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PyPSA-BD: An Open-source model for planning sustainable power sector for Bangladesh

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***Abstract*— The necessity of decarbonizing the power sector has become central to achieving sustainable development goals on a global scale. Despite its significance, the application of electricity sector modeling remains limited, especially in developing nations such as Bangladesh. This study aims to bridge this gap by utilizing open data and open-source code to conduct a comprehensive analysis of Bangladesh's power system transition up to 2050. Specifically, Python for Power System Analysis (PyPSA) is employed to develop a customized model named PyPSA-BD. Leveraging ERA5 reanalyses data, we construct cost-optimized models that consider various national policies, with particular emphasis on pivotal years such as 2030, 2041, and 2050. Through a comparative analysis with official reports from the Bangladesh Power Development Board (BPDB), Power Grid Company of Bangladesh (PGCB), and Integrated Energy and Power Master Plan (IEPMP) 2023, this research sheds light on key insights crucial for policy formulation, effective management, and strategic investment planning within Bangladesh's power sector.**

***Index Terms*--Decarbonization of power sector, Energy transition, Open-Source Modelling, PyPSA-BD, Sustainable development.**

I. Introduction

Sustainable development demands urgent action to decarbonize the power sector, particularly in nations experiencing rapid growth in energy consumption, such as Bangladesh. At this pivotal juncture, Bangladesh must expand its power generation capabilities while simultaneously mitigating environmental impacts and ensuring economic stability [1], [2]. Python for Power System Analysis (PyPSA) is a critical tool in this endeavor, offering robust insights for optimizing the energy sector's shift toward low-carbon solutions [3].

This study presents PyPSA-BD, a customized adaptation of the PyPSA-Earth model [4], designed to evaluate and develop decarbonization pathways for Bangladesh's power sector up to the year 2050. PyPSA-BD draws on the successful applications of PyPSA in diverse geopolitical settings, including South Africa [5], Kazakhstan [6], Vietnam [7], Germany[8], India[9], and the UK[10]. These precedents demonstrate the model's capacity to generate energy solutions that strike a balance between sustainability and economic feasibility, while also incorporating relevant policy and environmental considerations.

A. Motivation

Bangladesh faces the critical challenge of expanding its power generation capacity while ensuring environmental sustainability and economic growth. The PyPSA-BD model is developed to address this challenge by providing a high-resolution, data-driven analysis of the country's power system, tailored to local conditions.

- **Global Decarbonization Alignment:** PyPSA-BD supports Bangladesh's efforts to align with global trends in reducing carbon emissions and integrating renewable energy sources into the power grid.
- **Local Context Adaptation:** The model leverages detailed spatial and temporal resolution capabilities to accurately reflect Bangladesh's geographical, infrastructural, and climatic characteristics.
- **Open-Source Collaboration:** PyPSA-BD benefits from the open-source nature of PyPSA-Earth, promoting transparency, continuous improvement, and access to global expertise.
- **Strategic Scenario Development:** The model enables the creation of strategic scenarios for Bangladesh's power sector, guiding policy formulation and investment decisions towards a sustainable energy future.

B. Contribution

This research offers several key contributions to the advancement of power system modeling and sustainable energy planning for Bangladesh:

i. Integrates national policy frameworks for comprehensive scenario analysis, aiding policy development and implementation.
ii. Optimizes strategies balancing economic costs and environmental sustainability, guiding the energy transition.
iii. Utilizes local datasets tailored to Bangladesh's specific energy conditions, enhancing accuracy and relevance of the analysis.

II. Bangladesh's power sector status

As of the fiscal year 2022-2023 [1], Bangladesh's power sector has experienced substantial growth, significantly expanded its capacity and diversified its energy sources. The total installed power generation capacity has reached 24,911 MW, reflecting a robust increase to meet the nation's rising demand. This includes contributions from various sectors: the public sector, with a capacity of 10,479 MW (including 6,233 MW from BPDB), joint ventures adding 1,861 MW, and the private sector, which primarily consists of Independent Power Producers (IPP) and Small Independent Power Producers (SIPP), contributing 8,494 MW. Additionally, rental and NENP (No Electricity No Payment) plants add 1,170 MW, while renewable energy projects contribute 459 MW, and power imports, mainly from India, account for 2,656 MW. The peak generation recorded in this fiscal year was 15,648 MW, with a total energy generation of 88,450 GWh, marking a 3.32% increase from the previous year's 85,607 GWh. The public sector generated 34,698 GWh, while the private sector, including the Rural Electrification Board (REB), contributed 35,679 GWh. Joint ventures accounted for 7,647 GWh, and imports provided 10,425 GWh. The Bangladesh Power Development Board (BPDB) continues to play a pivotal role in the power sector, overseeing planning, coordination, and distribution. The fuel mix in Bangladesh's power generation is diverse as shown in Figure 1, with gas being the predominant fuel source, contributing 11,372 MW or 45.65% of the total capacity. Furnace oil accounts for 6,492 MW or 26.06%, coal contributes 2,692 MW or 10.81%, and diesel adds 1,010 MW or 4.05%. Renewable energy sources, primarily solar, contribute 459 MW or 1.84%, while hydro power provides 230 MW or 0.92%, and imports make up 2,656 MW or 10.66%. Financially, BPDB's bulk energy sales to distribution utilities reached 84,450 GWh, a 3.48% increase from the previous year, while retail sales from BPDB's distribution zones totaled 12,070 GWh. BPDB's extensive distribution network includes 4,036 km of 33 kV lines, 16,586 km of 11 kV lines, and 28,896 km of 0.4 kV lines. This network supports the distribution of power to BPDB's 3,980,433 consumers. The sector's strategic planning aims to further diversify fuel sources, reduce dependency on gas, and increase the share of renewable energy. This includes ongoing construction of 29 power generation projects totaling 10,881 MW. These efforts are part of a comprehensive plan to add 20,416 MW of new generation capacity from July 2023 to December 2027, reflecting the sector's commitment to sustainable growth and energy security [2].

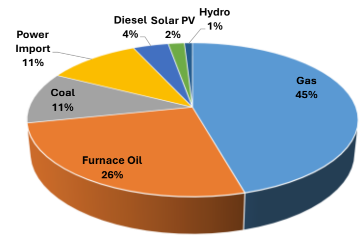


Figure 1. Installed Capacity of Bangladesh Power Sector as of June 2023

III. Literature Review

Energy Transition pathway analyses in developing economies are limited. Notable works include those by Handayani et al. [11] for ASEAN, Ayuketah et al. [12] for Cameroon, Bamisile et al. [13] for China, Kanugrahan and Hakam [14] for Indonesia, Shakya et al. [15] for Nepal, Shahid et al. [16] for Pakistan, and Limmeechokchai et al. [17] for Thailand. These studies as summarised in Table I highlight the critical need for comprehensive net-zero analyses in developing countries.

The scarcity of such analyses for Bangladesh underscores the urgency for focused research in this region. Thorough assessments are crucial to explore how Bangladesh can balance expanding electricity access with the necessity of achieving net-zero emissions. Such studies will offer valuable insights for policymakers and stakeholders involved in the sustainable energy transition, aiding in the formulation of informed strategies for Bangladesh's power sector. This concise literature review aligns with the need to explore sustainable power sector pathways for Bangladesh, addressing the critical gaps in existing research.

TABLE I. Summary of Key Literature covered

Reference	Region	Model Name	Net-Zero Target Year	Key Findings
[11]	ASEAN	LEAP	2050	Emphasizes renewable energy and storage; renewables and storage are more cost-competitive than carbon capture.
[18]	Japan	MARKAL	2050	Full decarbonization by 2040; advanced CO2 removal technologies necessary.

[16]	Pakistan	LEAP	2040	Significant electricity demand growth; diverse energy mix; need for increased safety in nuclear deployment and renewable resource utilization.
[19]	Cambodia, Laos, Myanmar	LEAP-NEMO	2050	Emphasizes renewable energy integration, grid interconnections, and environmental and social impact considerations.
[15]	Nepal	LEAP	2050	Without measures, CO2 emissions rise significantly; additional measures reduce pollutants and improve energy security and equity.
[20]	India	TIMES	2070	Requires substantial investment in renewables and green hydrogen; coal capacity and CO2 emissions rise until 2040 then decrease.
[14]	Indonesia	LEAP	2060	100% renewable energy by 2060; essential role of nuclear and storage; decommissioning of fossil-fuel facilities required.
[12]	Republic of Cameroon	LEAP-NEMO	2045	Heavy reliance on hydropower; need for grid unification; frequent outages in urban areas.
[6]	Kazakhstan, Central Asia	PyPSA-KZ	2060	Significant increase in wind power generation; new transmission lines needed; scenarios show increased renewable contribution and decreased coal usage.

IV. Methodology

This study utilizes advanced energy system modeling with the PyPSA framework, including PyPSA, PyPSA-Earth, and PyPSA-BD, to analyze and optimize power systems. These models integrate renewable energy, and storage solutions, and address regional challenges like grid stability.

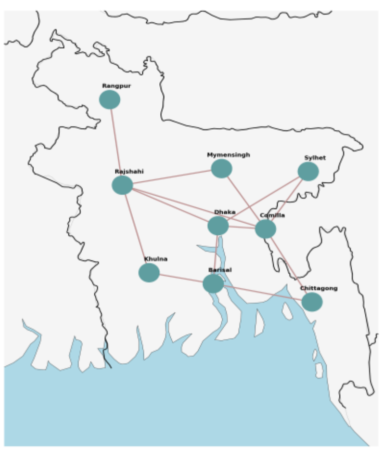


Figure 2. Regions of the Bangladesh power sector in PyPSA-BD model

A. *PyPSA*

PyPSA is an open-source toolkit [21] for modeling and optimizing electrical power systems over various time frames. It supports detailed modeling of generators, renewable energy sources, and storage systems, integrating power management with other energy sectors. The toolkit employs linear optimization to balance operational needs with long-term planning, minimizing system costs within physical and technological constraints.

B. *PyPSA-Earth*

PyPSA-Earth extends PyPSA to a global scale [4], enabling comprehensive energy system planning. It integrates detailed spatial and temporal data, maintaining an open-source approach for transparent decision-making. The model customizes data processing for regional analyses, using diverse data sources from open repositories.

C. *PyPSA-BD*

PyPSA-BD is tailored to Bangladesh's energy system, enhancing accuracy by incorporating local data from BPDB and PGCB. This model supports policy shaping, corporate analytics, and research, ensuring an accurate representation of regional demand and network structures. PyPSA-BD's high-resolution modeling, dynamic framework, diverse analytical capabilities, adaptability, and transparency make it essential for strategic energy planning in Bangladesh.

D. *Key Strengths of PyPSA-BD*

- Accurately represents Bangladesh's energy characteristics.
- Facilitates comprehensive long-term planning.
- Supports technology evaluation, supply diversification, and power system analyses.
- Integrates new datasets and country-specific constraints seamlessly.
- Ensures reproducible results and clear documentation.

PyPSA-BD empowers stakeholders in Bangladesh to make informed decisions on infrastructure investments, policy formulation, and strategic energy development, supporting the sustainable growth of the country's energy sector.

E. *Mathematical Formation of the PyPSA-BD*

The PyPSA-BD model, an adaptation of the PyPSA framework for Bangladesh's energy system, uses linear optimization to minimize total annualized costs while maintaining energy balance and operational feasibility. The model's equations and constraints are derived from established methodologies in ref [3], [4], [22].

The primary goal is to minimize the total annual system costs (AC), encompassing both capital expenditures (CAPEX) and operational expenditures (OPEX) for generation, storage, and transmission systems. This objective function is mathematically represented by equation 1 as follows:

$$\min_{F_\ell, G_{n,r}, H_{n,s}, E_{n,s}, f_{\ell,t}, g_{n,r,t}, h_{n,s,t}, suc_{n,r,t}, sdc_{n,r,t}} \Bigg[\sum_{l} C_\ell . F_\ell + \sum_{n,r} C_{n,r} . G_{n,r} + \sum_{n,r,t} (w_t . o_{n,r} . g_{n,r,t} + suc_{n,r,t} + sdc_{n,r,t} + \sum_{n,s} C_{n,s} . H_{n,s} + \sum_{n,r} \hat{C}_{n,s} . E_{n,s} + \sum_{n,r,t} w_t . o_{n,s} . [h_{n,s,t}]^+ \Bigg] \quad (1)$$

Where, F_ℓ: Branch capacity, C_ℓ: Fixed costs per branch capacity, $C_{n,r}$: Fixed costs per generation capacity, $G_{n,r}$: Generator capacities, w_t: Period weight, $o_{n,r}$: Variable cost, $g_{n,r,t}$: Unit dispatch, $suc_{n,r,t}$: Startup cost, $sd_{cn,r,t}$: Shutdown cost, $C_{n,s}$: Fixed costs per storage capacity, $H_{n,s}$: Storage power capacity, $\hat{C}_{n,s}$: Fixed costs per storage energy capacity, $E_{n,s}$: Storage energy capacities, $o_{n,s}$: Variable dispatch cost, $[h_{n,s,t}]^+$: Positive storage dispatch, ℓ: Branch, s: Storage technology, t: Time, r: Technologies, n: Bus.

The objective function is constrained by demand-supply balance, storage balance (energy and capacity), power flow, generator capacity, and energy storage limits. Additionally, it includes constraints on power flow limits (cyclic energy storage and greenhouse gas emissions reduction). Detailed mathematical descriptions of these constraints are provided in the referenced literature [3], [4], [22] and are omitted here due to page limitations.

F. Model Inputs

The PyPSA-BD model integrates various input parameters for comprehensive energy system analysis. Geographic data includes grid topology (layout of buses, transmission lines, substations) and regional demand profiles (electricity demand by region). Generation data encompasses installed capacity (thermal and renewable sources) and fuel costs/availability. Economic data covers investment costs (new infrastructure), operational costs (fixed/variable), and startup/shutdown costs for thermal plants. Technical data includes plant efficiency, storage characteristics (capacity, charge/discharge rates, efficiency), and transmission limits. Policy data involves emission and renewable energy targets. Scenario data provides future projections for demand, fuel prices, and technology costs. These inputs enable robust modeling for the PyPSA-BD framework.

V. RESULTS AND DISCUSSION

To analyze the scenarios of Bangladesh's power sector the entire power sector of the country has been divided into nine regions for the simplicity of the analysis. These regions are depicted in Figure 2.

A. Scenario Description:

To investigate potential pathways for Bangladesh's energy sector, three scenarios were developed using the PyPSA-BD model. These scenarios incorporate different assumptions about energy policies, technological progress, and economic factors to offer a detailed understanding of potential routes to achieving a sustainable and resilient power system. The scenario developed in this research is presented in Table II.

TABLE II. SCENARIO DESCRIPTION AND ASSUMPTIONS

Scenario Name	Ref.	Year	Description and Assumptions
Scenario - I	[23]	2030	Achieve a 15% share of clean energy in the generation mix; significant investments in solar and wind energy, aligned with the National Determined Commitment (NDC).
Scenario - II	[24]	2041	Attain a 40% share of clean energy; no new coal power projects; integration of battery storage for enhanced energy security, consistent with MCPP objectives.
Scenario - III	[25]	2050	Achieve a 100% clean energy share; implementation of strong energy and environmental policies; expansion of renewable energy and transmission on existing infrastructure; combination of battery and hydrogen storage; reliance on solar, wind, and nuclear power only.

B. Analysis of Scenario I

The details of the optimized results of the scenario I has been depicted by Table III and Figure 3 and 4. As is seen from Table, by 2030, the energy mix in Bangladesh aims for a 15% share from clean power sources, increasing investments in solar and wind energy as part of the Mujib Climate Prosperity Plan. The annual demand is projected to reach 189 TWh, with a total installed capacity of 43.725 GW. Gas remains the dominant source with 15.344 GW, while coal and oil contribute 12.646 GW and 8.18 GW, respectively. Solar capacity rises to 4.865 GW, generating 20.19 TWh, and wind capacity is minimal at 0.06 GW. Nuclear and hydro capacities are modest, with 2.4 GW and 0.23 GW, respectively. This scenario results in a total generation of 191.58 TWh, with clean generation contributing 28.48 TWh, accounting for 15% of the total. The total system cost is estimated at 5.21 billion euros.

TABLE III. SCENARIO OPTIMIZATION RESULTS

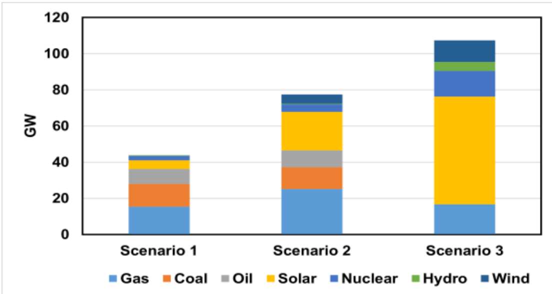
		Scenario 1	Scenario 2	Scenario 3
		15% Clean Power	40% Clean Power	100% Clean Power
	Year	2030.00	2041.00	2050.00
Annual Demand (TWh)		189.00	335.00	473.00
Capacity (GW)	Gas	15.34	25.15	16.65
	Coal	12.65	12.14	0.00
	Oil	8.18	9.18	0.00
	Solar	4.87	21.37	59.72
	Nuclear	2.40	4.20	14.20
	Hydro	0.23	0.23	4.85
	Wind	0.06	5.14	11.90
	Total	43.73	77.40	107.31
Storage (GW)	Battery	0.37	14.49	22.00
	Hydrogen	0.00	0.14	6.58
Total Storage (GW)		0.37	14.63	28.58
Generation (TWh)	Gas	77.03	109.66	0.00
	Coal	60.97	52.90	0.00
	Oil	22.14	40.01	0.00
	Solar	20.27	93.07	286.73
	Nuclear	7.45	18.30	78.10
	Hydro	0.71	1.00	20.80
	Wind	0.19	22.32	51.04
Storage (TWh)	Battery	2.82	9.74	78.16
	Hydrogen	0.00	0.01	12.74
Storage Total (TWh)		2.82	9.75	90.90
Total Generation (TWh)		191.58	347.01	527.57
All Clean Generation	TWh	28.48	134.69	474.90
	Percentage	15%	40%	100%
Total System Cost (Billion Euro)		5.21	8.03	7.51

C. *Analysis of Scenario II*

By 2041, Bangladesh's power sector aims for a significant increase in clean energy, reaching 40% of the generation mix. The annual demand is expected to rise to 335 TWh, with a total installed capacity of 77.396 GW. The shift involves no new coal projects and the introduction of battery storage. Gas capacity increases to 25.146 GW, coal remains at 12.137 GW, and oil rises to 9.18 GW. Solar capacity surges to 21.365 GW, generating 93.07 TWh, and wind capacity grows to 5.138 GW. Nuclear and hydro capacities increase to 4.2 GW and 0.23 GW, respectively. This scenario results in a total generation of 337.26 TWh, with clean generation contributing 134.6924 TWh, making up 40% of the total. The total system cost is estimated at 8.03 billion euros. Figure 5 shows a week-long dispatch of the scenario II while Table III shows the optimization statistics of the scenario.

D. *Analysis of Scenario III*

This scenario is optimized considering several key assumptions like the hydrogen storage has been introduced alongside the battery storage and hydro generation has increased due to consideration of pumped storage hydro option. By 2050, the goal is to achieve a 100% clean power sector in Bangladesh. The annual demand is projected to reach 473 TWh, with a total installed capacity of 107.31 GW. This scenario includes strong energy and environmental policies, development of renewable energy, and the use of existing



infrastructure. Gas, coal, and oil capacities are phased out, while solar capacity dramatically increases to 59.715 GW, generating 324.95671 TWh. Wind capacity reaches 11.895 GW, nuclear 14.2 GW, and hydro 4.85 GW. The total generation in this scenario is 474.9 TWh, entirely from clean energy sources. The total system cost is estimated at 7.51 billion euros, reflecting the efficiency gains and reduced operational costs of a fully renewable system.

Figure 3. Optimized installed capacity in the scenarios

Although the phasing out of both gas and coal in Bangladesh by 2050 is nearly impractical, however, this research explored this option to verify the probability and as per the optimized model's result it is found that under strict consideration of different storage technology and the highest utilization of solar, wind, hydro and nuclear technology it is achievable.

E. Discussions and Ploicy Recommendation

The results of the three scenarios highlight Bangladesh's potential pathways for transitioning to a sustainable power sector. In Scenario I (2030), achieving a 15% clean energy share requires substantial investments in solar and wind energy, with an annual demand of 189 TWh and a total system cost of 5.21 billion euros. Scenario II (2041) sees a significant increase to 40% clean energy, eliminating new coal projects and integrating battery storage, leading to an annual demand of 335 TWh and a system cost of 8.03 billion euros. Finally, Scenario III (2050) aims for a 100% clean energy mix by phasing out gas, coal, and oil, with a strong focus on solar, wind, nuclear, and hydro, achieving an annual demand of 473 TWh at a system cost of 7.51 billion euros. Each scenario demonstrates the incremental steps and investments needed to

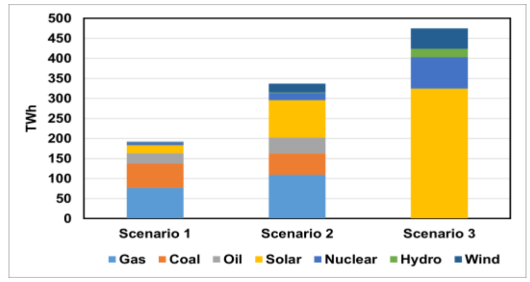


Figure 4. Optimized demand of the scenarios

increase the share of clean energy, emphasizing the importance of technology, policy, and economic factors in driving this transition.

To achieve these ambitious energy targets, Bangladesh should enhance investment incentives for solar and wind projects to meet the 2030 goals, ensuring alignment with the Mujib Climate Prosperity Plan. For the 2041 objectives, policies to phase out coal and incentivize battery storage solutions are essential to enhance energy security. By 2050, comprehensive policies should be established to phase out fossil fuels, focusing on expanding capacities for solar, wind, nuclear, and hydro, along with advanced storage technologies like batteries and hydrogen. Additionally, promoting research and development in renewable energy and storage solutions is crucial to ensure the feasibility and sustainability of a fully renewable power system.

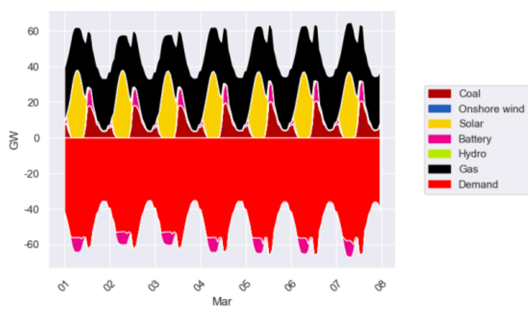


Figure 5. Dispatch of seven days in 2040 scenario

VI. Limitations

- The model's accuracy depends on high-quality, detailed input data, which may not always be available for Bangladesh, leading to potential inaccuracies in results.
- Reliance on projections for future costs and technological advancements poses a risk, as these may not occur as predicted, impacting the model's feasibility and cost-effectiveness.
- The scenarios assume consistent and supportive policy environments. Changes in policy could disrupt the implementation and success of the proposed pathways.

VII. Conclusions

This research utilizes the PyPSA-BD model to explore potential pathways for Bangladesh's energy sector, focusing on achieving sustainable and resilient power systems. The analysis of three scenarios highlights the incremental steps and investments required to transition from 15% clean energy by 2030 to 100% clean energy by 2050. Key findings emphasize the importance of substantial investments in renewable energy, the integration of advanced storage technologies, and supportive policy frameworks. Despite data quality and future projection uncertainties, the study provides a robust framework for policymakers and stakeholders to strategize the development of Bangladesh's power sector towards a sustainable future.

VIII. ACKNOWLEDGEMENT

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IX. DATA AVAILABILITY

The technological and cost data of this research are available in this link (https://github.com/FiruzAhamed/PyPSA-BD). These open-source files are reproduceable and can be used to further explore the future scenarios of Bangladesh’s power sector transition.

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