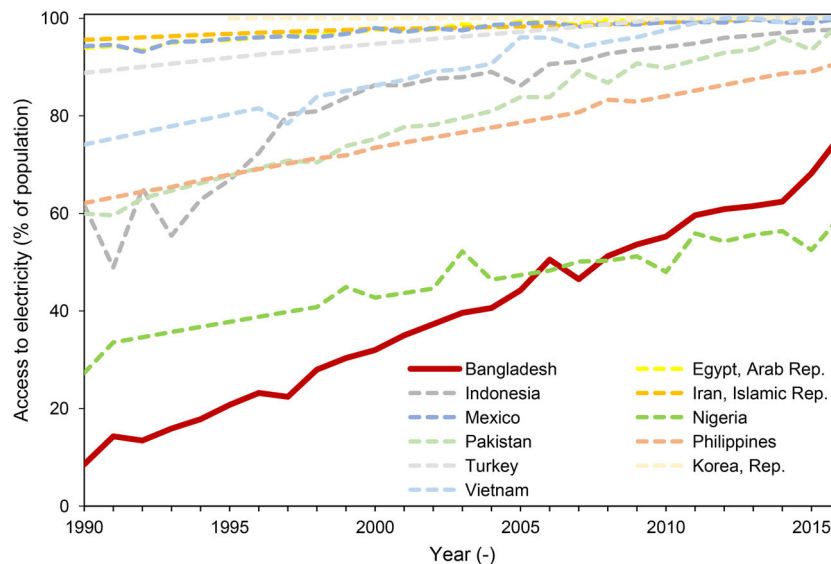


Figure 17. Access to electricity in N-11 countries as a percentage of the population (1990–2016); data source [2].

respectively [2]. By 2016, the service sector was accounted for adding 56.5% value of GDP (59% increase in 56 years). On the other hand, value-added agricultural GDP reduced to 14.8% in 2016 (74% reduction in 56 years) [2]. However, the most substantial increase in value-added in GDP—237% increase between 1960 and 2016—was from the manufacturing industry sector. In 2016, the manufacturing industry sector contributed 17.9% in GDP, only 5.3% in 1960. The annual growth in the manufacturing sector was 11.7% in 2016 (Figure 18B).

In 2011, 51% of the value added by the manufacturing industry was from the textile and clothing industries (Figure 18C). In 1984–85, only 384 ready-made garments (RMG) factories were operational in Bangladesh, with 0.12 million workers. The factory number elevated to 4482 and employed 4 million workers by 2016–17 [47]. The RMG export reached US\$28.2 billion, which was 82.23% of the total export in 2016–17 [47]. Studies showed that Bangladesh RMG might export US\$50 billion by 2021 [48], which will be 77% higher than that of 2016–17. The massive growth of the manufacturing and service sector, especially the RMG sector, requires a large amount of electricity and largely influenced the electricity demand in 2014, where 34% of the total demand was from the industry sector in Bangladesh [1]. However, according to the global competitiveness report, 2014–2015, Bangladesh ranked 130 among 144 countries in infrastructure quality [1]. Bangladesh's overall infrastructure score was 2.8, lower than its RMG manufacturing counterparts such as India, China, Cambodia, Sri Lanka, Pakistan, Vietnam and Thailand [49]. Notably, in the case of electricity

infrastructure, Bangladesh scored only 2.5 (ranked 124 out of 144), which was even lower than countries with a lower ranking in infrastructure quality, such as Myanmar, whose ranking was 117 in 2014–15 with 2.8 scores quality [49]. Under these circumstances, the Bangladesh government is rapidly escalating the electricity generation and T&D infrastructure to meet the increasing demand in the industry sector.

Lower renewable potential

Studies such as [12,50] showed that Bangladesh had solar, wind, biogas, biomass, and micro-hydro potential. However, apart from solar, the others offer relatively lower potential. In terms of hydro, Bangladesh—mostly flat elevation with some hill areas in the northeast and southeast regions—has a limited potential [51]. In addition to the active 230 MW at Kaptai, Sangu and Matamuhuri showed 140 MW and 75 MW installed capacity potential for large (>10 MW) hydropower plants. Another study reported that Bangladesh had a 500–3500 MW hydroelectricity potential; however, the generation target was 1500–2000 MW in 2015–20, only 230 MW was operational by 2019 [13]. In terms of small (less than 10 MW) hydropower, Bangladesh has 124 MW potential of generation [51]. Although PSMP 2016 showed a small hydro potential of 60 MW [7]. Bangladesh had 637 MW wind power potential (excluding the flood-prone land) [52]. Also, another study reported that Bangladesh had 100 MW of technical wind potential, but only 3 MW was achieved by 2019 [13].

In terms of land use, about 60% are arable land in Bangladesh [2]. Therefore, agricultural residues

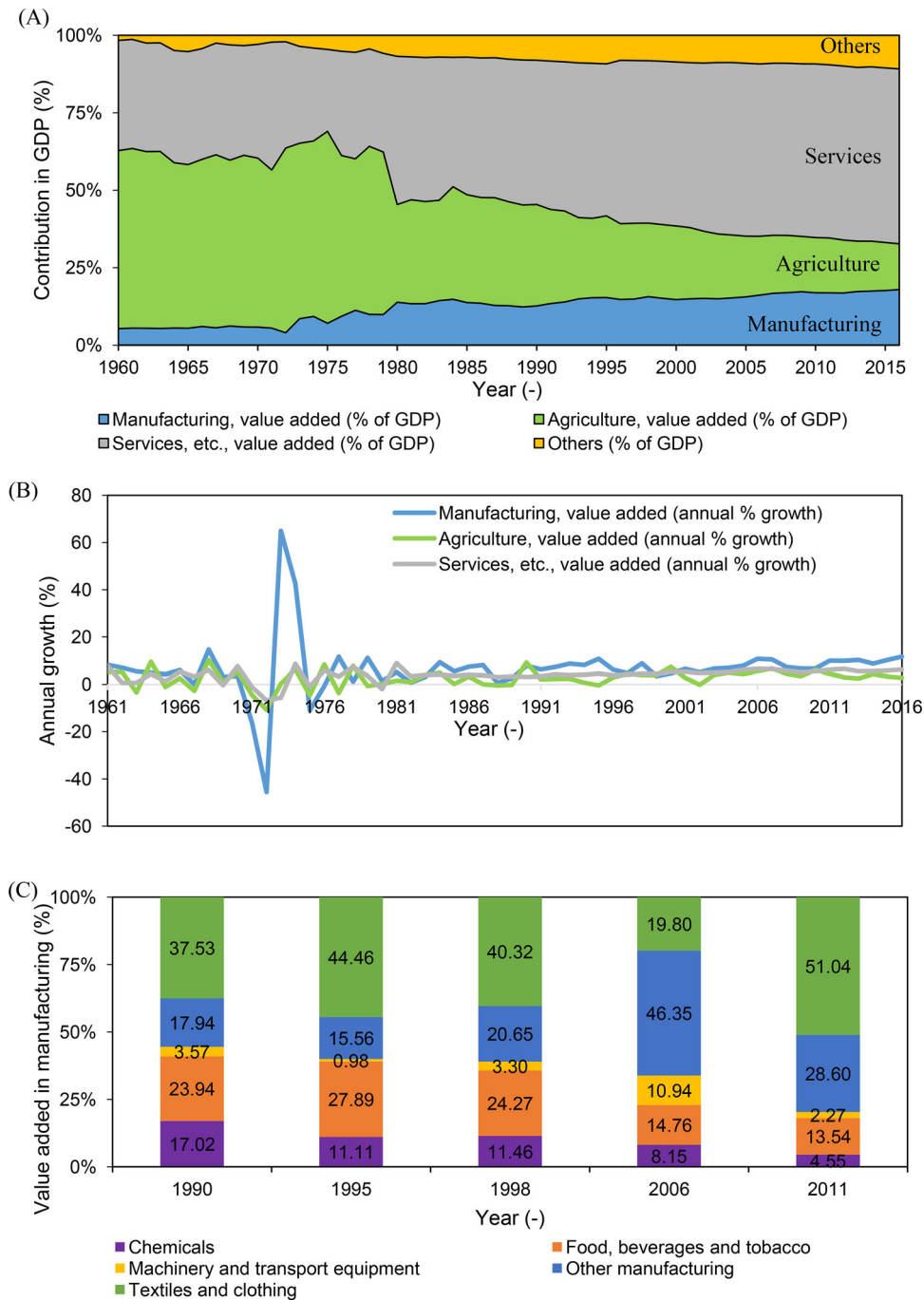


Figure 18. (A) Contribution of agriculture, service and manufacturing industries in Bangladesh (1960–2016), (B) Annual growth rate in agriculture, service and manufacturing industries in Bangladesh (1961–2016), (C) Value added by different manufacturing industries in Bangladesh in different years; data source [2].

such as rice husk could be used for biomass-based generation. Bangladesh’s total biomass generation capacity was estimated to be 275 MW as biomass generation may depend on agriculture activities to act as a barrier and increase levelised energy cost (LECs) [6]. Furthermore, the technical potential of biomass and biogas was estimated to be 1200 MW in Bangladesh; however, only 18-20 MW of biogas generation from animal waste and 1 MW energy from waste was achieved by 2019 [13].

The maximum renewable energy generation potential for Bangladesh was estimated from solar. According to PSMP 2016, Bangladesh has 1400 MW

energy generation potential from solar parks only in non-agriculture land [7]. Another study reported 3000–5000 MW of technical solar potential for Bangladesh [13]. The significant barriers for large-scale solar parks were limited fiscal space, commercial funding, track record of private sector financing, policy incentives, legal and regulatory framework, data, skilled labour, and seasonal flooding [6]. In terms of solar rooftop and solar home systems (SHS), Bangladesh had 635 MW and 100 MW installed capacity potential, respectively. The estimated solar irrigation potential was 545 MW [6]. Although the estimated solar

generation potential of Bangladesh was 2680 MW (annual generation would be 3710 GWh), compared to the future electricity demand—the estimated demand of 82000 GWh in 2020 and 307000 GWh in 2040 [7]—the contribution of solar will be only 1.2% in 2040. Other energy generation technologies such as fuel cell, wave, tidal, geothermal, and solar thermal are not viable for Bangladesh shortly, mainly due to the lack of technical know-how of the new technologies [51].

Recommendations

The renewable energy generation scope in Bangladesh is low. Therefore, PSMP 2016 targeted an emission intensive future for Bangladesh's electricity generation sector. But the following non-emissive energy may decarbonise Bangladesh's future electricity supply sector:

1. **Nuclear power:** Bangladesh has started to establish the first 2400 MW nuclear power plant in Rooppur, Pabna, with technical and financial assistance from Russia. Rooppur 1 (1200 MW) and Rooppur 2 (1200 MW) will be operational in 2024 and 2025, respectively [7]. Bangladesh even depends on Russia to get rid of nuclear waste. According to PSMP 2016, Bangladesh may increase the installed capacity up to 7200 MW by 2041 [7]. Nevertheless, Bangladesh should increase the installed nuclear capacity to replace planned fossil fuel-based electricity generation. However, the safety, waste and technical concerns related to increased nuclear generation capacity must be addressed.
2. **Electricity import:** Bangladesh imported electricity from India (approx. 9% of the total maximum generation of 11623 MW in 2018 [1]), which will increase significantly by 2041 (18% of the 60000 MW [7]). Also, a recent policy update in India —'Guidelines for Import/Export (Cross Border) of Electricity-2018' (Figure 2)— paved the way for Bangladesh to import electricity (predominantly hydroelectric) from Nepal and Bhutan through Indian transmission lines and the cross-border energy imports are expected to rise 3500–8500 MW (by 2031) and 9000 MW (by 2041) [7]. Therefore, the future of decarbonising Bangladesh's energy infrastructure may significantly contribute to renewables from neighbouring countries such as Nepal and Bhutan. Almost all their electricity came from hydro,

and they had significant untapped hydro potential. However, such regional energy collaboration might face significant geopolitical, environmental and management challenges, which needs to be explored and addressed.

3. **Floating solar power plants:** Most of the land use in Bangladesh is agricultural land to feed the world's eighth-largest population, where rice is the staple. Therefore, establishing large solar parks on arable land will be counterproductive to ensure food security. Thus, the PSMP 2016 proposed a 1400 MW solar park on non-agriculture land. On the other hand, Bangladesh is a riverine country with the most significant delta globally. There is 24000 km of rivers in Bangladesh [53]. Therefore, Bangladesh may explore the potential of floating solar power plants on the rivers and water bodies like projects in China, India, South Korea, and Saudi Arabia [54]. However, two significant concerns of such floating solar parks in Bangladesh are natural disasters (seasonal floods) and intermittence. Due to social-economic-environmental issues of battery storage [55,56] and Bangladesh's low Pumped-storage hydroelectricity potential, exploring innovative technologies—such as Gravity/Gravitational energy storage [57,58], compressed/liquified gas [59,60], green hydrogen [61–63]— might assist in solving the intermittence issues.

Conclusion

Bangladesh will anticipate a rapid exponential increase in electricity demand as a rapidly growing world economy. The energy sector has been getting a massive makeover in the last decade to meet the high demand, which will continue up to the following two to three decades. The demand growth profile had been slowly growing since 1971, which took a significant leap in the 2000s, and it will eventually keep elevating as per current studies and master plans. Therefore, the demand sector and the supply and T&D components of the electricity sector have been observing rapid growth.

The present electricity generation fuel mix is natural gas dominating. However, the energy mix will be dominated by fossil fuel in the future, and most of the power plants would operate with imported LNG, petroleum and coal. According to PSMP 2016, Bangladesh would import 60 Mt coal,

and 70% of the gas demand would be supplied from imported LNG in 2041. Already, the dependency on imported petroleum-based rental and quick rental power plants proved to be a questionable endeavour, which elevated the generation cost and exposed Bangladesh's energy sector to the volatile global petroleum market. The further dependency on imported LNG and coal may pose a more severe constraint on the generation sector and the economy of Bangladesh. Moreover, the decarbonisation commitments and the target of supplying necessary electricity to all people create a new line of debate if the fossil fuel-based future will do better than harm.

We found several primary drivers behind the rapid development of the emissions-intensive electricity sector in Bangladesh. First, the combined effect of rapid population and GDP growth influenced the sizeable middle class and their buying capacity, which may have elevated energy demands rapidly by increasing the buying capacity of the rising middle class in Bangladesh. Second, the service and manufacturing industry sector was another driver behind energy demand growth. Bangladesh's agriculture sector contributed 14.8% of the GDP in 2016, which was 59.6% in 1972. On the other hand, the service and manufacturing industry sector increased to 74.4% in 2016, from 38.3% in 1972. The third driver behind the rapid demand was the high growth in energy security, as the country aimed at 100% access to grid electricity by 2021, denoting massive growth in consumers. Under such high demand scenario, Bangladesh's limited renewable energy potential nudged the energy development towards emissions-intensive generation. This study recommended exploring nuclear generation, (hydro) electricity import from Nepal and Bhutan, and floating solar power plants to decarbonise the dependency on emissions-intensive fuel mix. Finally, suppose the government goes further with the current master plan without considering the environmental implications of the fossil fuel dependent on the energy system. In that case, Bangladesh might become one of the major GHG emitters in the world. When most countries are progressing towards emissions reduction, Bangladesh's high emissions based energy development would eventually undermine the worldwide effort of keeping global temperature rise below 2°C in the twenty first century, as per the Paris agreement and COP21.

Disclosure statement

The authors declare no competing interests.

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Data availability statement

The data that support the findings of this study are available in BPDB and World Bank. These data were derived from the following resources available in the public domain:

- <http://www.bpdb.gov.bd/>
- <http://data.worldbank.org/>

Notes

1. BPDB was created by presidential Order No. 59 after bifurcation of former Bangladesh Water and Power Development Authority [64].
2. No data for 66 kV after 2008-09 [64].
3. First started in 2013-14 with 82.35 km in Bangladesh [64].
4. The Next Eleven (N-11) are the eleven countries — Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, the Philippines, Turkey, South Korea and Vietnam — which are identified to have the potential of becoming the world's largest economies in the 21st century along with Brazil, Russia, India, China and South Africa (BRICS) countries [64].
5. According to the World Bank, "Services correspond to ISIC divisions 50-99 and they include value added in wholesale and retail trade (including hotels and restaurants), transport, and government, financial, professional, and personal services such as education, health care, and real estate services. Also included are imputed bank service charges, import duties, and any statistical discrepancies noted by national compilers as well as discrepancies arising from rescaling. Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs. It is calculated without making deductions for depreciation of fabricated assets or depletion and degradation of natural resources. The industrial origin of value added is determined by

the International Standard Industrial Classification (ISIC), revision 3.” [64].

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