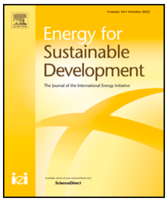
Energy for Sustainable Development 83 (2024) 101560

Contents lists available at ScienceDirect

Energy for Sustainable Development

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



Power sector transition plan of a coal-rich region in India with high-resolution spatio-temporal data based model

Sourish Chatterjee [a,*], Joyashree Roy [b,a], Arijit Mukherjee [a], Oleg Lugovoy [c,d], Anupam Debsarkar [a]

[a] *Global Change Programme, Jadavpur University, Kolkata, India*
[b] *South and South East Asia Multidisciplinary Applied Research Network on Transforming Societies of Global South, Asian Institute of Technology, Thailand*
[c] *Environmental Defense Fund, USA*
[d] *Optimal Solution LLC, USA*

ARTICLE INFO

Keywords:
Energy system modeling
Sustainable energy transition
Demand side flexibility
Hourly electrical load
Capacity expansion planning

ABSTRACT

This paper argues that a fit-for-purpose model and datasets are necessary to generate transition pathways for the electricity generation sector at the subnational level. We present the methodology, data, and results focusing at a sub-national level, the state of West Bengal in India. The approach can be generalized for any region with necessary customization. By utilizing high-resolution spatio-temporal input datasets, this study proposes a power sector capacity expansion model to compute three sets of transitional scenarios and one set of the current-as-usual scenario. These scenarios consider sub-national energy carrier-resource constraints and are solved to identify the most economically cost efficient future transition pathway for the electricity sector in West Bengal. Based on the least-cost solution, computations determine the optimal energy mix, operations, investments, and emissions for alternative scenarios. The results show that integrating demand-side flexibility (DSF) as a balancing option can lead to transformative outcomes. Compared to the current capacity expansion trend (ScenCA), adopting a thermal mix renewable scenario with intraday load-shifting (ScenTMDSF) could reduce 77% of CO_2 emissions by 2040. This does not necessitate early retirement of existing thermal power plants, total investment increases by 13% compared to ScenCA. Without DSF as a balancing option, an additional 26% investment is required compared to the current-as-usual scenario for 2040. Transitioning to 100% renewable energy (ScenREN) requires 30% more investment, early retirement of 5.34 GW of thermal capacity, and nearly 2.7 times more storage battery capacity. These numbers help in understanding the magnitude of the financial resource and kind of technological need for the developing countries not only from the point of view of equitable climate action from burden sharing and just transition principles but also provides practical example of need for redirecting global capital for creating global good through subnational scale actions.

Introduction

Motivation

In developing countries, policy acts as a catalyst for the early adoption of technologies and facilitates energy transitions. This enables access to investment flows, influences systemic changes through learning by doing, facilitates multiple functions of technology innovation systems (Butt, Roy, & Some, 2024), helps avoid the burden of costs from accumulated stranded assets (Löffler, Burandt, Hainsch, & Oei, 2019) in the longer run, and aids in planning for a just transition (Agrawal, Pathak, Jana, Unni, & Shukla, 2024; Heffron & McCauley, 2022). Inadequate actions to close the global greenhouse gas emissions gap (United Nations Environment Programme, 2023) and the increasing need for transformative actions (IPCC Report, 2022; United Nations Environment Programme, 2020) are driving scientific research to find innovative solutions tailored to local contexts around the world (Fankhauser et al., 2022; Oshiro, Masui, & Kainuma, 2018; Rosenbloom & Meadowcroft, 2022). It is clear from the various global assessments that electricity will dominate the future energy service delivery for technological, economic, social and environmental benefits (Edenhofer et al., 2011; Gasanzade, Witte, Tuschy, & Bauer, 2023). Political debate on coal phase-down has created opportunities as well as new challenges for coal-rich regions (Janardhanan & Tamura, 2020; United Nations Climate Change Conferences, 2023) that needs global attention. Nations or sub-national entities with high coal-dependent power sectors need innovative planning to bring transformative change

---

* Corresponding author.
E-mail addresses: sourish.ju09@gmail.com, sourishc.gcp.rs@jadavpuruniversity.in (S. Chatterjee).

https://doi.org/10.1016/j.esd.2024.101560
Received 9 July 2024; Received in revised form 21 August 2024; Accepted 15 September 2024

for sustainability (García-García, Carpintero, & Buendía, 2020), requiring in-depth evidence-based scientific studies to design transition pathways. Techno-economic energy models that consider local specificities and evidence can serve as powerful practical decision tools, providing crucial information for initiating visioning and co-designing flexible alternative pathways and negotiating options with stakeholders.

The power sector is a significant revenue generator and politically important economic sector, serving as essential infrastructure for socio-economic development (Pietzcker, Osorio, & Rodrigues, 2021). The long lifetime of assets in the electric power sector necessitates investment decisions based on transparent assumptions and evidence used in modeled pathways in the near term (Chang et al., 2021; Dagoumas & Koltsaklis, 2019; Hong et al., 2020). For a developing country like India, the imperative is to engage in a visioning process for a future power system through capacity expansion energy modeling. This approach will offer evidence to assess early mover's advantage and attract investment in power sector infrastructure with a lifespan of at least 25 years (Bazilian et al., 2021; García-García et al., 2020; Jin, Shi, & Zhang, 2021; United Nations Environment Programme, 2020).

Before starting model building and application it is important to understand at what scale the transition planning is going to be implemented. At national (Kanitkar, Banerjee, & Jayaraman, 2019; Lugovoy et al., 2021) or subnational scale? Constitutionally in India the "Electricity" is in the concurrent list which means a system of shared responsibility in decision-making between the national and subnational authorities, with states having all the decision making power for implementation of projects and plans. Moreover, States in India vary widely in terms of diversity in natural resource base. Coal-rich states face increasing pressure to transition to cleaner energy sources to meet environmental targets and address climate change concerns (Agrawal et al., 2024; Isoaho, Goritz, & Schulz, 2016; Pressburger et al., 2022). Proper capacity expansion modeling exercise facilitates the exploration of transition pathways by assessing the feasibility of integrating renewable energy technologies and implementing emissions reduction strategies. In this backdrop our objective is to choose a coal rich region with moderate solar/wind potential and access to necessary data, develop a model using an open-source modeling platform, and ensure transparency in the underlying assumptions as per the state's policy.

Thus far, there have been very few studies reported for specific Indian subregions. Karunanithi et al. examined the economic and environmental impact of renewable energy sources (RES) introduction in the state of Tamil Nadu (TN), India, using the Long-Range Energy Alternative Planning system (LEAP) (Karunanithi, Saravanan, Prabakar, Kannan, & Thangaraj, 2017). However, a comprehensive state-level visualization and co-design process with full transparency, triggering public debate, which is crucial for an inclusive transition in a coal-rich state, has not been initiated. We have selected state of West Bengal, which is coal-rich with moderate solar energy potential and where land acquisition for renewable capacity expansion, similar to many other countries, is complex (Bose, 2015; Halder et al., 2022). By modeling the energy transition pathways in a coal-rich state like West Bengal, valuable insights and lessons learned can also be shared with other regions facing similar challenges. This can also facilitate knowledge exchange, collaboration and negotiations to expedite the adoption of clean energy solutions nationwide.

The EU has already embraced a policy aimed at optimizing energy service demand to balance trade and mitigate supply shortages. Demand-side measures have been put into effect to reap benefits in both the short and long term (D'Ettorre et al., 2022). However, coal-rich subregions and countries burdened with providing essential energy access find it daunting to initiate discussions or envision transitions away from coal in the near term. With this motivation, the authors developed demand-side flexibility (DSF) enabled energy transition pathways for West Bengal to systematically phase out traditional unabated fossil fuel-based energy sources in favor of a clean energy future within a specified timeframe.

Key contributions

To analyze the technical feasibility and economic impact of decarbonizing India's electric power sector on a national scale, the Indian Zero Carbon Energy Pathways (IDEEA) has been already developed as a high-resolution optimization energy modeling tool and package (IDEEA, 2024). In this study, we have developed a one-region open-source energy model for a coal-rich state like West Bengal (WB). This can be considered as the sub-national IDEEA model, we call it WB-IDEEA. It is important to understand that this is not merely a downscaling exercise; rather, the fundamental principle of the least cost solution from the national IDEEA platform is retained. However, the technology mix and constraints are tailored to align with state power regulations and policy guidelines, as well as the spatial availability of requisite natural resources.

The novelty and major contributions of the present study can be summarized as follows:

- Developed an open-source capacity expansion energy model tailored for a coal-rich sub-region in India.
- Investigated the potential least-cost transition pathways for a coal-dependent state like West Bengal using the developed model.
- Use of MERRA2 reanalysis data sets, reporting for each district in the State of West Bengal to get the average solar radiation in the form of the plane of array irradiance to enhance model outcome quality and help in deriving policy implications.
- Considering local constraints of resources and state policy, a total of 48 futuristic scenarios in three branches (4 scenarios × 4 years modeled × 3 cases for each year: base, low, & high) have been created and solved to analyze the least cost capacity expansion planning.
- Incorporated hourly load data and district-level land use data to refine the model.
- Analyzed modeled operations, storage requirements, investments and CO_2 emission projection up to 2040 in five-year intervals.
- Implications of utilizing the demand side flexibility on storage and land requirements are also explored.

The overall results indicate that by enabling demand-side flexibility and retiring thermal power plants after their full operational lifetime, it is possible to achieve 92% of installed capacity from renewable sources by 2040, assuming current baseline demand growth. This scenario would require utilizing 0.87% of West Bengal's total land area for solar capacity expansion. However, to reach a 100% renewable energy mix by 2040, 1.32% of the total land area (1171 square kilometers) would need to be allocated, and 5.86 GW of thermal capacity would have to be retired before lifetime. This land resource can come from various types, including green fields, rooftops, and water bodies, though such granular distinctions are beyond the scope of this paper. We estimate land requirements for both high and low demand growth scenarios compared to the baseline demand growth, with land requirement values ranging from 1.56% to 1.09% respectively. Assuming baseline demand growth and a land constraint allowing a maximum of 1% land usage for solar capacity expansion, 583.82 GWh of battery storage would be required by 2040 in a thermal mix scenario without demand-side flexibility (ScenTM). However, this battery storage requirement decreases by almost 90% in a thermal mix scenario with demand-side flexibility (ScenTMDSF).

Organization

The rest of the paper is organized as follows: Section "Related research" summarizes the relevant literature on energy system modeling with demand-side flexibility (DSF). Section "Power sector transition challenges for West Bengal" deals with the power sector transition challenges for West Bengal. The model specifications, data inputs and the objective function are outlined in Section "Methodology". In Section "Alternative decarbonization scenarios", we present the alternative decarbonization scenarios. Results and discussions are given in Section "Results and discussion" and finally, conclusions are drawn from this study in Section "Conclusions".

Related research

Energy system modeling for energy transition

Over the last decade, open-source energy system modeling platforms have evolved through community efforts, formulating transformative pathways effectively. Several countries have made significant progress in long-term energy system modeling and planning, using customized models to inform their energy policy decisions (Gaur, Das, Jain, Bhakar, & Mathur, 2019; International Energy Agency, 2022; Zappa, Junginger, & Van Den Broek, 2019). These energy modeling tools ensure that decisions are based on sound analysis and stakeholder input, leading to more effective and sustainable energy policies. Numerous open-source energy modeling platforms, such as OSeMOSYS, MESSAGEix, PyPSA, EnergyRt, and SWITCH, have emerged to build custom energy models tailored to specific needs. However, most of these models are generic, relying on open-source data or requiring users to collect granular field data to develop scenarios for a particular region. Furthermore, the energy landscape and the needs of policymakers differ from country to country. Therefore, a region-specific model framework that incorporates all granular ground data into a comprehensive package is highly beneficial. This approach can help to build transitional pathways that consider local complexities and challenges.

Hansen et al. reported the 100% renewable energy transition pathways for the German energy system from a technical and economic perspective in a cost-effective manner (Hansen, Mathiesen, & Skov, 2019). This study highlights the most significant challenge for the transition is the resource constraint (Hansen et al., 2019). The major energy transition pathways of the USA are viewed in the context of the past six decades with recognition of socio-technical factors and a multi-level perspective (Saundry, 2019). With an hourly resolution and 5 year time interval (2015 to 2050), two transition pathways have been proposed (Child, Kemfert, Bogdanov, & Breyer, 2019) for Europe to achieve 100% RE power sector by 2050 using LUT Energy System Transition Model. Using the MESSAGEix, a dynamic systems-optimization modeling framework, a case study has been reported for Male, Maldives (Hunt et al., 2021). This study established the significance of DSCD (Deep Seawater Cooling and Desalination) technology that can supply 49 MWt of cooling and 1 m^3/s of water simultaneously with an electricity consumption of 12 MWe. Very recently, a least cost investment planning and potential energy mix have been reported by Hassen et al. to replace coal in Mauritius (Hassen, Surroop, & Praene, 2023). Using the OSeMOSYS open-source modeling framework for the span 2015 to 2040, this study (Hassen et al., 2023) established the requirement of potential investment in storage batteries to accommodate more variable generating technologies and exploit local resources such as biomass and solid waste. A study by Maximillian et al. investigated the 2060 net zero planning for Nigeria using the PyPSA-Earth modeling framework (Parzen et al., 2023). Using an hourly resolution energy model simulated for India, Gulagi et al. demonstrate that renewable energy options are the most cost-effective for achieving a net-zero future energy system (Gulagi, Bogdanov, & Breyer, 2018). In Ref. Giannelos et al. (2021), a stochastic optimization model is applied to India's transmission network to identify the optimal expansion strategy for the period from 2020 to 2060. Amratha et al. used a mixed-integer linear programming model to evaluate the effectiveness of various energy policies within the Indian context (Amrutha, Balachandra, & Mathirajan, 2018).

To achieve a timely net zero target, transitional pathways have to be framed not only from the national scale but also from the sub-national and local levels. In fact, according to the United Nations, cities are responsible for over 70% of global energy-related carbon dioxide emissions (IPCC Report, 2022). Sub-national energy models can help to understand their energy usage and greenhouse gas emissions, identify opportunities for reducing them, and develop effective strategies for achieving net zero emissions by 2050. These models can provide insights into the current energy mix and identify the most cost-effective and efficient pathways for transitioning to renewable energy sources. In Xiao, Simon, and Pregger (2019) strategic implementation of long-term integrated energy transition pathways have been evaluated for two coastal metropolitan regions of eastern China. Dallavalle et al. explored the potential advantages of hybrid waves and solar installation to maximize the exploitation of renewable sources by minimizing the need of a fossil-based backup system (Dallavalle, Cipolletta, Moreno, Cozzani, & Zanuttigh, 2021). This study has been performed for the Canary Islands of Tenerife.

Demand side flexibility

There are multiple ways to facilitate the transition to a low-carbon and cost-effective sustainable energy system with integration of variable clean and renewable green energy sources while managing peak demand and balancing the electricity grid (Heffron, Körner, Wagner, Weibelzahl, & Fridgen, 2020; Kohlhepp et al., 2019; Stavrakas & Flamos, 2020). The benefits of utilizing DSF through intra-day load management into the energy system (IPCC Sixth Assessment Report, 2022) is also seen as a means to avoid investment in a high-cost supply capacity expansion plan (Sioshansi, 2020). DSF through various IOT applications (Aduda, Labeodan, Zeiler, Boxem, & Zhao, 2016; Ahammed & Khan, 2022; Sharda, Singh, & Sharma, 2021) combined with market incentive mechanisms provides a solution to these challenges by allowing electricity demand to be adjusted to match the available supply from renewable energy sources (Helistö, Kiviluoma, & Holttinen, 2018). For example, by incentivizing consumers to shift their energy usage to times when renewable energy generation is highest, can significantly reduce the need for costly infrastructure investments (McKenna et al., 2021; Thakur & Chakraborty, 2016). So far, the majority of these studies are performed for the European countries (D'Ettorre et al., 2022; Forouli et al., 2021; Scheller, Burkhardt, Schwarzeit, McKenna, & Bruckner, 2020). Heffron et al. (2020) present insights for policy-makers to show how the industrial demand side flexibility has the unique potential of fostering a sustainable and inclusive industrial development and a just transition towards a low-carbon economy in the context of countries. The social perspective on demand response is investigated in D'Ettorre et al. (2022) for Denmark, France, Italy and Spain. Competitive flexibility options can also reduce household storage capacity by up to 9% (Scheller et al., 2020). Several studies show that demand-side measures can play a critical role in balancing the grid and integrating renewable energy in the Indian context (Ahammed & Khan, 2022; Balasubramanian & Balachandra, 2021; Bhongade, Dawar, & Sisodiya, 2021; Sambasivam & Xu, 2023). A 20% increase in the capacity factor and a 40% reduction in the cost of solar electricity is possible in Karnataka by shifting agricultural load from nighttime to daytime (Sambasivam & Xu, 2023). Another study, using Karnataka's electricity system as a case study, suggested that demand response interventions are highly effective in minimizing demand variability and monthly energy bills, even for consumer sectors (Balasubramanian & Balachandra, 2021).

Power sector transition challenges for West Bengal

West Bengal has nearly 9% coal reserves in India (Ministry of Coal, Govt. of India, 2023), mainly located in the Raniganj coalfield. This coalfield covers an area of about 1530 square kilometers in the districts

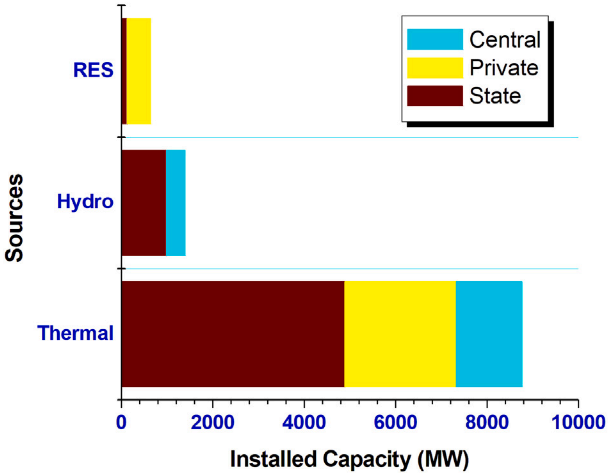


Fig. 1. Source wise installed capacity of West Bengal.

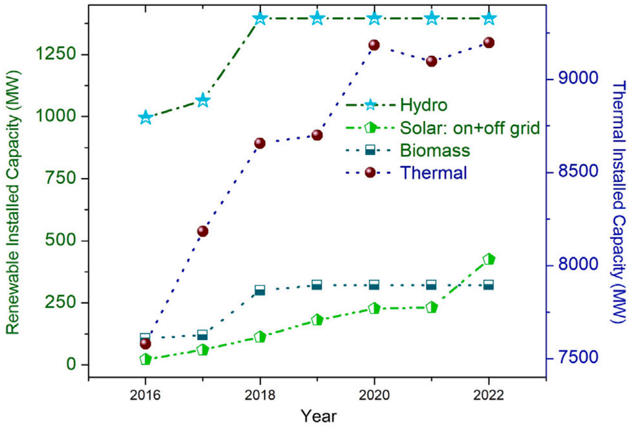


Fig. 2. Year wise increment in installed capacity of renewable sources.

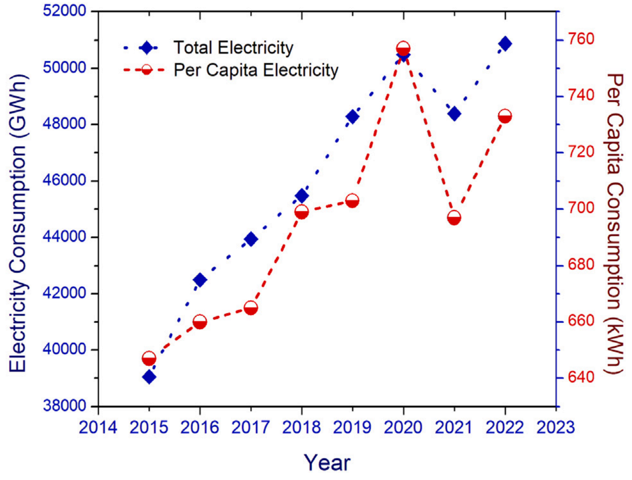


Fig. 3. Yearwise electricity consumption of West Bengal.

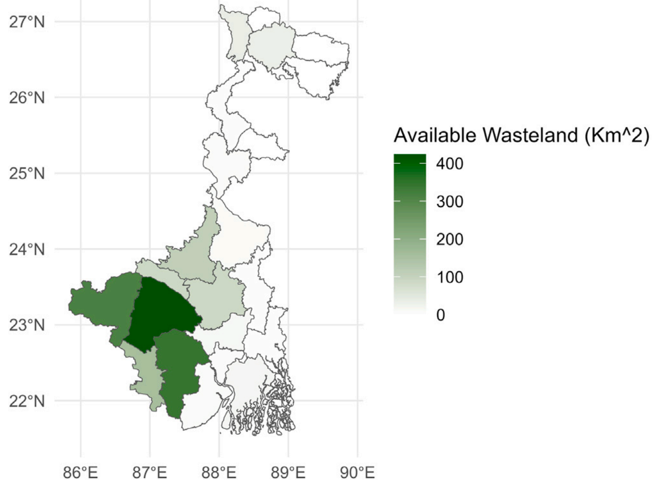


Fig. 4. Available wasteland for solar capacity expansion.

of Bardhaman, Birbhum, Bankura, and Purulia (Samanta, 2015). Apart from the Raniganj coalfield, there are other smaller coalfields in the state, including the Barjora, Mejia, and Salanpur coalfields (Ministry of Coal, Govt. of India, 2023; The West Bengal Power Department Corporation Limited, 2023). As a result, thermal power generation remains the primary source of electricity in the state. As of 2024, West Bengal's installed thermal power capacity is around 8763.34 MW, which is about 81% of the total installed capacity. Considering the shares from both state and central, the hydro capacity is 12.9% of the total installed capacity (Central Electricity Authority, GOI, 2024). These shares are clearly depicted in Fig. 1. As per the latest available report, West Bengal has a 1439.7 MW hydro capacity (Ministry of New and Renewable Energy, GOI, 2024). The on-grid solar and biomass capacity are 197.97 and 348.36 MW (Ministry of New and Renewable Energy, GOI, 2024).

Fig. 2 illustrates the annual growth in the installed capacity of thermal and renewable energy sources. The most significant growth has occurred in solar energy, with an increase of over 1800% since 2016, rising from a capacity of 22 MW in 2016 to 424 MW in 2022. In contrast, the increases in hydro and biomass capacities are much smaller, at 23.5% and 37.9%, respectively. The smallest growth in installed capacity is observed in thermal power plants, with an 18% increase. The year-wise increment in net electricity consumption and per capita electricity consumption of WB is shown in Fig. 3. In 2021, both the per capita and total electricity consumption were reduced due to the COVID19 outbreak.

The state has a large agricultural sector, and there is a significant amount of agricultural waste generated every year, such as rice straw, wheat straw, sugarcane bagasse, and maize stalks. This waste can be used as a feedstock for biomass power plants. In addition to agricultural waste, the state also has a significant potential for generating biomass from municipal solid waste, industrial waste, and forestry waste. According to a report by the Ministry of New and Renewable Energy, the estimated potential for biomass power in West Bengal is around 6663 MW (GOI, 2015) as suggested by the state nodal agency. The State is also emphasizing the development of hydropower generation capacity. WBSEDCL has identified the potential to develop 6300 MW of hydropower which includes a pumped storage potential of 4800 MW and 1500 MW of canal falls (West Bengal State Electricity Distribution Company Limited, 2023).

Land availability for capacity expansion

The highly decarbonized electricity system in West Bengal demands a high penetration of solar energy that requires a significant amount of land to be procured. Land that is not in use (deserts, wasteland, etc.) can be a very good option for setting up a solar power plant (Mahtta, Joshi, & Jindal, 2014; Van de Ven et al., 2021). As per the Department of Land Resources, only 1654.99 km^2 wasteland is available in West Bengal (Land Use & Cover Monitoring Divn, ISRO, Dept. of Space, GOI, 2016). The district-wise available wasteland is shown in Fig. 4.

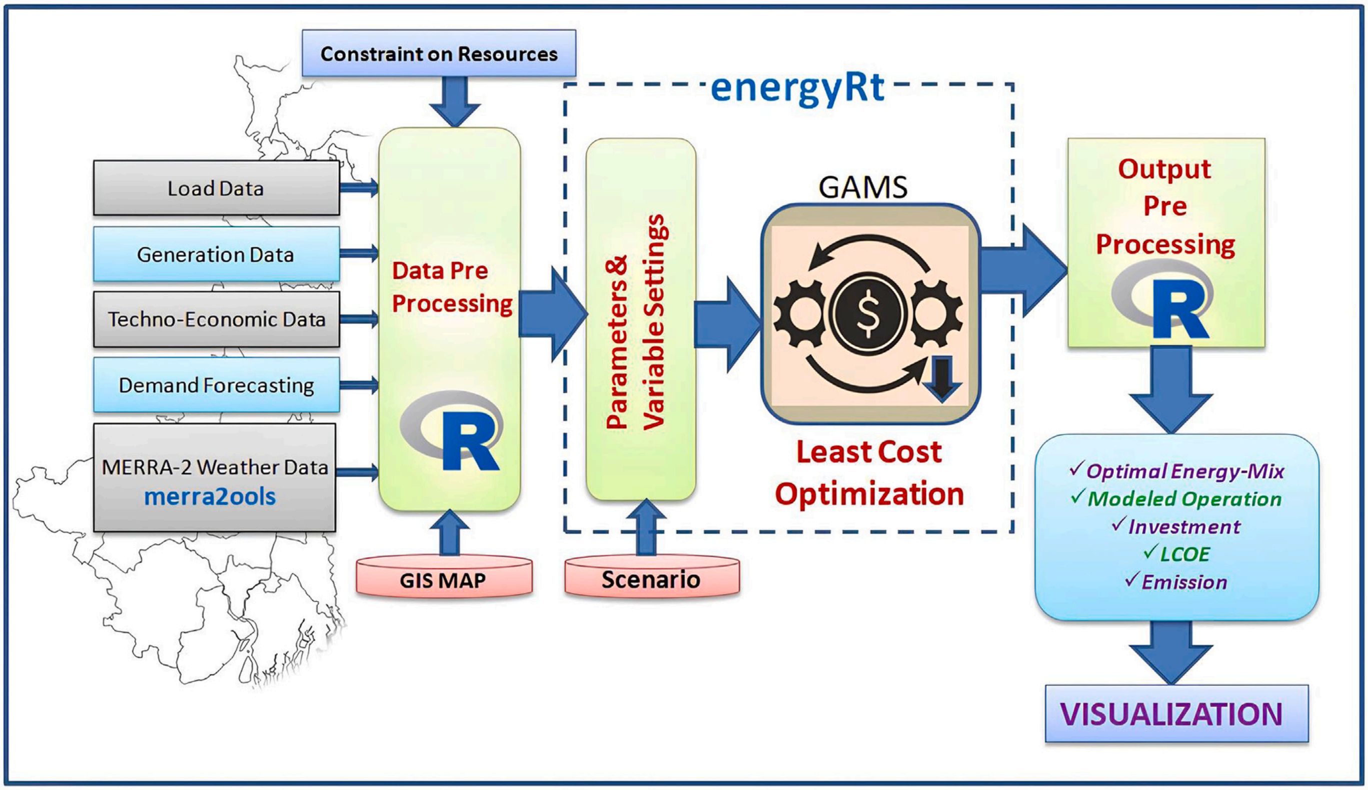


Fig. 5. Schematic architecture of WB-IDEEA model.

Methodology

Following the architecture of the national scale IDEEA model (IDEEA, 2024) one region sub-national power sector model is developed, called "WB-IDEEA". The technology mix and constraints are customized following state power regulations, policy guidelines, and spatial resource endowment of solar energy. The entire model is compiled using an open-source code in R in alliance with several existing CRAN packages and two dedicated energy-modeling packages called 'energyRt' (Lugovoy & Potashnikov, 2022) and 'merra2ools' (Lugovoy Oleg & Gao Shuo, 2021). EnergyRt package is a set of classes, methods, and functions that parse large datasets to a high-level mathematical programming and optimization tool and import results back to R. In the WB-IDEEA model we have used GAMS (GAMS Development Corp, 2023) to solve the optimization problem and get the least cost solution. The other important package merra2ools offers a set of tools to evaluate the hourly output potential of solar energy sources fetched from the MERRA-2 global reanalysis data subset. The schematic architecture of the WB-IDEEA model is shown in Fig. 5.

Model specification

The sub-national model (WB-IDEEA) adopts a least-cost electricity generation capacity-expansion framework. The objective function of the present study is given as:

$$Z = \min \sum_{y} \left(C_y^{Total} \times DF \right)$$

$$subject\ to:$$

$$NCap_{hydro,y}^{Tech} \leqslant Y_y \qquad (1)$$

$$NCap_{biomass,y}^{Tech} \leqslant \beta_y$$

$$A_{land}^{solar} \leqslant \kappa A_{land}^{WB}$$

here Y_y, β_y and κ are the constant terms, depending on different scenarios and modeling years. A_{land}^{WB} is the total area of West Bengal and $NCap$ is the new capacity addition for a particular generating technology. Depending upon the availability of wasteland the value of κ is selected. DF is the discount factor and C_y^{Total} is the total cost associated with capacity expansion for a particular scenario and given by:

$$C_y^{Total} = \sum_t \left(Eac_{t,y}^{Tech} \right) + \sum_t \left(OMC_{t,y}^{Tech} \right) + \sum_{su} \left(C_{su,y}^{Supply} \right) + \sum_{sto} \left(OMC_{sto,y}^{Storage} \right) + \sum_{sto} \left(Eac_{sto,y}^{storage} \right) + C_y^{Trade} + \sum_{comm} \left(C_{comm,y}^{Tax} \right) - \sum_{comm} \left(C_{comm,y}^{Sub} \right) \qquad (2)$$

where (t) is the index of technology considered for a given scenario; (y) stands for the set of model years; (su) and (sto) are denoted as the index for per unit supply and storage respectively. In the present study, thermal, hydro, biomass and solar are taken as major generating technologies and storage battery is considered as balancing technologies from the supply side. 'comm' is denoted as the index for commodities like electricity, carbon dioxide, coal, etc on which the government can impose tax or grant subsidy. There is also a provision to incorporate all these taxes and subsidies in our model ($C_{comm,y}^{Tax}$, $C_{comm,y}^{Sub}$) as per the government policy. Eac and OMC are the Annualized investment cost and operational and maintenance cost respectively. The annualized investment cost for a particular technology ($Eac_{t,y}^{Tech}$) depends on the new capacity ($NCap$) and the early retired capacity ($RCap$) of the same technology, expressed by:

$$Eac\_t, y^{Tech} = \sum_{yp} \left(Ec_{t,yp}^{Tech} \times \left(NCap_{t,yp}^{Tech} - \sum_{ye} \left(RCap_{t,yp,ye}^{Tech} \right) \right) \right) \qquad (3)$$

Here $Ec_{t,y}^{Tech}$ equivalent annualized cost per unit capacity. Three different aliases for the set 'year' (y,yp,ye) are used to separate the summation process in GAMS environment. Accordingly, the annualized cost for storage is expressed as:

$$Eac_{sto,y}^{Storage} = \sum_{yp} \left(Ec_{sto,yp}^{Storage} \times NCap_{sto,yp}^{Storage} \right) \qquad (4)$$

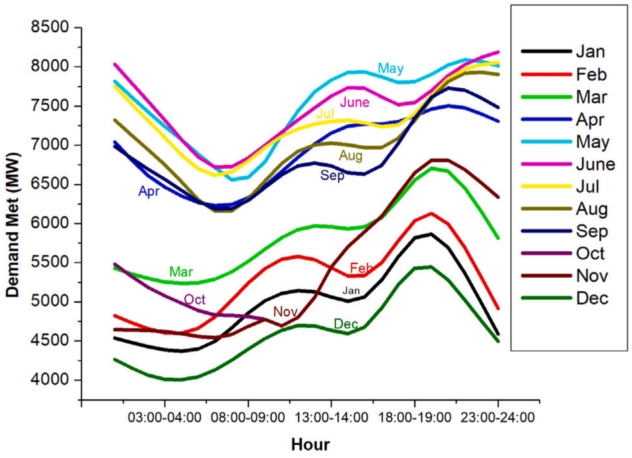


Fig. 6. Hourly average load profile of WB.

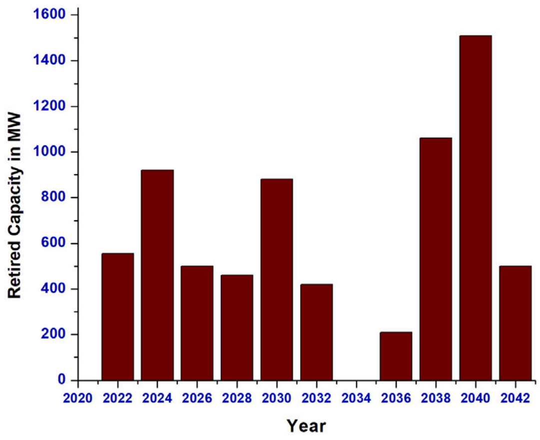


Fig. 7. Yearwise capacity retirement of thermal power plants.

We have considered Fixed and variable operational and maintenance cost (FixOM and VarOM) separately to compute total OM cost associated with a particular technology. It is given as

$$OMC^{Tech}_{t,y} = FixOM^{Tech}_{t,y} \times Cap^{Tech}_{t,y} + \sum_{s} VarOM^{Tech}_{t,y,s} \times Act^{Tech}_{t,y,s} \tag{5}$$

where $Cap^{Tech}_{t,y}$ is the total installed capacity of the technology and $Act^{Tech}_{t,y,s}$ is the activity level of the technology. Only fixed operating and maintenance cost is associated with storage battery given as:

$$OMC^{Storage}_{sto,y} = FixOM^{Tech}_{sto,y} \times Cap^{Storage}_{sto,y} \tag{6}$$

The total trade cost for our one region subnational model is expressed as:

$$C^{Trade}_{y} = \sum_{i,comm,s} Iprice_{i,y,s} \times Irow_{i,comm,y,s} - \sum_{e,comm,s} Eprice_{e,y,s} \times Erow_{e,comm,y,s} \tag{7}$$

Here $Iprice$ and $Eprice$ are the per unit import and export cost for electricity.

Data input to model

To run the model we need data: load data at a granular scale, generation data, and cost data. The calibration of energy models is an essential step in validating their accuracy and reliability for various applications, such as predicting energy consumption, optimizing energy systems, assessing energy efficiency measures, and evaluating renewable energy integration. Calibration of the model for the base year is the first step. To avoid any biases we have purposely considered 2019 as our base year, the pre COVID19 year.

Load data

The West Bengal demand with one-hour resolution (8760 slices in a year) is collected from the National Load Despatch Centre and used for the simulation. The hourly average load profile for all the months around the year is shown in Fig. 6. It has been observed that the peak demand occurs after 19:00 Hrs in the evening. The peak time for electricity load in West Bengal typically occurs during the early evening hours, usually between 6:00 pm and 9:00 pm. A maximum peak demand of 8190 MW occurred in the summer month of June while in the winter season (December) only 5443 MW peak demand was observed. The aggregated yearly energy demand in 2019 was 54609 MW with an annual load factor of 82.9%.

Generation data

We have used the daily generation data of 20 thermal power stations and 3 hydro power plants (National Power Portal, CEA, 2023). Considering 40 years of lifetime for each thermal power plant the year-wise assumed capacity retirement profile is shown in Fig. 7. Retirement of old plants can reduce the O&M cost (Maamoun et al., 2022). As per the 2019 data, average daily generation varies between 238.07 GWh and 179 GWh. It peaks in May while the minimum value is observed in December. Even though generation data of all the thermal and hydro power plants in West Bengal are incorporated for the calibration process, we have not considered the primary renewable energy-related generation data as it is very negligible and scattered /offgrid in 2019 and are also not available from official sources. However, historical weather data along with the actual capacity of the individual solar plant are used as a proxy to estimate hourly solar energy generation.

Cost data & related technological assumptions

Depending on different factors such as investment and O&M cost of different generating technologies, operating lifespan and other technological considerations the optimal energy mix might lean towards a combination of technologies that provide stability, affordability, and sustainability. Based on the inputs from different national and regional stakeholders, we have considered the data as given in Table 1.

District-wise solar radiation using merra2ools

As mentioned earlier, in this model we have used merra2ools package to estimate the hourly output potential of solar energy for all the districts of West Bengal. This package uses MERRA-2 database (Lugovoy Oleg & Gao Shuo, 2021) of long-term time series data on a global grid of size 576 × 361. These datasets offer a spatial resolution of 0.5° latitude × 0.625° longitude. In the present study, we have fetched the solar irradiance data from 51 grid positions as shown in Fig. 8. It has been observed from Fig. 8, that more than one grid point may be assigned for each district depending upon the size and location. In such cases, the average solar potential of the district ($I^{district}_{POA}$) is computed as:

$$I^{district}_{POA} = \frac{\sum_{j=1}^{m} \left(I^{j}_{POA} \times A^{j} \right)}{\sum_{j=1}^{m} A^{j}} \tag{8}$$

where,

$$I^{j}_{POA} = I^{j}_{POA,d} + I^{j}_{POA,df} + I^{j}_{POA,g} \tag{9}$$

Here, $I^{j}_{POA,d}$, $I^{j}_{POA,df}$ and $I^{j}_{POA,g}$ are the direct, diffused and reflected component of the solar irradiance on jth grid point of a district. m is the total number of grid points shared by a district.

Table 1
Cost and related technological parameters.

Parameters	Value
Thermal investment cost	$1400 million /GW
Solar investment cost	$600 million/GW
Hydro investment cost	$2000 million/GW
Biomass investment cost	$610 million/GW
Storage battery cost	$120 million/kWh
Hydro OM cost (fixed)	$40 million/GW
Solar OM cost (fixed)	$15 million/GW
Thermal OM cost (var)	$0.02/kWh
Biomass OM cost (fixed)	$30 million/GW
Thermal supply cost	$0.7 million/GWh
Thermal efficiency	0.35
Biomass supply cost	$0.3 million/GWh
Biomass efficiency	0.4
Hydro AF	0.52
Biomass AF	0.7
Thermal AF	0.85
Thermal OL	40 years
Hydro OL	60 years
Solar OL	25 years
Storage battery OL	15 years
Charging efficiency	0.8
Storage efficiency	0.85
Biomass OL	25 years
Ramp up time thermal	6 h
Ramp down time thermal	4 h

Table 2
Demand multiplying factor for different model years.

Year	Baseline scenario	Optimistic scenario	Pessimistic scenario
2019 (base year)	1	1	1
2025 (model year)	1.45	1.46	1.37
2030 (model year)	1.92	1.98	1.73
2035 (model year)	2.48	2.65	2.18
2040 (model year)	3.17	3.54	2.79

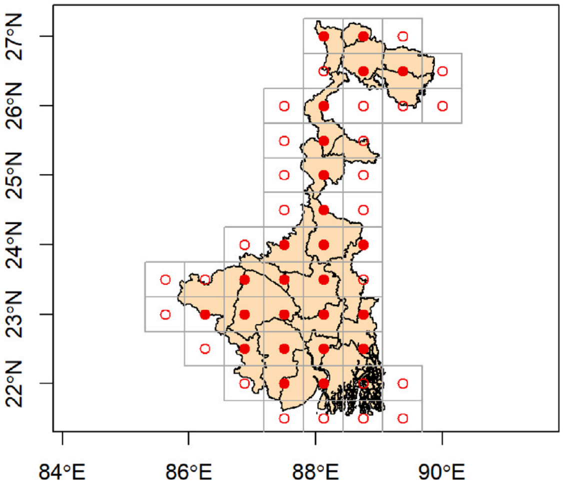


Fig. 8. MERRA 2 reanalysis data grid.

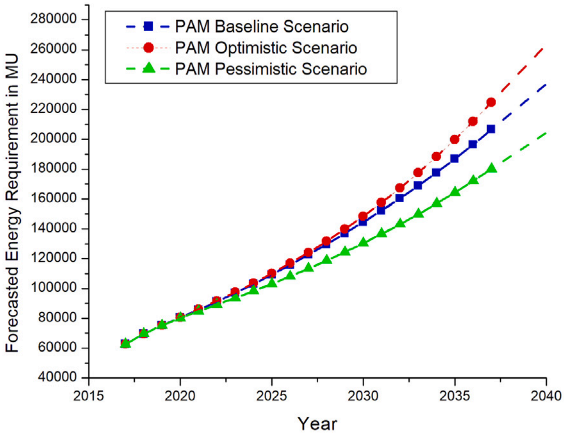


Fig. 9. Forecasted energy growth of West Bengal upto 2040.

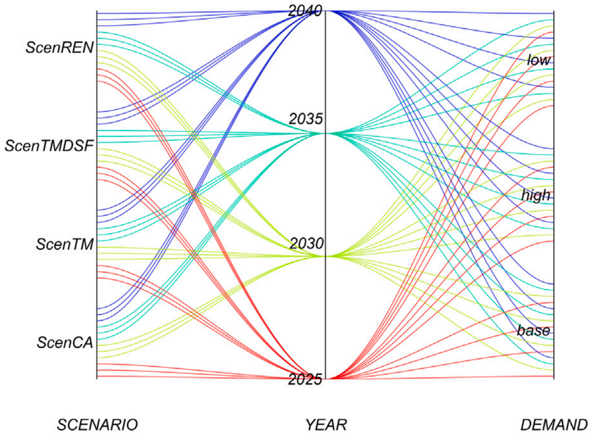


Fig. 10. Three parallel branches of scenarios.

Energy demand growth

In this study, we refer to the Central Electricity Authority (CEA) long-term forecasting report (Central Electricity Authority, India, 2019) to forecast the future demand under BAU, pessimistic and optimistic conditions. In our study, we called it as base, low and high demand respectively. The BAU/ base case assumes that GDP at the all-India level will continue to grow at the average compound annual growth rate (CAGR) of about 7.3% obtained from 2000–01 to 2017–18 and there will be no significant deviations from these past trends. In the optimistic growth scenario (high demand), the all-India GDP is assumed to grow at 8% and in the pessimistic growth scenario (low demand), the all-India GDP is assumed to grow at 6.5% for all future years (up to 2037). We have extrapolated the results obtained from the PAM model (Central Electricity Authority, India, 2019) up to 2040. This is shown in Fig. 9. The demand multiplying factors w.r.t the base year 2019 have been determined from this result and tabulated in Table 2.

Alternative decarbonization scenarios

The present study considers one set of current as usual and three sets of transitional scenarios for the state of West Bengal. Each set of scenarios are designed and solved for the year 2025, 2030, 2035 and 2040 as shown in Fig. 10. The generation, stock and balancing options for each scenario are in Table 3.

Current as usual scenario (ScenCA)

In this scenario, we have considered the energy mix as per actual status in the year 2019 where a high thermal dependency exists. Apart from the thermal generation existing hydro, solar and biomass capacity are also considered as a stock. It has been assumed that all the proposed solar projects will be functional and ready for generation. As Fig. 2 suggested, there has been hardly any capacity addition in hydro and biomass energy in the last five years. So, the present hydro (1396 MW) and biomass capacity(320 MW) are considered as stock in this particular scenario.

Table 3
Four branches of scenario.

Scenario	Abbreviation	Stock	Capacity addition	Balancing options	Year
Current as usual	ScenCA	Thermal, Solar, Hydro, Biomass	Thermal	Nil	2025, 2030, 2035, 2040
Thermal mix	ScenTM	Thermal, Solar, Hydro, Biomass	Solar,Hydro,Biomass	Storage Battery	2025, 2030, 2035, 2040
Thermal mix with DSF	ScenTMDSF	Thermal, Solar, Hydro, Biomass	Solar,Hydro,Biomass	Storage Battery, DSF	2025, 2030, 2035, 2040
100% renewable	ScenREN	Solar, Hydro, Biomass	Solar,Hydro,Biomass	Storage Battery, DSF	2025, 2030, 2035, 2040

Thermal-mix scenario (ScenTM)

Here, we have assumed no addition of thermal capacity post-2019 period. However, existing thermal plants will continue to contribute (assuming no premature retirement) to the future generation mix but as per the capacity retirement plan presented in Section “Data input to model”. We restrict the land acquisition for additional solar installation to a maximum 1% of available land and accordingly put constraint κ in the model. To utilize the biomass and hydro potential of West Bengal as mentioned in Setion “Methodology”, we have included these generating technologies with a maximum upper limit (Y_y, β_y). As mentioned in Section “Power sector transition challenges for West Bengal”, West Bengal has a hydro and biomass potential of 6300 MW & 6630 MW respectively (GOI, 2015; West Bengal State Electricity Distribution Company Limited, 2023). In this study, it has been assumed that West Bengal will explore and utilize the above-mentioned maximum biomass and hydro potential by 2050 and the increment will follow a linear path. Battery storage is considered as an effective balancing option in this scenario.

Thermal-mix scenario with DSF (ScenTMDSF)

This scenario includes an important additional feature over ScenTM. We have incorporated demand-side flexibility as a balancing method that helps intraday load shifting and has the potential to reduce battery storage and land requirements for solar installations. Very recently a state (Punjab) in India shifted their office timing to flatten the peak consumption. In this scenario constraint on the land availability for solar installation is also the same as ScenTM, i.e maximum of 1%. One of our goals is also to check how far in optimum choice demand side flexibility strategy can help to reduce the land requirement.

100% Renewable scenario (ScenREN)

In the previous two scenarios (ScenTM and ScenTMDSF) thermal generation stock as per the year-wise retirement plan without any premature closure is used in the electricity generation process. Even in the year 2040, 5.86 GW thermal capacity has been utilized which is a reasonably large number. To work out an optimal solution which can help in removing this thermal back-up we relax the assumption on the limit to land availability for solar expansion in this scenario. Apart from thermal, all available renewable energy sources are considered here and both battery storage and DSF options are considered as balancing technologies.

Results and discussion

In this Section, first we present the district-wise solar potential to identify the possible hotspots (a cross section of high irradiance and availability of unused/waste land) for future solar capacity expansion planning. Next, we discuss and analyze the findings related to alternative decarbonization scenarios illustrated in Section “Alternative decarbonization scenarios”.

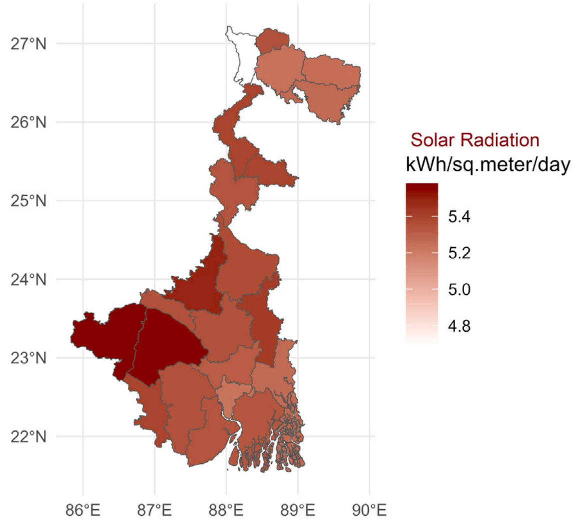


Fig. 11. District wise solar potential.

Hot-spots for solar capacity expansion

Based on the MERRA2 reanalysis dataset, the district-wise average daily solar potential for West Bengal is computed and shown in Fig. 11. The maximum potential of 5.6 $\mathrm{kWh/m^2}$ is observed in the Purulia district while Darjeeling possesses the minimum value of solar irradiance of 4.55 $\mathrm{kWh/m^2}$. From Fig. 11, it can be clearly observed that Purulia, Bankura, Birbhum, Nadia and Uttar Dinajpur districts have higher potentials in terms of solar radiation. However, we also need unused/ wastelands to identify the hot-spots for installing solar power plants. As an example, Nadia district has sufficiently high solar radiation of 5.4 $\mathrm{kWh/m^2}$, however only 2.9 square km of wasteland is available in Nadia. So, both land availability and higher solar irradiance are essential to identify the prime locations (districts) for solar capacity expansion. Interestingly, Purulia and Bankura districts have the maximum solar potential and available wastelands as well.

By taking into account both these parameters, the front runners for solar capacity expansion in West Bengal are Purulia, Bankura, Birbhum, Bardhaman and West Midnapore district. A total of ~ 1520 square km wasteland are there in those five districts which is almost 1.7% of the total land area of West Bengal. The month-wise average solar radiation of those districts is shown in Fig. 12. The result shows that solar radiation is maximum from March to May while the minimum value of solar irradiance can be noticed in the rainy season (June to August).

Scenario analysis

The transitional scenarios are developed to understand how thermal capacity can be phased out over time. This has been done under the assumptions of land availability as explained above and also storage capacity expansion needs which vary with the inclusion or exclusion of DSF strategy. We need to understand the cost will vary under various scenarios and each scenario has underlying technology choices and policy decisions to be made early on to get on the desired transition paths.

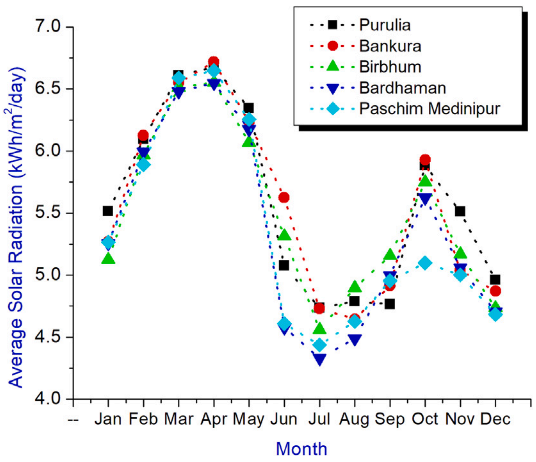


Fig. 12. Monthly average solar radiation in potential hotspots.

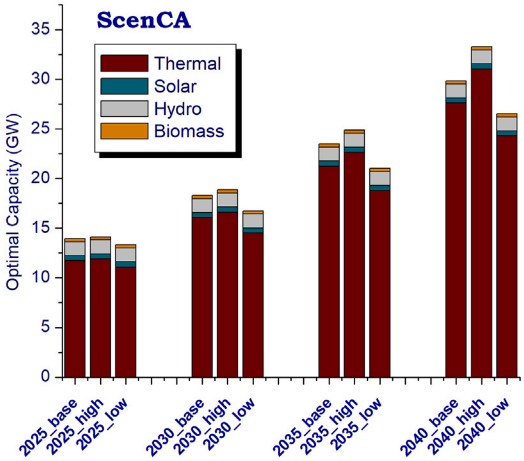


Fig. 13. Optimal installed capacity for scenario ScenCA.

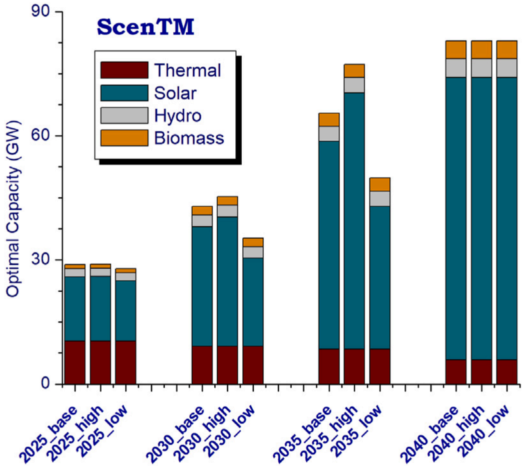


Fig. 14. Optimal installed capacity for scenario ScenTM.

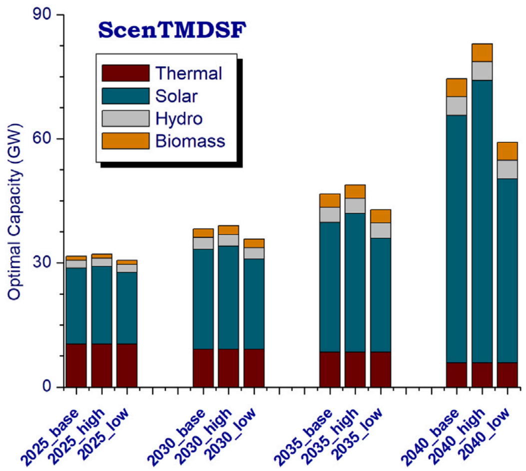


Fig. 15. Optimal installed capacity for scenario ScenTMDSF.

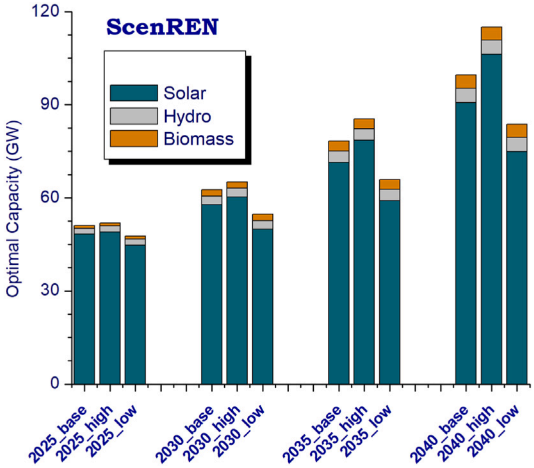


Fig. 16. Optimal installed capacity for scenario ScenREN.

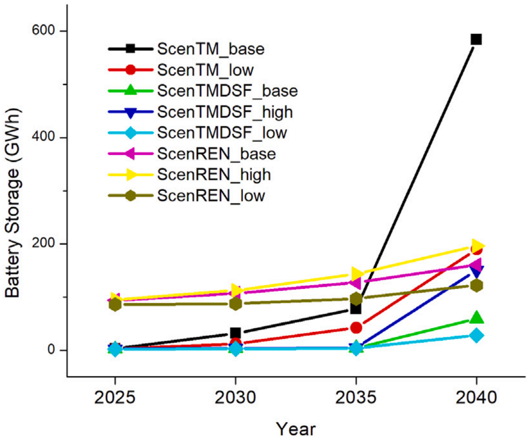


Fig. 17. Required battery storage capacity for different scenarios.

Optimal generating capacity and storage requirement

The estimated optimal installed capacity in various years for all four sets of scenarios (ScenCA, ScenTM, ScenTMDSF, ScenREN) are shown in Figs. 13–16 respectively. The share of renewable energy defines the variations in optimal capacity between scenarios. In coal-dominated ScenCA, the required optimal thermal capacity in 2040 will be increased by 2.4 to 3 times in low and high-demand cases respectively compared to the 2019 base year. Compared to the current as-usual trend of an insignificant amount of RES addition observed over the last decade, 22 GW of additional thermal capacity has to be installed before 2040 to meet the baseline demand. In the scenarios (thermal mix transitional scenarios -ScenTM, ScenTMDSF) where the thermal dependency is gradually phased out as we assume a timely thermal capacity retirement plan, maximum demand is served by the solar technology. It can be observed that in ScenTM (2040), the solar installed capacity is identical for baseline, high and low demand. This is because; in this scenario, we have forced the model to use a maximum of 1% land for solar capacity expansion. For all baseline, high and low demand (for the year 2040) the land use reaches the maximum threshold, however, the storage requirement is not the same for these three sets of demands. In order to meet the peak load especially for high and baseline demand growth in ScenTM scenario, a very high battery storage is required compared to other scenarios. The storage requirement for different transitional scenarios is shown in Fig. 17. It can be observed that in 2040, 583 GWh of storage is required for ScenTM considering baseline demand growth. However, the storage requirement is reduced by almost 90% if DSF is adopted (ScenTMDSF). Considering high demand growth, the ScenTM scenario requires 6399 GWh storage capacity. In contrast, the storage requirement can be substantially reduced to 150.54 GWh by adopting DSF as another balancing option.

In the ScenTM scenario, apart from battery storage, all other generations are restricted by an upper threshold. Solar generation is restricted due to maximum land constraint as mentioned before. In this scenario for 2040, the maximum thermal capacity is limited to 5.86 GW as per the thermal retirement plan. Both biomass and hydro have an upper ceiling as mentioned in Section ‘‘Alternative decarbonization scenarios’’. Thus whenever an excess load/ demand is encountered (evening peak) storage remains the only option. However, if we relax the thermal (new thermal generation is allowed) then the storage requirement will be substantially reduced. However, in the ScenTMDSF there is another balancing option in the form of demand-side flexibility that shifts some of the peak load which in turn reduces the storage requirement.

For the year, 2025 and 2030 the storage requirement gap between these two scenarios is not so wide because of higher thermal penetration. However, as the demand increases over the years, thermal capacity gradually reduces which in turn widens up the storage requirement difference between these two scenarios. Unlike ScenTM and ScenTMDSF no constraint on land availability is imposed for ScenREN. Considering baseline demand growth, the required solar capacities for this set of scenarios are 48.24 GW, 57.7 GW, 71.43 GW and 90.65 GW respectively for the years 2025, 2030, 2035 and 2040. The storage requirements in these scenarios are higher than ScenTMDSF, due to the absence of thermal backup in this scenario. However, the hydro and biomass capacity is identical with ScenTMDSF and equal to its maximum potential assumed for respective years.

Hourly energy mix and excess generation

In renewable energy-based systems, it is important to understand the impact of seasonality on the power system. In Section ‘‘Hot-spots for solar capacity expansion’’, we discuss this considering spatial resource availability, i.e., by administrative districts of the state as that gives more localized administrative decisions and investment opportunities and planning. Solar radiation is maximum in the summer months and minimum at the time of monsoons. So, the hourly energy mix of all the transitional scenarios is presented in this section for summer, the rainy season and the entire year. In order to briefly illustrate the hourly energy mix pattern, results are shown in Figs. 18–20 for the year 2040 and baseline demand growth.

In the case of ScenTM scenario, it can be observed that thermal back-up is not at all used in the daytime of summer while in the monsoon season thermal back-up is required even in daytime as the number of sunny hours declines. Hydro generation is also not utilized most of the days in the summer season when solar irradiation is comparatively high. However, at the time of monsoon, hydro becomes an important source even in the daytime. Considering 6 h storage back-up, the required storage capacity is 97.3 GW. The battery storage process is represented in figure by STGBTR in the negative y-axis. There is no excess generation of electricity for this scenario considering the 2040 baseline demand. However, in 2025, 2030 and 2035 the excess generations are there. The excess generation for all the transitional scenarios considering baseline demand growth is shown in Fig. 21.

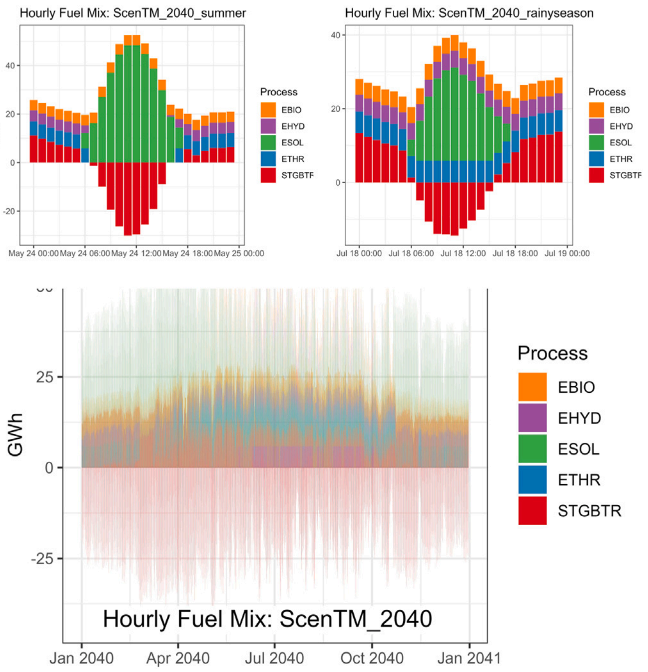


Fig. 18. Hourly modeled operation for ScenTM (2040).

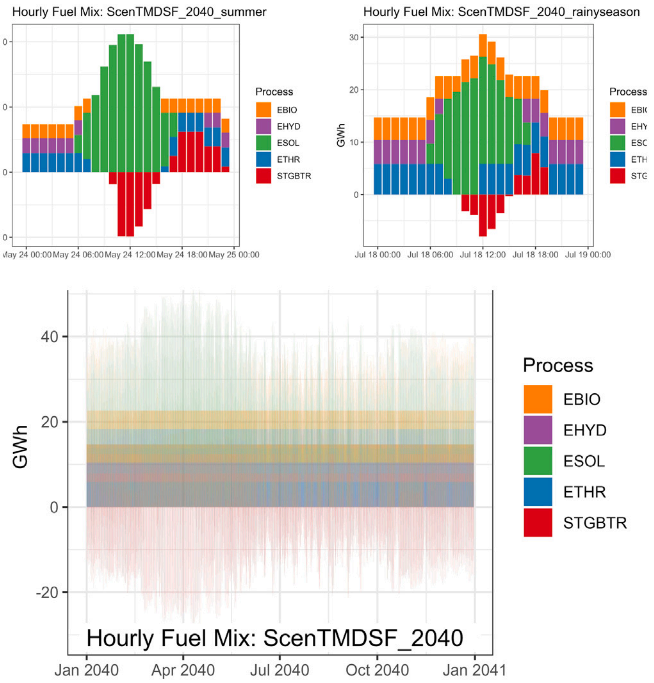


Fig. 19. Hourly modeled operation for ScenTMDSF (2040).

Fig. 19 shows the hourly energy mix for the ScenTMDSF scenario. In the rainy season, more hydro electricity is utilized in comparison with summer days to compensate the reduction in solar generation. Also, more biomass and thermal power is in operation compared to summer days. However, the storage input time (charging hours) is comparatively lower with respect to ScenTM due to available demand

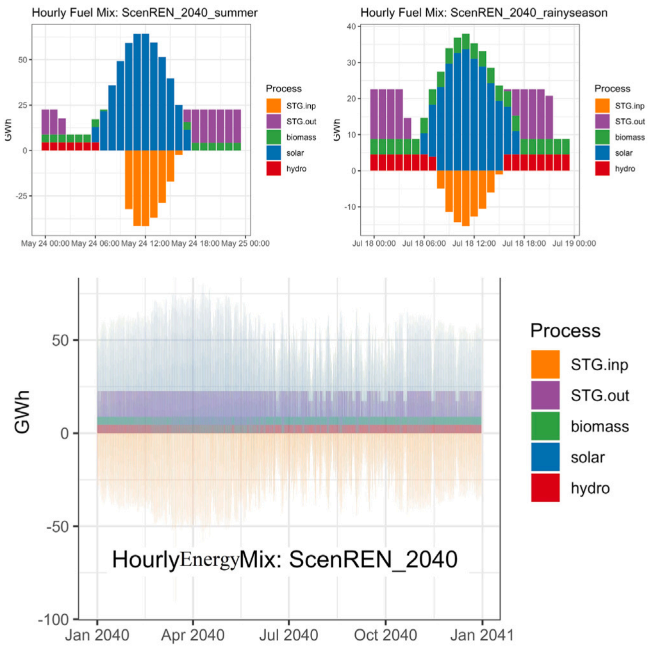


Fig. 20. Hourly modeled operation for ScenREN (2040).

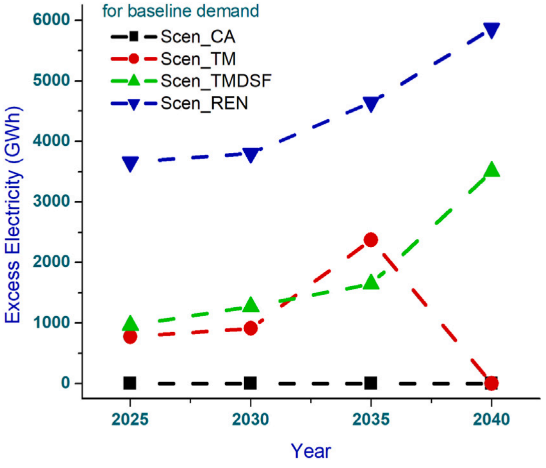


Fig. 21. Excess electricity generation (yearly) for all scenarios with baseline demand growth.

flexibility in this scenario. Only 9.9 GW of storage capacity is required in this scenario while the excess generation is 3503 GWh for 2040 baseline demand. The excess electricity generations are 961.4 GWh, 1273.3 GWh and 1645.31 GWh respectively for the years 2025, 2030 and 2035. Almost 80% of the excess generation is clustered in the morning hours (9 AM to 11 AM) when substantial solar generation is possible compared to small load demand. The hourly energy mix for the 100% renewable scenario (ScenREN) is shown in Fig. 20. The results suggest that 26.8 GW of storage is required (2040 baseline demand) and its use is maximum in the rainy season compared to the summer time. As the thermal share of this scenario is zero, the excess generations are also on the higher side compared to ScenTMDSF for all years. This is clearly depicted in Fig. 21. In contrast to ScenTMDSF scenario, excess generation is almost 4 times for baseline demand in 2025, gradually reduces to 2 times in 2040.

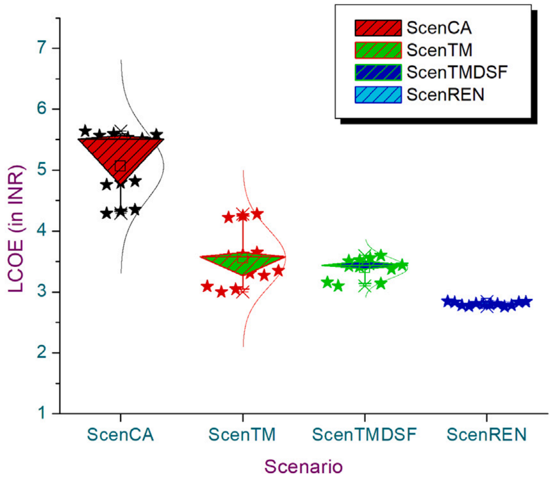


Fig. 22. LCOE.

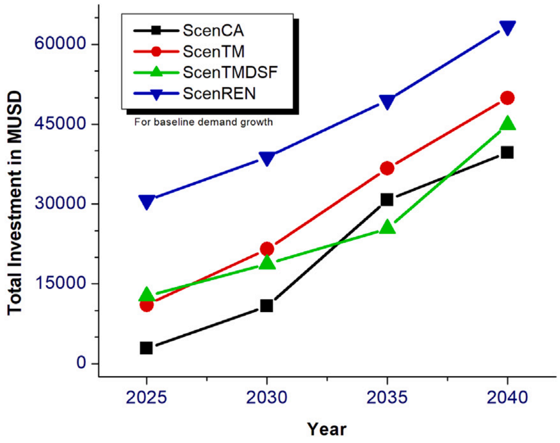


Fig. 23. Total investment cost for capacity expansion in different scenario.

Levelized cost of electricity and total investment cost

The levelized cost of electricity (LCOE) is another important metric to assess the economic viability and competitiveness of different scenarios with different electricity generation technologies. In this work, we have studied LCOE of 4 distinct scenario branches, each having twelve (4 × 3) different variants in terms of demand growth and year. This is shown in Fig. 22. Maximum LCOE is observed for ScenCA due to higher investment and maintenance cost of thermal power plant. It increases gradually over the years with the retirement of existing thermal power plants. In comparison with the ScenCA, almost 18% reduction in average LCOE is observed for the thermal mix scenario with DSF (ScenTMDSF). This value reduces further in case of 100% renewable scenario where thermal share drops with phasing out and DSF is also used. However, very high overnight cost/ investment ($63414 million for 2040 baseline demand) is associated with this scenario as shown in Fig. 23. However, the investment can be substantially reduced if DSF can be adopted with existing thermal stock.

Land requirement for solar capacity expansion

It has already been mentioned in Section "Alternative decarbonization scenarios" that the upper limit of land constraint for ScenTM & ScenTMDSF is restricted to 1% of the total WB land area. However, in many branches of those scenarios, the required land for solar capacity expansion is below the maximum threshold. As per the optimal energy mix, Fig. 24 depicts the land requirement of all branches of three transitional scenarios (ScenTM, ScenTMDSF, ScenREN). Considering

Table 4
Comparison between three transitional scenarios for 2040.

Scenario	Land required (% of total area)	Storage (GW)	LCOE (INR)	Investment (thousand Cr.INR)	Emission (MtCO2e)
ScenTM	1	97.3033333	4.25	412.3804066	27.434
ScenTMDSF	0.87	9.96166667	3.14	370.5790713	38.319
ScenREN	1.32	26.7916667	2.81	523.6747939	0

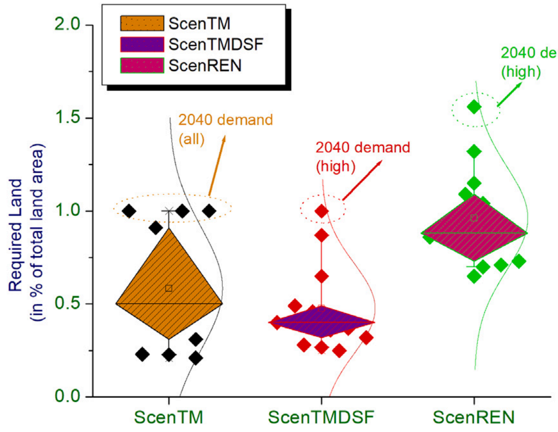


Fig. 24. Required land for solar capacity expansion.

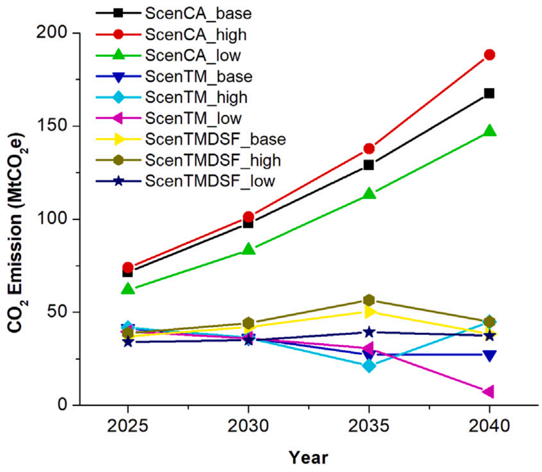


Fig. 25. Carbon dioxide emission in different scenario.

baseline demand growth, only 0.23% of land is required in ScenTM for the year 2025 and touched the maximum threshold for the year 2040 (for baseline, high and low demand growth). However, only 0.87% land is required in the case of ScenTMDSF (for baseline demand growth). Only in case of high demand growth 1% land is required at ScenTMDSF scenario. As, there is no land constraint for ScenREN, the required land is more than 1%. For the year 2040, 1.6% land is required considering high demand growth. Close observation of all the transitional scenarios in Fig. 24 reveals that the minimum land requirement is needed for ScenTMDSF.

Carbon dioxide emission

The projected emissions for different scenarios with thermal share are shown in Fig. 25. Compared with 2025, the carbon dioxide emission may increase around 2.4 times if the current as-usual trend continues till 2040. However, hardly any increment in emission can be observed if solar-dominated ScenTM or ScenTMDSF transitional pathways are followed. In spite of having exactly the same thermal capacity, the emission in ScenTMDSF scenario is marginally high compared with ScenTM. This is because, in the ScenTMDSF scenario, use of thermal is comparatively high whereas, in ScenTM scenario, the maximum capacity is used only for a certain duration as per the least cost optimization.

Discussion

According to the National Institute of Wind Energy (NIWE), West Bengal's potential wind power density reaches a maximum of 200 watts per square meter at a height of 100 m, a figure significantly lower than that of other regions in India. Additionally, the coastal districts of West Bengal face the threat of cyclones and super cyclones, rendering wind infrastructure investments high-risk endeavors. Hence, for West Bengal, potential renewable energy sources include solar, hydro, and biomass, offering alternative avenues for green energy.

Considering the baseline demand growth for the year 2040, Table 4 presents a comparative analysis of various parameters across three transitional scenarios. Notably, the thermal mix scenario with DSF (ScenTMDSF) requires the least amount of land area for solar capacity expansion, investment, and battery storage.[1] Despite these reductions, it still achieves a 77.1% decrease in emissions compared to the current as-usual scenario (ScenCA). Thus, exploring demand-side flexibility as a complementary strategy to manage electricity demand through load shifting becomes imperative. This can be achieved by leveraging consumer-specific load data and introducing tailored incentives, such as time-of-use pricing mechanisms. However, this cannot happen without policy intervention, as the expansion and distribution of renewable energy are increasingly involving private companies, while the retirement of thermal capacity largely falls within the public sector. Therefore, it is essential to develop detailed public–private partnerships. This requires the establishment of new institutional arrangements through task forces or the creation of new institutions at both the national and state levels. Through this open-source model-building effort, we developed a power sector capacity expansion planning model at the subnational level for one of India's coal-rich regions, exploring alternative pathways. This model helps in identifying the broader non-techno-economic challenges necessary for a successful cleaner energy transition, such as the scale of land acquisition and investment needs. However, our findings indicate that even under the current high-thermal scenario, an investment of 39,674.24 million USD (327,630 crore INR) will still be required to meet the 2040 demand (see Fig. 23). By increasing the investment by an additional 13%, a cleaner power system with multiple sustainable development benefits can be achieved. Although a comprehensive cost–benefit analysis, including wider costs and benefits, would help prioritize among multiple goals, this is beyond the scope of this paper. Additionally, this approach could lower the levelized cost of electricity by 44%, offering significant advantages for long-term planning.

This study focuses on minimizing generation costs under various scenarios but does not include the cost differentials associated with transmission and distribution (T&D) infrastructure, land acquisition costs, or the cost of retraining labor for alternative systems. However, these factors could be considered with real data and various power distribution assumptions in future research. Additionally, this study does not address how investments will be mobilized or at what cost. The study raises several follow-up research questions that could shape

---

[1] 6 h battery storage is considered.

future research agendas. While we explored various realistic future scenarios for the state of West Bengal, the model is flexible enough to accommodate other scenarios as well. We do not provide results for rural versus urban or sector-specific demand/load-based assessments, as data were not available from official sources. However, we do have spatial scale resource availability data. The model is also capable of addressing seasonal issues from both supply and demand perspectives. Such analysis with this model could be valuable for regular policy analysis in utility-scale studies.

Conclusions

This paper emphasizes the importance of tailored models and datasets to develop sustainable transition pathways for the electricity sector in a coal-rich sub-region within India's federal structure. The optimal solution, aiming for a 100% renewable scenario by 2025, suggests an immediate shutdown of 10.4 GW of thermal capacity and the addition of 48.24 GW of solar capacity. However, these figures appear overly ambitious, given the substantial stranded assets and investment required for such rapid solar capacity expansion, which the state may not be able to afford. Nonetheless, our proposed model offers flexibility in design to address crucial questions regarding technologically, resource-based, and economically feasible transition pathways for a coal-rich region like West Bengal. In the transitional scenario (ScenT-MDSF) for 2040, it is indicated that through a systematic phase-out of thermal stations in alignment with their retirement schedules, along with the adoption of 15% intra-day load shifting and an investment of only 1.25% of the state's GDP over the next 17 years, it is possible to achieve a significant 77% reduction in emissions. Implementing this solar-dominated future pathway would require only 0.84% of the total land area and nearly 10 GW of battery storage. These findings strongly support optimism regarding the feasibility of energy transition for the state, provided that scientifically grounded transition plans are put into action.

The study also demonstrates that there is an enormous challenge for subnational entities, especially in developing countries, to engage in this visioning process and understand the magnitude of the transition challenges in both the near and long term. This includes determining the scope for energy carrier-specific capacity addition in an economically efficient way and deciding whether to move first or last based on financial arrangements. However, this study shows that it is possible to scientifically develop this essential information, even for developing countries, by focusing efforts on context-specific model building and accessing necessary resources and developmental need-based data before any sectoral dialogue begins at the subnational, national, or international levels. Support for continuing these studies by mobilizing local experts and institutions from each state or country at various levels requires the attention of global research funding. Such scientific studies can only be carried out by engaging appropriately trained human resources who can dedicate their time, energy, and intellectual capacity to addressing global common problems through national and subnational actions. Current global efforts to allocate large funds exclusively to a handful of global-scale integrated assessment models overlook these local context-specific challenges and fail to enrich the global dialogue with diverse realities supported by scientific evidence from a wide variety of contexts, which are necessary to develop a truly global solution with built-in nuances.

CRediT authorship contribution statement

Sourish Chatterjee: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joyashree Roy:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Arijit Mukherjee:** Validation, Data curation. **Oleg Lugovoy:** Software, Methodology. **Anupam Debsarkar:** Writing – review & editing, Resources, Project administration.

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.

Acknowledgment

We gratefully acknowledge the support and funding provided by the Environmental Defense Fund (EDF) for this research.

References

Aduda, K., Labeodan, T., Zeiler, W., Boxem, G., & Zhao, Y. (2016). Demand side flexibility: Potentials and building performance implications. *Sustainable Cities and Society*, *22*, 146–163.

Agrawal, K., Pathak, M., Jana, K., Unni, J., & Shukla, P. (2024). Just transition away from coal: vulnerability analysis of coal districts in India. *Energy Research & Social Science*, *108*, Article 103355.

Ahammed, M. T., & Khan, I. (2022). Ensuring power quality and demand-side management through IoT-based smart meters in a developing country. *Energy*, *250*, Article 123747.

Amrutha, A., Balachandra, P., & Mathirajan, M. (2018). Model-based approach for planning renewable energy transition in a resource-constrained electricity system—A case study from India. *International Journal of Energy Research*, *42*(3), 1023–1039.

Balasubramanian, S., & Balachandra, P. (2021). Effectiveness of demand response in achieving supply-demand matching in a renewables dominated electricity system: A modelling approach. *Renewable and Sustainable Energy Reviews*, *147*, Article 111245.

Bazilian, M. D., Carley, S., Konisky, D., Zerriffi, H., Pai, S., & Handler, B. (2021). Expanding the scope of just transitions: Towards localized solutions and community-level dynamics. *Energy Research & Social Science*, *80*, Article 102245.

Bhongade, S., Dawar, R., & Sisodiya, S. (2021). Demand-side management in an indian village. *Journal of the Institution of Engineers (India): Series B*, 1–9.

Bose, S. (2015). *The messy politics of land acquisition in West Bengal*. The Ohio State University.

Butt, M. H., Roy, J., & Some, S. (2024). Policy as a catalyst in shaping mobility sector transition for developing countries. *Environmental Research Letters*, *19*(2), Article 024039.

Central Electricity Authority, GOI (2024). Installed capacity. https://cea.nic.in/annual-report/?lang=en. (Accessed 15 August 2024).

Central Electricity Authority, India (2019). Long term electricity demand forecasting 2019. https://cea.nic.in/wp-content/uploads/2020/04/Long_Term_Electricity_Demand_Forecasting_Report.pdf. (Accessed 19 April 2023).

Chang, M., Thellufsen, J. Z., Zakeri, B., Pickering, B., Pfenninger, S., Lund, H., et al. (2021). Trends in tools and approaches for modelling the energy transition. *Applied Energy*, *290*, Article 116731.

Child, M., Kemfert, C., Bogdanov, D., & Breyer, C. (2019). Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. *Renewable Energy*, *139*, 80–101.

Dagoumas, A. S., & Koltsaklis, N. E. (2019). Review of models for integrating renewable energy in the generation expansion planning. *Applied Energy*, *242*, 1573–1587.

Dallavalle, E., Cipolletta, M., Moreno, V. C., Cozzani, V., & Zanuttigh, B. (2021). Towards green transition of touristic islands through hybrid renewable energy systems. A case study in Tenerife, Canary Islands. *Renewable Energy*, *174*, 426–443.

D'Ettorre, F., Banaei, M., Ebrahimy, R., Pourmousavi, S. A., Blomgren, E., Kowalski, J., et al. (2022). Exploiting demand-side flexibility: State-of-the-art, open issues and social perspective. *Renewable and Sustainable Energy Reviews*, *165*, Article 112605.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Kadner, S., Zwickel, T., et al. (2011). *Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change*. Cambridge University Press.

Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., et al. (2022). The meaning of net zero and how to get it right. *Nature Climate Change*, *12*(1), 15–21.

Forouli, A., Bakirtzis, E. A., Papazoglou, G., Oureilidis, K., Gkountis, V., Candido, L., et al. (2021). Assessment of demand side flexibility in european electricity markets: A country level review. *Energies*, *14*(8), 2324.

GAMS Development Corp (2023). The general algebraic modeling language, 42.5.0. URL https://www.gams.com/latest/docs/UG_License.html. (Accessed 5 January 2023).

García-García, P., Carpintero, Ó., & Buendía, L. (2020). Just energy transitions to low carbon economies: A review of the concept and its effects on labour and income. *Energy Research & Social Science*, *70*, Article 101664.

Gasanzade, F., Witte, F., Tuschy, I., & Bauer, S. (2023). Integration of geological compressed air energy storage into future energy supply systems dominated by renewable power sources. *Energy Conversion and Management*, *277*, Article 116643.

Gaur, A. S., Das, P., Jain, A., Bhakar, R., & Mathur, J. (2019). Long-term energy system planning considering short-term operational constraints. *Energy Strategy Reviews*, *26*, Article 100383.

Giannelos, S., Jain, A., Borozan, S., Falugi, P., Moreira, A., Bhakar, R., et al. (2021). Long-term expansion planning of the transmission network in India under multi-dimensional uncertainty. *Energies*, *14*(22), 7813.

GOI (2015). Union civil performance renewable energy report 34, chapter 6. https://cag.gov.in/uploads/download_audit_report/2015/Union_Civil_Performance_Renewable_Energy_Report_34_2015_chap_6.pdf.

Gulagi, A., Bogdanov, D., & Breyer, C. (2018). The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India. *Journal of Energy Storage*, *17*, 525–539.

Halder, B., Banik, P., Almohamad, H., Al Dughairi, A. A., Al-Mutiry, M., Al Shahrani, H. F., et al. (2022). Land suitability investigation for solar power plant using GIS, AHP and multi-criteria decision approach: a case of megacity Kolkata, West Bengal, India. *Sustainability*, *14*(18), 11276.

Hansen, K., Mathiesen, B. V., & Skov, I. R. (2019). Full energy system transition towards 100% renewable energy in Germany in 2050. *Renewable and Sustainable Energy Reviews*, *102*, 1–13.

Hassen, B. N., Surroop, D., & Praene, J. P. (2023). Phasing-out of coal from the energy system in mauritius. *Energy Strategy Reviews*, *46*, Article 101068.

Heffron, R., Körner, M.-F., Wagner, J., Weibelzahl, M., & Fridgen, G. (2020). Industrial demand-side flexibility: A key element of a just energy transition and industrial development. *Applied Energy*, *269*, Article 115026.

Heffron, R. J., & McCauley, D. (2022). The 'just transition' threat to our energy and climate 2030 targets. *Energy Policy*, *165*, Article 112949.

Helistö, N., Kiviluoma, J., & Holttinen, H. (2018). Long-term impact of variable generation and demand side flexibility on thermal power generation. *IET Renewable Power Generation*, *12*(6), 718–726.

Hong, T., Pinson, P., Wang, Y., Weron, R., Yang, D., & Zareipour, H. (2020). Energy forecasting: A review and outlook. *IEEE Open Access Journal of Power and Energy*, *7*, 376–388.

Hunt, J. D., Weber, N. d. A. B., Zakeri, B., Diaby, A. T., Byrne, P., Leal Filho, W., et al. (2021). Deep seawater cooling and desalination: Combining seawater air conditioning and desalination. *Sustainable Cities and Society*, *74*, Article 103257.

IDEEA: Indian zero carbon energy pathways optimization model. (2024). URL https://github.com/ideea-model. R Package Version 0.0.29.9000, https://ideea-model.github.io/IDEEA/index.html.

International Energy Agency (2022). Global energy and climate model documentation. https://iea.blob.core.windows.net/assets/2db1f4ab-85c0-4dd0-9a57-32e542556a49/GlobalEnergyandClimateModelDocumentation2022.pdf.

IPCC Report (2022). *Climate change 2022: Impacts, adaptation and vulnerability*: *Tech. rep.*, Cambridge, UK and New York, USA: Cambridge University Press, URL https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryVolume.pdf.

IPCC Sixth Assessment Report (2022). *Demand, services and social aspects of mitigation*: *Tech. rep.*, Cambridge, UK and New York, USA: Cambridge University Press, http://dx.doi.org/10.1017/9781009157926.007, URL https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter05.pdf.

Isoaho, K., Goritz, A., & Schulz, N. (2016). *Governing clean energy transitions in China and India: A comparative political economy analysis*: *Tech. rep., WIDER working paper*.

Janardhanan, N., & Tamura, K. (2020). The sociopolitical dynamics of coal transition in India. *International Studies*, *57*(2), 171–185.

Jin, W., Shi, X., & Zhang, L. (2021). Energy transition without dirty capital stranding. *Energy Economics*, *102*, Article 105508.

Kanitkar, T., Banerjee, R., & Jayaraman, T. (2019). An integrated modeling framework for energy economy and emissions modeling: a case for India. *Energy*, *167*, 670–679.

Karunanithi, K., Saravanan, S., Prabakar, B., Kannan, S., & Thangaraj, C. (2017). Integration of demand and supply side management strategies in generation expansion planning. *Renewable and Sustainable Energy Reviews*, *73*, 966–982.

Kohlhepp, P., Harb, H., Wolisz, H., Waczowicz, S., Müller, D., & Hagenmeyer, V. (2019). Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: A review of international field studies. *Renewable and Sustainable Energy Reviews*, *101*, 527–547.

Land Use & Cover Monitoring Divn, ISRO, Dept. of Space, GOI (2016). Wasteland maps: 2015-16 on 1:50,000 scale. https://dolr.gov.in/sites/default/files/West%20Bengal_0.pdf. (Accessed 19 February 2023).

Löffler, K., Burandt, T., Hainsch, K., & Oei, P.-Y. (2019). Modeling the low-carbon transition of the European energy system-a quantitative assessment of the stranded assets problem. *Energy Strategy Reviews*, *26*, Article 100422.

Lugovoy, O., Jyothiprakash, V., Chatterjee, S., Sharma, S., Mukherjee, A., Das, A., et al. (2021). Towards a zero-carbon electricity system for india in 2050: Ideea model-based scenarios integrating wind and solar complementarity and geospatial endowments. *Energies*, *14*(21), 7063.

Lugovoy, O., & Potashnikov, V. (2022). energyRt: Energy systems modeling toolbox in R, development version. URL https://github.com/energyRt/energyRt. R package version 0.01.21.9003.

Lugovoy Oleg & Gao Shuo (2021). MERRA-2 subset for evaluation of renewables with merra2ools R-package: 1980–2020 hourly, dryad, dataset. https://doi.org/10.5061/dryad.v41ns1rtt. (Accessed 22 February 2023).

Maamoun, N., Chitkara, P., Yang, J., Shrimali, G., Busby, J., Shidore, S., et al. (2022). Identifying coal plants for early retirement in India: a multidimensional analysis of technical, economic, and environmental factors. *Applied Energy*, *312*, Article 118644.

Mahtta, R., Joshi, P. K., & Jindal, A. K. (2014). Solar power potential mapping in India using remote sensing inputs and environmental parameters. *Renewable Energy*, *71*, 255–262.

McKenna, R., Hernando, D. A., ben Brahim, T., Bolwig, S., Cohen, J. J., & Reichl, J. (2021). Analyzing the energy system impacts of price-induced demand-side-flexibility with empirical data. *Journal of Cleaner Production*, *279*, Article 123354.

Ministry of Coal, Govt. of India (2023). Coal reserves. https://coal.gov.in/en/major-statistics/coal-reserves. (Accessed 15 March 2023).

Ministry of New and Renewable Energy, GOI (2024). State wise installed capacity of renewable power. https://mnre.gov.in/physical-progress/. (Accessed 15 August 2024).

National Power Portal, CEA (2023). Daily generation report. https://npp.gov.in/dgrReports. (Accessed 15 February 2022).

Oshiro, K., Masui, T., & Kainuma, M. (2018). Transformation of Japan's energy system to attain net-zero emission by 2050. *Carbon Management*, *9*(5), 493–501.

Parzen, M., Abdel-Khalek, H., Fedotova, E., Mahmood, M., Frysztacki, M. M., Hampp, J., et al. (2023). PyPSA-Earth. A new global open energy system optimization model demonstrated in Africa. *Applied Energy*, *341*, Article 121096.

Pietzcker, R. C., Osorio, S., & Rodrigues, R. (2021). Tightening EU ETS targets in line with the European green deal: Impacts on the decarbonization of the EU power sector. *Applied Energy*, *293*, Article 116914.

Pressburger, L. D., Evans, M., Yu, S., Cui, Y., Somani, A., & Iyer, G. C. (2022). *A comprehensive economic coal transition in south Asia*: *Tech. rep.*, Richland, WA (United States): Pacific Northwest National Laboratory (PNNL).

Rosenbloom, D., & Meadowcroft, J. (2022). Accelerating pathways to net zero: Governance strategies from transition studies and the transition accelerator. *Current Climate Change Reports*, *8*(4), 104–114.

Samanta, P. (2015). Impact assessment and changes analysis of land use/land cover due to open cast coal mining activity: A case study of raniganj coal field area. *International Journal of IT, Engineering and Applied Sciences Research*, *4*(5), 17–27.

Sambasivam, B., & Xu, Y. (2023). Reducing solar PV curtailment through demand-side management and economic dispatch in Karnataka, India. *Energy Policy*, *172*, Article 113334.

Saundry, P. D. (2019). Review of the United States energy system in transition. *Energy, Sustainability and Society*, *9*(1), 4.

Scheller, F., Burkhardt, R., Schwarzeit, R., McKenna, R., & Bruckner, T. (2020). Competition between simultaneous demand-side flexibility options: the case of community electricity storage systems. *Applied Energy*, *269*, Article 114969.

Sharda, S., Singh, M., & Sharma, K. (2021). Demand side management through load shifting in IoT based HEMS: Overview, challenges and opportunities. *Sustainable Cities and Society*, *65*, Article 102517.

Sioshansi, F. (2020). *Variable generation, flexible demand*. Academic Press.

Stavrakas, V., & Flamos, A. (2020). A modular high-resolution demand-side management model to quantify benefits of demand-flexibility in the residential sector. *Energy Conversion and Management*, *205*, Article 112339.

Thakur, J., & Chakraborty, B. (2016). Demand side management in developing nations: A mitigating tool for energy imbalance and peak load management. *Energy*, *114*, 895–912.

The West Bengal Power Department Corporation Limited (2023). Coal mines in WB. https://wbpdcl.co.in/mines. (Accessed 15 March 2023).

United Nations Climate Change Conferences (2023). Summary of global climate action at cop 28. https://unfccc.int/sites/default/files/resource/Summary_GCA_COP28.pdf. (Accessed 11 May 2024).

United Nations Environment Programme (2020). The adaptation gap report 2020. https://www.unep.org/resources/adaptation-gap-report-2022. (Accessed 9 May 2023).

United Nations Environment Programme (2023). Emissions gap report 2023. https://wedocs.unep.org/bitstream/handle/20.500.11822/43922/EGR2023.pdf. (Accessed 11 May 2024).

Van de Ven, D.-J., Capellan-Peréz, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., et al. (2021). The potential land requirements and related land use change emissions of solar energy. *Scientific Reports*, *11*(1), 1–12.

West Bengal State Electricity Distribution Company Limited (2023). Hydro potential of westbengal. https://wb.gov.in/business-power-energy-industry.aspx. (Accessed 19 February 2023).

Xiao, M., Simon, S., & Pregger, T. (2019). Scenario analysis of energy system transition-A case study of two coastal metropolitan regions, eastern China. *Energy Strategy Reviews*, *26*, Article 100423.

Zappa, W., Junginger, M., & Van Den Broek, M. (2019). Is a 100% renewable European power system feasible by 2050? *Applied Energy*, *233*, 1027–1050.