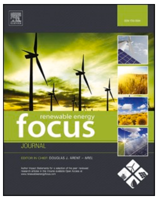
Renewable Energy Focus 52 (2025) 100655

Contents lists available at ScienceDirect

Renewable Energy Focus

journal homepage: www.elsevier.com/locate/ref



PyPSA-BD: A customized model to explore decarbonized energy transition for developing country

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ARTICLE INFO

Keywords:
Power capacity expansion model
Sustainable energy transition
Job prospects
Electricity sector modeling
Open Source Model
Socio Economic impact
Energy policy

ABSTRACT

This article provides high-resolution, evidence-based insights towards power sector planning for a developing country. We consider the PyPSA-BD model as a cutting-edge contribution as it's a fully customized adaptation of PyPSA-Earth for Bangladesh to identify challenges and opportunities for transitioning to a decarbonized power system through counterfactual validation of inputs from national official statistics with a spatial resolution of 30km x 30km and an hourly temporal resolution. Its open-source framework is helpful for future researchers and decision-makers in developing countries like Bangladesh to develop more scenarios to answer any policy-relevant questions as per national need. With 2019 as a reference year, scenarios for 2030, 2041, and 2050 align with national renewable energy integration and decarbonization targets revealing cost-effective generation expansions, diversification of installed capacity through renewable energy penetration, net employment generation, additional land and investment requirement. Model results show that the 2019 installed capacity of 18.94 GW will grow to 61.45 GW by 2030, 102.36 GW by 2041, and 281.52 GW by 2050. By 2050, a storage capacity of 28.5 GW will be required to maintain grid stability. This transition could create approximately 6.7 million jobs and reduce generation costs to 7.63 BDT/kWh by 2050, requiring 3690.85 sq.km of land. Achieving these outcomes will demand an annual investment of approximately 1.99% of Bangladesh's 2023 GDP from 2025, underscoring the need for national and international finance mobilization. The results guide policymakers to develop sustainable energy transition strategies for Bangladesh that provide power supply security at both spatial and temporal scale.

Introduction

The transition to a decarbonized power sector is critical for achieving long-term sustainability, particularly for rapidly developing nations. Eventually, a country will gain if it can plan early on for a decarbonized power sector growth path, a top priority in the global energy transition conversation [1]. For a fast-growing country like Bangladesh [2] where energy demand is increasing rapidly [3], early planning for a decarbonized power sector is essential for balancing economic growth and environmental sustainability. Python for Power System Analysis (PyPSA) helps in understanding how to optimize the power sector expansion plan with varying decarbonization targets. This research develops the PyPSA-BD model, a customized adaptation of PyPSA-Earth [4], to address Bangladesh's geographic, infrastructural, and policy challenges. This model is specifically designed to optimize capacity expansion and decarbonization strategies, offering valuable insights for policymakers as the nation transitions to a low-carbon energy system by 2050. The application of this model which has been successful in various geopolitical contexts, including South Africa [5], Kazakhstan [6,7], Vietnam [8], Germany [9,10], India [11], and the UK [12], provides a framework that effectively balance sustainability and economic viability while considering policy, social and environmental challenges. The proposed PyPSA-BD model is a significant advancement in power system modeling for Bangladesh as it integrates open data and national spatial resolution and considers local policy directives to predict the expansion trajectory. A comparative analysis using data and future projections from key entities such as the Bangladesh Power Development Board (BPDB), Power Grid Bangladesh PLC (PGCB), Power System Master Plan (PSMP) 2016 [13], and Integrated Energy and Power Master Plan

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https://doi.org/10.1016/j.ref.2024.100655
Received 13 September 2024; Received in revised form 5 November 2024; Accepted 17 November 2024

Nomenclature

Abbreviations

APSCL	Ashuganj Power Station Company Limited
ASEAN	Association of Southeast Asian Nations
BCPCL	Bangladesh-China Power Company Limited
BDT	Bangladeshi Taka
BPDB	Bangladesh Power Development Board
BRPL	B-R Powergen Ltd.
CAES	Compressed-Air Energy Storage
CCS	Carbon Capture and Storage
CEPA	Carbon Emissions Pinch Analysis
CCGT	Combined Cycle Gas Turbine
EDF	Environment Defense Fund
EGCB	Electricity Generation Company of Bangladesh
FOM	Fixed Operation and Maintenance Cost
GAMS	General Algebraic Modeling System
GENeSYS-MOD	Global Energy System Model
GW	Gigawatt
HSD	High-Speed Diesel
IEEFA	Institute for Energy Economics and Financial Analysis
IEPMP	Integrated Energy and Power Master Plan
IRENA	International Renewable Energy Agency
IPP	Independent Power Producer
Km	Kilometer
LAES	Liquefied-Air Energy Storage
LEAP	Long-range Energy Alternatives Planning
LEAP-NEMO	Long-range Energy Alternatives Planning - Networked Energy Model
MARKAL	MARKet ALlocation
MCET	Multi Country Energy Transition
MCPP	Mujib Climate Prosperity Plan
MW	Megawatt
NDC	Nationally Determined Contribution
NENP	No Electricity No Payment
NREL	National Renewable Energy Laboratory
NWPGCL	North-West Power Generation Company Limited
OPERA	Optimization Planning Energy Resources Analysis
OSM	OpenStreetMap
PBS	Palli Bidyut Samity (Rural Electrification Board)
PGCB	Power Grid Bangladesh PLC
PHES	Pumped-Hydro Energy Storage
PSMP	Power System Master Plan
PyPSA	Python for Power System Analysis
PyPSA-BD	Python for Power System Analysis - Bangladesh Model
PyPSA-GB	Python for Power System Analysis - Great Britain Model
PyPSA-KZ	Python for Power System Analysis - Kazakhstan Model
Q. Rental	Quick Rental
REB	Rural Electrification Board
RPCL	Rural Power Company Limited
Sq.km	Square Kilometer
SSP 2	Shared Socioeconomic Pathway 2
TES	Thermal Energy Storage
TIMES	The Integrated MARKAL-EFOM System
TWh	Terawatt-hour
VOM	Variable Operation and Maintenance Cost
VRE	Variable Renewable Energy

Symbols	*Description*
C_{ℓ}	Annualized fixed costs allocated per unit of capacity
$C_{n,r}$	Annuitized fixed costs per capacity of generation for each technology r at bus n
$C_{n,s}$	Storage technology's fixed cost per unit capacity
$\hat{C}_{n,s}$	Fixed cost of $E_{n,s}$ at bus n
$d_{n,t}$	Electricity demand
$e_{n,s,0}$	Initial stored energy
$e_{n,s,T}$	Final stored energy
$e_{n,s,t}$	Total stored energy
$\widetilde{e}_{n,s,t}$	Lower bound on the state of charge
$\overline{e}_{n,s,t}$	Upper bound on the state of charge
$E_{n,r}$	Maximum energy capacity
$E_{n,s}$	Energy storage capacity
EM^{max}	Maximum allowable emissions.
$f_{\ell,t}$	Power flow through branch ℓ at time t
F_{ℓ}	The capacity of each individual branch ℓ
$g_{n,r,t}$	The power output of the generator
$G_{n,r}$	Installed capacity of the generator
$H_{n,s}$	Maximum discharging capacity
$[h_{n,s,t}]^{+}$	Storage dispatch's positive component
$h_{n,s,t,inflow}$	Incoming flow (e.g., river input into a reservoir)
$h_{n,s,t,spillage}$	Spillage
$h^{+}_{n,s,t}$	Storage technology's charging power
$h^{-}_{n,s,t}$	Storage technology's discharging power
$\lambda_{n,t}$	Bus's marginal price
ℓ	Individual branch
n	Bus
$o_{n,s}$	Variable cost of the dispatch
$o_{n,r}$	Unit dispatch associated variable cost
r	Technologies
s	Storage technology
$sdc_{n,r,t}$	Shutdown cost when unit dispatch is activated
$suc_{n,r,t}$	Startup cost when unit dispatch is activated
t	Time
w_t	Weight for the period t
x_{ℓ}	The series inductive reactance of branch ℓ
$\eta_{\ell,t}$	Link's efficiency loss
$\eta_{n,s,0}$	Self-discharge rate (energy leakage)
$\eta_{n,s,+}$	Charging efficiency
$\eta_{n,s,-}$	Discharging efficiency
$\sum_r g_{n,r,t}$	Total generation at bus n for all technologies r
$\sum_s h^{+}_{n,s,t}$	Charging for all storage technologies s
$\sum_s h^{-}_{n,s,t}$	Discharging for all storage technologies s
$\sum_{\ell} \alpha_{\ell,n,t} . F_{\ell,t}$	The net flow of power into bus from all branches ℓ at time t, where $\alpha_{\ell,n,t}$ indicates the direction of the flow
$\sum_{\ell} C_{\ell,c}$	Sum over all branches ℓ that are part of cycle c in the network

(IEPMP) 2023 [3] offers valuable policy-relevant insights into the need for strategic infrastructure. These insights are crucial for crafting policies in the near term to secure a decarbonized power sector for Bangladesh. The PyPSA-BD model has global relevance as it offers a practical framework for other developing nations facing similar multidimensional challenges to meet growing demand and secure decarbonization need for their power sectors while keeping it affordable. Model's open-source nature allows easy access for future development and customization for making it dynamically adaptable to changing national contexts with limited resources. This enables trained human capacity to maintain a cost-effective energy planning and policy development.

This research aims to design strategic scenarios for the power sector using PyPSA-BD, aligning with the national growth aspirations, targets for integrating renewable energy, and participation in global decarbonization goals. Countries worldwide are integrating renewable energy sources into their power grids, utilizing software like PyPSA to inform their strategic energy policies. The PyPSA-Earth model offers highly detailed spatial and temporal resolution data essential for creating accurate and adaptable energy system models. PyPSA-BD leverages the PyPSA model's capability to accommodate the specific characteristics of Bangladesh's power sector, including its geographical, infrastructural, and policy goals. PyPSA-Earth encourages open-source collaboration, which is crucial for building a model that is accessible and can be improved through contributions from a global community. The PyPSA-BD model can benefit from further community expertise and by maintaining transparency and continual development in its energy planning. The reconstruction of power grid topology using the latest datasets from OpenStreetMap [14], combined with customized data from PGCB [15-17] and BPDB annual reports (2019 and 2023) [18,19] and web-statistics [20,21], ensures that PyPSA-BD can provide a highly detailed and accurate representation of Bangladesh's existing power system, addressing the research question: 1) How can these integrated data sources optimize capacity expansion planning and design decarbonization strategies for Bangladesh's electricity sector? 2) How much investment, land, and employment will be required for this transition? 3) What role will energy storage play in maximizing and the best use of renewable energy sources? The major contributions of this article are the following:

i) PyPSA-BD is developed with all necessary characteristics for Bangladesh: geographic, infrastructural, climatic, and electricity sector.
ii) High spatial and temporal resolution is included for modeling the variability of renewable energy sources for optimizing grid operations.
iii) Co-optimization of investment and operational strategies through PyPSA-BD to provide a dynamic framework for comprehensive long-term planning.
iv) To enhance model accuracy, detailed, country-specific datasets include those from the BPDB, PGCB, and national energy plans.
v) PyPSA-BD (like PyPSA-Earth) is an open-source model with transparency and reproducibility with potential to foster collaboration and continuous improvement.

The rest of the paper is structured as follows: Section 2 briefly overviews Bangladesh's electricity sector and review of decarbonized power sector pathways literature. Section 3 presents the methodology, focusing on scenario development, model inputs, and assumptions. Section 4 outlines the results, including model validation, scenario outcomes, and their insights. Section 5 discusses the results covering the generation and installed capacity mix, investment needs, job creation, land requirements, cost of generation, policy recommendations, and scope for future works. Section 6 provides the concluding remarks.

Brief Overview of Bangladesh Electricity Sector

Bangladesh's strategic vision to become a developed nation by 2041 [22] hinges on expanding its energy infrastructure, particularly in renewables, to ensure accessible, affordable, and uninterrupted electricity for all citizens. With over 730 MW of solar capacity already installed and plans to add another 1,625 MW of solar and 200 MW of wind power [23], the country is taking significant steps toward its decarbonization goals while addressing national energy security and public health [3]. This progress reflects Bangladesh's commitment to diversifying its energy mix and improving energy security while reducing reliance on fossil fuels [3,22,23]. Additionally, distributing more than 6 million solar home systems across rural areas has played a crucial role in enhancing energy access and sustainability [24]. Policy reforms, such as the Power System Master Plans of 2010 and 2016 and Integrated Energy and Power Master Plan of 2023, continue to guide these efforts, focusing on energy diversification and system resilience [13,25].

Installed Capacity and Generation

In June 2023, Bangladesh's power sector total installed capacity of 24,911 MW (Table 1) with participation from the public sector (42%), joint ventures (7.5%), IPP/SIPP (34%), no Electricity no payment plants (3.2%), Rural Electrification Board (1%) [18]. National capacity is complemented by 2,656 MW of cross-border power imports from India, enhancing its energy security.

Gas dominates the installed capacity with a significant share of 44.97% (Figure 1) [18], coal has gone up from 4.81% in the year 2008 to 24.31%, furnace oil 22.62%, imported power constitutes 4.27%, diesel, although relatively minor, contributes 290 MW, representing 1.07%. The country's solar PV installations contribute 1.69%, wind energy 0.22%, and hydroelectric power accounts for 0.85%. Despite these modest figures, the country's renewable energy sector is gradually gaining momentum, in line with national decarbonization targets. In terms of generation, gas dominates with 46,013 GWh, representing 52.02% of the country's electricity generation mix [18]. Furnace Oil is the next major contributor, generating 18,323 GWh and a 20.71% share, indicating the country's strategic energy reliance beyond gas. Coal's contribution of 10,081 GWh (11.40%) and high-speed diesel (HSD) of 2,327 GWh (6.21%). 10.425 GWh (10.08%) electricity is imported from neighboring country India. Renewables, though currently representing a small share, are expected to play a more prominent role in the future, as evidenced by the generation of 671 GWh (0.76%) from solar PV and 610 GWh (0.69%) from hydroelectric sources. However, scaling up renewables remains challenging, as infrastructure, investment, and grid integration will be crucial to achieving a more sustainable energy mix. These figures illustrate Bangladesh's reliance on fossil fuels and highlight the potential for renewable energy to contribute significantly to the country's decarbonization strategy in the coming decades. To support this transition, approximately 3,800 MW of solar PV from 41 different projects are in various stages of development, along with an additional 392 MW of wind power from nine projects, all slated to be connected to the national grid in the near future [18].

Demand

Bangladesh's electricity demand has grown significantly, rising fivefold from 3,033 MW in 2000-01 to 15,648 MW in 2022-23 [17,18] (Figure 2) due to the country's economic expansion, population growth, and enhanced electrification efforts. During the same period, per capita generation increased by 314%, from 125.13 kWh to 517.89 kWh, while per capita consumption grew by 429%, from 87.83 kWh to 464.13 kWh [17,18]. This increase (as is seen in Figure 3) in per capita figures

Table 1
2023 capacity and generation Overview

Sectors	Installed Capacity (MW)	Generation (MWh)
Public Sector		
BPDB	6233	17433
APSCL	1394	6983
EGCB	957	4153
RPCL	182	941
NWPGCL	1401	4700
B-R Powergen Ltd. (BRPL)	312	506
Joint Venture (BCPCL)	1861	7647
Private Sector		34253*
IPP/SIPP	8494	
Rental	373	
NENP (no Electricity no Payment)	797	
REB (for PBS's only)	251	1426
Power Import	2656	10425
Total	24911	88450

Source: BPDB annual report 2023 [18]. * The private sector's 34253 MWh consists of 30,447 MWh from IPP and 3,806 MWh of SIPP/Rental/Q. Rental/NENP

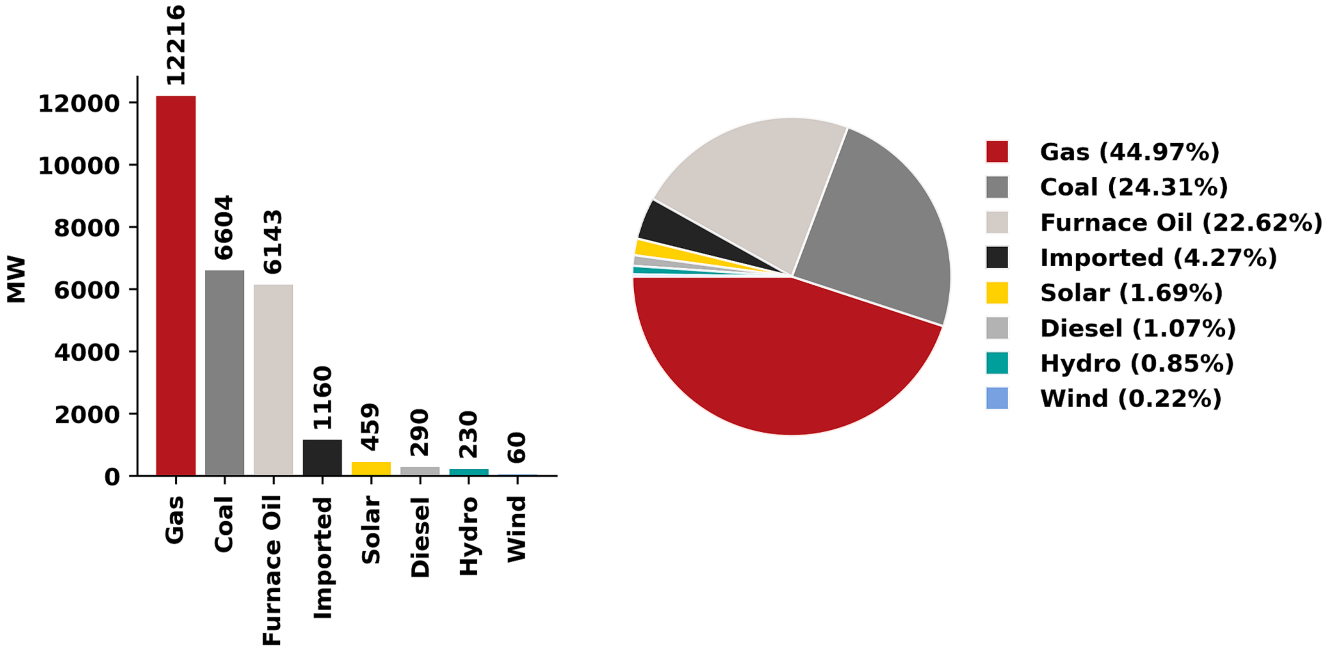


Figure 1. Installed capacity of Bangladesh power sector Source: BPDB: Power generation unit [21]

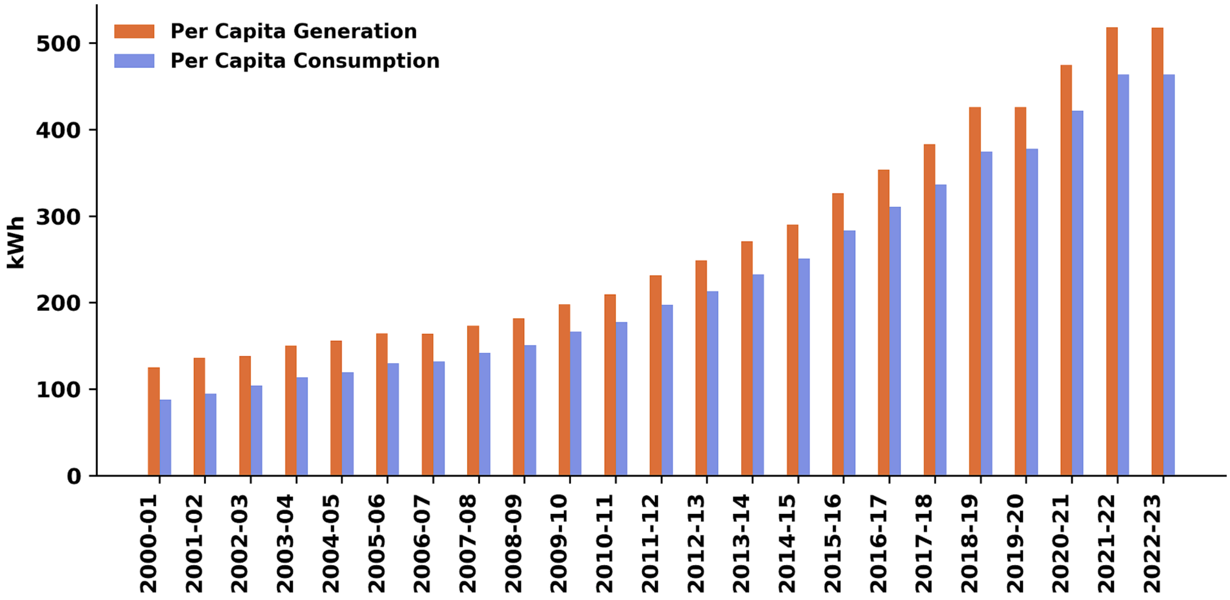


Figure 2. Maximum forecasted demand vs demand served Source: BPDB: Power generation unit [18]

underscores not only the rising standard of living but also the enhanced capacity of the power sector to cater to the individual energy needs of a growing consumer base. As Bangladesh looks toward 2041 and 2050, ensuring sufficient capacity expansion and integrating renewable energy into the grid will be essential to balancing demand with decarbonization efforts.

Decarbonized Power Sector Analysis: Literature Review

Tables 2 and 3 compare model types/results/features based on selected future decarbonized and renewable energy-based electricity sector transition pathways literature. Notably, while several studies have examined decarbonized scenarios in developed countries, such as those in the EU, Netherlands, Italy, Portugal, UK, Norway, Turkey, Montenegro, USA, Canada, and Japan, such analyses are lacking for developing countries.

Handayani et al. [1,34], Ayuketah et al. [27], Bamisile et al. [26], Kanugrahan and Hakam [40], Shakya et al. [36], Shahid et al. [33], and Limmeechokchai et al. [43,44] have explored decarbonized pathways in ASEAN, Cameroon, China, Indonesia, Nepal, Pakistan, and Thailand, respectively. The models used in these studies include LEAP, LEAP-NEMO, and EnergyPLAN. The models used in these studies include LEAP, LEAP-NEMO, and EnergyPLAN. The comparison of these models with PyPSA is shown in Table 3. As seen, the proposed PyPSA-BD model surpasses these models not only in being cost-effective and open-sourced but also in offering higher temporal and spatial resolution, more detailed power flow analysis, unit commitment, multi-regional optimization, and the ability to handle high renewable energy penetration scenarios. These features make PyPSA-BD more cutting-edge, suitable for comprehensive energy transition planning, especially in developing

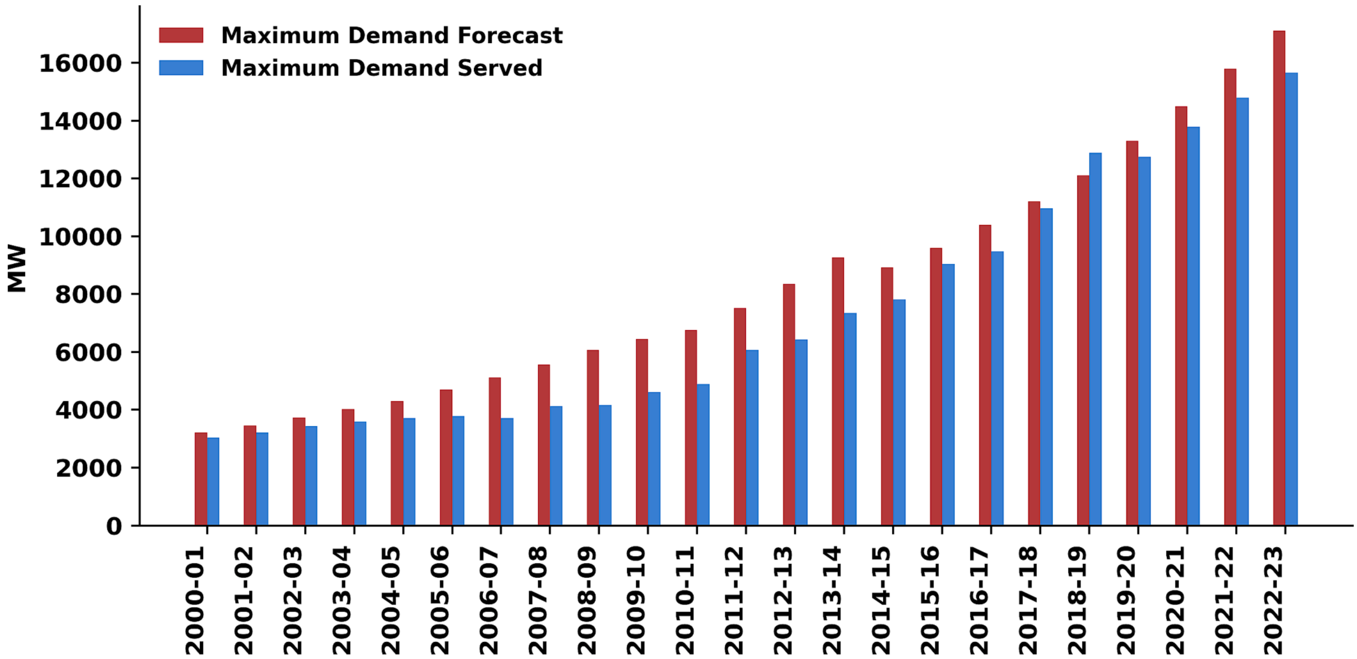


Figure 3. Per Capita Generation VS Consumption. Source: BPDB (Power generation unit) [18]

countries like Bangladesh, and underscores the novelty of the current research effort and results.

Table 3 compares various energy system modeling tools utilized in decarbonization studies, highlighting their features and applications. Models like EnergyPLAN [26] and LEAP [33] are frequently used for regional and national energy system analyses, focusing on policy impacts and renewable integration. LEAP and LEAP-NEMO [27,34] emphasize sector-coupling and pathway optimization for ASEAN and Cameroon. Models such as MARKAL [29,41], TIMES [39], and GENeSYS-MOD [38] are robust in pathway optimization and transport modeling, aiding in long-term energy planning for Japan, India, and Kazakhstan. Tools like PyPSA-KZ [7] and PyPSA-GB [12] offer open-source platforms for simulating future energy scenarios, ensuring transparency and collaborative development in Great Britain and Kazakhstan. These models collectively facilitate strategic energy planning, enabling the transition to decarbonization of the electricity sector through diverse methodologies and technological integrations.

PyPSA offers a flexible open-source platform with detailed spatial and temporal data integration, high-resolution modeling for renewable energy variability, and energy storage solutions. This high spatial resolution enables the modeling of an energy system at the regional level, such as for an entire country, with flexibility to divide it into multiple subregions and for planning purposes. These subregions can represent larger administrative areas, such as counties, or smaller ones, like provinces, or at any scale depending on the scope of the analysis. This helps in site planning for solar and wind energy infrastructure. Similarly, the model's high temporal resolution accommodates time series data used in dispatch analyses, allowing intervals that range from sub-hourly to hourly or beyond, as needed to meet the specific requirements of the energy modeling approach. Its adaptability to policy changes, data availability, real-world constraints, and continuous community-driven updates make it well-suited for long-term electricity sector planning. These features make PyPSA ideal for developing the PyPSA-BD model, tailored to Bangladesh's specific geographic, infrastructural, and policy needs as it transitions toward decarbonization. PyPSA-BD uses open datasets like OpenStreetMap to reconstruct energy systems, making it adaptable to various regions and easily modifiable to meet local needs. This flexibility allows users to create detailed, region-specific energy models that support effective planning and decision-making.

For developing countries, PyPSA-BD's affordability and adaptability are key advantages. Its open-source nature eliminates costly licensing fees, making it accessible for low-income regions. Additionally, the model's ability to handle diverse data sources and align with local policies makes it well-suited for countries with fragmented or evolving energy infrastructures, providing a cost-effective and adaptable solution for optimizing long-term energy planning and decarbonization strategies.

Methodology

This study employs advanced energy system modeling using the PyPSA framework, which includes PyPSA [42], PyPSA-Earth [4,45] and the newly developed PyPSA-BD in this paper that due to it's open-source nature enables continuous updates, enhancements, and transparency. Researchers and stakeholders worldwide can collaborate, modify, and validate the model, ensuring that it evolves in line with technological advancements and emerging data sources. Such globally applicable models help in intercountry comparison of global decarbonization efforts. PyPSA, an open-source toolkit from the Frankfurt Institute for Advanced Studies, is designed for modeling and optimizing electrical power systems. It integrates steady-state network analysis with multi-period optimization, supporting detailed modeling of conventional generators, renewable energy sources with spatial and temporal scale details, and storage systems. Unlike LEAP, which focuses on scenario-based energy modeling without detailed network analysis, or MARKAL, which optimizes predefined technology options but lacks spatial and temporal detail, PyPSA offers greater flexibility and scalability. It handles large networks and extensive time series data, employing linear optimization to minimize system costs while adhering to real-world constraints. PyPSA's open-source nature allows for continuous customization and community-driven improvements, making it particularly well-suited for the evolving energy challenges in Bangladesh. This model offers comprehensive tool for analyzing and optimizing Bangladesh's power system, focusing on integrating renewable energy sources, storage solutions and addressing context specific challenges.

PyPSA-Earth extends PyPSA's capabilities globally, enabling comprehensive energy system planning with detailed spatial and temporal data across various regions. This extension is crucial for large-scale

Table 2
Summary of selected literature exploring net zero future

Reference	Overview	Target Year	Region	Model Name	Key Findings
[26]	Evaluates the transition of Sichuan Province, China, to net-zero emissions with 100% renewable energy integration.	2050	Sichuan, China	EnergyPLAN	- Current policies won't achieve net-zero by 2050.- Three renewable energy strategies are feasible. - Importing clean electricity is the most cost-effective.
[1]	Explores ASEAN's transition to net-zero by 2050, focusing on renewable energy and storage.	2050	ASEAN	LEAP	- ASEAN must maximize renewable resources.- Energy storage and VRE are critical. - Renewables and storage are more cost-effective than carbon capture.
[27]	Assesses Cameroon's generation mix evolution, long-term costs, and policy benefits.	2045	Cameroon	LEAP-NEMO	- As of 2019, 74.7% of electricity is hydropower.- Infrastructure is divided into three grids, and unification will be done by 2035. - Frequent outages over 24 hours, even in cities.
[28]	Examines the UK's nuclear capacity integration for net-zero emissions.	2050	UK	highRES	- Heat, EV, and energy demand vary with weather.- Nuclear cost-effectiveness is variable. - BECCS and long-term storage are vital.
[29]	Investigates Japan's strategies for net-zero by 2050 using scenario analysis.	2050	Japan	MARKAL	- Decarbonize electric power by 2040.- Renewable power must dominate. - CO2 removal tech needed, especially in industry.
[30]	Analyzes pathways for the Netherlands to meet climate goals with reduced emissions.	2050	Netherlands	OPERA	- Electrification and renewables are crucial.- Flexibility options like demand response are necessary. - Hydrogen emerges as a key energy carrier.
[31]	Focuses on improving Canada's power system flexibility for renewable integration.	2050	Canada	COPPER & SILVER	- Expand transmission and storage infrastructure.- Wind capacity estimates need correction. - Enhance wind curtailment, congestion management, and load shedding.
[32]	Analyzes the UK's decarbonization processes for power and industry sectors.	2050	UK	Energy System Optimization Framework	- Power and industry must cut emissions by 90%.- Industry decarbonization pathways are unclear. - Low-carbon production and power sector changes can reduce BECCS reliance.
[33]	Projects Pakistan's future electricity demand and evaluates sustainable supply pathways.	2040	Pakistan	LEAP	- Significant growth in electricity consumption expected.- Diverse energy mix, increased nuclear and renewable capacities. - Need for safety in nuclear and renewable expansion.
[34]	Analyzes renewable energy integration in Cambodia, Laos, and Myanmar's grids.	2050	Cambodia, Laos, Myanmar	LEAP-NEMO	- Laos exports electricity significantly, Myanmar does less.- Grid interconnections reduce emissions and costs. - Renewable development must consider environmental and social impacts.
[35]	Analyzes Norway's future energy demands and environmental impacts.	2050	Norway	LEAP	- Norway relies heavily on renewables, mainly hydropower.- Net decrease in energy consumption observed. - Focus on renewable investments, particularly wind.
[36]	Examines Nepal's pathways to net-zero emissions, focusing on pollution, energy security, and equity.	2050	Nepal	LEAP	- CO2 emissions projected to rise without additional measures. - Additional measures drastically reduce pollutants and improve energy security.
[37]	Examines measures for reducing carbon emissions in the UK's power sector.	2050	UK	CEPA	- Incremental biomass and renewables necessary for 2030.- Transition to renewables and CCS vital for 2050. - Sustainable biomass with CCS achieves net-zero.
[38]	Examines hydrogen import requirements for Japan's net-zero plans.	2050	Japan	GENeSYS-MOD	- Hydrogen is valuable for specific sectors; imports impact energy transformation.- Extensive electrification needed without hydrogen imports. - Large renewable investments required in all scenarios.
[39]	Models India's power sector decarbonization pathways, focusing on renewable energy, nuclear, storage, and hydrogen.	2070	India	TIMES	- Coal capacity and CO2 emissions increase until 2040, then decrease.- Transition cost comparable across technologies. - $550 billion annually required for zero-emission transition.
[40]	Assesses Indonesia's power sector net-zero feasibility by 2060 with renewable energy.	2060	Indonesia	LEAP	- Nuclear and storage enable 100% renewable energy by 2060 at the lowest cost. - Decommission fossil-fuel plants, develop renewables.
[41]	Explores India's feasibility of achieving net-zero by 2050, emphasizing electrification and energy efficiency.	2050	India	MARKAL	- Heavy investment in electrification, efficiency, and decarbonized fuels needed.- Heavy freight and industry may struggle to fully decarbonize. - Carbon sequestration necessary for residual emissions.
[12]	Presents PyPSA-GB, an open-source power system model for Great Britain.	2050	Great Britain	PyPSA-GB	- First open-source model for GB, aiding policy and operations.- Useful for wind curtailment and flexibility options. - Open-source allows peer review, transparency, and collaboration.
[6]	Scenario analysis of Kazakhstan's energy transformation by 2060 using TIMES.	2060	Kazakhstan	TIMES	- Renewable expansion, coal phaseout required.- Strategic initiatives like tree planting and green hydrogen adoption are planned. - Uncertainties in global energy necessitate predictive scenario analysis.
[7]	Models Kazakhstan's energy sector to phase out coal and increase renewables by 2040.	2060	Kazakhstan, Central Asia	PyPSA-KZ	- Coal exit boosts wind power generation.- New transmission line with 30% renewable share transforms coal-dependent regions. - Increased wind and solar energy and decreased coal use for carbon-neutral energy.

Source: Compiled by authors

Table 3
Comparison of energy system modeling tools

Model Name	Reference	Language	Free and Open	Power Flow	Transport Model	Unit Commitment	Sector-Coupling	Pathway Optimization
EnergyPLAN	[26]	C++	No	Yes	No	No	Yes	Yes
LEAP	[1,33,35,36,40]	Windows	No	No	No	No	Yes	Yes
LEAP-NEMO	[27,34]	Windows	No	No	No	No	Yes	Yes
highRES	[28]	Unknown	No	Yes	No	Yes	No	Yes
MARKAL energy model	[29,41]	GAMS	No	Yes	Yes	Yes	No	Yes
OPERA	[30]	N/A	No	Yes	No	Yes	No	Yes
COPPER and SILVER	[31]	N/A	No	Yes	No	Yes	Yes	Yes
Energy system optimization framework	[32]	N/A	No	Yes	No	Yes	Yes	Yes
Carbon emissions pinch analysis (CEPA)	[37]	Excel-based	No	No	No	No	Yes	Yes
GENeSYS-MOD	[38]	Python	Yes	Yes	Yes	Yes	No	Yes
TIMES-based optimization model	[39]	GAMS	No	Yes	Yes	Yes	No	Yes
PyPSA	[5,7,8,12,42]	Python	Yes	Yes	No	Yes	Yes	Yes
TIMES	[6,29]	GAMS	No	Yes	Yes	Yes	No	Yes

Source: Compiled by authors

network analysis and multi-period optimization, as demonstrated in projects like Nigeria's 2060 net-zero goal [4]. PyPSA-BD, a localized adaptation of PyPSA-Earth, incorporates data specific to Bangladesh, enhancing precision in generation and investment planning. It supports energy sector decision-making and policy development by allowing the integration of new datasets and country-specific constraints, such as emission reduction targets and renewable energy targets. By leveraging the open-source nature of PyPSA-BD, policymakers and researchers in Bangladesh can ensure the energy transition strategies with flexibility e and transparency, allowing for continuous adaptation as new challenges and opportunities arise. PyPSA-BD's design ensures reproducibility and clear documentation, making it a reliable tool for Bangladesh's energy transition.

The mathematical formulations, including objective function equations and constraints (demand and supply balance, storage, and power flow), are adapted from existing literature on PyPSA [4,42,45,46] and can be seen in Appendix A.

Model Inputs

The PyPSA-BD model utilizes a variety of inputs to represent and simulate the Bangladesh power system accurately. Table 4 summarizes the input data used with source in PyPSA-BD to simulate the future electricity sector scenario.

In the inputs, handling data inaccuracies involved a thorough comparison among various available open-source official data sources from the Bangladesh Power Development Board (BPDB), Power Grid Bangladesh PLC (PGCB), and National Energy Plans. In cases of discrepancies, such as variations in power plant capacity, installation year, efficiency, commissioning date, retrofit date, operational lifetime, or geographic coordinates (latitude and longitude), the open-source data were corrected by replacing them with verified data from national official reports. Our goal was to use national official data sources wherever available.

Scenarios and Assumptions

Four overarching scenarios have been explored to explore the future power sector expansion pathways for Bangladesh. These scenarios incorporate various assumptions regarding energy policies, technological advancements, and economic factors to provide feasible least-cost expansion pathways. Table 5 summarizes the scenarios and assumptions.

The selection of 2030, 2041, and 2050 as key years for the scenarios is grounded in phases mentioned in Bangladesh's national planning frameworks. The year 2030 aligns with Bangladesh's commitments under the Mujib Climate Prosperity Plan (MCPP), where significant progress in renewable energy integration is targeted. The year 2041 corresponds with the government's Vision 2041 and MCPP, which aims to achieve an upper-middle-income status, necessitating large-scale energy infrastructure developments and increased renewable energy penetration. Finally, 2050 is chosen as it represents the long-term decarbonization goal set by both national plans, including the Integrated Energy and Power Master Plan (IEPMP), to achieve a fully decarbonized power sector in line with international climate targets. These timelines reflect critical milestones in national energy policies and global climate commitments.

The scenarios in this study are based on specific assumptions, but various uncertainties could influence the results. Demand fluctuations could arise from unexpected economic growth, changes in industrial activity, or accelerated adoption of electric vehicles and energy-efficient technologies, leading to either higher or lower electricity consumption than projected. Technological innovations, such as breakthroughs in energy storage, grid technologies, or renewable generation efficiency, may significantly lower costs and alter the optimal energy mix. Additionally, shifts in energy policies—such as stricter carbon regulations, renewable energy incentives, or delays in policy implementation—could impact the pace and direction of the energy transition. Recognizing these uncertainties is crucial to interpreting the scenario results, as they may influence the feasibility, cost, and timing of the proposed pathways. However, the strength of the model can be easily customized to the dynamic policy landscape.

Results

PyPSA-BD Model Validation Using Reference Scenario

The PyPSA-BD model, representing Bangladesh's power sector through 27 buses corresponding to the nine administrative regions (Figure 4 a), was validated using 2019 actual data to ensure accuracy in long-term investment planning. The 2019 reference scenario was selected to ensure that the base year reflects the most recent pre-pandemic state of Bangladesh's power sector. The assumptions in this scenario are based on national energy sector reports, providing a reliable foundation for projecting future scenarios. Sub-national demand profiles were scaled according to 2019 data from BPDB and PGCB [18,19]. The cost assumptions in the reference scenario are presented in Table 6. The investment costs, fixed and variable operation and maintenance (FOM and VOM) costs, and lifetime for each technology were sourced from IEPMP 2023 and BPDB reports, ensuring the cost data align with market values in Bangladesh.

Table 4
Inputs for PyPSA-BD model

	Input Parameter	Description	Data Source
Geographic Data	Grid Topology	Information about the physical layout of the power grid, including locations of buses, transmission lines, and substations (presented in Figure B.14).	Open Street Map (OSM) [14]
	Regional Demand Profiles	Data on electricity demand for different regions vary based on population density, industrial activity, and climate.	Shared Socioeconomic Pathways (SSP 2) [47], BPDB Annual Report 2023 [18], PGCB Annual Report 2023 [17]
Generation Data	Installed Capacity	Installed capacities of all types of power plants	Open Street Map (OSM) [14], BPDB Annual Report 2023 [18], PGCB Annual Report 2023 [17]
	Fuel Costs and Availability	Information on the availability and cost of fuels used in fossil fuel-based generating stations.	IEPMP 2023[3], BPDB Annual Report 2023 [18], PGCB Annual Report 2023 [17]
Economic Data	Investment Costs	Capital costs for building new generation and transmission infrastructure.	IEPMP 2023[3], IEEFA 2023 [48], and REF [49]
	Operational Costs	Fixed and variable operational and maintenance costs for power plants and transmission infrastructure.	
	Startup and Shutdown Costs	Costs associated with starting up and shutting down thermal power plants.	
Technical Data	Efficiency	Efficiency of power plants	BPDB Annual Report 2023 [18], PGCB Annual Report 2023 [17], Open Street Map (OSM) [14]
	Storage Characteristics	Capacity, charge/discharge rates, and efficiency of energy storage systems like batteries and hydro storage.	
	Transmission Limits	Capacities and operational constraints of transmission lines.	
Policy and Regulatory Data	Emission Targets	National or regional targets aimed at lowering greenhouse gas emissions.	IEPMP 2023[3], NDC Report 2021 [23], MCPP [50],
	Renewable Energy Targets	Targets for the percentage of electricity to be produced from different renewable sources	
Scenario Data	Future Projections	Projections of future electricity demand, fuel prices, and technology costs.	Shared Socioeconomic Pathways (SSP 2) [47], IEPMP 2023[3], REF [49]

Table 5
Scenario assumptions

Scenario Name		Reference	Year	Assumptions
Reference Scenario		[17,18]	2019	This scenario validates the PyPSA-BD model without additional policy implementations using 2019 data from BPDB and PGCB, reflecting the existing generation mix and capacities.
Scenario - I	Base Case		2030	The 2030 default scenario is optimized without additional policies.
	30% RE	[50]		This scenario assumes 30% of the generation mix from renewable energy, with increased solar and wind investments, reflecting commitments under the Mujib Climate Prosperity Plan (MCPP).
Scenario - II	Base Case		2041	The 2041 default scenario is optimized without additional policies.
	40% RE	[50]		In this scenario, 40% of the generation mix comes from renewable energy, introducing battery and hydrogen storage while excluding new coal projects, aligning with the Mujib Climate Prosperity Plan.
Scenario - III	Base Case		2050	The 2050 default scenario is optimized without additional policies.
	Decarbonized Case	[3]		This scenario assumes strong energy and environmental policies, focusing on renewable energy development and transmission using existing infrastructure, with the generation mix limited to clean energy sources (solar, wind, hydro, and nuclear).

Network Topology and Length

The PyPSA-BD model's transmission network was compared with PGCB data, showing close alignment across voltage levels (Table 7 and Figure 5). For instance, the PyPSA-BD model reports 4043 Km for 230 kV lines, closely matching PGCB's 4236 Km. Similar precision is observed for 400 kV and 132 kV lines, confirming the model's reliability. These comparisons confirm that the model accurately reflects the current transmission infrastructure, ensuring that the model developed can serve as a reliable tool for future network planning and optimization.

Validation of Demand, Capacity, and Generation

The PyPSA-BD model accurately reflects 2019 electricity demand, closely aligning with BPDB's reported 62.037 TWh. This alignment, illustrated in Figure 3, underscores the model's ability to accurately mirror the existing system, making it a reliable tool for future energy demand projections.

Assumptions regarding installed capacity were cross-referenced with official BPDB figures and international datasets from IRENA, ensuring the capacity for each energy source was up-to-date and accurate. For example, while a 62 MW solar capacity was initially underrepresented in open-source datasets, the PyPSA-BD model adjusted for this by incorporating the latest solar installations from BPDB. The total installed capacity in the 2019 reference scenario, as shown in Table 8, is 18,973 MW, closely matching BPDB's reported figure of 18,941 MW. This level of precision enhances the model's ability to reflect the current energy

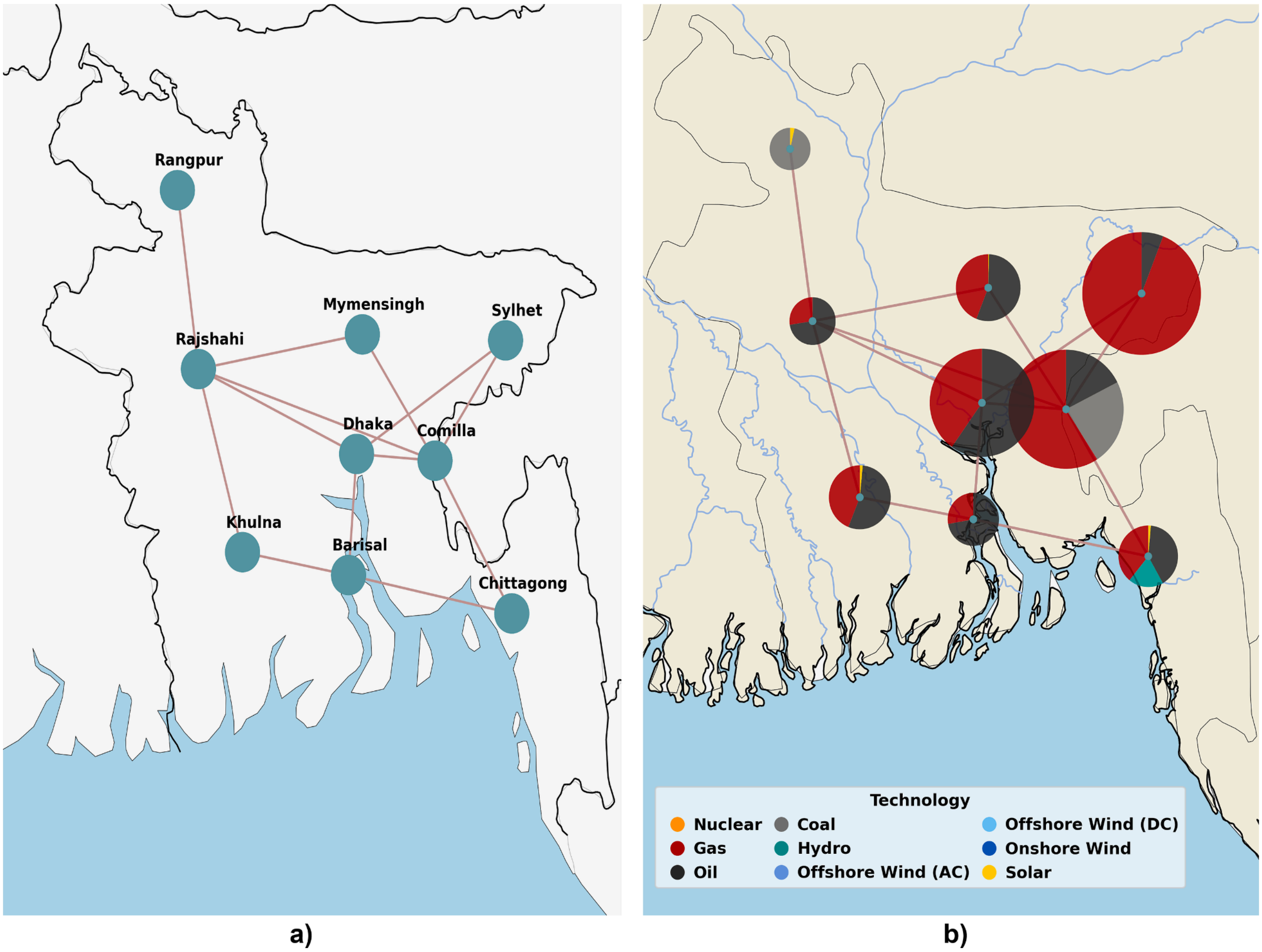


Figure 4. a) Simplified model of Bangladesh power system utilized in PyPSA-BD b) Spatial distribution of installed capacity in 2019

Table 6
Assumption of cost for the 2019 model scenario

Technology	Lifetime (years)	Investment Cost (EUR/kW)	FOM (% of Capital Cost)	VOM (EUR/ MWh)
Coal	40	1143.78	2.5	4.25
Gas	25	807.44	3	1.7
Oil	20	571.89	4	6.8
Solar PV	25	538.42	1	0.0085
Wind	25	1225.35	2	1.02
Hydro	50	1004.8	2.5	1.7

Note: 1 Euro = 132.36 BDT as of 20 August 2024; The cost data are sourced from IEPMP 2023 [3], IEEFA 2023 [48], BPDB Annual Report 2023 [18] and REF [49]

Table 7
Comparison of transmission line length at different voltage levels.

Voltage (kV)	400	230	132	66
PGCB	2190	4236	8555	271
PyPSA-BD	2078	4043	8210	-

Source: PGCB Electricity Transmission [48]

infrastructure accurately, especially for emerging technologies such as solar.

The model's power generation capacity (Table 9) also strongly aligns with BPDB and IRENA data, further validating its accuracy. For example, gas generation is consistently reported at 48,306 GWh by the PyPSA-BD model and BPDB, confirming the model's reliability in representing major energy sources. However, variations in solar generation between the PyPSA-BD model (104 GWh), BPDB (39 GWh), and IRENA (374.03 GWh) highlight the dynamic nature of solar deployment in Bangladesh, where rapid capacity additions are continuously reshaping the generation landscape.

The optimized total electricity demand in the 2019 scenario is presented in Figure 6, that shows comparisons of the demand with our word in data [52], enerdata statistics [53] and BPDB's 2019 annual report [19], while Figure 4 (b) shows the spatial distribution and diversity of energy sources of various generation technologies across Bangladesh as modeled in PyPSA-BD. Each pie chart represents the generation capacity mix at different bus locations, corresponding to the administrative regions of Bangladesh. The cost of assumption of power generation technologies is summarized in Table 9 for the 2019 reference scenario.

Analysis of Scenario I: 2030

Scenario I, guided by the MCPP [50], targets a 30% clean energy share in the generation mix by 2030. Along with regulatory initiatives to diversify energy sources and minimize fossil fuel reliance, the scenario expects increased investment in renewable technologies, notably solar and wind. Cost details and the spatial distribution of installed capacities across regions are presented in Table 10 and Figure 7, respectively. Figures B1 to B4 in Appendix B describe installed capacities and power dispatch, while Table B1 summarizes capital investment, land needs, and job creation insights.

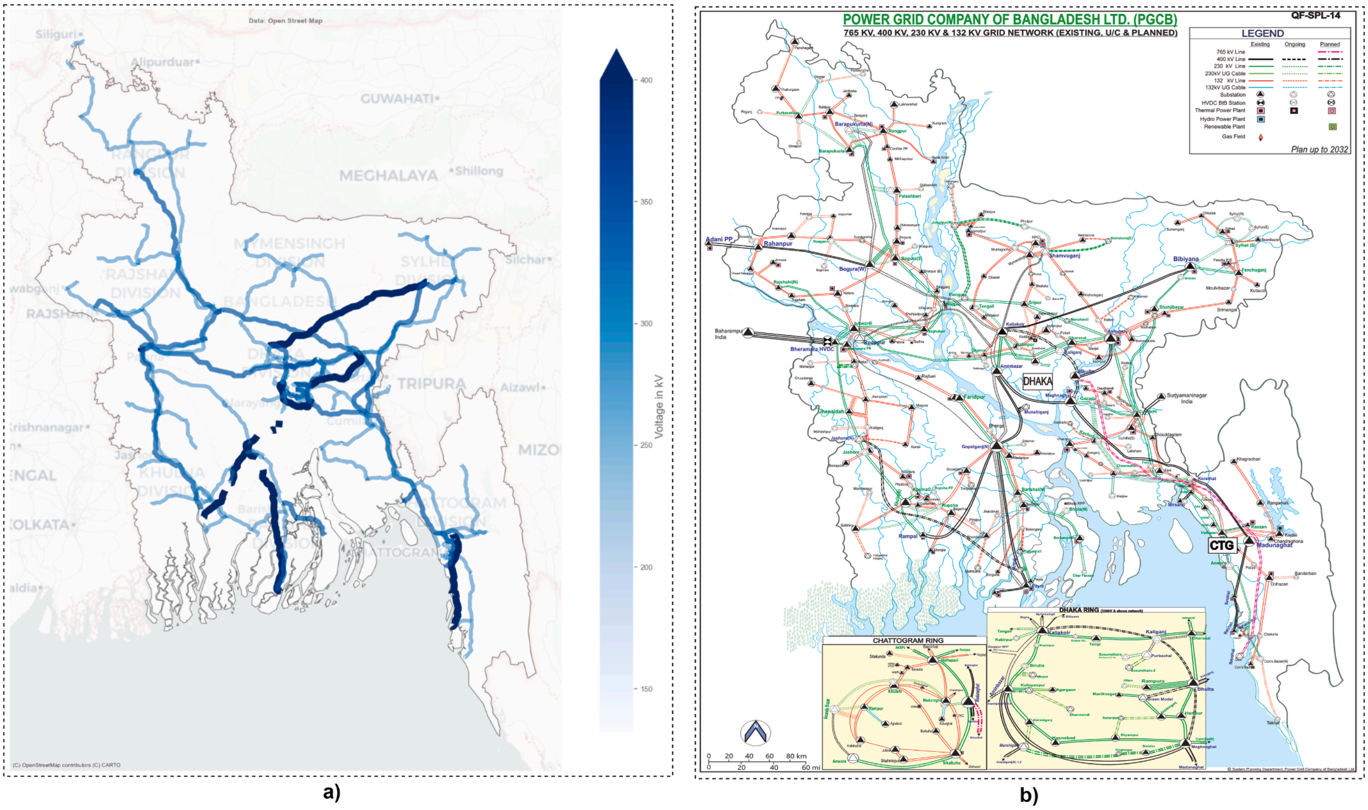


Figure 5. Power transmission map of Bangladesh by a) Open Street Map in PyPSA-BD b) PGCB

Table 8
Comparison of installed capacity in 2019

	PyPSA-Default (MW)	IRENA-19 (MW)	BPDB -19 (MW)	PyPSA-BD (MW)
Gas	7878.01	11252.00	10877.00	10877.00
Oil	7015.17	10080.00	6140.00	6140.00
Coal/ Import	975.49	1768.00	1664.00	1664.00
Hydro	227.00	230.00	230.00	230.00
Solar	0.00	343.27	30.00	62.00
Total	16095.67	23673.27	18941.00	18973.00

Source: BPDB 2019 annual report [19], IRENA data [51], PyPSA-Default and PyPSA-BD (Model generated result)

Table 9
Comparison of power generation

	IRENA-19 (GWh)	BPDB-19 (GWh)	PyPSA-BD (GWh)
Gas	52182.9	48306	48306
Oil	12071.48	13448	13448
Coal/Import	3401.01	8016	8016
Hydro	812.16	725	725
Solar	374.03	39	104

Source: BPDB 2019 annual report [19], IRENA data [51], PyPSA-BD (Model generated result)

Installed Capacity and Power Dispatch

The 2030 base case projects a total installed capacity of 66.78 GW, with coal dominating at 45.75 GW (69%), followed by gas at 13.84 GW (21%), oil at 4.28 GW (6%), and nuclear at 2.40 GW (4%). Renewables remain marginal, with solar at 0.27 GW (0.40%), hydro at 0.23 GW (0.34%), and wind at 0.0014 GW (0.0021%), indicating a continued reliance on fossil fuels. Scenario I for 2030 projects a total capacity of 61.82 GW, with a target of 30% renewable energy. Gas leads with 23.05 GW (37.28%), followed by solar at 21.76 GW (35.22%). Coal's share drops to 6.62 GW (10.72%), oil to 7.10 GW (11.48%), while nuclear remains at 2.40 GW (3.88%). Wind and hydro contribute 0.30 GW (0.49%) and 0.23 GW (0.37%), with battery storage at 0.37 GW (0.60%), showing a significant shift towards renewables, which account for 35.71% of the total capacity.

Key Insights

Considering the expansions in the scenario – I compared to the reference scenario:

- The model projects a 42.85 GW increase in total capacity, mainly from solar (21.69 GW), wind (0.30 GW), battery storage (0.37 GW), and nuclear (2.40 GW), signaling a shift towards renewables and reduced reliance on fossil fuels.
- The required capital expenditure is €40.01 billion, with significant investments in solar (€11.34 billion), gas (€15.16 billion), and nuclear (€12.96 billion), reflecting a €15.36 billion increase over the base case.
- Land use for this expansion totals 336.65 sq.km (0.23% of total land area), primarily for solar (307.27 sq.km), with wind requiring 3.58 sq.km, gas 24.63 sq.km, and nuclear 1.165 sq.km.
- The scenario is expected to create 657,610 new jobs, led by solar (591,160), with gas and nuclear contributing 28,849 and 32,880 jobs, respectively, emphasizing the economic benefits of renewable energy growth.

Analysis of Scenario II: 2041

This scenario targets a 40% clean energy share by 2041, aligned with the MCPP vision. Key assumptions include stopping new coal projects and adding battery and hydrogen storage for energy security. Table 11 outlines cost assumptions. Figure 8 shows the spatial distribution of capacities, with Figures B5 to B8 in Appendix B comparing installed

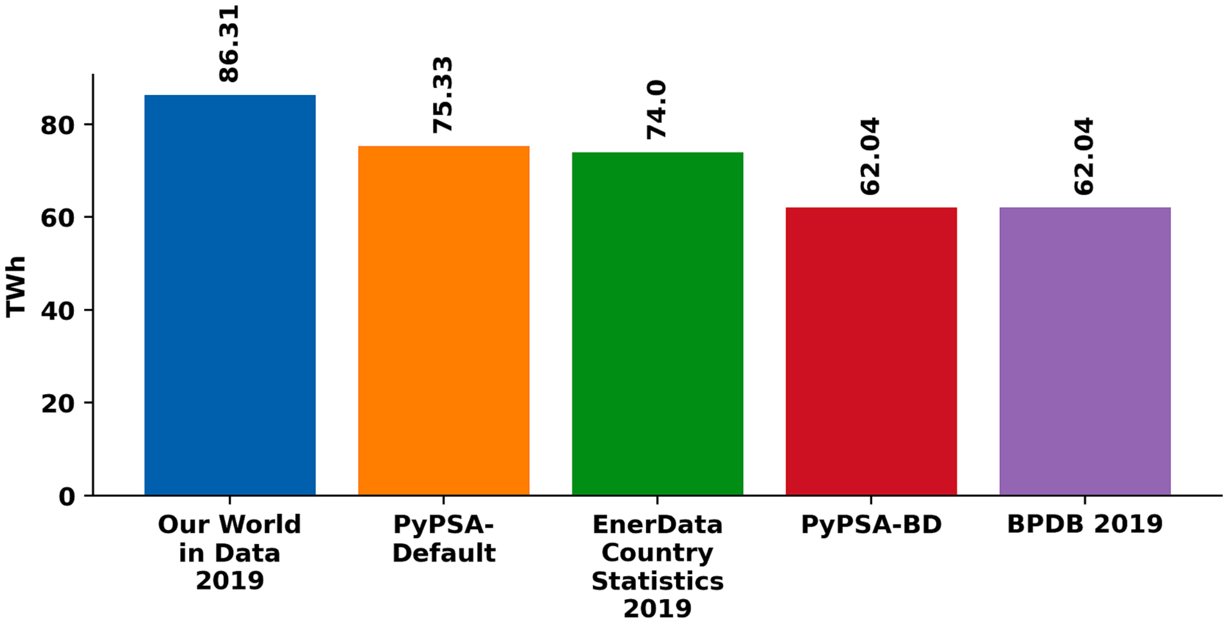


Figure 6. Comparison of PyPSA-BD demand in 2019 with other sources

Table 10
Assumption of cost for scenario - I

Technology	Lifetime (years)	Investment Cost (EUR/kW)	FOM (% of capital cost/ year)	VOM (EUR/ MWh)
Coal	40	1764.99	2.7	3.5
Gas	25	1245.88	2.92	4.5
Oil	20	1080.00	3.8	6
Solar PV	25	522.82	1.95	0.001
Wind	25	1696.28	1.93	1.35
Hydro	50	1080.00	2.5	2
Nuclear	60	5400.00	2.5	2.4

Note: 1 Euro = 132.36 BDT as of 20 August 2024; The cost data are sourced from IEPMP 2023 [3], IEEFA 2023 [48], BPDB Annual Report 2023 [18] and REF [49]

capacities and power dispatch for the base case and the 40% renewable scenario. Table B2 compares capacity expansion, capital costs, land, and job creation.

Installed Capacity and Power Dispatch

In the 2041 base case, total installed capacity is projected to reach 114.30 GW, a substantial increase from 18.94 GW in 2019. The energy mix is dominated by coal (40.03%, 45.75 GW) and solar (38.08%, 43.52 GW), with smaller contributions from gas, wind, oil, nuclear, and hydro. No battery or hydrogen storage technologies are included, indicating continued reliance on conventional sources. Power dispatch is projected at 314.03 TWh, with coal (35.78%) and solar (30.93%) as the leading contributors, while gas, nuclear, wind, oil, and hydro play minor roles.

The total installed capacity in the 2041 PyPSA-BD model-based optimal scenario is 112.28 GW. Solar becomes the dominant source, accounting for 55.90% (62.76 GW), followed by gas (16.13%, 18.11 GW), battery storage (12.90%, 14.49 GW), and a reduced coal share (5.90%, 6.62 GW). Hydrogen storage is introduced but remains minimal. Power dispatch reflects these changes, with gas (38.04%) and solar (37.38%) leading, while battery storage, wind, hydro, and nuclear make notable contributions. The scenario demonstrates a clear transition toward renewables, with battery storage emerging as a critical component.

Key Insights

Considering the expansions in scenario II compared to scenario – I:

- In Scenario II, total installed capacity expands by 60.76 GW, with major increases in solar (41.4 GW), wind (5.09 GW), battery storage (14.12 GW), and a modest addition of hydrogen storage (0.14 GW). This represents a significant shift towards renewable energy, building on the advancements made in Scenario I.
- The required capital expenditure is €33.01 billion, with significant investments directed towards solar (€22.85 billion) and wind (€8.9 billion). It represents a €13.84 billion increase over the base case, underscoring the financial commitment necessary to achieve a 40% renewable energy mix.
- Land requirements for this expansion total 649.51 sq.km (0.43% of total land area), with solar accounting for 587.93 sq.km, wind 61.59 sq.km, and minimal land use for battery and hydrogen storage.
- The scenario is projected to generate approximately 1,209,677 new jobs, led by solar (1,128,237 jobs) and wind (81,440 jobs), highlighting the significant employment potential associated with scaling up renewable energy infrastructure.

Analysis of Scenario III: 2050

Scenario III aims for a 100% clean energy mix by 2050, supported by strong energy and environmental policies. It focuses on fully developing renewable energy sources alongside extensive battery and hydrogen storage integration to ensure energy security. Cost assumptions are detailed in Table 12, while Figure 9 shows the spatial distribution of capacities. Appendix B (Figures 20, 21) compares installed capacities and power dispatch, with Table B3 outlining capital investments, land requirements, and job creation. Figure B13 highlights Bangladesh's solar and wind energy potential.

Installed Capacity and Power Dispatch

By 2050, installed capacity in the base case reaches 177.06 GW, with solar leading at 98.68 GW (55.73% of the total). Coal remains significant at 45.75 GW, and gas contributes 13.84 GW, while oil, nuclear, hydro, and wind have minimal roles, highlighting a shift towards more sustainable energy sources. Power dispatch totals 439.92 TWh, with coal generating 158.63 TWh, solar 136.88 TWh, and gas 115.83 TWh, reflecting the ongoing transition in energy sourcing. In the 2050 model-based decarbonized scenario, installed capacity increases to 310.30 GW, with solar power constituting 67.87% (210.61 GW) and wind 18.67%

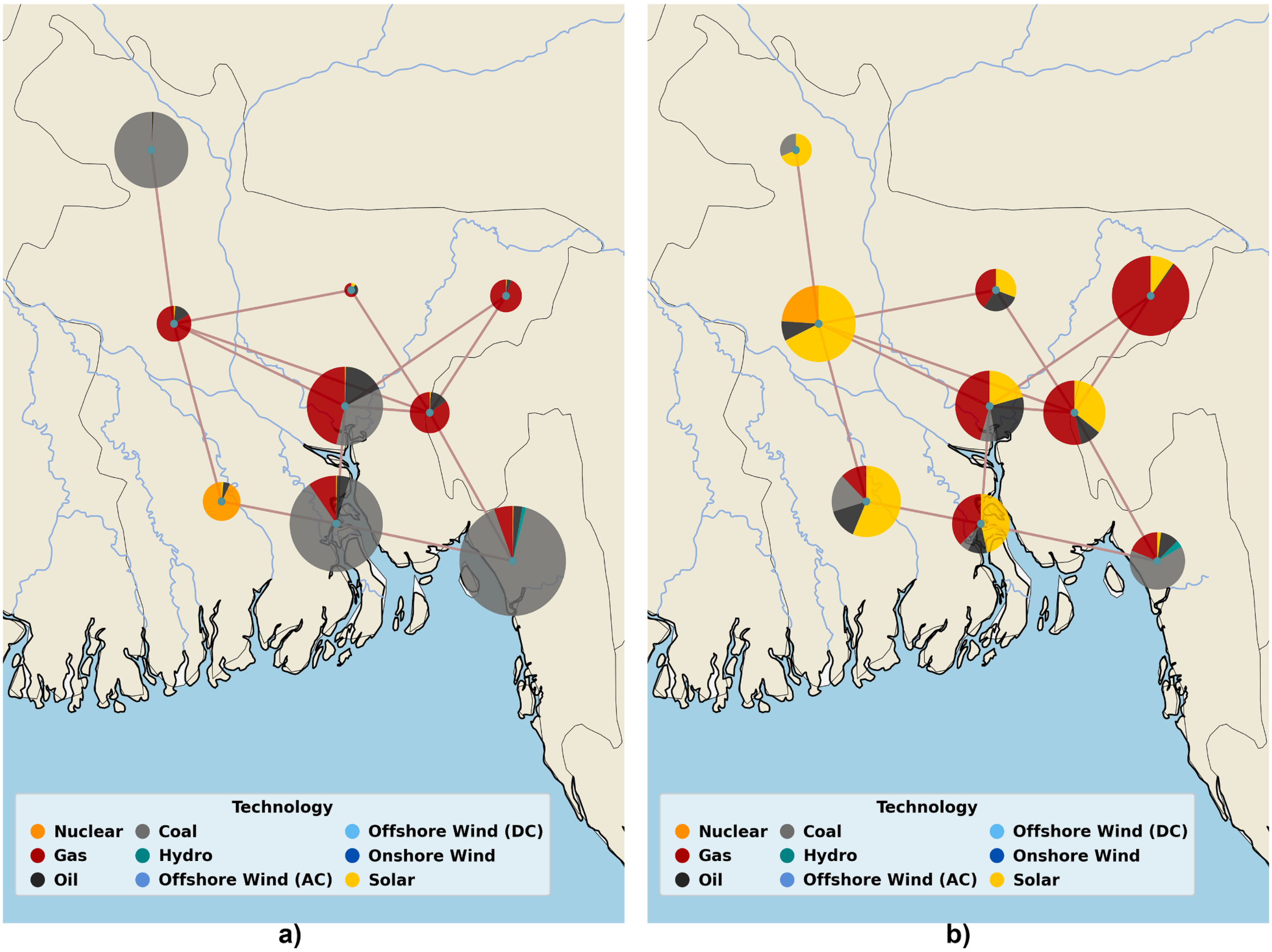


Figure 7. Optimized installed Capacity of scenario - I a) Base Case b) 30% RE Case

(57.94 GW), showing a robust shift towards renewables. Solar leads the power dispatch with 197.62 TWh, or 44.92% of the total 439.90 TWh, underscoring its vital role despite the variability introduced by its capacity factor. Wind energy and battery storage, contributing to 23.82% (104.77 TWh) and 21.29% (93.64 TWh), respectively, for stabilizing the grid during fluctuating solar output. Nuclear and hydrogen power, providing 4.93% (21.68 TWh) and 4.59% (20.19 TWh), further diversify the energy portfolio. This configuration highlights the imperative for comprehensive renewable infrastructure and sophisticated grid management to effectively sustain decarbonization goals.

Key Insights

Considering the expansions in scenario III compared to reference scenario – II:

- The 100% clean energy driven decarbonized scenario will need an expansion plan for 214.36 GW installed capacity, with significant contributions from solar (147.85 GW) and wind (52.56 GW), alongside increases in battery storage (7.51 GW) and hydrogen storage (6.44 GW). This strategic capacity expansion plan would need the aggressive push from now towards a fully clean energy-based system by 2050.
- The required capital expenditure for this scenario is €221.28 billion, with solar accounting for €72.62 billion and wind for €141.84 billion over a period of 25 years. We do not specify the resource mobilization plan in this paper but can be considered as a separate research effort to understand the nuances of the challenge. This represents a €218.40 billion investment in 25 years compared to the base case expansion, reflecting the magnitude of investible fund mobilization required to achieve a fully decarbonized energy mix.
- The land requirements for this scenario totals 2,735.40 sq. km (1.48% of the total land area of Bangladesh), with solar demanding the largest share at 2,099.48 sq. km, followed by wind at 635.92 sq. km. How this land use can be implemented at a spatial scale needs separate effort by taking into other sectoral land use distribution map along with a large-scale renewable energy deployment plan. The latter can also use rooftops of built environment, waterscape and many other innovative technological solutions.
- Employment potential in this scenario is projected to reach approximately 4,869,815 jobs, driven predominantly by solar (4,028,935 jobs) and wind (840,880 jobs). Despite the considerable financial and spatial demands, the substantial job creation underscores the socioeconomic benefits of transitioning to a decarbonized energy system.

Comparable studies indicate that Bangladesh's electricity demand is projected to grow significantly by 2030. For instance, Ref. [54] estimates the demand at 159 TWh, while Ref. [55] predicts around 200 TWh, and the Integrated Energy and Power Master Plan (IEPMP) [3] suggests 188 TWh. Ref. [56] predicts demand to be around 160 TWh. The PyPSA-BD model, with its prediction of 186 TWh, closely aligns with these estimates, particularly matching the IEPMP's latest projections.

Similarly, for 2040, Ref. [54] projects demand at 315 TWh, while the

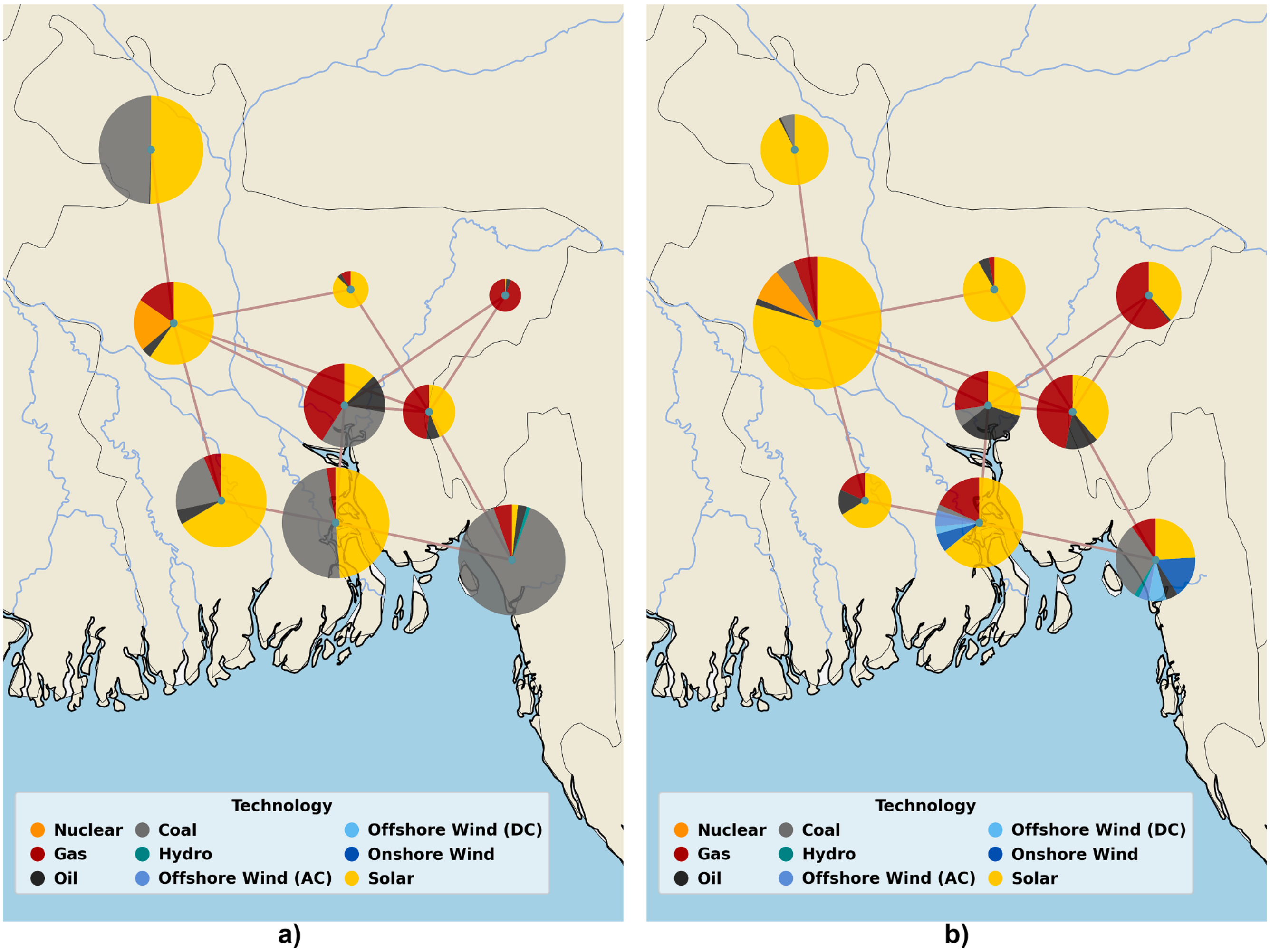


Figure 8. Optimized installed capacity of scenario – II a) Base case b) 40% renewable energy case

IEPMP estimates it at 333 TWh. The PyPSA-BD model projects a demand of approximately 314 TWh by 2041, which is closely aligned with both studies. For 2050, PyPSA-BD forecasts a demand of 440 TWh, which is close to the IEPMP's projection of 486 TWh. These comparisons highlight the accuracy of the PyPSA-BD model in reflecting Bangladesh's power system dynamics and demonstrate its reliability in forecasting long-term energy demand, aligning well with both national and independent estimates.

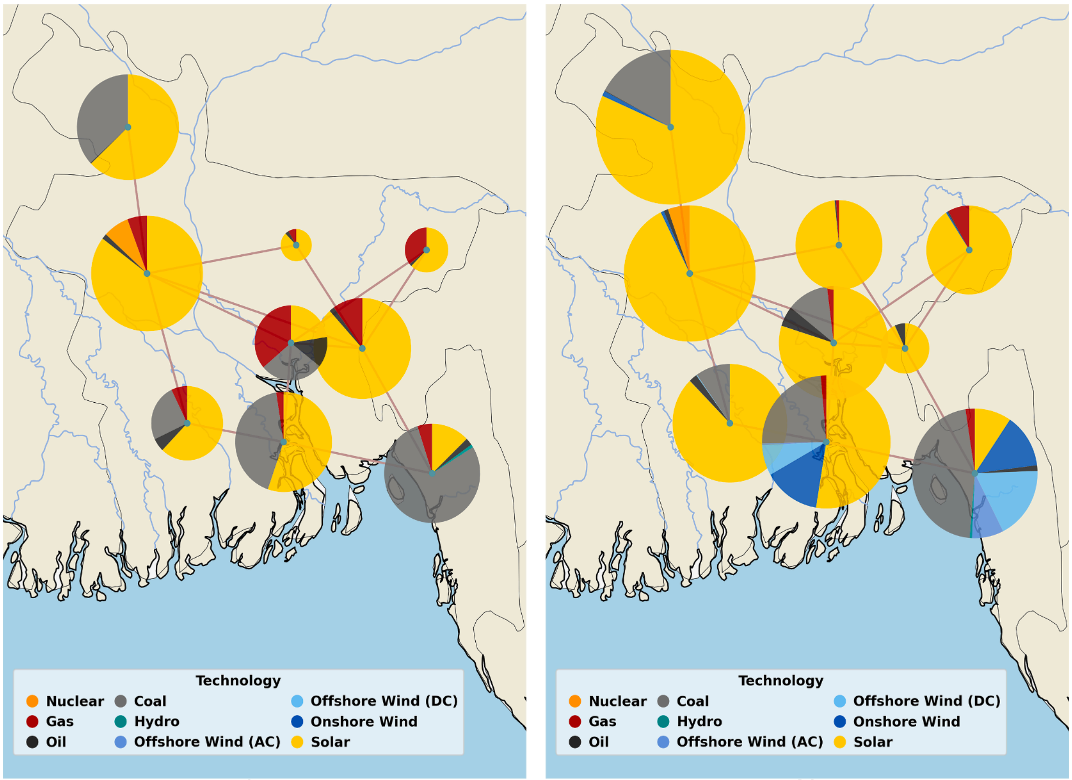
The generation and installed capacity mix have not been compared in this section, as these factors vary depending on scenario assumptions in each study. The differences in generation mix projections are influenced by the varying policies and renewable energy targets considered in different scenarios, making direct comparisons less straightforward. This analysis confirms that the PyPSA-BD model is well-calibrated for predicting future energy demand in Bangladesh, making it a valuable tool for national energy planning and policymaking.

Discussion

The Model-based Results and Energy Balance

The PyPSA-BD model-based optimized results across the three scenarios with differing levels of RE penetration (Table 13)—30% RE by 2030, 40% RE by 2041, and 100% decarbonization by 2050—demonstrate Bangladesh's techno-economically feasible transition phases towards a sustainable energy future. The potential of wind and solar energy across Bangladesh is presented in Figure B13. So, one major finding is that RE resources are available in Bangladesh to meet the rising demand. In Scenario I, fossil fuels dominate the energy mix, with natural gas contributing 48% (88 TWh), coal 10% (18.98 TWh), and oil 1% (2.51 TWh). Clean energy sources include nuclear at 9.5% (17.53 TWh), hydro at 1% (1.9 TWh), wind at 1% (2.3 TWh), and solar providing 28% (51.49 TWh), ensuring a 30% share of renewable energy in the generation mix. The demand is projected at 185.83 TWh, which is closer to IEPMP 2023's Advanced Technology Scenario (188 TWh) [3] and a bit higher than the projection of IEEFA (159.7 TWh) [57]. By Scenario II (2041), the shift towards renewables becomes more pronounced, with solar generation increasing to 39% (117.37 TWh) and wind adding 3% (9.43 TWh). By 2041, battery storage capacity rises to 14.49 GW, reflecting a growing need for storage solutions to maintain grid stability as renewable penetration increases.

In Scenario III (2050), the energy system is transformed with solar and wind together account for 93% of total power generation, contributing 197.62 TWh and 104.77 TWh, respectively. Battery storage capacity reaches 22 GW, complemented by hydrogen storage at 6.58 GW, indicating a strong emphasis on balancing the grid amid high renewable penetration. The expansion of renewable energy capacity is expected to vary considerably across different regions. As illustrated in Figure B13, Bangladesh's northern areas (Sylhet, Mymensingh, Rangpur, Rajshahi) have substantial solar power potential, while the southern coastal regions are better suited for wind energy (Barisal, Chittagong and Khulna). This geographic variation is consistent with the model's projections for solar and wind deployment. Figure 9 (b) further demonstrates that solar generation is concentrated in the north, whereas wind power is



a) b)

Figure 9. Optimized installed capacity of scenario – III a) Base case b) Decarbonized scenario

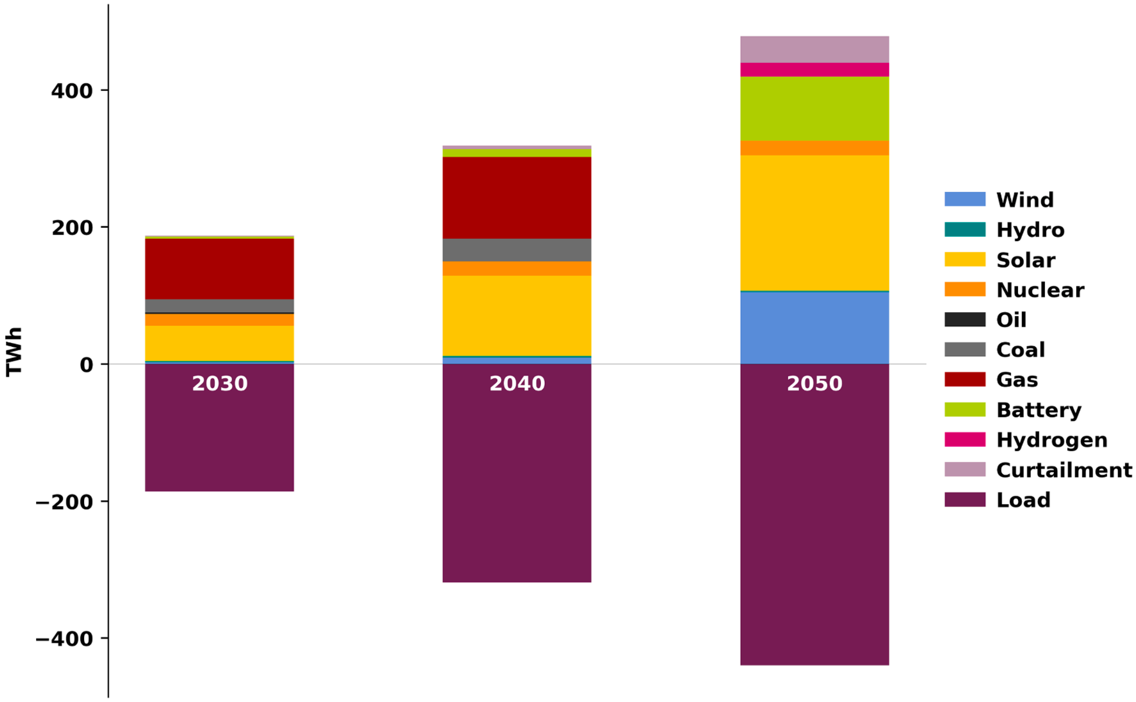


Figure 10. Energy balance of the optimized model in scenario – I (30% RE), II (40% RE) and III (Decarbonized)

predominantly sourced from the coastal south. These findings emphasize the regional suitability for specific types of renewable energy. More granular scale studies can, in the future, help in deciding on the location of plants in an optimal solution scenario. This is, however, not included here but can be a future research question with multiple other land use pattern maps at the comparable resolution level.

The energy balance (Figure 10) reveals that as renewable energy integration increases, so do the challenges of managing curtailments and load demands. Curtailments rise from 1.54 TWh in 2030 to 4.52 TWh in 2041 and dramatically to 38.64 TWh by 2050, highlighting the growing

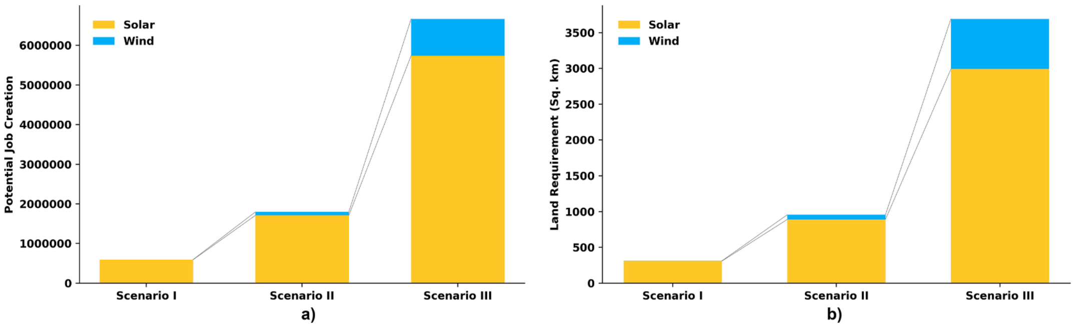


Figure 11. a) Job creation by RE across the scenario b) Additional land requirement by RE across the scenario

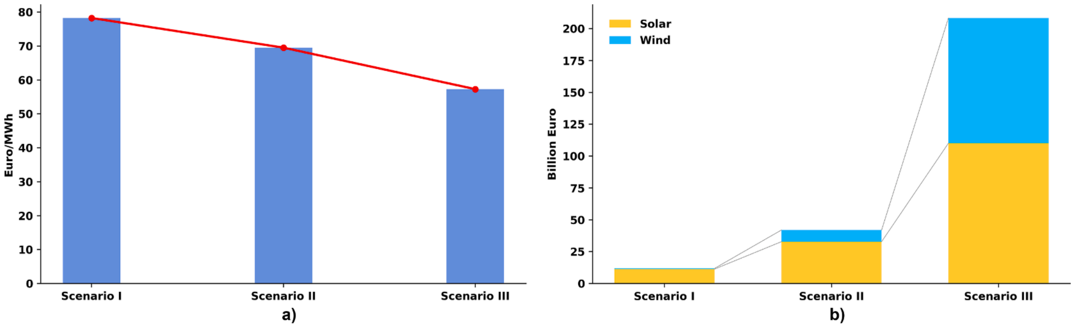


Figure 12. a) Generation cost across the scenario b) Investment requirement by RE across the scenario

difficulty in fully utilizing renewable energy due to grid limitations and mismatches between timings of generation and demand despite provision for storage. This progression underscores the critical challenges in a decarbonized scenario where there arises the need for advanced grid infrastructure and management, expanded storage solutions, and enhanced grid flexibility to optimize renewable energy usage and ensure a reliable energy supply as Bangladesh moves toward its decarbonization goal.

Table 11
Assumption of cost for in 40% renewable energy case of Scenario - II

Technology	**Lifetime (years)**	**Investment Cost (EUR/kW)**	**FOM (% of capital cost/ year)**	**VOM (EUR/ MWh)**
Coal	40	2051.6	2.74	3
Gas	25	1380	2.98	2.1
Oil	20	1242	3.96	8.5
Solar PV	25	552	1.84	0.01
Wind	25	1748	1.89	2.1
Hydro	50	1288	2.39	2.1
Nuclear	60	5060	2.5	2

Note: 1 Euro = 132.36 BDT as of 20 August 2024; The cost data are sourced from IEPMP 2023 [3], IEEFA 2023 [48], BPDB Annual Report 2023 [18] and REF [49]

Table 12
Assumption of cost for the decarbonized case of Scenario - III

Technology	Lifetime (years)	Investment Cost (EUR/kW)	FOM (% of capital cost/ year)	VOM (EUR/ MWh)
Coal	40	2698.884	1.7756	3.7076
Gas	25	1905.095	2.6588	2.6128
Oil	20	1380	3.68	8.28
Solar PV	25	491.1438	2.0148	0
Wind	25	2127.287	1.8216	2.208
Hydro	50	1472	2.484	2.024
Nuclear	60	4600	2.3	1.84

Note: 1 Euro = 132.36 BDT as of 20 August 2024; The cost data are sourced from IEPMP 2023 [3], IEEFA 2023 [48], BPDB Annual Report 2023 [18] and REF [49]

Forced Outages of Power Plants:

By 2041, under the 40% renewable energy scenario, oil-based generation facilities, with a total capacity of 6.85 GW, will be largely idle, generating only 0.0018 TWh of electricity. This minimal output is overshadowed by the rise of 42 GW of solar PV and 5 GW of new wind capacity, which shows that renewable energy sources can replace the existing import-dependent oil-based power plants. IEEFA's report on

Table 13
Optimized results of PyPSA-BD: scenario statistics

		Scenario I 30% RE	Scenario II 40% RE	Scenario III Decarbonization
Year		**2030**	**2041**	**2050**
Annual Demand (TWh)		185.83	314.04	439.90
Capacity (GW)	Solar	21.76	62.81	210.61
	Gas	23.05	28.11	3.92
	Oil	7.10	6.85	0.00
	Coal	6.62	6.62	6.42
	Wind	0.30	5.39	57.94
	Nuclear	2.40	2.40	2.40
	Hydro	0.23	0.23	0.23
Total		61.45	112.36	281.52
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
Power Dispatch (TWh)	Gas	88.31	119.46	0.00
	Solar	51.49	117.37	197.62
	Coal	18.98	33.10	0.00
	Nuclear	17.53	21.02	21.68
	Wind	2.30	9.43	104.77
	Hydro	1.90	1.98	1.99
	Oil	2.51	0.0018	0.00
Total (TWh)		183.38	302.37	326.07
Storage (TWh)	Battery	2.82	11.67	93.64
	Hydrogen	0.00	0.0034	20.19
Storage Total (TWh)		2.81	11.66	113.83

Bangladesh's energy transition [58] which has analyzed three days per month from March 2022 to February 2023, also shows that the expanded wind and solar capacity has the potential to set aside the import-dependent oil-based power generation. The existing oil-based power plants are also expected to fulfil their full-service lifetime by 2050.

In the decarbonized scenario for 2050, gas and coal power plants, with installed capacities of 3.92 GW and 6.42 GW, respectively, will cease power generation (3 to 12 years early phaseout for coal and 1 to 5 years of gas-based power plants), meaning early shutdowns before their planned lifetime. This gives an estimate of the likely magnitude of stranded assets (around 23.47 million euros for coal power plants and 19.35 million Euro). Given this long-term scenario, transition strategies need to be planned from today to avoid other economy-wide impacts like job loss and the need to retrain human capacity to shift to new energy system jobs from existing ones.

Capital Investment

The investment to enable transition in Bangladesh's energy sector as modelled compared to the 2019 reference scenario (Table 14, Figure 12 b) over a period of 5 to 25 years increases significantly across the three scenarios:

- In scenario – I, with continued reliance on fossil fuels, investment in gas leads to €15.17 billion, while for solar, €11.34 billion. Wind and battery storage have smaller investments of €0.51 billion and €0.04 billion, respectively.
- The shift towards 40% RE in scenario - II will need higher investments in solar (€32.81 billion) and wind (€9.14 billion). Battery storage and hydrogen started growing, requiring €1.45 billion and €0.13 billion, respectively. Gas sector investment was reduced to €9.01 billion, and nuclear requires a one-time investment of €12.96 billion.
- In the decarbonized scenario III, solar and wind need substantial investment with €110.08 billion and €98.28 billion, respectively, over 31 years of time. Hydrogen investment rises to €6.25 billion, and battery storage requires €2.20 billion. No further investments are planned for gas or nuclear, marking a full transition to renewables.

Bangladesh has already invested €0.76 billion in the renewable energy sector between 2019 and 2023 to create around 397 MW of solar capacity (1.84% of 2023's installed capacity mix) [59]. To meet the 30% renewable energy target by 2030, the country must increase its annual investment to €2.21 billion from 2025 onwards, focusing primarily on solar and wind energy. For the 40% renewable energy target by 2041, this annual investment requirement will rise to approximately €2.42 billion.

Achieving the ambitious decarbonized scenario, which envisions a generation mix dominated by solar, wind, hydro, and nuclear, supported by battery and hydrogen storage, under strict regulatory conditions, will necessitate a significantly higher annual investment of around €7.98 billion from 2025. This figure represents approximately 1.99% of Bangladesh's total GDP in 2023 (€399.51 billion) [60], highlighting the magnitude of the financial resource mobilization need for a low-carbon energy future compatible with the global common good.

Looking into other countries' investment needs, India will need €6.60 trillion in new investments for its renewable energy sector by 2050 [61], Thailand €33.94 billion by 2037 [62], China €6.71 trillion by 2050 [63], and Nepal will require €3.85 billion by 2030 and €16.05 billion by 2050 [64] to meet their respective decarbonization goals. However, these numbers mentioned in the country sources are not based on PyPSA model-based studies. However, comparisons with these numbers show that financial requirements for Bangladesh's energy transition are reasonably competitively low which might be useful to mention to get visibility in global bids for funds. PyPSA model-based past studies for other countries do not extend to investment numbers.

Job Creation Potential

The transition towards higher renewable energy integration in Bangladesh's energy sector is expected to generate significant job opportunities comprising both direct and indirect positions in construction, manufacturing, and plant operations [65,66] compared to the capacities of 2019 (Table 14, Figure 11 a). Referring to [66], each MW of extended solar capacity will add around 27 new jobs out of which around 24% would be in the manufacturing sector, 72% in construction and the rest of the 4% will be on the operation and maintenance sector. Besides, wind energy will generate around 16 new jobs per MW

Table 14
Comparative scenario analysis

Scenario Name		Scenario I 30% RE	Scenario II 40% RE	Scenario III Decarbonized
Year		2030	2041	2050
Power Generation Cost (Euro/MWh)		78.28	69.54	57.31
Capacity expansion comparing with the reference scenario	Oil	0.96	0.71	0
	Solar	21.70	62.75	210.55
	Wind	0.30	5.39	57.94
	Gas	12.17	7.23	0
	Nuclear	2.40	2.40	2.40
	Coal	4.96	4.96	4.76
Potential new jobs creation due to capacity expansion comparing with the reference scenario	Solar	591271	1709883	5737433
	Wind	4800	86240	927040
	Gas	28850	17142	0
	Nuclear	32880	0	0
	Coal	82963	0	0
Investment requirement (Bl. Euro) comparing with the reference scenario	Solar	11.34	32.81	110.08
	Wind	0.51	9.14	98.28
	Gas	15.17	9.01	0
	Nuclear	12.96	0	0
	Battery	0.04	1.45	2.20
	Hydrogen	0	0.13	6.25
Land requirement (Sq.km) comparing with the reference scenario	Solar	308.11	891.02	2989.78
	Wind	3.63	65.22	701.07
	Gas	2.43	1.45	0
	Coal	14.04	0	0
	Nuclear	1.20	0	0
	Oil	0.23	957.69	3690.86

Table 15
Breakdown of job creation across the scenarios

Scenario Name		Scenario I 30% RE	Scenario II 40% RE	Scenario III Decarbonized
Year		2030	2041	2050
Solar	Manufacturing	145377	420412	1410672
	Construction	423111	1223586	4105686
	Operation and Maintenance	22783	65885	221075
Wind	Manufacturing	3045	54709	588091
	Construction	1680	30184	324464
	Operation and Maintenance	75	1348	14485
Gas	Manufacturing	11321	6727	0
	Construction	15825	9403	0
	Operation and Maintenance	1704	1013	0
Nuclear	Manufacturing	3120	0	0
	Construction	28320	0	0
	Operation and Maintenance	1440	0	0
Coal	Manufacturing	26762	0	0
	Construction	55507	0	0
	Operation and Maintenance	694	0	0

comprising around 63% in the manufacturing, 35% in the construction and 2% in the operation and maintenance. Table 15 shows a breakdown of job creation by wind and solar capacity extension across the three scenarios.

- The shift to 30% RE (scenario – I) by 2030 is projected to create approximately 740,764 new jobs, with the majority (596,071) in renewable energy sectors. Solar leads with 591,271 jobs with 145,792 jobs in manufacturing sector, followed by smaller contributions from wind (4,800 jobs), gas (28,850 jobs), coal (82,963 jobs), and nuclear (32,880 jobs).
- By 2041, with 40% RE, total job creation will increase to 1,813,265, with a substantial rise in renewable energy jobs (1,796,123). Solar continues to dominate with 1,709,883 jobs out of which 1,645,622 jobs would be long-term in manufacturing and construction while wind adds 86,240 jobs and 84,892 of these jobs are long term. Gas-related jobs would be 17,142, and coal, due to no longer capacity expansion, would not account for job creation.
- In the decarbonized scenario for 2050, job creation surges to 6,664,473, entirely driven by renewable energy. Solar is the most significant contributor, generating 5,737,433 jobs with almost 5,517,982 jobs in construction and manufacturing sector while wind adds 927,040 jobs with around 912,555 long-term jobs. By this stage, no jobs are expected from fossil fuels, reflecting a full transition to a renewable energy workforce.

The renewable energy sector in Bangladesh had generated approximately 1.37 million jobs by 2019 [67]. Aiming for a decarbonized energy sector by 2050 could potentially create an additional 6.67 million jobs, averaging around 256,000 new jobs per year starting in 2024. This job creation will have a broad societal impact, benefiting both urban and rural populations, and will contribute to overall economic development. However, as the energy sector transitions away from fossil fuels, approximately 117,000 jobs are expected to be lost from coal and gas-based power plants in 2050. By 2041, nearly all oil-based power plants will be out of operation, which might result in a further job loss of around 19,500 positions. This transition represents a net positive for employment across all socio-economic groups, though attention must be given to ensuring equitable access to new job opportunities and training programs for reskilling and upskilling. Overall, the transition to a decarbonized electricity sector in Bangladesh is expected to result in a net increase in job creation. Workers who may lose their jobs due to forced or regular plant outages can be retrained and redeployed in the renewable energy sector, where the shortage of skilled labor has been identified as a significant barrier to expansion, as noted in the literature [68].

Land Requirements and Generation Expansion

This study helps to answer a long-standing perceptive question [68]: how much land will Bangladesh need for RE transition, and would that be available? Table 15 and Figure 11 b highlight our estimates of land requirements necessary to accommodate model-based renewable energy expansion plans as Bangladesh transitions towards higher renewable penetration. The land requirements for extended-capacity power plants are 0.0142 sq. km/MW for solar, 0.0002 sq. km/MW for gas, 0.0121 sq. km/MW for wind, and 0.0004 sq. km/MW for nuclear [18,47,69,70].

In Scenario I (30% RE by 2030), an additional 42.49 GW of installed capacity (including 22 GW of renewable energy) will require approximately 330 Sq.km of land (0.22% of total land area), with 312 Sq.km dedicated to solar and wind.

- In Scenario II (40% RE by 2041), the expansion increases to 83 GW (68 GW of renewable energy), necessitating around 958 Sq.km of land (0.65% of total land area), nearly all of which (956 Sq.km) is allocated for solar and wind installations.
- By 2050, the land requirement will surge to 3,690 Sq under the decarbonized scenario. Km (2.49% of total land area) to support a 262 GW expansion driven entirely by renewable energy. This includes 3,000 Sq.km for solar and 700 Sq.km for wind, reflecting the significant spatial demands of a fully renewable energy system.

Out of the installed capacity expansion compared to the 2019 reference scenario, 8.85 GW has already been installed by August 2024 as per BPDB's national installed capacity [21]. The land requirements for the installed RE capacities can be met from various sources like rooftops, wastelands, floating solar, and coastal areas. A study from NREL [71] shows that Bangladesh has a solar potential of up to 240 GW (210 GW projected by PyPSA-BD in 2050 decarbonized scenario) with 1.5% (2227 Sq.km) of the total land area. According to Energy Tracker Asia [72], with an estimated 1,500 Sq.km of ponds and 2,500 Sq.km of shallow water areas, Bangladesh has a significant floating solar potential [71]. According to the Bangladesh Environmental Lawyers Association (BELA) and the Coastal Livelihood and Environmental Action Network (CLEAN), this land requirement can be met by utilizing Khas land, water bodies, and rooftops. Bangladesh has over 34.21 lakh acres (13,844.30 sq. km) of Khas land (Government vested land) across 61 districts, and approximately 38.74% of this land (5,224.72 sq. km) is suitable for ground-mounted solar photovoltaics and wind energy projects, which more than covers the required area for renewable expansion as estimated by our model without encroaching on productive agricultural land. Additionally, around 5,000 sq. km [72] of usable rooftop space can be utilized for rooftop solar PV installations.

Power Generation Cost

The model-based analysis reveals that the country can reduce power generation costs as the penetration of renewable energy sources grows in Bangladesh's power sector's energy mix. This results from the increasing global cost reduction advantage accruing in favor of solar and wind power. In 2030, under the 30% renewable energy scenario, the power generation cost is estimated to be 78.28 Euro/MWh (10.42 BDT/kWh). It is notably cheaper than the current generation cost of 11.33 BDT/kWh, as reported in BPDP's 2023 annual report [18]. By 2041, with a 40% renewable energy mix, the generation cost further decreases to 69.54 Euro/MWh (9.26 BDT/kWh). In the decarbonized scenario of 2050, where renewable sources dominate the energy mix, the cost drops even more significantly to 57.31 Euro/MWh (7.63 BDT/kWh).

This downward trend (Figure 12 a) in power generation costs underscores the socio-economic benefits and possible enhancement in affordability with distributional benefits by increasing renewable energy penetration. Higher renewable integration reduces the per-unit cost of electricity and decreases Bangladesh's dependence on expensive, import-dependent fossil fuels. This transition could alleviate the financial burden of subsidies in the power sector, which amounted to 2.54 billion Euro in 2023 [73], contributing to a more sustainable and economically viable energy system.

Global Context of the Bangladesh's Decarbonization Effort

To contextualize the proposed model-based transition for Bangladesh to achieve by mid-century the decarbonization target for the power sector is comparable with other developing countries in the region. Study [61] for India, with its target of 30% renewable energy by 2030 and 100% clean energy by 2050, focuses heavily on solar and wind, similar to Bangladesh. However, both nations face grid integration, financing, and upgrading infrastructure challenges. A study on ASEAN countries [1] (Brunei, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam) under their net-zero scenarios aims for 81% of power generation from variable renewables, with solar PV and storage contributing 78% and wind 10%. This reflects Bangladesh's transition, prioritizing solar energy with growing wind power capacity. A study [34] projects 100% renewable energy by 2050 in Cambodia, Laos, and Myanmar. These nations, already obtaining 50% of their energy from hydropower, plan to meet the rest through non-hydro renewables and storage. Wind will contribute 34%, 26%, and 25% of the energy mix, with solar making up 1.5 GW, 11%, and 18%, respectively, highlighting a similar approach to Bangladesh's renewable focus.

This comparison contextualizes Bangladesh's decarbonization efforts within the broader transition strategies of other developing nations, emphasizing the commonalities in goals for renewable energy integration and the challenges of scaling up clean energy systems.

Policy Implications and Recommendations

Alternative decarbonization scenarios and pathways developed through our modeling effort provide some concrete guidelines on what are techno-economically feasible solutions the national government can consider while trying to implement policies and actions in place to achieve 2030 and 2041 RE penetration goals and how it can also go further in raising national ambition in keeping with global mid-century zero carbon goal. It is clear that the implementation plan can be staggered over the next 25 years. However, planning and strategies need to be preceded by an inclusive decision with the country involving various stakeholders to codesign the path forward as power sector infrastructure has a long lifetime and should not create any new lock-in [74] and the possibility of adding to the stranded asset [75]. Once a course of action is decided through a consultation process and a high level of decision-making, the transition plan and strategy need to be developed. In many countries, it is happening through the Transition management team/transition task force [74,76–79]. SREDA [24] is now mandated to tackle the obstacles and challenges in the renewable energy and energy efficiency markets to enhance renewable energy generation in Bangladesh so that an additional institutional structure can be added.

Several key actions starting from now at the national scale can be governed appropriately to ensure a successful transition with justice. Based on the insights from the model, the following recommendations for actions for national policymakers are derived.

The government of Bangladesh might consider adopting a comprehensive policy to achieve a 100% renewable energy-based power sector by 2050. This transition requires immediate actions in key areas, including identifying and securing land for renewable energy projects, mobilizing necessary investments, and modernizing the transmission infrastructure to integrate variable renewable energy seamlessly. Human capacity development (which literature [2,68] identified as a key barrier to the renewable energy transition in Bangladesh) through specialized upskilling, reskilling training programs and university-level courses can train a new generation of engineers and policy implementers in the renewable energy sector is also essential. Furthermore, there should be a focus on procuring appropriate renewable technologies and fostering international cooperation for technology transfer, investment-grade financial resource mobilization, codesign, knowledge-building and expertise sharing. A dedicated transition management task force, similar to those in other countries—such as the Energy Transition Taskforce (ETTF) in the Greater Mekong Subregion [77] and the GREEN Action Task Force [78] for Eastern Europe, the Caucasus, and Central Asia, Taskforce Energy Transition [79] in Netherlands, Just Transition Commission [76] in Scotland—can govern transition with a dedicated focus to ensure proper necessary coordination and address potential land-use conflicts, resource mobilization and monitor implementation. Large-scale workforce retraining programs, including international training opportunities, will be vital to equip workers with the necessary skills for renewable energy-related jobs. Effective coordination among national entities like the Sustainable and Renewable Energy Development Authority (SREDA), Infrastructure Development Company Limited (IDCOL), the power division of the Government of Bangladesh (GoB), PGCB, BREB, the Ministry of Power Energy and Mineral Resources, and the Ministry of Environment, Forest & Climate Change will also be essential.

Future research should prioritize decarbonization strategies by focusing first on techno-economic feasibility, identifying cost-effective solutions that can be implemented with immediate impact. For instance, modifying land use policies to facilitate renewable energy (RE) projects, incentivizing rooftop utilization, and repurposing vested lands for RE expansion are crucial steps that require interministerial coordination. These actions create a foundation for RE infrastructure that is affordable, scalable, and adaptable to Bangladesh's unique needs, making it essential to address these areas first.

Once foundational, feasible strategies are in place, research should emphasize long-term impact by implementing policies that promote resilience and scalability. This phase includes building a robust legal and regulatory framework to attract foreign investment. Establishing clear contractual obligations, secure revenue streams, and interest protection will improve investor confidence and sustain investment momentum. Additionally, ensuring due diligence, minimizing corruption, and upholding transparent governance can mitigate risks and align long-term investments with Bangladesh's 2030 and 2041 and 2050's RE targets, maximizing social and environmental benefits.

Finally, to prevent the possibility of accumulated stranded assets loss and to minimize financial losses from underutilized or stranded infrastructure, the research must assess infrastructure durability and adaptability. This analysis should guide policy adjustments and investment directions, helping Bangladesh avoid future risks by developing flexible, forward-compatible systems. By prioritizing feasibility, long-term impact, and stranded asset risk reduction in this sequence, the country can lay a sustainable pathway for a resilient and economically viable transition to a renewable energy-based power sector.

Study Limitations and Directions for Future Research

The unique contribution of this study is developing the PYPSA-BD model for the first time and scenario development to guide national action. However, we are aware that while finding a solution to one research question, many new research questions arise, and in the space of one research paper, we cannot answer all others that are no less relevant. So, we highlight some of these research areas which can form the future research agenda:

The current model incorporates only battery and hydrogen storage systems. Other storage technologies, such as Compressed-Air Energy Storage (CAES), Liquefied-Air Energy Storage (LAES), Pumped-Hydro Energy Storage (PHES), Flywheel Energy Storage, and Thermal Energy Storage (TES), are not included as they are currently not prioritized in the national policy frameworks. Future studies should explore these alternative storage solutions to evaluate their impact on system performance and optimization.

As regards data accuracy and assumptions, while the current model incorporates hourly load data, half-hourly data are also available but were not used in this study given the broader goal of setting up the model and validation. This could be considered for future research based on the accuracy level of need given the policy targets and stakeholders concerned. Furthermore, although 15-minute load data as well as sector-specific load data are also used in some literature to design control systems to improve demand projection and supply management with higher penetration of variable renewable energy sources, we could not access this data publicly. One can provide a more nuanced understanding of the impact of sectoral load management and change in capacity additions needed, scenarios of structural change and impact on the power sector expansion plan. It clearly shows how to access what kind of official data will be beneficial for sector coupling. Integrating these elements could enhance the model's ability to simulate and optimize energy consumption patterns and cross-sector interactions. Future research should focus on incorporating these aspects to deliver a more inclusive evaluation of the energy system.

The model does not account for advanced technologies such as Carbon Capture and Storage (CCS) in coal or Combined Cycle Gas Turbine (CCGT) power plants. Including these technologies in future model, iterations could offer insights into their potential contributions to reducing carbon emissions and improving overall system efficiency.

For higher order, RE penetration needs planning for long-term grid infrastructure. Details transmission network model is not included in this capacity expansion study. While this study underscores the economic benefits of possible job creation, a detailed analysis of its impact across different societal sectors requires an economy-wide model and human resource planning can be taken up to understand the challenges of just transition. This broader assessment falls outside the scope of the current research but will be addressed in future studies.

High renewable energy penetration, particularly from intermittent sources like solar and wind, can cause grid stability issues due to fluctuations in generation and demand. Although the current model includes storage as a backup, future research should include detailed stability analysis, focusing on frequency and voltage control in addressing the grid stability challenge.

Considering the new set of research needs and the scope of future work we can suggest some priorities, The most immediate priority should be addressing grid stability concerns and storage and appropriate IoT technology integration for managing load through demand side shifts (DSF) strategies [80,81] through extension of this model. Demand-side management and sector coupling are also critical areas that can optimize energy consumption and reduce the supply-side burden. Following this, the focus can be broadened to transmission infrastructure planning, as the increased renewable capacity will demand substantial upgrades to the existing grid [7,12,81]. Incorporating sectoral load data is important for a more detailed understanding of the economic impacts while exploring additional storage technologies like Compressed-Air Energy Storage (CAES) and Pumped-Hydro Energy Storage (PHES) will be vital for improving system performance. Lastly, future research should consider the inclusion of advanced technologies such as Carbon Capture and Storage (CCS) and Combined Cycle Gas Turbines (CCGT) to assess their potential to reduce emissions and enhance efficiency. This prioritization ensures that the most pressing challenges are addressed first while allowing for progressive exploration of longer-term solutions.

Conclusion

This research develops the PyPSA-BD model, a tailored adaptation of the PyPSA-Earth model, to evaluate potential decarbonization pathways for Bangladesh's power sector up to 2050. The model offers a comprehensive platform for evaluating the techno-economic feasibility of transitioning to a low-carbon power system by incorporating official datasets on power plants, including details on technology, efficiency, capacity, service lifetime, and geographical location, as well as cost data such as discount rates, capital costs, fixed and variable operation and maintenance costs, and fuel costs, alongside energy sector planning from key entities like BPDB, PGCB, and IEPMP 2023. The results are on possible capacity expansion levels and decarbonization strategies for Bangladesh, the scale of investment, land, and employment necessary for this energy transition, and the pivotal role of energy storage in optimizing the utilization of renewable resources. As these are the long-lasting critical infrastructure of a country, better long-term planning should happen now, which can be enriched by the findings of these model-based results.

Key findings from the model show that targets for transition to 30% renewable energy by 2030, 40% by 2041, and full decarbonization by 2050 are technically feasible from economic cost efficiency and land availability. However, what kind of land and how much should be coming from rooftop areas of the built environment under what business models need to be worked out from now for gradually phased expansion of the RE penetration. As renewable energy penetration increases, storage facilities with planned end-of-the-life handling mechanisms will need to be in place from the beginning to enhance social acceptability and avoid unintended consequences of mismanaged battery disposal. As renewable energy penetration helps reduce generation costs, the modeled scenarios are socially beneficial from both job creation and affordability aspects. By 2050, solar and wind are projected to dominate the energy landscape, contributing around 25% (197.62 TWh) and 24% (104.77 TWh) of the generation, respectively. To ensure grid reliability amid this transition, the utilization of battery and hydrogen storage has been found to be essential.

The implications of these findings for Bangladesh's energy policy are significant. Reduced dependency on fossil fuel imports, coupled with lower generation costs, will enhance both energy security. Additionally, expanding the renewable energy sector presents a valuable opportunity for economic development, with an additional 6.67 million new jobs by 2050 compared to the 2019 level, helping to drive growth. Achieving these goals, however, will require an annual investment of 7.98 billion euros from 2025 onwards, highlighting the significant institutional reforms and financial resource mobilization needed for a sustainable and resilient energy future.

While the PyPSA-BD model provides a strong foundation for starting the transition planning process, further research can refine the technical and infrastructural need assessment for grid stability, especially as renewable penetration increases. Institutionally formal search for procuring advanced storage technologies, sectoral load predictions, and demand-side management strategies, which can reduce the supply-side decarbonization burden, needs to continue.

CRediT authorship contribution statement

Firuz Ahamed Nahid: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Joyashree Roy:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

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.

Acknowledgement

The authors would like to acknowledge that this research is funded by the Environment Defense Fund (EDF), USA, through the Multi Country Energy Transition (MCET) project. The authors acknowledge the contributions of Dr. Hasan Mahmud and Mr. Avrojyoti Barua for their support in official data collection and data cleaning. The authors acknowledge the contribution of Oleg Lugovoy, Maximilian Parzen, and his team to the training and community support via Discord.

Data Availability statement

The code and data required to replicate the results and illustrations are accessible through PyPSA-Earth v0.3, with detailed instructions at https://github.com/FiruzAhamed/PyPSA-BD_Paper.

Appendix

Appendix. - A

Detailed Model Description of PyPSA-BD:

It employs linear optimization to minimize the total annualized costs while ensuring the power network's energy demand-supply balance and operational feasibility. The equations and constraints are adapted from ref. [4,42,46].

Objective Function

The goal of the objective function is to reduce the total yearly system costs (AC), which include both capital (CAPEX) and operational (OPEX) costs for generation, storage, and transmission systems:

The objective function [42] is given by equation 1 as follows:

$$\underset{F_\ell, G_{n,r}, H_{n,s}, E_{n,s}, f_{\ell,t}, g_{n,r,t}, h_{n,s,t}, suc_{n,r,t}, sdc_{n,r,t}}{min} \left[\sum_{l} C_\ell . F_\ell + \sum_{n,r} C_{n,r} . G_{n,r} + \sum_{n,r,t} (w_t . o_{n,r} . g_{n,r,t} + suc_{n,r,t} + sdc_{n,r,t} + \sum_{n,s} C_{n,s} . H_{n,s} + \sum_{n,r} \widehat{C}_{n,s} . E_{n,s} + \sum_{n,r,t} w_t . o_{n,s} . \left[h_{n,s,t}\right]^+ \right] \tag{A.1}$$

Where,

F_ℓ	The capacity of each individual branch ℓ
C_ℓ	Annualized fixed costs allocated per unit of capacity
$C_{n,r}$	Annuitized fixed costs per capacity of generation for each technology r at bus n
$G_{n,r}$	Generator capacities
w_t	Weight for the period t
$o_{n,r}$	Unit dispatch associated variable cost
$g_{n,r,t}$	Unit dispatch
$suc_{n,r,t}$	Startup cost when unit dispatch is activated for
$sdc_{n,r,t}$	Shutdown cost when unit dispatch is activated
$C_{n,s}$	Storage technology's fixed cost per unit capacity
$H_{n,s}$	Storage units' power capacity
$C\hat{}_{n,s}$	Fixed cost of $E_{n,s}$ at bus n
$E_{n,s}$	Energy storage capacity
$o_{n,s}$	Variable cost of the dispatch
$[h_{n,s,t}]^+$	Storage dispatch's positive component
ℓ	Individual branch
s	Storage technology
t	Time
r	Technologies
n	Bus

Demand-Supply Balance

$d_{n,t}$ the electric demand must be met by generation, storage, or energy flows from other branches. This is expressed by equation 2.

$$\sum_{r} g_{n,r,t} + \sum_{s} h_{n,s,t} + \sum_{\ell} \alpha_{\ell,n,t} . F_{\ell,t} = d_{n,t} \leftrightarrow w_t . \lambda_{n,t} \forall n, t \tag{A.2}$$

Where,

$\alpha_{\ell,n,t}$	$= -1$ if line ℓ originates at bus n
$\alpha_{\ell,n,t}$	$= 1$ if ℓ is a line or transformer and ends at n
$\alpha_{\ell,n,t}$	$= \eta_\ell$ if ℓ terminatesat n
$\eta_{\ell,t}$	Link's efficiency loss
$\lambda_{n,t}$	Bus's marginal price.

Storage Constraint: Energy Balance and Capacity Limit

The storage unit's energy levels $e_{n,s,t}$ must be steady over time and constrained by the storage capacity $E_{n,s}$. The energy balance for storage is given by equation 3, and capacity limits for the storage is given by equation 4.

$$e_{n,s,t} = \eta_{n,s,0}\, e_{n,s,t-1} + \eta_{n,s,+} \cdot w_t \left[h_{n,s,t}\right]^+ - \eta_{n,s,-} \cdot w_t \left[h_{n,s,t}\right]^- + w_t \cdot h_{n,s,t,inflow} - w_t \cdot h_{n,s,t,spillage} \tag{A.3}$$

$$\widetilde{e}_{n,s,t} \cdot E_{n,s} \leq e_{n,s,t} \leq \overline{e}_{n,s,t} \cdot E_{n,s} \forall n, s, t \tag{A.4}$$

Where,

$\eta_{n,s,0}$	Self-discharge rate (energy leakage)
$\eta_{n,s,+}$	Charging efficiency
$\eta_{n,s,-}$	Discharging efficiency
$h_{n,s,t,inflow}$	Incoming flow (e.g., river input into a reservoir)
$h_{n,s,t,spillage}$	Spillage
$\tilde{e}_{n,s,t}$	Lower bound on the state of charge (usually set to 0, indicating the storage cannot be negative)
$\bar{e}_{n,s,t}$	Upper bound on the state of charge (typically set to 1, indicating the storage cannot exceed its capacity)

Power Flow Constraints

Kirchhoff's Current Law (KCL), presented by equation 5 [42] ensures that the total currents coming and exiting a node (bus) is zero, reflecting the conservation of energy, while Kirchhoff's Voltage Law (KVL), presented by equation 6 [4] ensures that the total around every closed loop's voltage difference in the network is zero, reflecting the physical realism of power flows.

$$\sum_{r} g_{n,r,t} + \sum_{s} h^{+}_{n,s,t} + \sum_{s} h^{-}_{n,s,t} + \sum_{\ell} \alpha_{\ell,n,t}.F_{\ell,t} = d_{n,t}\forall n,t \tag{A.5}$$

$$\sum_{\ell} C_{\ell,c}\cdot x_{\ell}\cdot f_{\ell,t} = 0\forall_{c,t} \tag{A.6}$$

Where,

$\sum_{r} g_{n,r,t}$	Total generation at bus *n* for all technologies *r*
$\sum_{s} h^{+}_{n,s,t}$	Charging for all storage technologies *s*
$\sum_{s} h^{-}_{n,s,t}$	Discharging for all storage technologies *s*
$\sum_{\ell} \alpha_{\ell,n,t}.F_{\ell,t}$	The net flow of power into bus from all branches ℓ at time *t*, where $\alpha_{\ell,n,t}$ indicates the direction of the flow
$d_{n,t}$	Electricity demand
$\sum_{\ell} C_{\ell,c}$	Sum over all branches ℓ that are part of cycle c in the network
x_{ℓ}	The series inductive reactance of branch ℓ
$f_{\ell,t}$	Power flow through branch ℓ at time *t*

Generator Capacity Constraints:

The generator capacity constraint ensures that the power output of each generator does not exceed its installed capacity. The constraint is given by equation 7.

$$0 \le g_{n,r,t} \le G_{n,r}\forall_{n,r,t} \tag{A.7}$$

Where,

$g_{n,r,t}$	The power output of the generator
$G_{n,r}$	Installed capacity of the generator

Storage Charging Constraint:

The constraint ensures that the charging and discharging power does not exceed the maximum charging capacity. The storage charging constraint is given by equation 8 and equation 9, respectively.

$$0 \le h^{+}_{n,s,t} \le H_{n,s}\forall_{n,s,t} \tag{A.8}$$

$$0 \le h^{-}_{n,s,t} \le H_{n,s}\forall_{n,s,t} \tag{A.9}$$

Where,

$h^{+}_{n,s,t}$	Storage technology's charging power
$h^{-}_{n,s,t}$	Storage technology's discharging power
$H_{n,s}$	Maximum discharging capacity

Energy Storage Constraints:

The energy storage constraints ensure that the stored energy on each bus does not exceed the storage capacity and stays within the allowable limits. The constraint is expressed by equation 10.

$$0 \leq e_{n,s,t} \leq E_{n,r} \forall_{n,s,t} \tag{A.10}$$

Where,

$e_{n,s,t}$	Total stored energy
$E_{n,r}$	Maximum energy capacity

Power Flow Limits

This ensures that the power flow $f_{\ell,t}$ through each branch ℓ at a given time t doesn't exceed its maximum capacity f^{max}_{ℓ}. The constraint is given by equation 11.

$$-f^{max}_{\ell} \leq f_{\ell,t} \leq f^{max}_{\ell} \forall \ell, t \tag{A.11}$$

Recovering Cyclic Energy Storage Constraint

This constraint ensures that the energy storage levels return to their initial state at the end of the optimization period:

$$e_{n,s,T} = e_{n,s,0} \forall n, s \tag{A.12}$$

Where T denotes the final and $e_{n,s,0}$ presents the initial stored energy.

Greenhouse Gas Emissions Reduction Constraint

This constraint ensures that the total greenhouse gas emissions do not exceed a specified target, denoted by equation 12 [4].

$$\sum_{n,rt} Em_{n,r} \cdot g_{n,r,t} \leq EM^{max} \tag{A.13}$$

Where, $Em_{n,r}$ is the emission factor for generation technology r at the bus n*, and* EM^{max} is the maximum allowable emissions.

Appendix - B

B.1. Scenario – I: (2030)

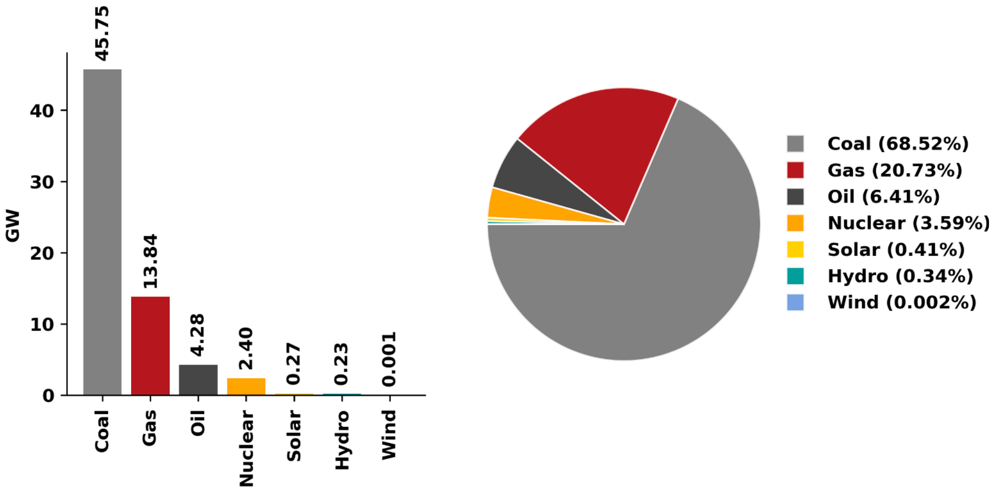


Figure B1. Installed capacity of base scenario – I

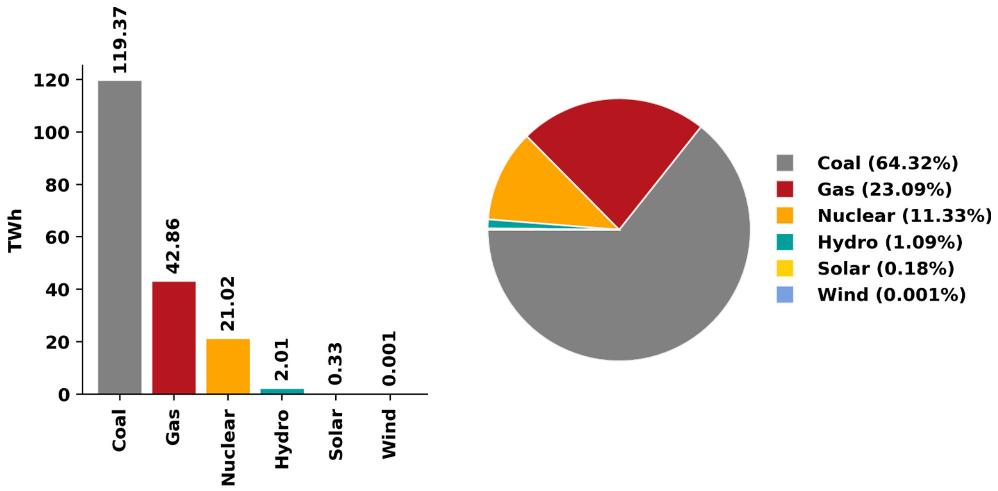


Figure B2. Power dispatch of base case in scenario – I

Table B1
Expansion of installed capacity and capital cost requirements

Energy Source	Capacity Expansion (GW)		Investment Requirement (Billion Euro)		Land Requirement (Sq.km)		Employment Potential	
	Vs. Ref. Case	Vs. Base Case	Vs. Ref. Case	Vs. Base Case	Vs. Ref. Case	Vs. Base Case	Vs. Ref. Case	Vs. Base Case
Wind	0.30	0.29	0.50	0.50	3.58	3.56	4720	4697
Solar	21.69	21.48	11.34	11.23	307.27	304.27	591160.58	585390
Battery Storage	0.37	14.49	0.037	1.45				
Gas	12.17	9.21	15.16	11.47	24.63	18.63	28849.59	21820
Nuclear	2.40		12.96		1.165		32880	
Total	36.93	45.47	40.01	24.65	336.65	326.47	657610	611908

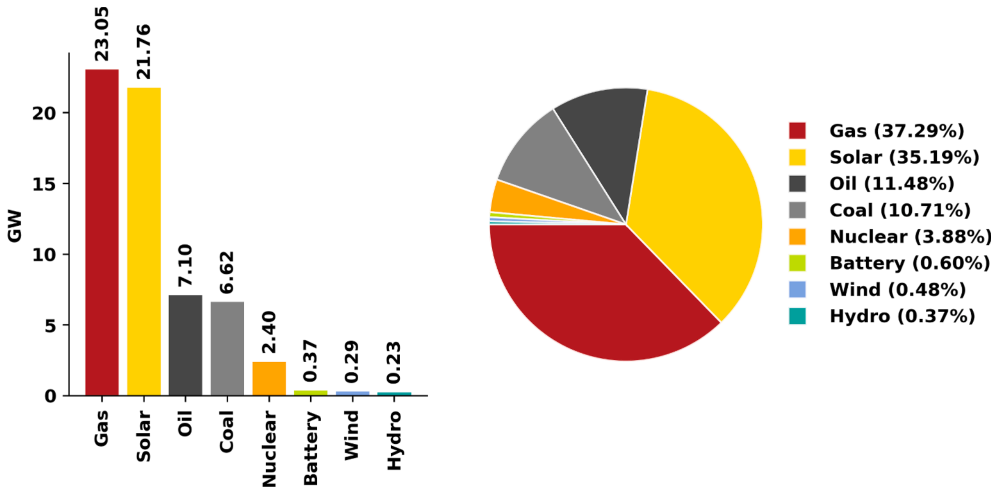


Figure B3. Optimized installed capacity of 30% renewable case scenario - I

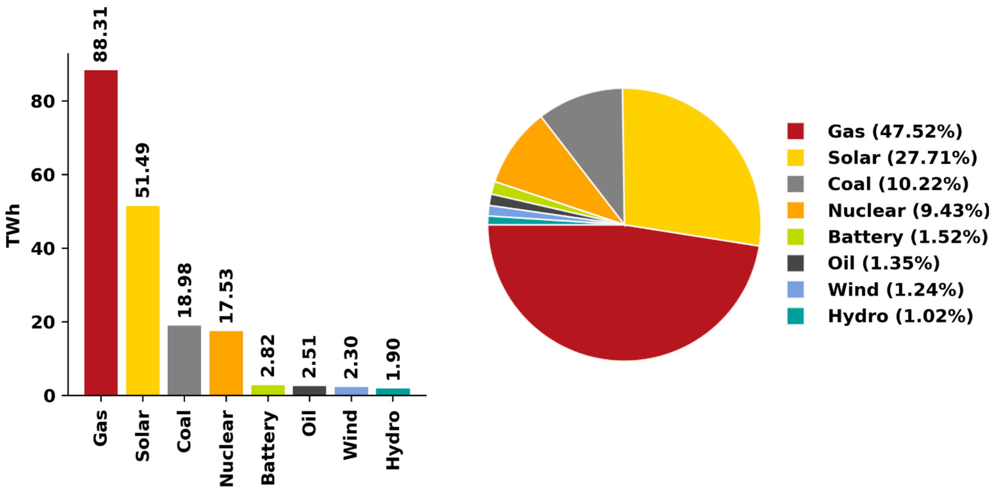


Figure B4. Optimized power generation of scenario - I

B.2. Scenario – II: (2040)

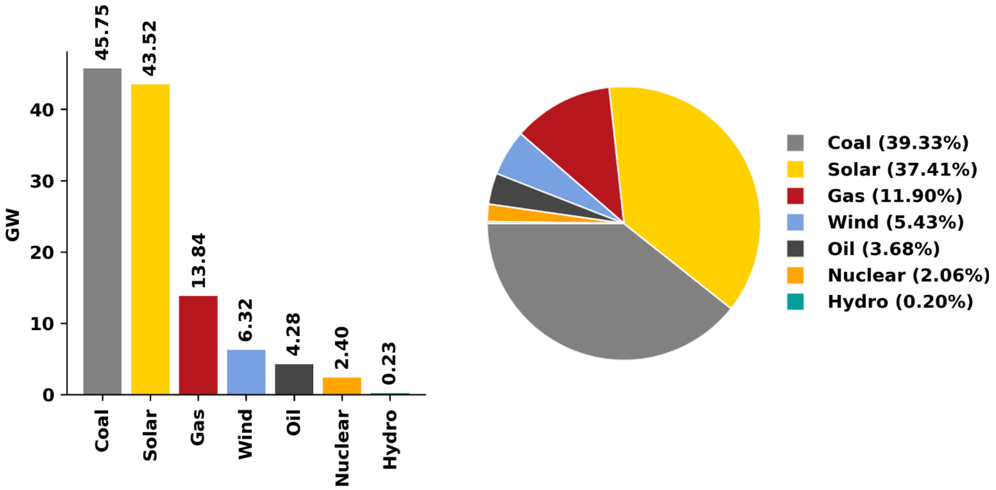


Figure B5. Base Case installed capacity of scenario - II

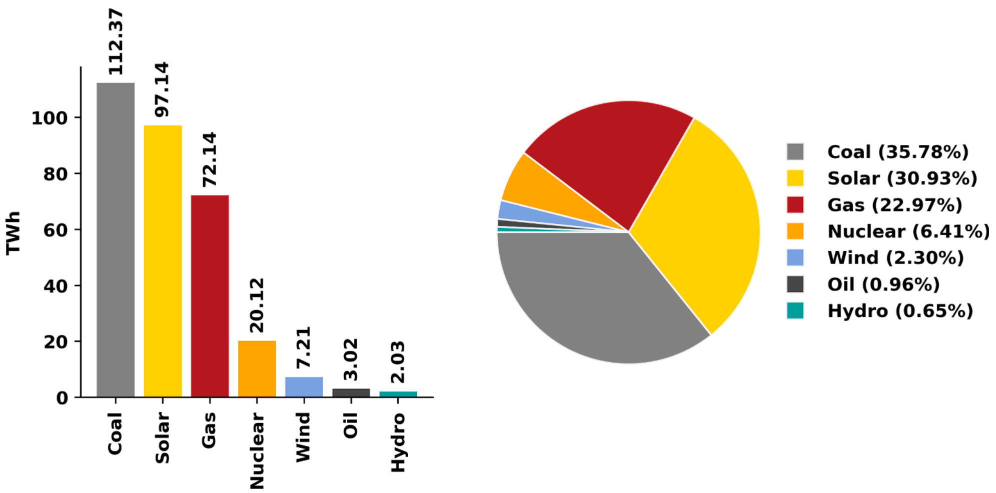


Figure B6. Base case power dispatch of scenario - II

Table B2
Capacity Expansion of Scenario – II: Capex, Land, and Employment Impact

Energy Source	Capacity Expansion (GW)		Investment Requirement (Billion Euro)		Land Requirement (Sq.km)		Employment Potential	
	Vs. Scenario - I	Vs. Base Case	Vs. Scenario - I	Vs. Base Case	Vs. Scenario - I	Vs. Base Case	Vs. Scenario - I	Vs. Base Case
Wind	5.09	1.11	8.9	1.94	61.59	13.4	81440	17718.4
Solar	41.4	19.24	22.85	10.62	587.93	273.16	1128237	524193.9
Battery Storage	14.12	14.49	1.13	1.16				
Hydrogen Storage	0.14	0.14	0.13	0.13				
Total	60.76	34.97	33.01	13.84	649.51	286.56	1209677	541912.3

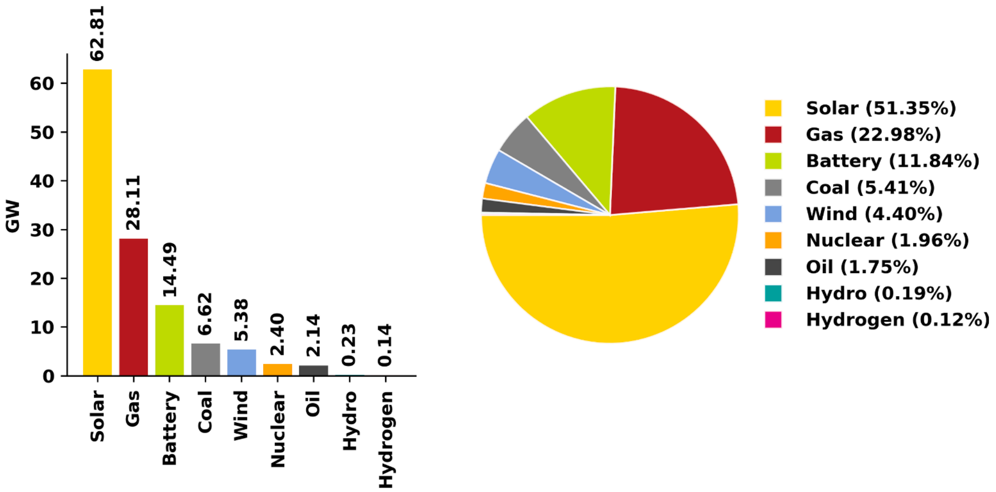


Figure B7. 40% Renewable Energy Case installed capacity of scenario - II

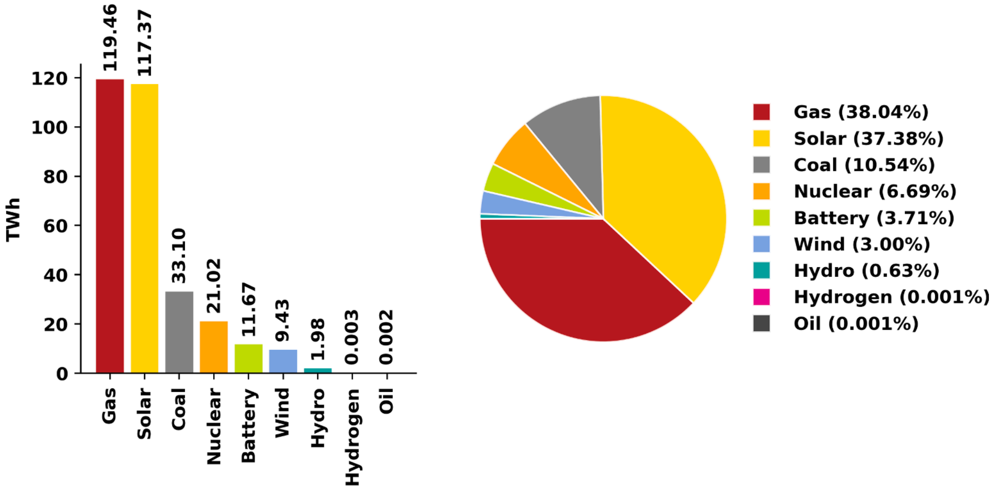


Figure B8. 40% Renewable Energy Case power dispatch of scenario - II

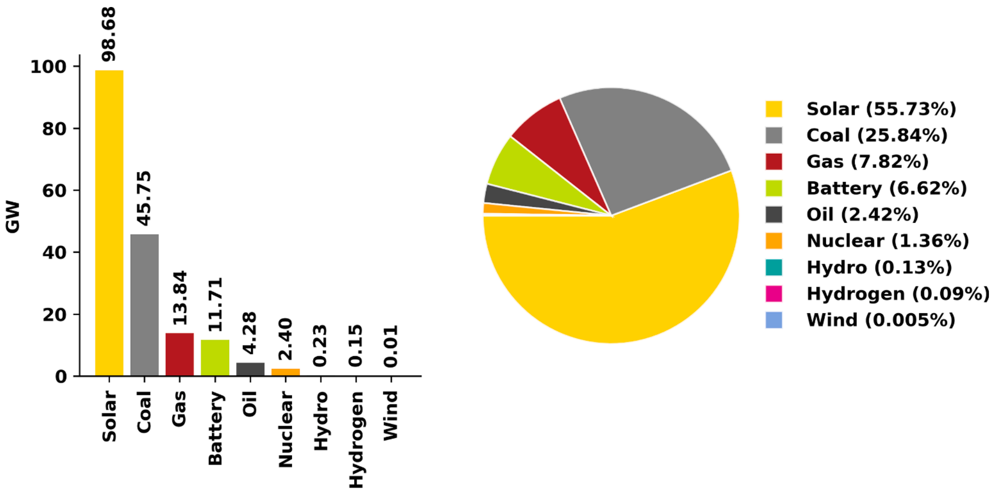


Figure B9. Base Case installed capacity of scenario - III

B.3. Scenario – III: (2050)

Table B3
Capacity Expansion of Scenario – III: Capex, Land, and Employment Impact

Energy Source	Capacity Expansion (GW)		Investment Requirement (Billion Euro)		Land Requirement (Sq.km)		Employment Potential	
	Vs. Scenario - II	Vs. Base Case	Vs. Scenario - II	Vs. Base Case	Vs. Scenario - II	Vs. Base Case	Vs. Scenario - II	Vs. Base Case
Wind	52.56	57.93	141.84	156.35	635.92	700.98	840880.00	926911.83
Solar	147.85	111.93	72.62	54.98	2099.48	1589.47	4028935.01	3050209.07
Battery Storage	7.51	10.29	0.71	0.97				
Hydrogen Storage	6.44	6.43	6.12	6.10				
Total	214.36	186.58	221.28	218.40	2735.40	2290.44	4869815.01	3977120.90

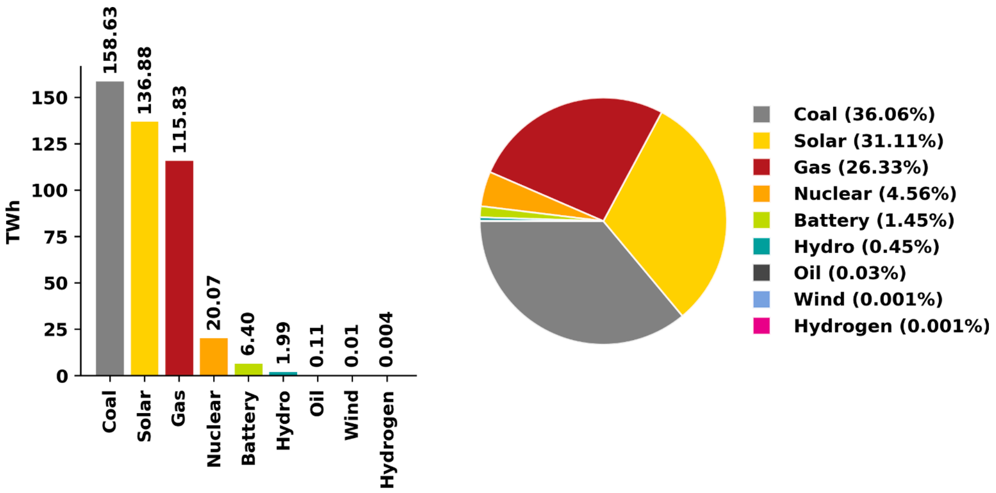


Figure B10. Base Case power dispatch of scenario - III

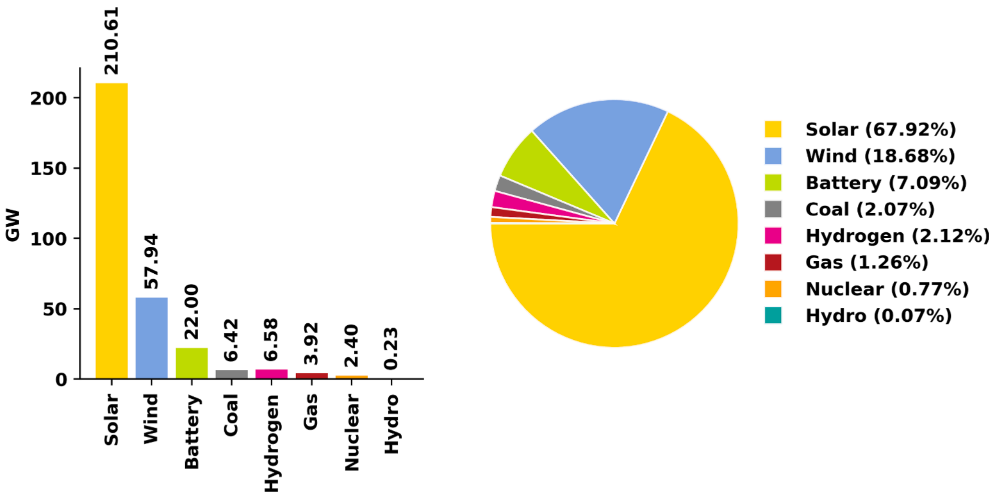


Figure B11. Decarbonized case installed capacity of scenario - III

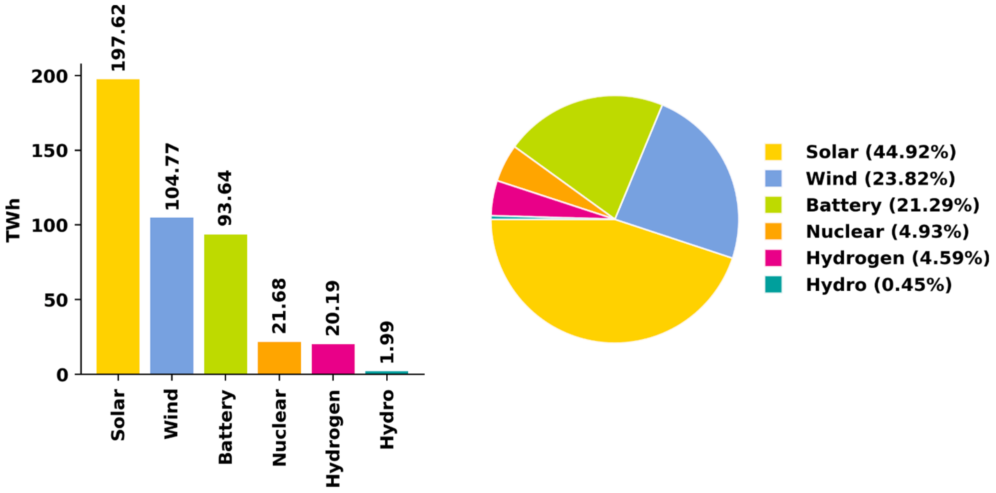


Figure B12. Decarbonized case power dispatch of scenario - III

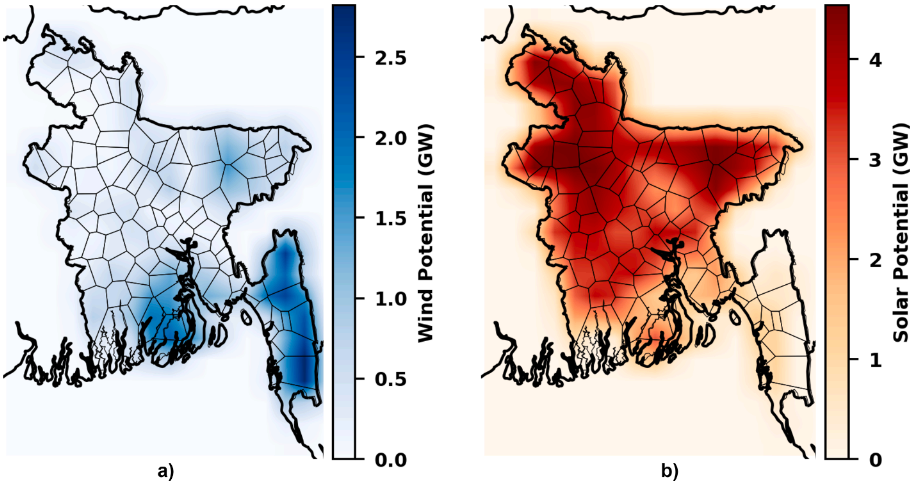


Figure B13. RE potential in Bangladesh based on a) Wind b) Solar

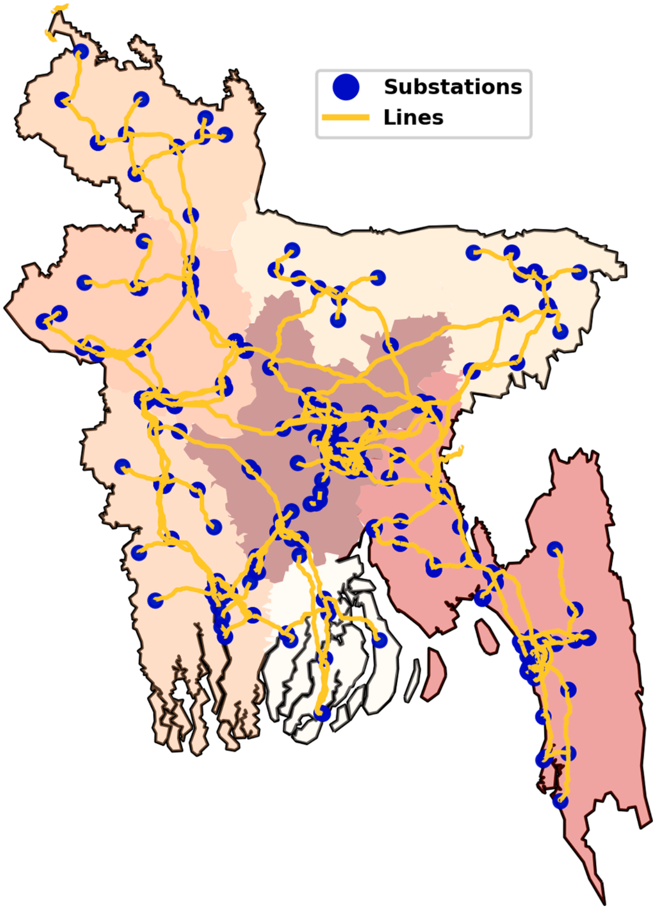


Figure B14. Substations and line connections in the optimized PyPSA-BD model

Data availability

The link to the data has been shared

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