Energy for Sustainable Development 79 (2024) 101416

Contents lists available at ScienceDirect

Energy for Sustainable Development

journal homepage: www.journals.elsevier.com/energy-for-sustainable-development

Although feasible, falling renewables costs might not benefit Bangladesh's energy sector's decarbonisation: Is this another 'debt-fossil fuel production trap'?

Kumar Biswajit Debnath [a,*], Monjur Mourshed [b]

[a] School of Architecture, Planning & Landscape, Newcastle University, Newcastle upon Tyne, UK
[b] School of Engineering, Cardiff University, UK

ARTICLE INFO

Keywords:
Cost of decarbonisation
Energy generation sector
Privatisation
Carbon pricing
Energy investment

ABSTRACT

As Bangladesh strives to transition from a least developed to a developed nation by 2041, a growing population and rising disposable income have spurred a growing middle class, escalating the demand for accessible energy. The government and the private sector have heavily invested in a fossil fuel-centric energy mix to meet this anticipated surge in demand. However, our research challenged this prevailing approach by developing a country-scale scenario-based input-output long-horizon energy planning model for demonstrating the economic viability of decarbonising Bangladesh's electricity generation sector by 2050, with a preference for renewables over fossil fuels, particularly in a low-emissions scenario. This study was among the first to evaluate which was the most recent Integrated Energy and Power Master Plan (IEPMP) with a long-horizon energy planning model and suggested that implementing strategic socio-economic development measures, such as privatisation, deregulation, transparency, energy demand reduction, equitable subsidy removal, and carbon pricing, could yield a 24 % cost reduction for developing a near-zero emissions electricity generation sector by 2050. Despite these potential benefits, current and future policies, entirely influenced by master plans developed by the Japan International Cooperation Agency, continue to rely heavily on imported coal, liquefied natural gas (LNG), hydrogen, ammonia, and nuclear energy, which raised concerns about the country being entangled in a 'debt-fossil fuel production trap.' We recommended a critical re-evaluation of existing energy policies. This caution was grounded in the suggestion that the nation should instead harness in-country resources and explore renewable-rich alternatives within its regional neighbouring countries, steering away from potential geopolitical, economic, and environmental pitfalls.

Introduction

As a rapidly developing lower-middle-income country, Bangladesh has maintained a steady growth of +5 % in the gross domestic product (GDP) since 2004, reaching 7.1 % in 2022 (WB, 2023). The country aims to become developed by 2041, requiring an annual GDP growth rate of 7.5–8 %. The bulk of the necessary economic growth would be expected to come from the manufacturing sector, a significant shift that started at the turn of this century. Manufacturing had higher energy intensities than the traditional agricultural sectors, which was evident between 2001 and 2014 (national energy consumption increased 3.17 times) (BPDB, 2023). With rising per capita income, a growing middle class fuelled the demand for convenient forms of energy. Considering the above drivers, the Bangladesh 2050 Pathways Model suggested 35 times higher energy demand than in 2010 by 2050 (BD2050, 2015).

In 2018, Bangladesh's electricity generation fuel mix was natural gas – oil – coal – renewable (hydro and solar) – imported (60.90 %–30.23 %–3.28 %–1.46 %–4.14 %) (BPDB, 2023), which reached 45.65 %–30.11 %–10.81 %–2.76 %–10.66 % energy mix in 2022–23 (BPDB, 2024). The progression of the energy mix followed the master plan of the Power System Master Plan 2016 (PSMP 2016), which moved the energy sector towards an imported coal-dominated electricity generation mix, where 50 % would be coal-based. Bangladesh revised the PSMP 2016 to the Integrated Energy and Power Master Plan (IEPMP) 2023 (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023). Moreover, the Government's approach to greenhouse gas (GHG) intensive

* Corresponding author.
E-mail address: kumar.debnath@newcastle.ac.uk (K.B. Debnath).

https://doi.org/10.1016/j.esd.2024.101416
Received 27 November 2023; Received in revised form 2 February 2024; Accepted 13 February 2024

electricity generation policies had already posed environmental threats in Bangladesh. As a result, conflicts such as Rampal occurred between environmental activists and the locals, and the Government when they proposed to establish 1320 MW imported coal-fuelled Rampal power plants would be constructed 14 km north of Sundarbans (the World's largest mangrove forest) due to the disputes over the land acquisition, deforestation, and concern over the effect of GHG emissions on the forest (EJA, 2017). Also, by increasing GHG emissions, the country would undermine the worldwide effort to keep global temperature rise in the 21st century between 2 and 1.5 °C, per the Paris Agreement and Conference of the Parties (COP) 21–28 (UN, "COP28 signals beginning of the end of the fossil fuel era," United Nations, 2024; UNFCC, 2015).

The Government and the private sector invested heavily in the energy sector. They would continue to build many new power plants to meet the substantial future demand (Moazzem & Ali, 2019). Most investments were financed by loans from international financing organisations — World Bank (WB), International Monetary Fund (IMF), and Asian Development Bank (ADB)— as well as domestic ones. On the other hand, Bangladesh is one of the world's most corrupt countries, and corruption is becoming more prevalent (DFID, 2013; Kabir, Taznin, Tanzima, Tabassum, & Rezwanul, 2021). According to Transparency International, Bangladesh ranked 147th out of 180 countries with a Corruption Perceptions Index (CPI) score of 25 (Denmark was ranked 1 with a 90 score), where a lower score denotes high corruption. In 2012, Bangladesh ranked 144th out of 174 countries with a CPI score of 26 (TI, "Corruption Perceptions Index," Transparency International, 2022). In contrast, according to previous studies, the cost of establishing power plants in Bangladesh was higher than the global average and might result from corruption in the energy sector (Debnath & Mourshed, 2018a; Moazzem & Ali, 2019). Moreover, the masterplans of energy development, such as PSMP 2006, 2010, and 2016 and the recent Integrated Energy and Power Master Plan (IEPMP) in 2023, were developed by Japan (Debnath & Mourshed, 2022; JICA,TEPCO, BPDB, & PGCB, 2010), which was one of the most significant bilateral funders of fossil fuel finance to global south countries between 2000 and 2018, and that their investments in fossil fuel projects far outweighed the funding deployed for renewable technologies (Woolfenden, 2023). Such investments had led countries from the global south to the "debt-fossil fuel production trap" (Woolfenden, 2023) — a complex interplay between high debt burdens and fossil fuel production in global south countries. It manifested as countries relying on anticipated fossil fuel revenues to repay debt, leading to overinflated expectations and substantial investments. This reliance perpetuates a vicious cycle where countries, instead of benefitting economically, incur further debt, erode long-term development prospects, and cause environmental and human harm. The debt burden became a significant barrier to phasing out fossil fuel production and transitioning to clean energy, creating vulnerabilities and inequalities within existing debt and financial systems.

Several studies were conducted on Bangladesh's energy sector development, renewable and solar energy potential, and cost. Mondal, A. H. et al. (2010) reviewed Bangladesh's renewable energy generation potential and concluded that ~55 GW of technical solar potential with some wind, biogas, and small hydro potential (Mondal & Denich, 2010). Das N. K. et al. (2020) investigated Bangladesh's present and future energy mix and emphasised importing electricity from neighbouring countries (Das, Chakrabartty, Dey, Gupta, & Matin, 2020). Das A. et al. (2018) explored an energy security framework, high power import, higher use of renewables and a combined high-power import-high renewables development scenario for Bangladesh, with the least cost optimisation model with Integrated MARKAL-EFOM System (TIMES) (Das et al., 2018). Mondal, A. H. et al. (2014) used the MARKAL model to evaluate different policy scenarios for deploying renewable energy technologies in Bangladesh (Mondal, Denich, & Mezher, 2014). Such optimisation methodologies had limitations in evaluating developing countries' variables involved in energy sector development (Debnath & Mourshed, 2018b). Masud et al. reviewed Bangladesh's current prospects for renewable energy. They suggested exploiting solar, wind, small-scale hydro, tidal, wave, nuclear and geothermal energy resources, privatisation and international investment (Masud, Nuruzzaman, Ahamed, Ananno, & Tomal, 2020). According to Gulagi et al., the costs associated with emissions could speed up the shift to entirely renewable energy. Nevertheless, eliminating these expenses would not significantly impact the energy system, as renewable sources would still account for 94 % of electricity production by 2050 (Gulagi, Ram, Solomon, Khan, & Breyer, 2020). Mabub et al. suggested that economic growth, access to local finance, and land availability were crucial factors in attracting Foreign Direct Investment (FDI) in renewable energy (Mahbub, Ahammad, Tarba, & Mallick, 2022). Anam et al. used the best-worst method (BWM) to rank 12 drivers of solar energy development in Bangladesh. They analysed the interrelationships among the drivers with the Integrated interpretive structural modelling (ISM)-MICMAC method (Anam, Bari, Paul, Ali, & Kabir, 2022). None of the existing literature investigated the decarbonisation cost and current and future masterplan's implications on pushing Bangladesh into a "debt-fossil fuel production trap". Furthermore, in contrast to the previous studies, we developed a bottom-up energy economics model to explore the cost of decarbonising Bangladesh's energy sector by 2050. Six emissions scenarios —business as usual (BAU), current policy (CPS), high-carbon (HCS), medium-carbon (MCS), low-carbon (LCS) and zero-carbon (ZCS)— and three economic conditions — high-, average- and low cost of capital, operation and maintenance (O&M), and fuel cost assumptions for the generation technologies— were combined to develop 18 different emissions-economic scenarios for the research (Table 1).

Materials and methods

Methods

Estimation and forecasting of the cost of reducing carbon emissions were significantly challenging due to exogenous (e.g., population, GDP) uncertainty, endogenous assumptions, and energy market volatility (Weyant, 1993). The significant limitations of existing global models were that they excluded developing countries' socioeconomic nuances and were typically created simplistically (Weyant, 1993). They were sometimes aggregated because of the need for appropriate data for the countries involved (Debnath & Mourshed, 2018b) and computational constraints due to model size.

The decarbonisation cost model had four components- the baseline input assumptions to the analysis, the specification of the control scenario being considered, the model structure employed to forecast, and the cost measure(s) reported (Weyant, 1993). The cost model would be an input-output model with a structure such as input → mathematical estimation and forecasting→ Output, based on the components. The analysis of existing Energy Planning Models (EMPs) in (Debnath & Mourshed, 2018b) revealed the shortcomings of models constructed by developed countries when adopted for developing contexts. The significant flaws in generalised EMP models were the inability of addressing the local contextual characteristics in a developing country, such as corruption, political instability, suppressed demand and climate change.

For this study, the BD 2050 energy and emissions model (BD2050,

Table 1
Scenario matrix.

Emissions scenarios	Economic scenarios		
	Low cost	Average cost	High cost
BAU	BAU-Low (B-L)	BAU-Average (B-A)	BAU-High (B-H)
CPS	CPS-Low (C-L)	CPS-Average (C-A)	CPS-High (C-H)
HCS	HCS-Low (H-L)	HCS-Average (H-A)	HCS-High (H-H)
MCS	MCS-Low (M-L)	MCS-Average (M-A)	MCS-High (M-H)
LCS	LCS-Low (L-L)	LCS-Average (L-A)	LCS-High (L-H)
ZCS	ZCS-Low (Z-L)	ZCS-Average (Z-A)	ZCS-High (Z-H)

2015) was utilised for baseline energy demand, supply, and emissions assumptions from 2020 to 2050 for the projection of demand, energy generation and GHG emissions because BD2050 was detailed bottom-up energy and emissions localised model developed for Bangladesh's energy demand and supply sector. The modelling approach of BD2050 was particularly suitable for Bangladesh to establish a cost model. The supply sector assumptions for Bangladesh were updated to forecast the potential of generation resources for different scenarios. The cost model extended the energy and emissions pathway model (Fig. 1). This study's proposed decarbonisation model had four interconnected layers: policy, socioeconomic, energy, and cost (Fig. 1). For reliable forecasting and decision-making, all these layers were significant for the cost of the decarbonisation model for developing and least developed countries. The socioeconomics, energy and cost layers had three parts- input variables, mathematical estimation and forecasting, and output variables. The policy layer fed into the input variables.

The BD 2050 model was developed for Bangladesh's energy sector planning from 2010 to 2050. The primary goal was to analyse the energy security in Bangladesh up to 2050 under different scenarios. The model had demand and supply domains. The demand domain comprised the building, industry, transport, agriculture, and food sectors. The supply domain included the operational and potential energy generation sources for Bangladesh, such as coal, natural gas, oil, nuclear, wind, solar, geothermal, hydro, waste, and biomass. Also, the energy fuel, transmission, and distribution sectors were modelled in BD 2050. The building sector was divided into rural, urban households, and commercial building sectors. Also, the transport sector had four categories: passenger, freight, international aviation, and shipping. A socioeconomic sector was also where demographic and economic analysis was undertaken to support other sectors' assumptions. Assumptions from BD 2050 were utilised for projecting electricity demand 2020–2050 (BD2050, 2015).

Cost model

The cost model had three parts- input, mathematical estimation and forecasting, and output (Fig. 1). The input's baseline cost assumptions were from the collected capital, operation and maintenance, and fuel cost data of power generation technologies (Table 2). The collected technology-wise cost data was estimated by multiplying with a forecasted installed capacity of the energy supply sector from 2020 to 2050. The baseline cost and energy assumptions utilised Eq. 1 to predict Bangladesh's total cost of energy generation sector development in 2020–2050. The outputs from the cost model were in USD (2020) value. The total energy demand, generation and GHG emissions from the BD 2050 model feed into the evaluation stage (Fig. 1), where the total cost,

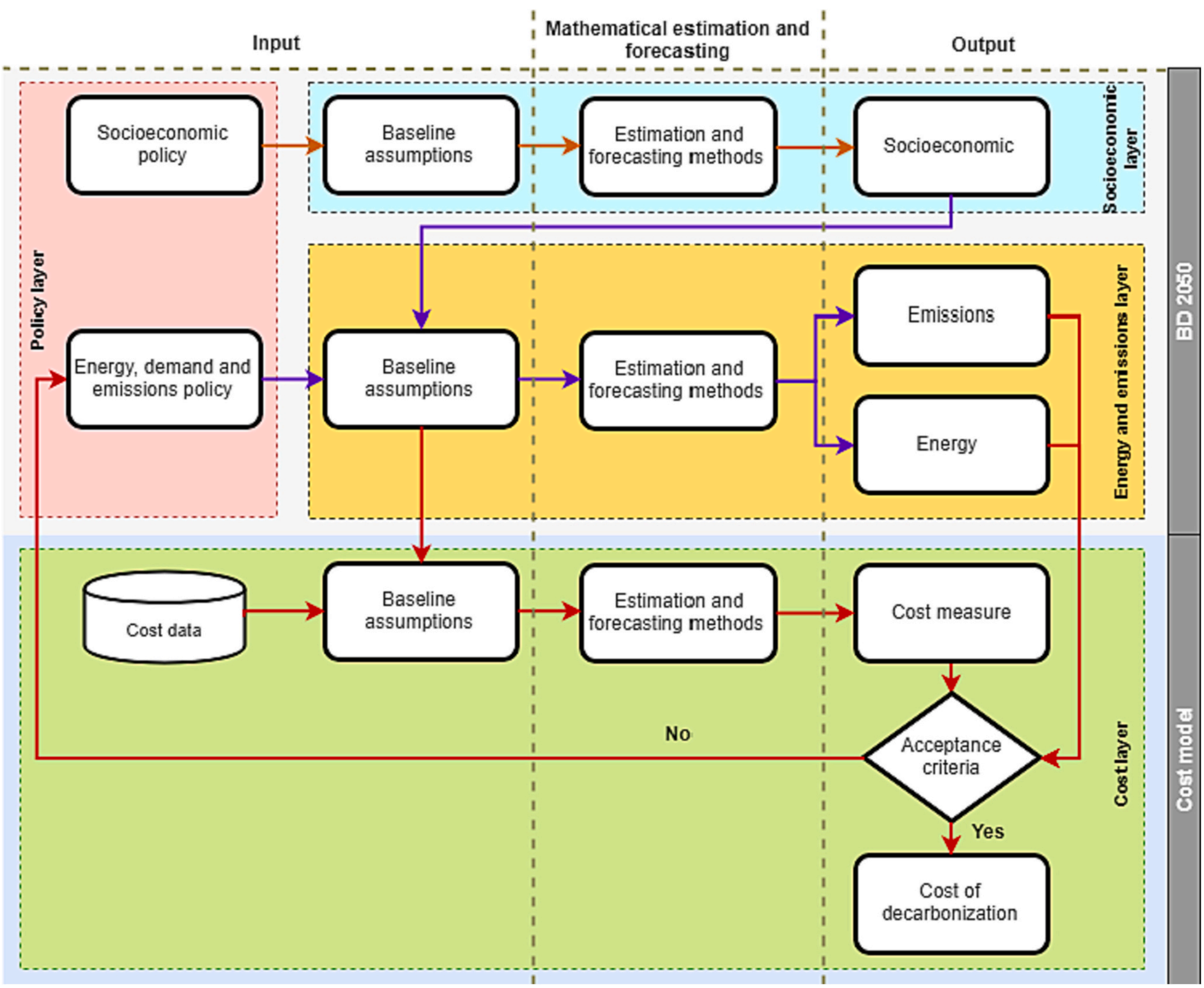

Fig. 1. Cost model structure (red lines denote the possible links and flow between BD2050 – 'Bangladesh 2050 Energy and Emissions Pathways' model and proposed cost model).

Table 2
Baseline cost assumption for different energy generation technology.

Fuel type	Generation technology	Capital cost (USD) per Installed capacity (kW)			O&M cost per unit generation (kWh)			Fuel cost per unit generation (USD/kWh)		
		High	Low	Annual change rate (%)	High	Low	Annual change rate (%)	High	Low	Annual change rate (%)
Natural gas	GT/ST, CCPP	1950	697	3	2.37* (BPDB, 2023; GoB, 2015a)	0.26* (BPDB, 2023; GoB, 2015a)	4.4	0.031 (JICA & TEPCO, 2011)		0.33
Coal	Subcritical	1924	1245	0.18	35** (IEA, 2022)	21** (IEA, 2022)	0.18	0.012 (JICA & TEPCO, 2011)		0.7
	Supercritical	2400 (IEA, 2022)	700 (IEA, 2022)	0.18	48** (IEA, 2022)	28** (IEA, 2022)	0.18	0.015 (JICA & TEPCO, 2011)		
	Ultra-supercritical	3820	800 (IEA, 2022)	0.18	56** (IEA, 2022)	32** (IEA, 2022)	0.18	0.015 (JICA & TEPCO, 2011)		
	Integrated Gasification Combined Cycle	2900 (IEA, 2022)	1100 (IEA, 2022)	0.18	77** (IEA, 2022)	50** (IEA, 2022)	0.18	0.015 (JICA & TEPCO, 2011)		
Oil	GT/ST	1654	550	1.57	31.32*	4.23*	4.5	0.055 (JICA & TEPCO, 2011)		0.34
Nuclear	Nuclear	5625	2000 (IEA, 2022)	0.13	133** (IEA, 2022)	112** (IEA, 2022)	−0.13†	6.77** (NEI, 2016)	0.8**	0.4
Renewable	Hydro	2128	1700 (IEA, 2022)	−0.3†	0.14*	0.053*	−0.6†	–	–	–
	Solar PV	4938.21†† (Debnath & Mourshed, 2018a) 700††† (IEA, 2022)	590†† (IEA, 2022; IRENA, 2019) 650††† (IEA, 2022)	0.6	21** (IEA, 2022)	18** (IEA, 2022)	0.6	–	–	–
	Geothermal	2980 (IEA, 2022)	2070 (IEA, 2022)	0.4	42** (IEA, 2022)	41** (IEA, 2022)	0.3	–	–	–
	Offshore wind	5390 (IEA, 2022)	4440 (IEA, 2022)	2.8	163** (IEA, 2022)	155** (IEA, 2022)	2.8	–	–	–
	Onshore wind	1890 (IEA, 2022)	1300 (IEA, 2022)	0.4	39** (IEA, 2022)	35 ** (IEA, 2022)	0.4	–	–	–
	Hydrogen	–	–	–	–	–	–	4.36# (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023)	2.82# (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023)	0.7
	Ammonia	–	–	–	–	–	–	632## (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023)	355## (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023)	0.5

* Unit: BDT/kWh,** Unit: USD/kW, # Unit: USD/kg-H_2, ## Unit: USD/ton-NH_3, † Cost increases, ††Large scale units, †††Building units.

unmet demand, and cost per unit emissions and unit generation were evaluated according to the acceptance criteria to find the cost of decarbonisation for Bangladesh under various emissions scenarios. For different sectors, the following equations were utilised:

$$T_y = \sum_{y\in Y}\sum_{a\in A}\sum_{f\in F}\left(I_{y,a}.C_{y,a} + I_{y,a}.O_{y,a} + U_{y,a}.F_{y,f}\right) \tag{1}$$

$$TD_y = \sum_{y\in Y} T_y^{C/D} - T_y^H \tag{2}$$

$$E_y = \sum_{y\in Y}\sum_{f\in F} I_{y,a}.LF_a.EF_f \tag{3}$$

$$CP_y = \sum_{y\in Y} E_y.CP \tag{4}$$

Here, y, a, and f denoted years, energy generation technologies and fuels, respectively. T_y was the total cost in US$(2020). $I_{y,a}$ and $U_{y,a}$ were the installed capacity and fuel use, and the units were kW (kilowatt) and kWh (kilowatt-hour), respectively. Also, $C_{y,a}$ and $O_{y,a}$ was the capital cost per installed capacity, and operation and maintenance cost per installed capacity; the units were $(2020)/kW and $(2020)/kW, respectively. $F_{y,f}$ was denoted as the fuel cost per unit generation, and the unit was $(2020)/kWh. TD_y was the total decarbonisation cost in US $(2020). T_y^C, T_y^D and T_y^Hwere denoted as the total cost under different carbon-intensive (CPS/HCS), decarbonisation (MCS/LCS/ZCS), and BAU scenarios, respectively, and the unit was $(2020)/kWh. E_y was the total GHG emission in $MtCO_2e$ (million tonnes of carbon dioxide equivalent). LF_a and EF_f were the load factor of the energy generation technology and the emissions factor for the fuel use per unit of energy generation. CP_y was the carbon pricing in bn $. In Eq. 4, CP was the high-average-low carbon pricing assumption.

For the discount factor calculation, the discount rate was 5 % annually (CIA, "The world factbook," Central intelligence agency, 2018). In the case of corruption, the cost analysis in (Debnath & Mourshed, 2018a) demonstrated a statistically significant relationship between the capital cost of establishing power plants and the level of corruption in Bangladesh. Modelling a socioeconomic parameter such as corruption was complex (Debnath & Mourshed, 2018b). In this model, corruption was not modelled as multiplier or index-based. In (Debnath & Mourshed, 2018a), public power plants demonstrated significantly high capital costs and better association with corruption than private ones. The upper limit of the cost model assumption was from the capital cost of the public power plants, as shown in Table 2. Moreover, the lower limit of cost assumptions was mainly the private sector cost as they showed the lowest in Bangladesh compared to the public ones. In the case of new-generation technologies, the world lower limit from the International Energy Agency (IEA) database (IEA, 2022) and International Renewable Energy Agency (IRENA) report (IRENA, 2019) was considered, as shown in Table 2. Decarbonisation costs refer to the difference between no emissions reduction, such as BAU and scenarios with emissions reduction strategies, which was estimated with Eq. 2. For example, the cost of decarbonising Bangladesh's energy generation sector under a zero-carbon scenario (ZCS) would be derived by subtracting the total cost of ZCS from the total cost of BAU in a specific year. The total GHG emissions under different scenarios were calculated with Eq. 3. The carbon pricing estimations were conducted using Eq. 4.

Limitations

The modelling approach took a comprehensive set of technologically and economically feasible energy generation alternatives to analyse different energy development pathways for Bangladesh up to 2050. Individually, the cost of decarbonising the energy sector could be examined under various scenarios, and the capability of the scenarios to supply the forecasted demand could be investigated. The model had some limitations. For example, instead of modelling endogenous learning curve effects, the study adopted exogenous cost data for the technologies not applied in Bangladesh. The learning curve effect states that the average time cost of power plants was reduced by a certain percentage when the cumulative volume of installed capacity of generation technology doubles to a geographical extent (i.e., Global, regional, country) (Jägemann, Fürsch, Hagspiel, & Nagl, 2013). Private and public natural gas and oil-based power plants were generally established in Bangladesh. However, the cost difference between private and public power plants was significant—moreover, gas-based generation public plant costs were increasing in Bangladesh (Debnath & Mourshed, 2018a). As per the literature, the cost of power plants was supposed to reduce with time (Neij, 2008). For the inconsistency in the cost evolution in Bangladesh, the costs of different generation technologies were considered constant variables in this cost model. However, coal and hydroelectric plants were among the ones with several units. Bangladesh had no nuclear, wind, wave, tidal, commercial solar PV or thermal. The exogenous cost was adopted from reliable resources such as IEA, IRENA, and other published studies for these renewable and nuclear technologies. Another significant limitation of the study was the lack of cost data for Bangladesh. The cost of the 61 power plants was collected and examined among the 113 operational power plants to analyse the cost of energy generation technologies. Any discrepancies or uncertainties in the cost data obtained from source materials could potentially influence the model's outcomes and subsequent results.

Emission-economic scenarios and assumptions

There were six different scenarios examined in this study: business as usual (BAU), current policy scenario (CPS), high-carbon scenario (HES), medium-carbon scenario (MCS), low-carbon scenario (LCS) and zero-carbon scenario (ZCS) for the energy generation sector (Fig. 2). The cost of decarbonisation critically depended on the economic conditions, and there were three economic conditions, low, average, and high-cost scenarios, considered in this research. The cost of decarbonisation analysis scenarios was defined in Table 1. Regarding future cost, the decarbonisation scenario assumptions ranged from very pessimistic 'high cost' to optimistic 'low cost' projections, as shown in Table 1. Low and high-cost assumptions were mentioned in Table 2. The average cost was the mean of low and high-cost assumptions. The high-cost range was assumed to be constant from 2020 to 2050. The lower cost range was assumed to reduce over time with the annual rate mentioned in Table 2. The high range of cost assumptions in some but not all energy generation technologies denoted the public sector cost associated with corruption. Low assumptions were related to global or Bangladesh's private sector lower assumptions from the cost data described in (Debnath & Mourshed, 2018a). The difference in future pessimistic high and optimistic low-cost assumptions was more significant for less mature technologies for Bangladesh, such as offshore, onshore wind, and nuclear, because of the higher uncertainty.

The cost of decarbonisation also depended on the demand for electricity. If the demands were high, the cost would increase to decarbonise the system. Reducing demand could also decrease the cost of decarbonisation. In this model, the demand was continually increasing under the BAU scenario of the BD2050 model. The effect of demand reduction on the cost of decarbonisation was out of the scope of this research. In the cost model, the capital, O&M fuel cost, and the installed capacity of power plants were considered variable over time. Other parameters, such as the power plant's generation efficiency factor, GHG emissions factors and technical lifetimes, were constant as per the BD2050 model (BD2050, 2015).

1. Business as usual (BAU)

BAU scenario for Bangladesh's energy sector referred to the continuation of the 2020 installed capacity and no newly built power generation capacity. Under this scenario, the base year's derating capacity was considered in the baseline assumptions from 2020 to 2050 (Fig. 2). The installed capacity of 1736 MW in 2020 would remain unchanged until 2050. Coal was 0.4 % of the total energy mix in 2020, and it was assumed to reach 7 % of the energy mix by 2050. The natural gas and (imported) Liquefied natural gas (LNG) based power plant's installed capacity was 11,284 MW in 2020. Gas and LNG were 53 % of the total energy mix in 2020, and they were assumed to be 32 % of the energy mix by 2050 (Fig. 2). Moreover, no new gas or LNG-based power plant would be built in Bangladesh until 2050 under BAU. According to IEPMP 2023, coal- and gas-based (+LNG), power plants will use ammonia and

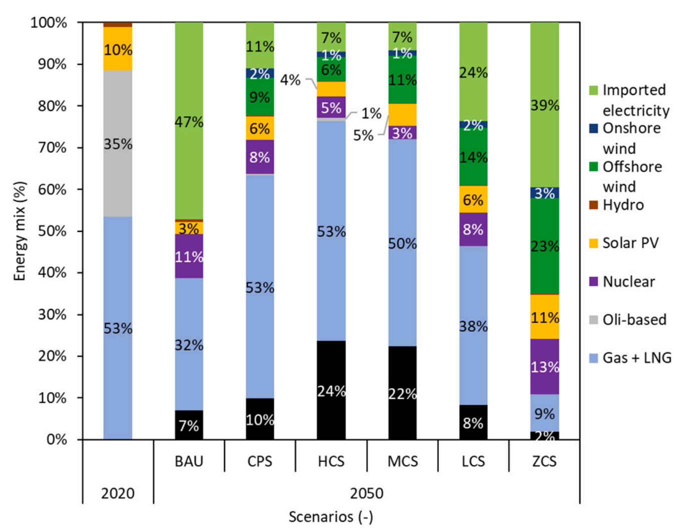

Fig. 2. Energy mix of Bangladesh in 2020 and analysed scenarios in 2050.

hydrogen by 2050 with different combinations under different scenarios (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023). Therefore, despite derating power plants over time and retirement, the gas and LNG-based power plant installed capacity would remain unchanged under BAU. The installed capacity for oil-based power plants was 7378 MW in 2020 (35 % of the energy mix). Under BAU, no new oil-based power plant would be built, and the installed capacity would be reduced to zero by 2040 due to derating and retirement. The retirement age of oil-based power plants was 3–15 years because of the Government's contracts, which were established to support peak load (MoF, 2009). On the other hand, Gas Turbines (GT) and Combined-Cycle Power Plants (CCPP) had an average lifespan of 30–40 years and an additional 12–25 years after extension (Lipiak, Bussmann, Steinwachs, & Lüttenberg, 2006). Therefore, cumulative oil-based power plants would retire before natural gas-based power plants.

Nuclear power plants were not operational in Bangladesh in 2020. There was a plan to build a new power plant in Rooppur by 2025, which is under construction. Therefore, the installed capacity would be zero in 2020 and 2104 MW by 2030 (according to the IEPMP 2023). Our model assumed no nuclear plant would be built in Bangladesh under BAU after that. Nuclear was assumed to reach 11 % of the energy mix by 2050. Bangladesh had a 20KW wind power installed capacity, established in Bangladesh as a small hybrid and stand-alone application at various public facilities (UNDP, 2013). Our model had a 3 MW onshore capacity but no large offshore installed capacity for wind-based power generation in 2020 (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023), which would remain the same until 2050. Bangladesh had no offshore wind, tidal range, stream, geothermal, biomass or wave-based power generation capacity in 2020 and was assumed to remain at zero until 2050 under BAU.

The solar photovoltaics (solar PV) installed capacity was in 2194 MW Bangladesh in 2020, where an 1814 MW grid was connected. The remaining installed capacity was off-grid Solar Home Systems (SHS) and solar irrigation. Under BAU, the total established installed capacity would be 2194 MW by 2050, although the lifespan of solar cells was assumed to be 25 years (Jordan & Kurtz, 2013). The only hydroelectric power plant in Kaptai (230 MW) was operational in 2020. It was assumed that under BAU, the installed capacity would remain the same up to 2050. Under BAU, 47 % of the energy mix would be from imported electricity (66 TWh) by 2050, elevated from 5.8 TWh in 2020.

2. Current policy scenario (CPS)

The current policy scenario (CPS) was developed with the present policies undertaken by the Government of Bangladesh for the supply sector development up to 2050. The IEPMP 2023 paved the future planning of the Bangladesh power sector from 2021 to 2050, which was prepared by the Japan International Cooperation Agency (JICA) and Institute of Energy Economics, Japan (IEEJ) for BPDB (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023). PSMP 2010 master plan focuses on coal-based generation increase to a fuel mix of coal-gas-others (50 %–25 %–25 %) by 2030 (JICA & TEPCO, 2011). However, the revised IEPMP 2023 showed a diverse energy mix with coal, gas-LNG, nuclear, hydrogen, wind, and others (2 %–46 %–5 %–16 %–15 %–16 %) by 2050 under the PP2041 scenario. The noticeable inclusion in the energy mix was hydrogen and ammonia, which would be using gas (+LNG) and coal plants to generate electricity (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023). All energy generation technologies in the model would maintain current government policies as assumptions from 2020 to 2050 (Fig. 2).

In coal power plants, the installed capacity would be 1736 MW by 2020, increasing to 10,520 MW by 2050. Coal would be 10 % of the energy mix by 2050 (Fig. 2). According to IEPMP 2023, Bangladesh's energy mix would have 46 % natural gas and LNG-based power generation by 2050. Furthermore, 16 % of the hydrogen would also operate in gas-based plants. Therefore, there would be 62 % installed gas capacity, LNG and hydrogen (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023). For our model, gas-based power plant capacity would be 81,164 MW by 2050 under CPS, accounting for 53 % of the energy mix in 2050 (Fig. 2). The installed capacity of oil-based power plants was 7378 MW in 2020. The government would keep relying on oil-based plants to supply the peak loads. Under the CPS, we assumed the installed capacity of oil-based power plants would be 1378 MW in 2050, accounting for 0.5 % of the energy mix.

In the case of the Rooppur nuclear power plant, one unit of 2000 MW would be operational by 2024, and another unit with 2000 MW would start supplying to the grid by 2025. Under CPS, we assumed the installed capacity would remain at 6850 MW by 2050, accounting for 8 % of the total energy mix (Fig. 2). There was no large offshore installed capacity in Bangladesh in 2020. The installed capacity of large offshore wind power plants was assumed to be 15,503 MW by 2050, according to IEPMP 2023 (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023), which would be 9 % of the energy mix. The onshore wind installed capacity was 3 MW in 2020 and would be 5000 MW by 2050, following the IEPMP 2023 plan (2 % of the energy mix). Bangladesh had no tidal range, tidal stream, wave-based, geothermal, biomass or waste-based power plant power generation capacity in 2020 and was assumed to remain at zero until 2050. The only hydroelectric power plant situated in Kaptai (230 MW) installed capacity was operational in 2020. Under CPS, the installed capacity would be 332 MW by 2050. According to Infrastructure Development Company Limited (IDCOL), there would be another 2000 MW grid-connected solar installed capacity in Bangladesh (IDCOL, "Projects and programs," Infrastructure Development Company Limited (IDCOL), 2017) and a 550 MW solar irrigation project (GoB, 2013). Total Solar PV installed capacity was 2194 MW in Bangladesh in 2020, which would be 18,000 MW by 2050, accounting for 6 % of the energy mix. Under BAU, 11 % of the energy mix would be from imported electricity (66 TWh) by 2050, elevated from 5.8 TWh in 2020.

3. High-carbon scenario (HCS)

Under the HCS, fossil fuels such as coal, natural gas, and oil-based energy generation would dominate the supply sector to meet the anticipated electricity demand by 2050. The coal power plant's installed capacity was 1736 MW in 2020, increasing to 34,085 MW by 2050. Coal would be 24 % of the energy mix in 2050 (Fig. 2). The cumulative installed capacity in natural gas, LNG and hydrogen-based power plants would follow the IEPMP 2023 master plan. The installed capacity was 11,284 MW in 2020. For our model, gas-based power plant capacity would be 126,402 MW by 2050 under HPS, accounting for 53 % of the energy mix in 2050 (Fig. 2). The installed capacity for the oil-based power plant was 7378 MW in 2020. Under the HCS, oil-based power plants would be 3558 MW by 2050, 1 % of the energy mix. Under the HCS, the nuclear-installed capacity was assumed to remain at 6890 MW up to 2050, following the IEPMP 2023 master plan. Solar PV's total installed capacity would increase to 18,000 MW by 2050. In the case of large offshore wind and hydroelectric plants, the installed capacity would be the same as CPS. The onshore wind capacity would be 4610 MW by 2050. Under the HCS assumption, no geothermal power plants would be operational by 2050.

4. Medium-carbon scenario (MCS)

In the medium-carbon scenario (MCS), the energy mix would be dominated by fossil fuels with support from renewables. The fossil fuel (coal, natural gas and LNG) electricity generation installed capacity would remain the same as HCS up to 2050. There would be no oil-based generation by 2050. Nuclear installed capacity would reduce to 4444 MW, accounting for 3 % of the energy mix by 2050. Solar PV's total installed capacity would increase to 28,000 MW by 2050. Therefore, solar PV would be 5 % of the total energy mix. In the case of large offshore, the total installed capacity would increase to 32,751 MW by 2050, accounting for 11 % of the energy mix. The installed capacity in 2050 would be the same as CPS and HCS for the onshore wind and hydro. Under MCS assumptions, no tidal, wave, or geothermal power plants will be operational by 2050.

5. Low-carbon scenario (LCS)

Under the low-carbon scenario (LCS), renewable and nuclear energy dominate Bangladesh's energy generation sector. As the PSMP 2010, 2016 and IEPMP 2023 master plans proposed a fossil fuel-dominating future supply sector, LCS would not be entirely fossil fuel-free. The cumulative coal and gas (+LNG) power installed capacity would maintain CPS up to 2050. No oil-based power plants would be operational by 2050 (Fig. 2). According to IEPMP 2023, the nuclear power installed capacity would be 2000 MW and 4000 MW in 2020 and 2025, respectively. Under the LCS, we assumed the installed capacity would be 9600 MW by 2050. The total installed capacity of Solar PV, offshore and

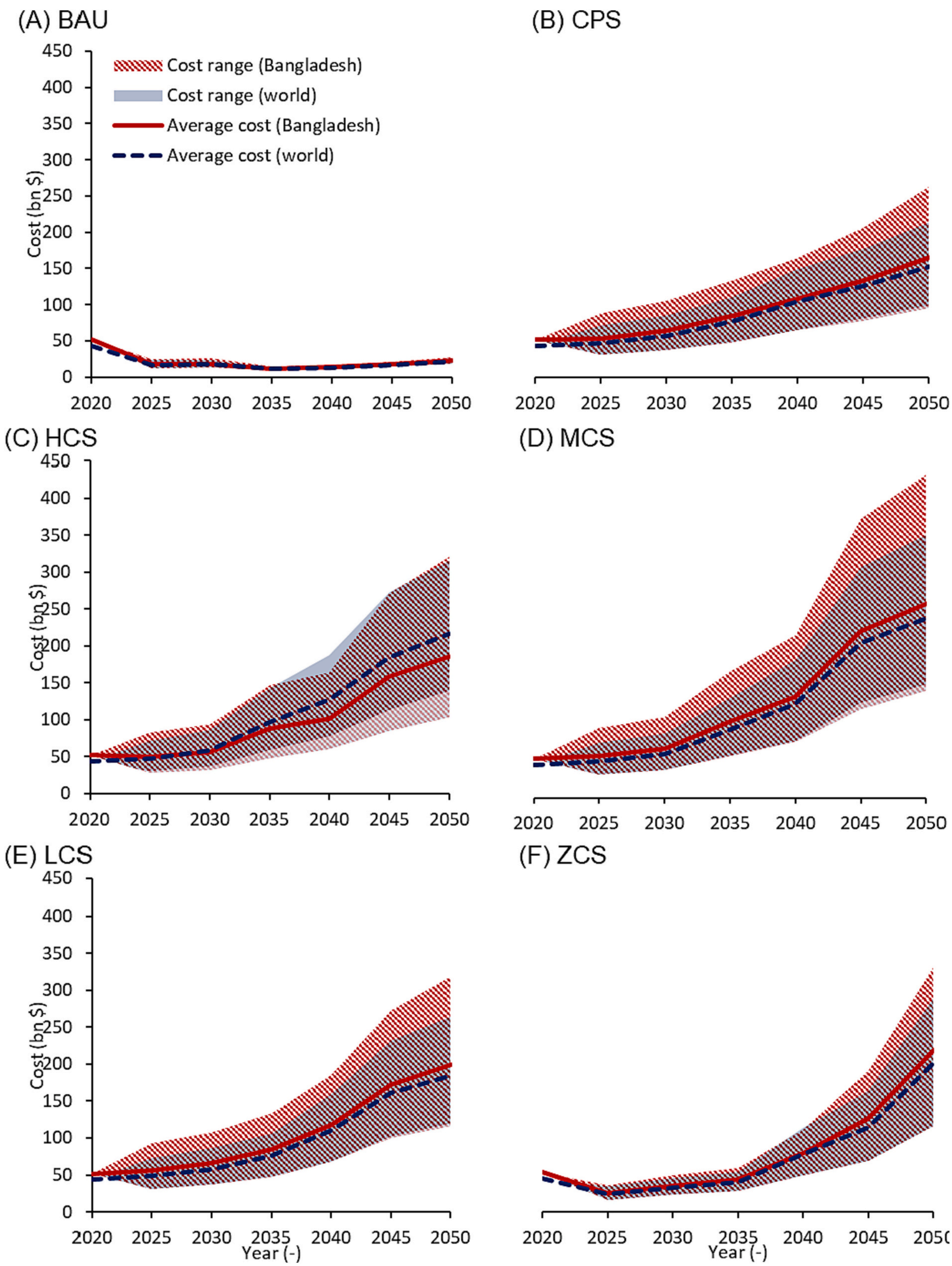

Fig. 3. Total cost (Bangladesh and global) under (A)BAU, (B)CPS, (C)HCS, (D)MCS, (E)LCS and (F)ZCS from 2020 to 2050.

onshore wind would be the same as HCS by 2050. Hydor installed capacity would be 470 MW by 2050, accounting for only 0.2 % of the energy mix. Under LCS's assumption, no geothermal, biomass, or waste-based power plants will be operational by 2050.

6. Zero-carbon scenario (ZCS)

In the zero-carbon scenario (ZCS), the energy mix would be dominated by renewable resources. Fossil fuel-based (coal, natural gas, and oil) energy generation would follow the BAU. The capacity installed for nuclear, solar PV-based, offshore, and onshore wind would be like LCS. The hydroelectric power installed capacity was 230 MW in 2020, which would be 545 MW by 2050, with 140 MW and 75 MW plants in Sangu and Matamuhuri (Mondal & Denich, 2010).

Results and discussion

Cost of decarbonisation for the electricity generation sector

Fig. 3 illustrated the total cost — estimated in billions (bn) US $(2020) and comprises capital, O&M, and fuel costs under emissions scenarios in a particular year — with the range of expenditure in a specific year with high-, average- and low-cost. The total cost of the electricity generation sector development in Bangladesh would increase under all the scenarios by 2050, with significant differences between scenarios with and without decarbonisation policies. Adopting GHG emissions reduction strategies, such as changing the energy mix and establishing new generation technologies, required substantial

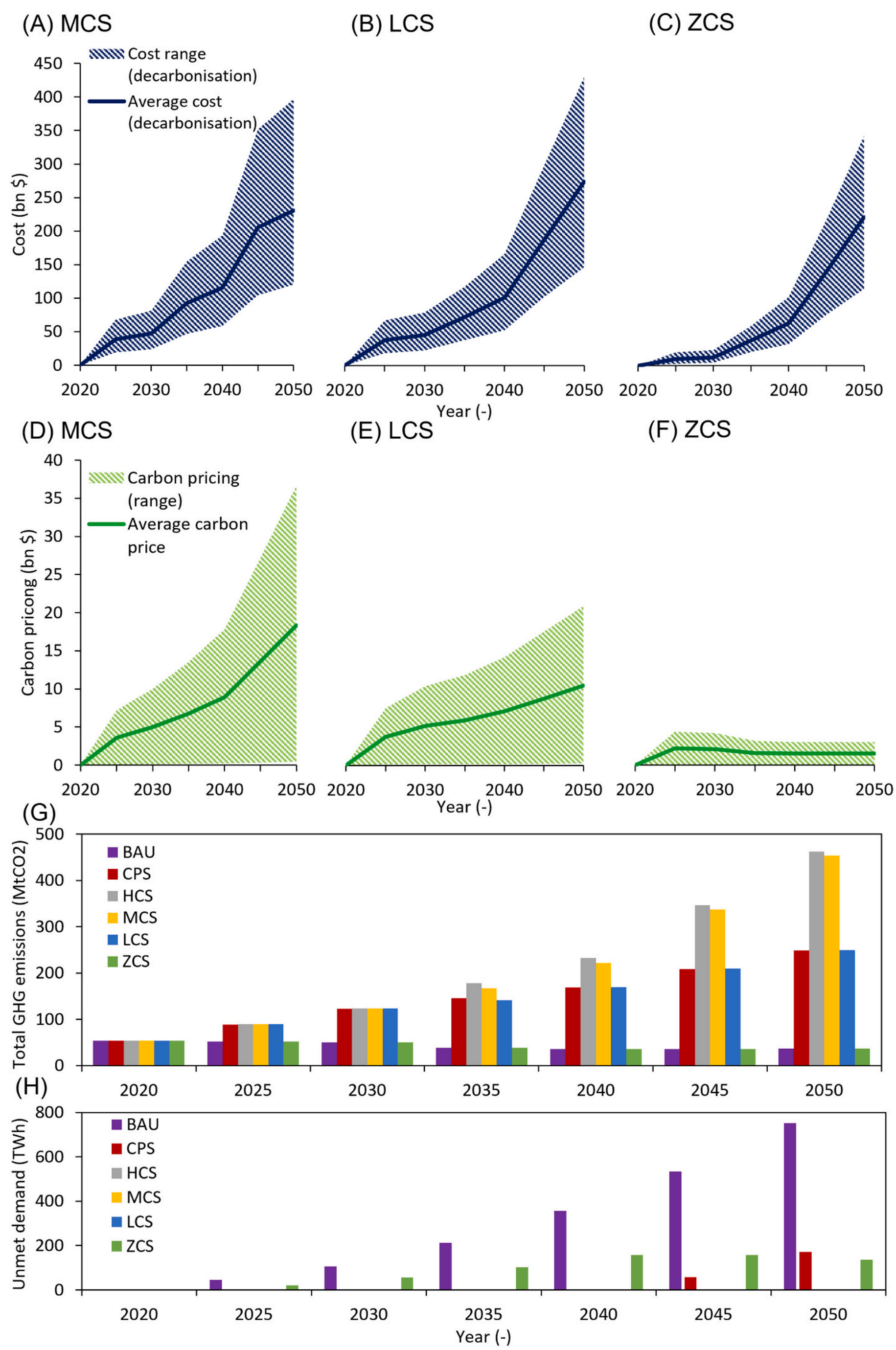

Fig. 4. Cost of decarbonisation under (A) MCS, (B) LCS and (C) ZCS from 2020 to 2050; Cost of decarbonisation with carbon pricing under (D) MCS, (E) LCS and (F) ZCS from 2020 to 2050; (G) Total GHG emissions under different analysed scenarios 2020–2050, (H) Unmet demand for analysed scenarios.

investments. Therefore, the total cost would increase linearly, approximately $19–$27 bn for BAU by 2050. Without significant decarbonisation policies and inclination towards fossil fuel-based generation under CPS and HCS, the total cost would be $ 93–321 bn by 2050. In comparison, the cost started to rise exponentially with the adoption of decarbonisation strategies under MCS, LCS, and ZCS and would reach approximately $457 bn by 2050 (Fig. 3). About 64 % of the CPS energy mix would be fossil fuel-based. Under HCS, 77 % of the energy generation would be fossil fuel-based, whereas only 19 % would be nuclear and renewable in 2050. Shifting from fossil fuel to renewables dominating the energy mix would exponentially increase decarbonisation costs by 2050 for MCS, LCS, and ZCS (Fig. 4A, B, C), predominantly because of the capital cost of renewable technologies and imported (renewable) electricity cost. The energy mix would have 28 % of the generated electricity from nuclear and renewable sources for MCS, which would elevate to 54 % under LCS in 2050. Under the ZCS, the energy mix would have the highest amount (89 %) of energy from nuclear and renewables (Fig. 2).

Under the BAU scenario, the average total cost of the electricity sector would be $23 bn — high- and low-cost estimates would be $27 bn and $96 bn, respectively, very close to the global range — by 2050, which would be 56 % lower than that of 2020 due to no new development (Fig. 3). If Bangladesh maintains its present policies in action, the average cost would be $162 bn in 2050 — $140 bn and $13 bn higher than that of BAU and the global average, respectively — under the CPS scenario with high- and low-cost range between $258 bn and $93 bn (Fig. 3). Therefore, the CPS average cost would increase 3.2 times by 2050 compared to 2020. The average cost would increase to $186 bn in 2050 under the HCS, with high- and low-cost estimates between $321 bn and $103 bn (Fig. 3). The difference between high and low estimates would be due to increased installed capacity and the cost difference between establishing power plants in the rest of the world, particularly in China (India in the case of solar PV) and Bangladesh.

Under the MCS, the average cost of electricity sector development would be $253 bn — 1.4 and 1.1 times higher than that of HCS and global average, respectively— in 2050. The energy sector's average capital cost would be $129 bn in 2050, a 1.23 times increment under MCS compared to HCS. The average cost would slightly increase to $296 bn by 2050 for LCS — 1.6 and 1.1 times higher than HCS and global average, respectively— with the high- and low-cost range between $457 bn and $165 bn. The average capital and import electricity costs would be 30 % and 51 % of the total under LCS. The energy sector's average cost would be higher up to 2050 under LCS than MCS because of the initially higher capital cost of renewable energy technologies and imported electricity costs. Under MCS, the average cost would be slightly higher than LCS in 2045, primarily because of the fuel cost (Fig. 5), which would be nearly 3 % lower than that of the projected estimate (Das et al., 2018) whereas under high renewables and electricity import scenario the cost was predicted to be $229 bn in 2045 with 125 $MtCO_2e$ emissions. Under the ZCS scenario, the average cost would reduce to $242 bn in 2050 — 1.3 and 1.1 times higher than HCS and global average, respectively— with the high- and low-cost range between $367 bn and $133 bn.

Among all the analysed scenarios, MCS offered Bangladesh's highest accumulated electricity sector cost in 2020–50 (Fig. 5). The capital, O&M, fuel, and imported electricity costs were 71 %, 12 %, 14 % and 3 % of the total accumulated cost of $51 bn in 2020, respectively (Fig. 5). Under C-A, the accumulated cost for 2020–2050 would be $654 bn, where 45 %, 6 %, 25 %, and 24 % will be capital, O&M, fuel and import electricity costs, respectively. The accumulated cost of M-A was $882 bn by 2050, higher than H-A ($838 bn), L-A ($870 bn) and *Z*-A ($634 bn). Under M-A, 55 % would be a capital cost, as the significant investment would be in solar PV, offshore, onshore wind and nuclear electricity generation, and fossil fuel-based ones. But the increase in imported electricity would increase to 33 % and 46 % of the accumulated cost under L-A and Z-A from M-A's 18 %. The accumulated cost of Z-A would be $20 bn lower than C-A in 30 years (2020–50).

The average cost of decarbonisation would be $231 bn in 2050 under MCS (Fig. 4A) —with high- and low-cost ranges between $397 bn and $120 bn, respectively, which translated into 91 % of the total average cost ($253 bn). The average cost of decarbonisation would slightly rise to $274 bn in 2050—with high- and low-cost ranges between $430 bn and $146 bn, respectively— under LCS, which means 92 % of the total cost ($296 bn). Therefore, decarbonising the electricity generation sector to renewables dominating the energy mix (LCS) would cost $43 bn more than the fossil fuel-intensive scenario (MCS). However, the average fuel cost would be 27 % lower for LCS than that of MCS in 2050. Under the ZCS, the average cost of decarbonisation would be reduced to $220 bn by 2050 (Fig. 4C). In 2050, the upper limit of decarbonisation cost for ZCS would be $341 bn. However, the lower estimate of cost under ZCS ($114 bn) would be lower than that of MCS ($120 bn) by 2050 due to the continuous reduction in the cost of renewables (predominantly solar PV, hydro and wind) which may continue in the future (IRENA, 2019; VDMA, 2020). Therefore, it might be possible for

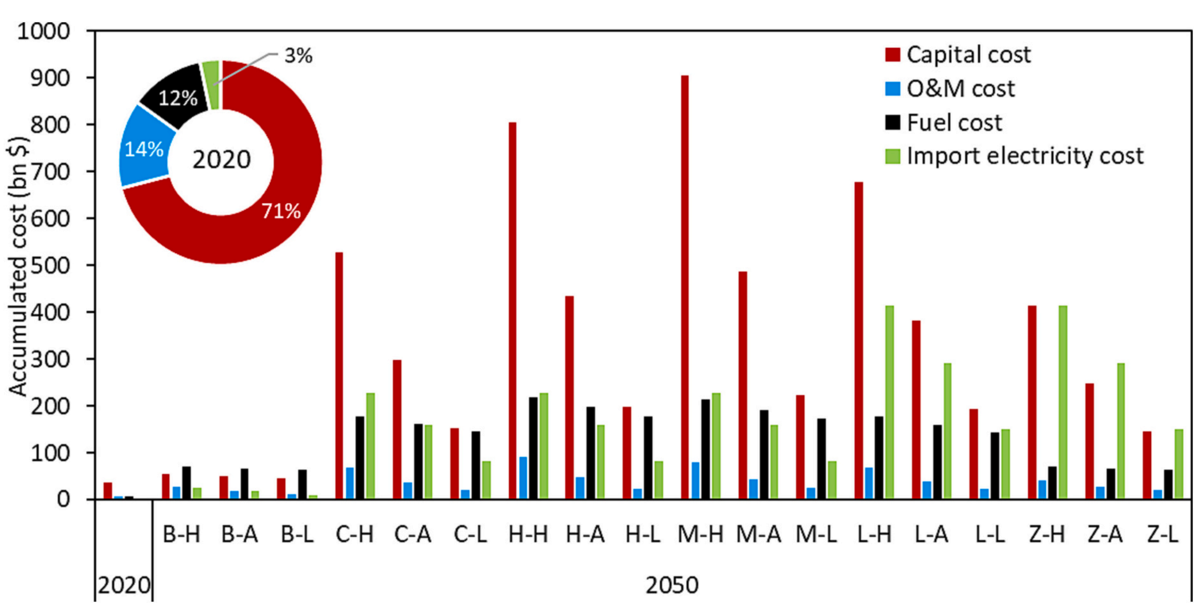

Fig. 5. Cost breakdown in 2020 and accumulated Capital, O&M, fuel and imported electricity cost under different analysed scenarios by 2050.

Bangladesh to develop a renewable dominating generation sector with near-zero emissions at a lower cost than fossil fuel-based high-emissions. The result was consistent with studies such as (Das et al., 2018), where the discounted cost of developing high-renewable and import-based scenarios would cost less than high emissions between 2012 and 2050. To establish at a lower cost, Bangladesh would have to develop the electricity generation sector with a cost like the private sector for fossil fuel-based power plants and lower global costs (predominantly from China and India) for renewable ones.

Drivers of decarbonisation cost

1. GHG emissions reduction

The GHG emissions from the electricity generation sector were 54.1 $MtCO_2e$ in 2020. Under the BAU scenario, the GHG emissions would reduce to 36.4 $MtCO_2e$, as no new power plant would be established (Fig. 4G). Under the present government policies driven by CPS, the total GHG emissions would rise to 248.4 $MtCO_2e$ by 2050, 4.6 times higher than in 2020 (Fig. 4G), primarily because of the planned fossil-fuel-based generation plants in the current policies. Gulagi et al. also showed that GHG emissions might rise to ~260 $MtCO_2e$ by 2050 due to Bangladesh's fossil fuel-dominated energy mix under current policies (Gulagi et al., 2020). Under a fossil fuel-dominated high-carbon scenario (HCS), GHG emissions would rise 8.6 times (462.3 $MtCO_2e$) by 2050 compared to 2020 (Fig. 4G). Under the MCS, the fossil fuel installed capacity would be close to HCS, and only renewables and nuclear power capacity would increase by 2050. The GHG emissions for MCS would be 453.6 $MtCO_2e$ by 2050 (Fig. 4G).

In the case of LCS (renewables and nuclear dominating the energy mix), due to the partial fossil fuel dependency in the energy mix, the total GHG emissions would rise 4.6 times (249.5 $MtCO_2e$) — total emissions would be reduced by 45 % and 46 % in 2050 under LCS compared to MCS and HCS — by 2050 (Fig. 4G). Under the ZCS, the total GHG emissions would not diminish entirely because of the already established and under-construction coal and gas power plants by 2020. Coal-based power plants started to be installed in Bangladesh in 2006 (BPDB, 2023). All the coal power plants will be operational even after 2050 because of their 40-year lifespan (Bohm, Herzog, Parsons, & Sekar, 2007; Odeh & Cockerill, 2008). However, the total emissions would be reduced by 92 % and 85 % in 2050 under ZCS (36.4 $MtCO_2e$) compared to MCS and LCS (Fig. 4G).

The emissions intensity of electricity generation was 0.68 $kgCO_2e/kWh$ in 2020, which would be 0.41 and 0.49 $kgCO_2e/kWh$ in 2050 under CPS and HCS, respectively. However, the emissions intensity would decrease to 0.45 and 0.30 $kgCO_2e/kWh$ for MCS and LCS, respectively. The LCS would offer lower electricity generation emissions per unit because of the higher concentration towards renewable and nuclear technologies. The lowest emissions intensity would be 0.07 $kgCO_2e/kWh$ under the ZCS in 2050 due to the significantly high renewables dominating the energy mix.

2. Technological maturity

Most fossil fuel-based power plants, particularly gas- and oil-based, were operational in Bangladesh for over three decades. However, coal-based power plants started operating in 2006. The existing Barapukuria coal-based power plant was sub-critical. The planned coal-based power plants would be ultra-supercritical (BPDB, 2023). Therefore, gas- and oil-based power plants were mature technologies; coal, nuclear, solar, wind, and geothermal were considered new technologies in Bangladesh. The difference between the high and low cost of matured technology was significantly lower than that of the new ones. As a result, the scenarios with emissions reduction strategies showed higher cost sensitivity than those of the HCS. The difference between the accumulated high and low capital cost range would be $608 bn in 2020–50 under HCS. The accumulated capital cost ranged from $906 bn to $223 bn in 2020–50 under the M-H and M-L scenarios (Fig. 5), a difference of $682 bn under MCS. Moreover, the accumulated cost difference between the high and low ranges would be $484 bn and $268 bn in 2020–50 under LCS and ZCS, respectively (Fig. 5). Studies suggest that mature technology reduced cost (Neij, 2008), which denoted that the cost of energy sector development in Bangladesh might decrease.

3. Demand reduction

The scenarios were analysed with the capability of meeting the projected electricity demand, which would be 300 TWh in 2035 and reach 838 TWh in 2050 under the BAU scenario (6 % annual GDP growth), which would be a significant increase — 192.7 TWh by 2035 under annual 6.8 % growth scenario—compared to (Mondal, Boie, & Denich, 2010). Therefore, the electricity demand was projected to be ten times higher in 2050 than in 2020, resulting in 752 TWh unmet demand by 2050 under BAU (Fig. 4H). Under CPS, the energy mix would be fossil fuel-based (64 %) by 2050, as per the IEPMP 2023 master plan (JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP), 2023) (Fig. 6), which would increase the electricity generation eight times by 2050, but there would be 171 TWh unmet demand (Fig. 4H). There would be no unmet demand in 2050 under the HCS, MCS and LCS, although the electricity generation would increase 10–12 times that of 2020 (Fig. 4H). The total generation would be 1002 TWh by 2050 under MCS, 12 times higher than in 2020 (Fig. 6). For LCS, the energy generation would elevate ten times (838 TWh) in 2050 compared to 2020. The ZCS also could not meet the electricity demand by 2050. There would be 135 TWh unmet demand (Fig. 4H) despite the six times generation increase in 2050 compared to 2020 under ZCS (Fig. 6).

Therefore, demand reduction could be essential for reducing Bangladesh's decarbonisation cost. The average cost of decarbonisation would be $235 bn and $278 bn under MCS and LCS, respectively. The average cost of decarbonisation could be $224 bn by 2050 under ZCS. ZCS-Average would not meet the projected demand (Fig. 4H) unless a 16 % reduction in projected demand by 2050 could make Bangladesh's energy sector's decarbonisation possible under ZCS.

4. Influence of corruption

The cost of public power plants showed a statistically significant relationship with corruption in Bangladesh (Debnath & Mourshed, 2018a). Under the decarbonisation scenarios, the country might develop the energy sector with a lower limit if corruption is under control. The high-cost estimation of decarbonisation would be $405 bn in 2050 under the MCS (Fig. 4A). Under lower corruption assumptions, the average cost of decarbonisation might be reduced by 42 % under MCS than that of the high estimate. Assuming the corruption level could be minimised to maintain the lower limit of the energy sector's future development cost, the low cost of decarbonisation might be reduced by 70 % under MCS compared to the high estimate. Similarly, the low-cost estimate of decarbonisation might be reduced by 67 % under LCS compared to LCS-High. If Bangladesh could control corruption and build power plants with a lower limit, the total cost would be $133 bn under the ZCS-Low scenario. In contrast, the lower limit of energy sector development for MCS would be $139 bn in 2050 (Fig. 3). Therefore, control of corruption and other drivers in the electricity sector might significantly influence the decarbonisation cost in Bangladesh, making the near zero-carbon electricity sector development cheaper than the fossil fuel-dominating one.

Recommendations for the electricity sector

With an energy-intensive future on the horizon, Bangladesh drafted the Integrated Energy and Power Master Plan (IEPMP) for 2050 to ensure an affordable, sustainable, and secure energy supply (Chowdhury, n.d.; Golam Moazzem, Mashiyat Preoty, Sadik, & Mallick, 2023). This study's findings could render the following recommendations for IEPMP and future masterplans:

1. Electricity market deregulation: Privatisation

The public or government-owned power plants showed higher than the global average capital cost, and the private sector was within the global cost range (Debnath & Mourshed, 2018a). Therefore,

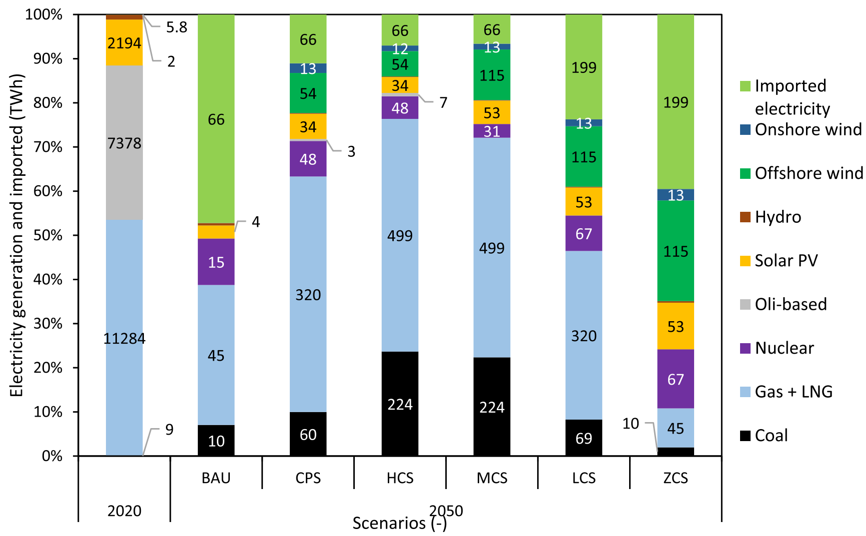

Fig. 6. Total electricity generation from different supply sectors in 2020 and 2050 under BAU, CPS, HCS, MCS, LCS and ZCS. The data labels on the bars were the generated electricity (in TWh) from that fuel/resource.

deregulation by privatising the power plant establishment might lead to lower capital costs. Bangladesh's energy sector started deregulation in 1997 to increase investment from the private sector. As a result, the private sector began to elevate, especially Oil-based Independent Power Producers (IPPs) and Rental Power Plants (RPPs) under 3–15 years of contracts. The IPP and RPPs were quick fixes to offset load shedding. Moreover, despite Bangladesh's limited oil reserves, deregulation through privatisation opened the rapidly growing energy generation market to the volatile international oil market (Mourshed, 2013). The Government might create better incentives and governance — government sponsorship and guarantees, financing assistance, tax exemptions or reductions and new market opportunities (Ke, Wang, & Chan, 2009)— for the private sector to embark on establishing energy mega-projects with more extended contracts.

2. Increasing transparency

"Quick Enhancement of Electricity and Energy Supply (Special Provisions) Act, 2010" enabled the Government to take swift energy sector initiatives while bypassing the 2006 public procurement law, with easy and quick procurement procedure outside the jurisdiction of the court (GoB, 2016) which raised significant concern regarding transparency (Choudhury et al., 2010). This temporary fix to solve the generation deficiency might have amplified the governance inefficiencies in the energy sector. Under the circumstances, though privatisation of power plant construction might lower the prevalence of direct corruption, it may also open opportunities for O&M and fuel management to the private sector. The Government could implement better regulations for greater transparency in the energy market, which may protect the public and the private sector from corruption.

3. Energy demand leads the market

Demand response management in Bangladesh was at its initial stage, which required significant research and training to establish, support and develop the smart grid and dynamic pricing. With the emergence and development of renewable energy resources, the demand lead market would offer better integration of wholesale and retail electricity markets with the supply sector. The energy demand lead market would allow policymakers and investors to understand and observe the characteristics and dynamics of Bangladesh's demand and supply sector. Demand reduction might significantly lower costs and decarbonise Bangladesh's energy sector by 2050.

4. Carbon pricing

According to Bangladesh's Intended Nationally Determined Contributions (INDC), there was no national initiative to introduce carbon pricing (GoB, 2015b), and it will depend on international initiatives (WB, 2019). Also, as the electricity market in Bangladesh had been highly subsidised by the Government (Timilsina, Pargal, Tsigas, & Sahin, 2018) and carbon pricing would increase electricity prices, the Bangladesh government had yet to take any initiative to impose carbon pricing (Gulagi et al., 2020). Our analysis — by considering \$1/tCO_2e as the low pricing, \$40 and \$80/tCO_2e as average and high pricing, respectively, according to (WB, 2019) — suggested that Bangladesh could cover 0.4–9.1 %, 0.2–4.6 % and 0.4–0.8 % of the cost of decarbonisation under MCS, LCS and ZCS, respectively, with carbon pricing the emissions from the fossil fuel-based electricity generation in 2020–2050 (Fig. 4D-F).

However, the potential negative impact on different socio-economic groups (particularly low-income groups) (Bowen, 2015; Dorband, Jakob, Kalkuhl, & Steckel, 2019) necessitates careful consideration, especially given the historical challenges many countries have faced in practically implementing such policies. Our findings suggested that, despite the current absence of national carbon pricing policies in Bangladesh, there would be an opportunity for the country to explore policy formation initiatives. These initiatives could help mitigate the potential burden on ongoing and future energy investments while acknowledging the need for sensitivity to the socio-economic implications. A more refined and nuanced set of policy implementation would be crucial as we move forward to balance achieving decarbonisation goals and ensuring equitable outcomes for all.

5. Removal of subsidies from the electricity generation sector

Bangladesh's electricity sector had been heavily subsidised, especially for fuel for generation and tariffs (Islam & Khan, 2017), which reduced production costs and provided cheaper electricity for customers. For our model, we used the fuel assumptions from the Bangladesh Power Development Board (BPDB), and the average electricity generation cost (including imported electricity) in 2020 was \$0.5/kWh, which would be \$0.73/kWh and \$0.33/kWh under both CPS and HCS in 2050. The cost range would be between \$1.16–\$0.42/kWh and \$0.56–\$0.18/kWh in 2050 under CPS and HCS, respectively. However, the average generation cost would increase to \$0.25 and \$0.31/kWh under MCS and LCS, respectively. The cost range would be between \$0.42–\$0.14/kWh and \$0.48–\$0.17/kWh in 2050 under MCS and LCS, respectively. Under the ZCS, the average generation cost would be \$0.36/kWh (cost range between \$0.20–\$0.55/kWh). The upper-cost estimation was significantly high under decarbonised scenarios due to the higher capital cost of renewables in Bangladesh than in the rest of the world. If Bangladesh can establish renewable power plants at costs resembling China or India, the generation cost would be around \$0.20/

kWh by 2050.

According to WB, the electricity generation cost increased by 32–34 % when subsidies were removed (Timilsina et al., 2018). Our model showed that with the WB estimation, without subsidies, the average decarbonised electricity generation cost would be $0.34, $0.42 and $0.49/kWh by 2050 under MCS, LCS and ZCS, respectively. The unsubsidised generation cost might be reduced to $0.14–$0.20/kWh in all decarbonised scenarios, with a lower capital cost of establishing renewable power plants. Although the per unit generation cost increased by $0.05–$0.07/kWh in lower estimates, if Bangladesh could develop the electricity sector, especially the renewables with the similar low costs of China or India, the Government's investment burden might reduce about 34 % annually upon removal of subsidies.

However, studies showed that removing fossil fuel subsidies impacted negatively predominantly on the low-income population in developing countries (Greve & Lay, 2023), demonstrating the critical need for nuanced implementation of the removal of subsidies that balance the imperative of decarbonisation with the potential socio-economic impacts on diverse income groups of the population. The goal should be to forge a path that achieves environmental sustainability and ensures equitable outcomes for all stakeholders in Bangladesh's energy landscape.

6. Navigating the ‘Debt-fossil fuel production trap’

As most of the energy sector investments had a significant (sometimes up to 90 %) portion of loans, Bangladesh might face a potential “debt-fossil fuel production trap” as it navigates the complexities of its energy transition. Evidence —disruption of coal power plant operation due to US dollar shortage (Varadhan & Chew, n.d.; Sajid, n.d.) and high dependency on other countries for nuclear, coal and liquid fuel (Choudhury et al., 2010)— suggested that Bangladesh might already be at the starting stage of ‘Debt-fossil fuel production trap’. The PSMP 2010, 2016, and IEPMP 2023 revealed a significant reliance on fossil fuels, mainly when decarbonisation strategies were limited. The projected increase in total costs, soaring exponentially under scenarios like the MCS, could potentially exacerbate the country's debt burden. The capital-intensive nature of renewable technologies, highlighted in the plan, contributed to the financial challenges. Moreover, the reliance on new and less mature technologies like ammonia co-firing and hydrogen in IEPMP, without clear justifications and considering their potential economic and environmental drawbacks, might pose further financial risks. Also, the IEPMP 2023 proposed that the ammonia and hydrogen be imported at a very high cost. In that case, geopolitical and US dollar-related issues might re-emerge. The emphasis on imported technologies and fuels and uncertainties in diplomatic relations for power imports might also strain the nation's economic resources. Alternatively, Bangladesh might explore larger-scale energy investment and electricity import from renewable-rich neighbours such as Nepal and Bhutan (Debnath & Mourshed, 2022). Already, Bangladesh imports coal-based electricity from India, which was counterproductive in the case of decarbonisation. Bangladesh initiated importing renewable electricity from Nepal through India's transmission lines (TBSnews, 2023). The South Asian Association for Regional Cooperation (SAARC) might be a great platform to enable regional energy collaboration by reducing geopolitical tension and exploring alternative options, such as currency swaps, to reduce the dependency on the US dollar for energy purchases.

Bangladesh must meticulously weigh the financial ramifications of its energy choices to evade the looming debt-fossil fuel production entanglement. Prioritising established renewable technologies, addressing corruption concerns, and exploring avenues for demand reduction could chart a more sustainable and economically prudent course. The challenge would be harmonising energy aspirations with fiscal wisdom to avert a costly and environmentally unsustainable trajectory.

Furthermore, the dissonance between the plan's projections and Bangladesh's clean energy targets, particularly the 40 % renewable energy commitment by 2041, raised doubts about the plan's viability and alignment with national objectives. The cost analysis underscored the potential economic challenges of the exponential rise in decarbonisation costs and uncertainties in technology adoption timelines. To sidestep the impending debt-fossil fuel production quagmire, Bangladesh must critically reassess its energy master plan, prioritising proven renewable technologies, stringent emission reduction policies, and transparent financial strategies.

Conclusion and policy implication

We showed that the medium- and low-carbon scenarios can meet the projected electricity demand of Bangladesh by 2050 — with emissions intensity of 0.45 and 0.30 kgCO_2e/kWh and the average decarbonisation cost of $231 bn and $274 bn, respectively — and create an electricity generation sector with low-emissions would be costlier that of a fossil-fuel dominating one in Bangladesh. Also, our results showed that by controlling corruption, market deregulation and increased transparency in the energy sector, Bangladesh might reduce 67–70 % (the difference between the high and low estimated cost) of the cost of decarbonisation by 2050 in the medium- and low-carbon scenario if the power plants —especially renewable ones— could be established with the capital cost similar or close to China and India, as their capital cost of establishing power plants were constantly lower than the global counterparts. Another primary driver for lowering the cost of decarbonisation was demand reduction. A 16 % reduction in demand by 2050 would progress Bangladesh's electricity sector towards the zero-carbon scenario with an average decarbonisation cost of $2240 bn, denoting a 92 % and 85 % reduction of GHG emissions by 2050 than the projected high carbon and current policy scenarios, respectively. The following were recommendations based on the analysis and results from this study:

- Increase the share of renewable energy in the overall energy mix as the costs of these renewables would be lower than those of fossil fuels, eventually dominating the energy mix.
- Increase emphasis on reducing electricity demand, which may decrease the necessity of establishing power plants and associated costs.
- Boost privatisation for the electricity generation sector to reduce corruption in the energy sector.
- Elevate transparency in the energy sector spending to reduce corruption in the energy sector.
- Implement carbon pricing while ensuring equitable outcomes for all population income levels. Our study shows that a high estimate of carbon pricing may reduce the average cost of decarbonisation by up to ~9 % in 2020–2050.
- Remove subsidies from the energy sector while maintaining equitable socio-economic impact for all income groups. We showed that removing the subsidies may reduce investment burdens on the Government, which could be minimised by progressing towards a decarbonised electricity generation sector.
- Identify debts from fossil fuel projects as illegitimate and cancelling them, scaling up grant-based climate finance, aligning finance with climate goals, and setting deadlines for shifting funds from fossil fuels to sustainable measures. The “debt-fossil fuel production trap” limited resources for transitioning to clean energy and exacerbated Global South countries' debt crisis, diverting funds from addressing the climate crisis and perpetuating dependence on fossil fuels. This entanglement called for ambitious debt cancellation, increased transparency, and a shift away from continued investment in fossil fuels to break free from this detrimental cycle.
- Explore larger scale energy investment and electricity import from renewable rich neighbours such as Nepal and Bhutan. Furthermore, explore SAARC and currency swaps with the regional neighbours to reduce geopolitical tension and dependency on the US dollar for energy sector decarbonisation.

Under the planned emissions-intensive future of Bangladesh's electricity generation sector, privatisation and increasing transparency in energy sector development, initiation of demand reduction strategies, carbon pricing, and removal of subsidies collectively might render the opportunity to assist in decarbonisation and sustainable investment of the future electricity sector of Bangladesh, while navigating the complexities of the "debt-fossil fuel production trap," paving the way for a sustainable and decarbonised electricity generation sector.

Author contributions

Conceptualisation, K.B.D. and M.M.; methodology, K.B.D. and M.M.; formal analysis, K.B.D.; investigation, K.B.D.; resources, K.B.D.; data curation, K.B.D.; writing—original draft preparation, K.B.D.; writing—review and editing, K.B.D. and M.M.; visualisation, K.B.D.; supervision, M.M. All authors have read and agreed to the published version of the manuscript.

Funding

This research was partly funded by the 'Decarbonisation of energy systems of South Asian developing economies through regional collaborations' project (Grant reference SENFC1–025) funded by First Flex Fund from the Engineering and Physical Sciences Research Council (EPSRC) Supergen Energy Networks Hub.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Anam, M. Z., Bari, A. M., Paul, S. K., Ali, S. M., & Kabir, G. (2022). Modelling the drivers of solar energy development in an emerging economy: Implications for sustainable development goals. *Resources, Conservation & Recycling Advances, 13*, Article 200068.
BD2050. (2015). Bangladesh 2050 Energy and Emissions Pathways [Online]. Available: http://calc.bd2050.org/.
Bohm, M. C., Herzog, H. J., Parsons, J. E., & Sekar, R. C. (2007). Capture-ready coal plants—Options, technologies and economics. *International Journal of Greenhouse Gas Control, 1*(1), 113–120.
Bowen, A. (2015). Carbon pricing: How best to use the revenue?. In *Policy Brief*. Grantham Research Institute on Climate Change and the Environment.
BPDB, Annual Reports, Bangladesh Power Development Board, 2023. [Online]. Available: https://bpdb.gov.bd/site/page/c4161d54-5b85-4917-a8d2-68a2d1b26dd4/Monthly-Annual-Report. [Accessed 20 November 2023].
BPDB. (2024). *Annual Report 2022–23*. Dhaka: Bangladesh Power Development Board.
Choudhury, S. R., Ali, M., Shamsuddin, A., Karim, Z., Mazumder, M. M., & Islam, A. M. M. A. (2010). *Evaluation of the Implementation of the Paris Declaration, phase – II, Country Evaluation Bangladesh*. Dhaka, Bangladesh: Natural Resources Planners Ltd.
Chowdhury, S. A. (7 October 2023). The many holes in Bangladesh's energy master plan. In *The Daily Star* [Online]. Available: https://www.thedailystar.net/opinion/views/news/the-many-holes-bangladeshs-energy-master-plan-3436956. (Accessed 21 November 2023).
CIA, "The world factbook," Central intelligence agency. (2018) [Online]. Available: https://www.cia.gov/library/publications/the-world-factbook/geos/bg.html [Accessed 2018].
Das, A., Halder, A., Mazumder, R., Saini, V. K., Parikh, J., & Parikh, K. S. (2018). Bangladesh power supply scenarios on renewables and electricity import. *Energy, 155*, 651–667.
Das, N., Chakrabartty, J., Dey, M., Gupta, A. S., & Matin, M. (2020). Present energy scenario and future energy mix of Bangladesh. *Energy Strategy Reviews, 32*, 100576.
Debnath, K. B., & Mourshed, M. (2018a). Corruption significantly increases the capital cost of power plants in developing contexts. *Frontiers in Energy Research, 6*, 8.
Debnath, K. B., & Mourshed, M. (2018b). Challenges and gaps for energy planning models in the developing-world context. *Nature Energy, 3*(3), 172–184.
Debnath, K. B., & Mourshed, M. (2022). Why is Bangladesh's electricity generation heading towards a GHG emissions-intensive future? *Carbon Management, 13*(1), 216–237.
DFID. (2013). *DFID's Anti-Corruption Strategy for Bangladesh*. Department for International Development.
Dorband, I. I., Jakob, M., Kalkuhl, M., & Steckel, J. C. (2019). Poverty and distributional effects of carbon pricing in low-and middle-income countries-a global comparative analysis. *World Development, 115*, 246–257.
EJA. (2017). Rampal thermal power plant at Sundarbans, Bangladesh. In *Environmental Justice Atlas* [Online]. Available: https://ejatlas.org/conflict/rampal-thermal-power-plant-rampal-bangladesh.
GoB. (2013). *500 MW Solar Programme 2012-2016: An initiative to promote renewable energy programme in Bangladesh*. Dhaka: Government of the People's Republic of Bangladesh.
GoB. (2015a). *Annual Report 2015*. Dhaka: Power Division, Ministry of Power, Energy and Mineral Resources (MPEMR).
GoB. (2015b). *Intended Nationally Determined Contributions (INDC), United Nations Framework Convention on Climate Change (UNFCCC)*.
GoB. (2016). *Quick Enhancement of Electricity and Energy Supply (Special Provisions) Act, 2010*. Dhaka: Ministry of Power, Energy & Mineral Resources, Government of the People's Republic of Bangladesh.
Golam Moazzem, K., Mashiyat Preoty, H., Sadik, S., & Mallick, M. A. (2023). *Draft Integrated Energy and Power Master Plan (IEPMP): Can it address the clean energy targets?* Dhaka: Centre for Policy Dialogue (CPD).
Greve, H., & Lay, J. (2023). "Stepping down the ladder": The impacts of fossil fuel subsidy removal in a developing country. *Journal of the Association of Environmental and Resource Economists, 10*(1), 121–158.
Gulagi, A., Ram, M., Solomon, A., Khan, M., & Breyer, C. (2020). Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh. *Renewable Energy, 155*, 899–920.
IDCOL, "Projects and programs," Infrastructure Development Company Limited (IDCOL). (2017) [Online]. Available: http://idcol.org/home/other_re.
IEA. (2022). *Power Generation Technology Costs and Assumptions in the WEO-2022 Stated Policies and Net Zero Emissions by 2050 scenarios*. International Energy Agency.
IRENA. (2019). *"Renewable Power Generation costs in 2018," International Renewable Energy Agency (IRENA)*. Abu Dhabi.
Islam, S., & Khan, M. Z. R. (2017). A review of energy sector of Bangladesh. *Energy Procedia, 110*, 611–618.
Jägemann, C., Fürsch, M., Hagspiel, S., & Nagl, S. (2013). Decarbonizing Europe's power sector by 2050—Analyzing the economic implications of alternative decarbonization pathways. *Energy Economics, 40*, 622–636.
JICA & TEPCO. (2011). *The study for master plan on coal power development in the people 's Republic of Bangladesh, Power System Master Plan 2010*. Energy and Mineral Resources, Ministry of Power: People's Republic of Bangladesh.
JICA, & IEEJ, "Integrated Energy and Power Master Plan (IEPMP). (2023). *Ministry of Power, Energy and Mineral Resources, Government of the People's Republic of Bangladesh*. Dhaka.
JICA,TEPCO, BPDB & PGCB. (2010). *Power System Master plan*. Dhaka: BPDB.
Jordan, D. C., & Kurtz, S. R. (2013). Photovoltaic degradation rates—An analytical review. *Progress in Photovoltaics: Research and Applications, 21*(1), 12–29.
Kabir, M. R., Taznin, B., Tanzima, A., Tabassum, R., & Rezwanul, K. (2021). A unique study of corruption in Bangladesh. *Saudi J. Humanities Soc Sci, 6*(1), 18–25.
Ke, Y., Wang, S., & Chan, A. (2009). Government incentives for private sector involvement in infrastructure PPP projects. *Journal of Tsinghua University. Science and technology, 49*(9), 1480–1483.
Lipiak, G., Bussmann, S., Steinwachs, C., & Lüttenberg, A. (2006). *Lifetime extension for SIEMENS gas turbines*. Cologne, Germany: Siemens.
Mahbub, T., Ahammad, M. F., Tarba, S. Y., & Mallick, S. Y. (2022). Factors encouraging foreign direct investment (FDI) in the wind and solar energy sector in an emerging country. *Energy Strategy Reviews, 41*, Article 100865.
Masud, M. H., Nuruzzaman, M., Ahamed, R., Ananno, A. A., & Tomal, A. A. (2020). Renewable energy in Bangladesh: Current situation and future prospect. *International Journal of Sustainable Energy, 39*(2), 132–175.
Moazzem, K. G., & Ali, M. (2019). *The Power and Energy Sector of Bangladesh: Challenges of Moving beyond the Transition Stage*. Dhaka: Centre for Policy Dialogue (CPD).
MoF. (2009). Invigorating Investment Initiative through Public Private Partnership: A Position Paper. In *Ministry of Finance, Government of Bangladesh*. Dhaka, Bangladesh.
Mondal, M. A. H., & Denich, M. (2010). Assessment of renewable energy resources potential for electricity generation in Bangladesh. *Renewable and Sustainable Energy Reviews, 14*(8), 2401–2413.
Mondal, M. A. H., Boie, W., & Denich, M. (2010). Future demand scenarios of Bangladesh power sector. *Energy Policy, 38*(11), 7416–7426.
Mondal, M. A. H., Denich, M., & Mezher, T. (2014). Deployment of renewable energy technologies in Bangladesh: Long-term policy implications in power sector. *Energy Strategy Reviews, 2*(3–4), 307–312.
Mourshed, M. (2013). Pitfalls of oil-based expansion of electricity generation in a developing context. *Energy Strategy Reviews, 1*(3), 205–210.
NEI. (2016). Nuclear cost in context. In *Nuclear Energy Institute*. Washington, DC.
Neij, L. (2008). Cost development of future technologies for power generation—A study based on experience curves and complementary bottom-up assessments. *Energy Policy, 36*(6), 2200–2211.
Odeh, N. A., & Cockerill, T. T. (2008). Life cycle analysis of UK coal fired power plants. *Energy Conversion and Management, 49*(2), 212–220.
Sajid, E. (18 January 2023). Coal power plants' operation under threat over dollar crisis. In *The Business Standard* [Online]. Available: https://www.tbsnews.net/bangladesh/energy/coal-power-plants-operation-under-threat-over-dollar-crisis-569878. (Accessed 24 November 2023).
TBSnews, "Bangladesh approves import of 40MW power from Nepal," The Business Standard, 06 December 2023. [Online]. Available: https://www.tbsnews.net/bangladesh/energy/bangladesh-approves-import-40-mw-power-nepal-752834. [Accessed 14 January 2024].
TI, "Corruption Perceptions Index," Transparency International, 2022. [Online]. Available: https://www.transparency.org/en/cpi/2022/index/bgd. [Accessed 2022].

Timilsina, G. R., Pargal, S., Tsigas, M., & Sahin, S. (2018). *How much would Bangladesh Gain from the Removal of subsidies on Electricity and Natural Gas?*. The World Bank.
UN, "COP28 signals beginning of the end of the fossil fuel era," United Nations. (2024) [Online]. Available: https://www.un.org/en/climatechange/cop28 [Accessed 14 January 2024].
UNDP. (2013). *Development of sustainable renewable energy power generation (SREPGen)*. United Nations Development Programme.
UNFCC. (2015). *Paris Agreement*. United Nations.
S. Varadhan and C. Chew, "Bangladesh's worst electricity crisis in a decade," Reuters, 7 June 2023. [Online]. Available: https://www.reuters.com/world/asia-pacific/bangladeshs-worst-electricity-crisis-decade-2023-06-07/. [Accessed 24 November 2023].
VDMA. (2020). International Technology Roadmap for Photovoltaic (ITRPV). In *Mechanical Engineering Industry Association (Verband Deutscher Maschinen- und Anlagenbau – VDMA)*. Frankfurt am Main.
WB. (2019). *State and Trends of Carbon Pricing 2019*. Washington DC: World Bank.
WB, "World DataBank," World Bank, 2023. [Online]. Available: http://data.worldbank.org/. [Accessed 20 November 2023].
Weyant, J. P. (1993). Costs of reducing global carbon emissions. *The Journal of Economic Perspectives, 7*(4), 27–46.
Woolfenden, T. (2023). *The debt-fossil fuel trap: Why debt is a barrier to fossil fuel phase-out and what we can do about it*. London: Debt Justice.