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ASSESSING THE IMPACTS OF EMISSION REDUCTION TARGETS ON ELECTRICITY PRICING AND CARBON MITIGATION COST IN THE BIMSTEC REGION

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ABSTRACT

The power sector is a major contributor to global greenhouse gas emissions, making the decarbonization of power grids a critical step toward achieving the commitments outlined in the Paris Agreement. In the BIMSTEC region—comprising India, Bangladesh, Bhutan, Myanmar, Nepal, Thailand, and Sri Lanka—countries face significant challenges due to the uneven distribution of energy resources and rapidly increasing energy demands. This study aims to explore strategies for decarbonizing the power grids of these member states through energy cooperation and the adoption of advanced technologies such as clean hydrogen and carbon capture and storage (CCS). A spatially disaggregated capacity expansion model, utilizing IBM CPLEX Optimization Studio, is developed to minimize total power system costs up to 2050. The model incorporates various policy scenarios to identify optimal pathways. Simulation results indicate that renewable energy sources such as wind, hydro, solar PV, and nuclear will dominate the energy mix, substantially reducing reliance on coal and natural gas under carbon regulation policies. Furthermore, hydrogen storage technology emerges as a crucial solution for addressing resource deficits and maintaining grid stability over both short and long-time horizons. The study also determines appropriate carbon tax rates per tonne of CO_2 to support emission reduction targets across different scenarios.

Keywords: BIMSTEC, Decarbonization, Power grid, Carbon tax, Electricity price

1. Introduction

The Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC) is a regional alliance comprising seven member nations: five from South Asia—Nepal, Bangladesh, India, Bhutan, and Sri Lanka—and two from Southeast Asia, Myanmar and Thailand[1]. Collectively, these countries represent a population exceeding 1.65 billion and boast a combined GDP of $3.75 trillion, positioning the region as one of the fastest-growing in the world [2]. The rapid economic development within BIMSTEC has led to a significant rise in electricity demand, underscoring the necessity for a cost-efficient and reliable electricity supply to sustain socio-economic progress[3]. The energy landscape of the region is diverse: Bangladesh, Myanmar, and Thailand primarily rely on natural gas and petroleum for power generation [4], while Bhutan and Nepal derive almost their entire electricity supply from indigenous hydropower resources[5]. India heavily relies on domestic and imported coal to meet its domestic electricity demand[6].

The BIMSTEC region is endowed with substantial natural resources, including 323 billion tonnes of coal, 664 million tonnes of oil, 144 trillion cubic feet (TCF) of natural gas, 11,346 million tonnes of biomass, and a potential for 331 GW of large-scale hydropower and 1,000 GW of renewable energy [7]. Recognizing the pivotal role of energy in driving socio-economic development, BIMSTEC has identified energy cooperation as a strategic priority[8]. This commitment is exemplified by initiatives such as the

BIMSTEC Energy Centre, established in 2005, which serves as a platform for fostering collaboration, facilitating knowledge exchange, and promoting best practices in energy development[2].

The BIMSTEC region faces considerable challenges in transitioning to low-carbon energy systems, despite its potential for sustainable energy development. India, the largest electricity consumer and carbon emitter in the region, relies on coal for over two-thirds of its electricity generation[9]. Between 2015 and 2018, carbon emissions in the BIMSTEC region doubled, with India leading in total emissions and Thailand and Bhutan recording the highest per capita emissions[10]. Climate change, driven by greenhouse gas emissions from fossil fuel consumption, poses a critical threat, prompting regional commitments to the Paris Agreement's goal of limiting global temperature rise[11]. Decarbonizing the power sector is essential to achieving this target and requires innovative measures, including expanding renewable energy integration, retrofitting existing facilities with carbon capture and storage technologies, and implementing carbon pricing mechanisms[12].

Cross-border power trade plays a pivotal role in the energy dynamics of the BIMSTEC region. Bhutan exports a substantial share of its electricity to India[13], while Bangladesh depends on electricity imports from India to meet their domestic energy needs[14]. There has been significant exchange of electricity between India and Nepal[15]. These bilateral trade arrangements underscore the advantages of regional collaboration in enhancing energy security and addressing variability in supply and demand[7]. To further strengthen regional energy integration, BIMSTEC member states have initiated projects such as the BIMSTEC Trans Power Exchange and Development Project, which aims to establish regional grid interconnections, optimize the utilization of energy resources, and facilitate cross-border electricity trade[1].

Hydropower constitutes a fundamental component of the BIMSTEC region's renewable energy portfolio, supported by the increasing potential of solar and wind energy[16]. However, the continued reliance on more cost-effective indigenous resources such as coal and natural gas has led to a significant rise in carbon emissions[17]. In response to the region's commitment to mitigating anthropogenic emissions, the member countries are prioritizing multilateral collaboration to develop cleaner energy sources[18]. Strategies such as the establishment of regionally integrated power grids and the implementation of carbon taxation are being explored as potential mechanisms to mitigate greenhouse gas emissions, although these measures are likely to result in higher electricity prices[19]. The evaluation of decarbonization strategies of power plants in the BIMSTEC region, along with the assessment on carbon taxation and electricity pricing, necessitates the development of flexible, spatially disaggregated, and dynamic models of power sector operations.

A study [20] provides an overview of key power sector models, detailing their spatial, temporal, and geographical resolutions, capabilities, and methodologies. Another study examines hypothetical decarbonization pathways for ASEAN's power sector from 2018 to 2050 using an integrated capacity expansion model[21]. Another study[22] explores how combining and sequencing carbon pricing, green innovation, and industrial policies—such as those adopted by California and the EU—can address political, environmental, and economic challenges in decarbonizing energy systems. Similarly, a paper[23] simulates the impact of volatile fuel prices and emissions pricing on generator profits in a liberalized electricity market, finding that a carbon tax reduces volatility for nuclear generators but increases it for fossil fuel plants, favoring optimal portfolios with higher nuclear shares.

This study seeks to bridge the existing research gap by formulating an advanced multi-regional power grid model for the BIMSTEC region. A detailed analysis of the results is conducted to provide insights into the advantages of cross-border power trade, optimal utilization of indigenous resources, and the effective harnessing of unevenly distributed energy resources to address fluctuating seasonal electricity demands and presents pathways for sustainable energy transition of one of the most populous and economically significant regions globally. Additionally, it examines the impacts of emission reduction targets, determines the appropriate levels of carbon taxes required to achieve these objectives, and analyzes their implications for electricity pricing.

2. Research methods

This study is done by developing a multi-regional capacity expansion model of BIMSTEC region designed to operate within defined technical constraints, employing linear programming methodologies to achieve cost minimization. The regional characteristics like electricity demand, resource availability, technological costs are given as input data in the model taking 2020 as the base year. The policy analysis is performed by developing various emission reduction scenarios in every five years, with an hourly temporal resolution for each year, extending through to 2050.

2.1 Model development

The fundamental framework of the developed model has been outlined in the authors' previous work [24][25]. The model encompasses three categories of hydropower plants, namely, run-of-river (ROR), pondage run-of-river (PROR), and storage hydropower plants. Additionally, it integrates two types of intermittent renewable energy sources, specifically solar photovoltaic (PV) and wind power, alongside hydrogen system components such as electrolyzer, steel storage tanks, and fuel cells as energy storage technologies. Electricity generated by the power plants is dispatched to the grid to meet demand. Any surplus electricity is converted into hydrogen using an electrolyzer and stored in a tank. The stored hydrogen can subsequently be reconverted into electricity when required. The model also facilitates the transfer of electricity between various substations through transmission lines and incorporates coal transportation via dedicated infrastructure.

The model operates under a set of defined constraints and utilizes linear programming techniques to achieve optimal solutions. It calculates the active power balance within the system on an hourly basis, encompassing an annual time frame of 8760 hours (365 days × 24 hours/day). Additionally, it determines the optimal generation mix required to meet electricity demand for a given exogenous load curve extending up to 2050 in every ten years, making 2030, 2040, and 2050 its representative years. The model also endogenously determines the optimal capacity expansion for the technologies under consideration through optimization processes. Furthermore, it accounts for three modes of fuel supply for thermal power plants—domestic production, inter-node transportation, and imports—with their respective shares determined endogenously within the model. The comprehensive mathematical formulations underpinning the developed model are presented in Ref. [24].

2.2 Study area

The BIMSTEC region is divided into 11 nodes: Bangladesh (BD), Bhutan (BT), Nepal (NP), Sri Lanka (LK), Myanmar (MM), Thailand (TH), and five distinct regions within India—North (IN), West (IW), South (IS), East (IE), and Northeast (INE). The division of India into regional nodes is based on its national grid structure to more accurately represent the resource availability and demand characteristics of each area. This study considers 18 power transmission lines for bulk electricity transfer between nodes, as illustrated in **Figure 1**. These include 11 cross-border transmission lines and 7 transmission lines within India's internal nodes. The maximum capacities of these transmission lines are derived from the national plans of the respective countries and relevant literature[26][27][28]. Substations are assumed to supply power to the node in which they are located or to adjacent nodes. Data on transmission lines have been sourced from the BIMSTEC Energy Outlook [7].

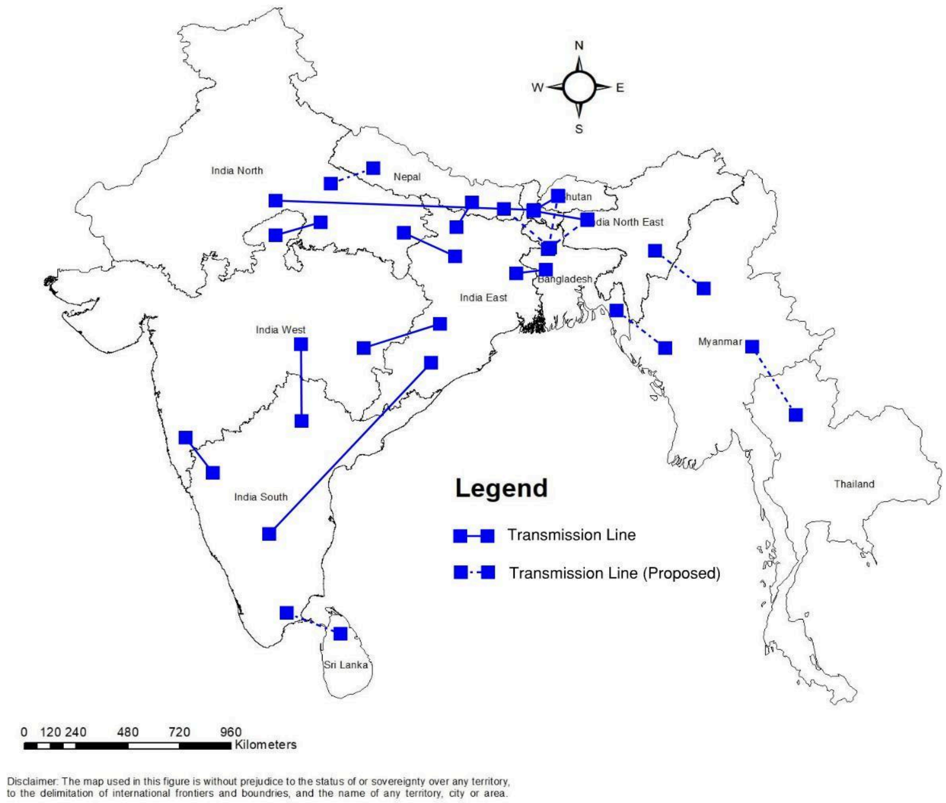

Figure 1: Geographic distribution of the nodes and the transmission lines considered in this model

2.3 Model input

The model integrates electricity demand projections and cost data obtained from various sources. Projections for Thailand extend to 2036, Myanmar to 2030, and Nepal and Bhutan to 2040, with extrapolated assumptions for the years 2040 and 2050. For India, electricity demand across its five nodes was estimated using a logarithmic regression model, based on projections provided by the Central Electricity Authority (CEA) in the 19th Electric Power Survey report, which covers states and union territories up to 2036–2037[29]. In the cases of Bangladesh and Sri Lanka, hourly electricity demand for representative years was forecasted using historical demand patterns, under the assumption of consistent daily and hourly demand coefficients.

The model incorporates resource inputs such as coal and natural gas reserves, along with the maximum potential for hydropower, solar photovoltaic (PV), and wind power across the analyzed nodes. Due to the minimal contribution of indigenous oil and limited data on nuclear fuel, only imported oil and nuclear fuel were included in the analysis. Node-specific maximum capacities for hydropower were projected based on planned and proposed expansion projects. Coal and gas production capacities were assumed to grow at historical rates, with 80% of coal and 20% of natural gas reserves allocated to power generation in India, and 60% of natural gas reserves allocated in Bangladesh.

The capacity factor for solar PV was derived from simulations, accounting for a 10% system loss. The daily availability factor for run-of-river (ROR) and partially regulated (PROR) hydropower projects in India and Thailand was calculated using daily generation records from the previous three years[30]. For Nepal, Myanmar, and Bangladesh, this data was obtained from their respective load dispatch centers, while for Bhutan and Sri Lanka, it was calculated based on monthly hydropower generation trends. The availability factor for hydropower storage projects was determined using the generation pattern of hydro ROR plants, while maintaining a constant annual availability factor. The model optimizes the operational schedule for hydro PROR and storage projects to achieve ideal performance.

The cost parameters for power plants, encompassing construction, operation, and maintenance, were obtained from various references [31]. The cost of hydropower is anticipated to increase due to the scarcity of low-cost resources, whereas the costs for solar photovoltaic (PV) and wind energy are projected to decline substantially. Battery costs were derived from Ref.[32], and data for pumped storage systems were based on ongoing Indian projects as outlined in Ref.[33]. Transmission line costs were estimated based on the connection type and distance, with inverter costs ranging from $0.5 to $0.75 per kilometer per kilowatt[34]. Coal transportation costs were set at $0.22 per kilometer per ton, while gas storage costs were estimated at $40 per ton.

Domestic coal and gas prices were predicted using cumulative production cost curves, with resources categorized into eight cost segments. In 2020, the import prices for coal, gas, and oil, inclusive of transportation and insurance, were $130, $250, and $300 per ton, respectively[35]. Future price fluctuations were aligned with the International Energy Agency's (IEA) projections under the New Policies Scenario (2015) [36]. The cost of nuclear fuel, including transportation, spent fuel management, and decommissioning, was estimated at $80 per ton [24]. Biomass costs, reported at $60 per ton in 2020, are projected to increase to $69 per ton by 2050. The technical attributes of various technologies were sourced from the Central Electricity Authority, as detailed in Ref.[29]. The technical assumptions are taken from different literatures [24][25].

2.4 Scenario design

This study developed six distinct scenarios to explore the implications of emission restrictions aimed at decarbonizing the economy. These scenarios are Business as Usual (BAU), 20% Emission Restriction (ER20), 40% Emission Restriction (ER40), 60% Emission Restriction (ER60), 80% Emission Restriction (ER80), 100% Emission Restriction (ER100). The BAU scenario represents the outcomes under India’s current carbon tax rate of approximately $7.5 per ton of CO_2. In contrast, the other scenarios impose progressively stringent emission restrictions to evaluate pathways for decarbonizing the electricity sector. For each representative year, the emission levels were defined to progressively achieve reduction targets by 2050. These targets were set at 20%, 40%, 60%, 80%, and 100% of the total CO_2 emissions projected for 2050 under the BAU scenario. Accordingly, the scenarios ER20, ER40, ER60, ER80, and ER100 correspond to emission reduction targets of 20%, 40%, 60%, 80%, and 100%, respectively.

3. Results and discussion

The computational experiments for each of the six previously described scenarios were conducted using IBM CPLEX Optimization Studio version 12.5.

3.1 Capacity and generation mix

The optimal capacity mix under six distinct scenarios is presented in **Figure 2**, revealing that emissions in the Business-as-Usual (BAU) scenario surpass the targets established in the Paris Agreement. Progressive emission reduction constraints are imposed across scenarios, decreasing emissions incrementally by 20% of BAU levels in scenarios ranging from ER20 to ER100 by 2050. The BAU scenario is predominantly characterized by coal-based generation as depicted in **Figure 3**; however, as emission restrictions become more stringent, the share of solar PV generation increases, while coal's contribution diminishes. Additionally, storage technologies such as pumped hydro storage and batteries gain prominence to ensure system reliability and to mitigate the intermittency associated with renewable energy sources. These findings underscore the critical role of solar PV in facilitating the decarbonization of the regional electricity sector.

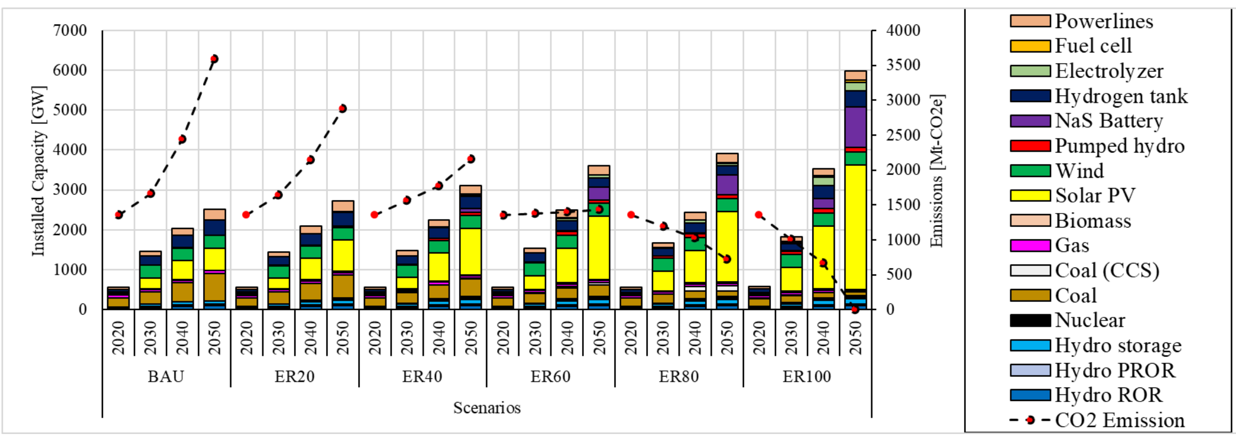

Figure 2: Optimal growth of capacity mix under six different scenarios

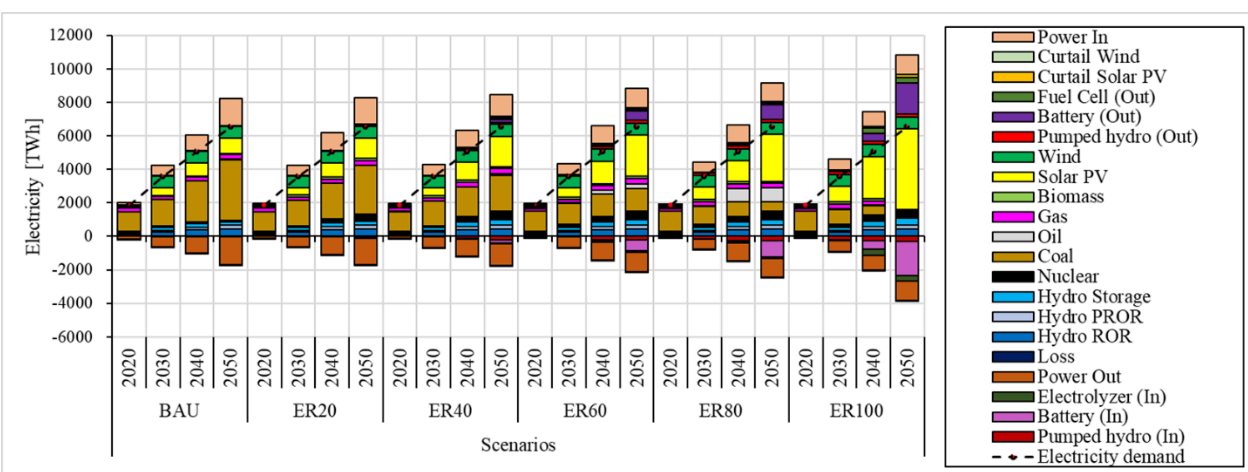

Figure 3: Transition of optimal generation mix

Hydropower, specifically ROR and PROR plants, dominate the capacity mix in Northeast India, Nepal, and Bhutan due to their cost-effectiveness. However, the share of hydropower storage and solar photovoltaic (PV) technologies increases significantly as emission restrictions become more stringent. **Figure 4** presents the optimal capacity configurations across 11 regions under the Business-as-Usual (BAU) and 100% Emission Reduction (ER100) scenarios for the year 2050. In the BAU scenario, the northern regions of India are primarily reliant on hydropower, the eastern regions depend on coal, while the southern and western regions exhibit a substantial share of wind power. Under the ER100 scenario, solar PV coupled with storage technologies experiences substantial growth, significantly reducing coal dependency by 2050. Additionally, the deployment of pumped hydropower and hydropower storage increases in Bhutan, Nepal, and Northeast India. In the BAU scenario, coal overwhelmingly dominates the generation mix in India's nodes by 2050, whereas in emission-restricted scenarios, renewable energy technologies—including solar PV, wind, and advanced battery storage systems—become the primary contributors.

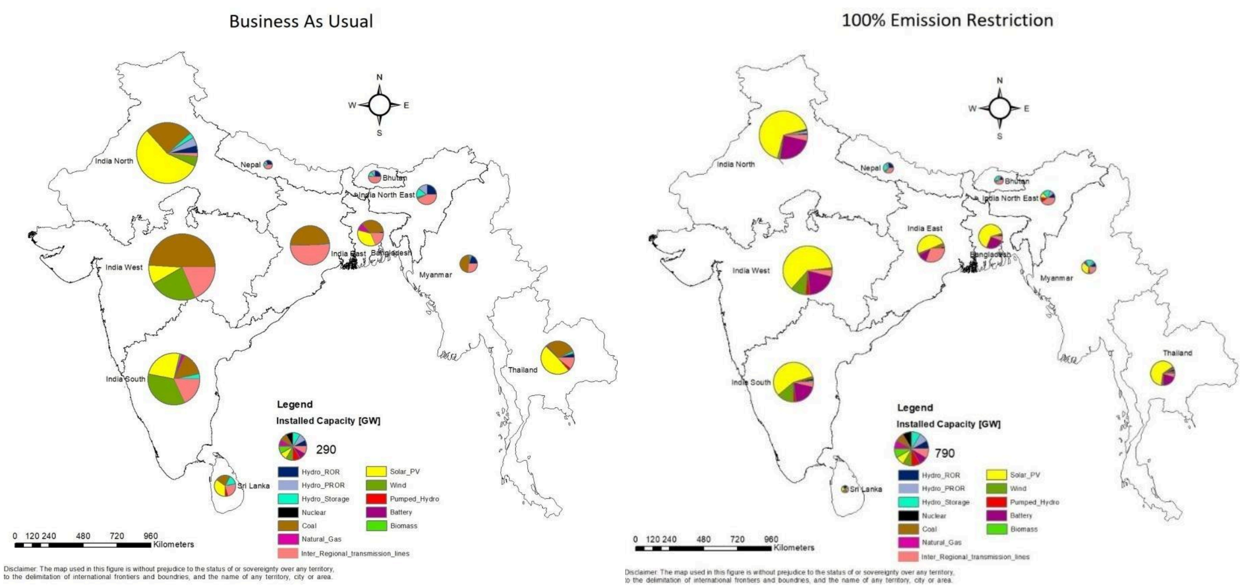

Figure 4: Optimal capacity mix of each node under BAU and ER100 scenarios

3.2 Cross-border power trade

In regions abundant in hydropower and coal resources, transmission lines are primarily utilized to evacuate surplus electricity within the respective nodes. Hydropower-dominated nodes consistently generate sufficient electricity to fulfill domestic demand while supplying resource-deficient nodes across all scenarios. Similarly, coal-rich nodes depend on locally available coal to satisfy their energy requirements. In contrast, the generation mix in resource-deficient regions exhibits significant variation depending on the scenario. Under the Business-as-Usual (BAU) scenario, coal remains the dominant energy source, whereas renewable energy technologies take precedence under emission-restricted scenarios. **Table 1** presents the transmission line capacities across the scenarios developed in this study. The maximum capacities of cross-border transmission lines are derived from national plans and other relevant literature. Cross-border transmission lines, with the exception of the India-South to Sri Lanka connection, are fully utilized across all scenarios through 2050. Meanwhile, the capacities of domestic transmission lines vary by scenario. Under emission-restricted scenarios, transmission capacities increase to support greater integration of hydropower, while the transmission of fossil fuel-based electricity decreases accordingly.

Table 1: Transmission lines capacity under considered scenarios

Transmission lines	Initial capacity (GW)	Maximum capacity (GW)	Capacity in 2050 (GW)					
			BAU	ER20	ER40	ER60	ER80	ER100
BD <=> BT	0.00	3	3.0	3.0	3.0	3.0	3.0	3.0
BD <=> IE	0.50	5	5.0	5.0	5.0	5.0	5.0	5.0
BD <=> INE	0.16	6	6.0	6.0	6.0	6.0	6.0	6.0
BD <=> NP	0.00	3	3.0	3.0	3.0	3.0	3.0	3.0
BD <=> MM	0.00	5	5.0	5.0	5.0	5.0	5.0	5.0
BT <=> IE	1.50	15	14.5	14.5	14.8	14.9	14.9	15.0
IN <=> NP	0.10	15	15.0	15.0	15.0	15.0	15.0	15.0
IS <=> LK	0.00	4	3.5	2.7	2.1	2.1	2.1	2.7
IE <=> NP	0.50	8	8.0	8.0	8.0	7.9	8.0	8.0
INE <=> MM	0.00	4	4.0	4.0	4.0	4.0	4.0	4.0
MM <=> TH	0.00	20	20.0	20.0	20.0	20.0	20.0	20.0
IN <=> IW	12.92	-	45.5	51.6	20.3	13.0	13.4	12.9
IN <=> IE	15.83	-	16.1	18.6	35.0	43.4	45.0	19.7
IN <=> INE	1.50	-	1.5	1.5	1.5	1.5	1.5	1.5
IW <=> IS	7.92	-	41.0	25.5	7.9	7.9	7.9	8.0
IW <=> IE	10.69	-	27.1	24.9	14.3	12.8	11.7	30.6
IS <=> IE	3.63	-	28.3	29.1	29.3	24.5	26.5	25.6
IE <=> INE	2.86	-	20.6	27.9	32.3	32.3	33.7	49.0

Figure 5 illustrates the cumulative electricity flow between nodes under the ER100 scenario. The proportion of electricity transmitted from India South to neighboring nodes decreases under emission-restricted scenarios, reflecting a reduction in electricity generation from thermal power plants. Conversely, the volume of electricity transmitted from India Northeast to neighboring nodes increases under the ER100 scenario compared to other scenarios. This shift occurs as hydropower emerges as a

more economically viable option due to the imposition of carbon taxes, which diminish the cost-competitiveness of fossil fuels.

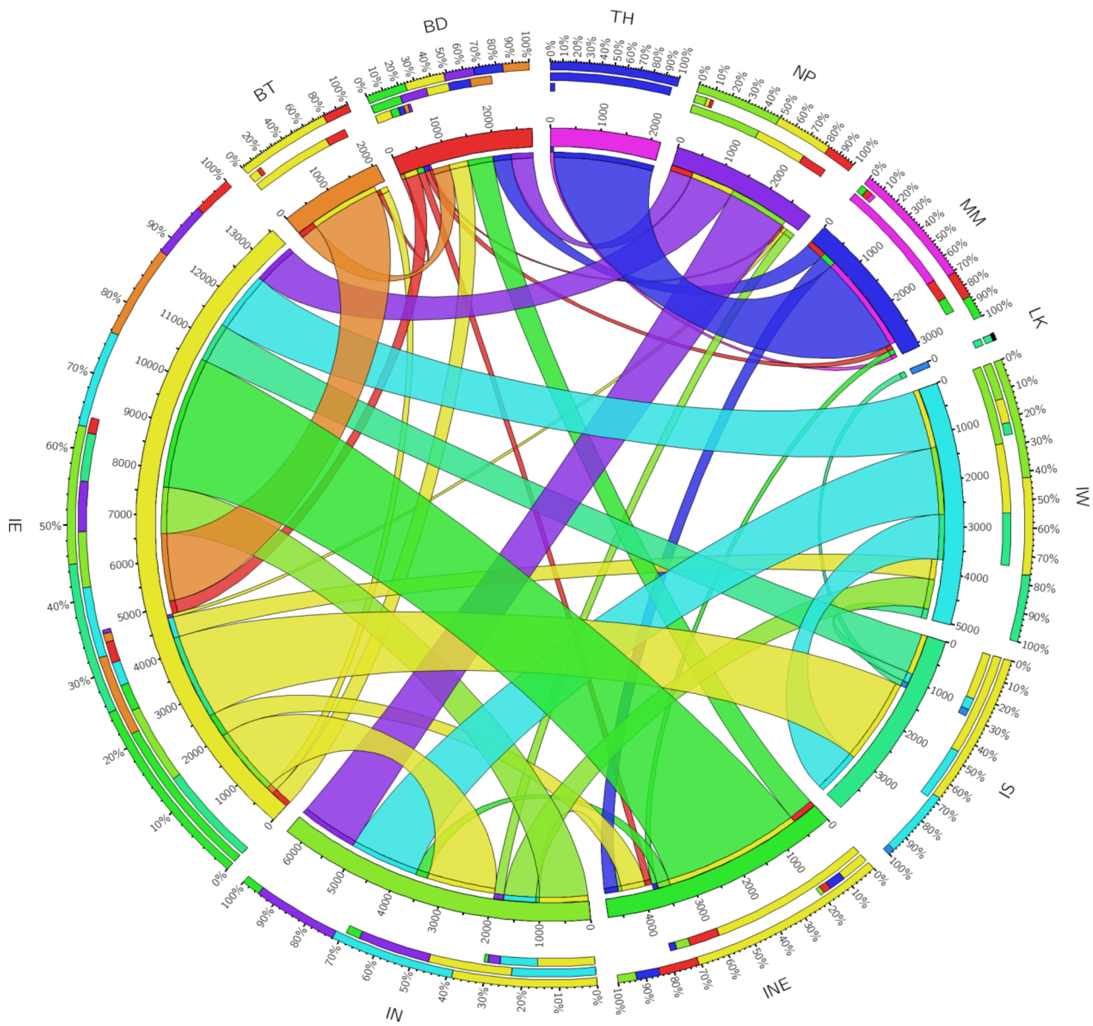

Figure 5: illustrates the cumulative electricity flow (2020–2050) between the nodes (in TWh) within the BIMSTEC region under the ER100 scenario. The names of the nodes are positioned outside the circular diagram. The three concentric bars, representing the percentage mix, correspond to electricity outflow, inflow, and the net difference, progressing from the outermost to the innermost circle, respectively. The color of each arc denotes the total volume of electricity—both incoming and outgoing—associated with a specific node. The flow bands connecting the nodes indicate the magnitude of power exchange between the nodes

3.3 Electricity price and carbon mitigation cost

Electricity prices exhibit an upward trend as emission restrictions become more stringent (**Figure 6**). Nodes with a fossil fuel-dominated generation mix experience a sharp increase in electricity prices, whereas the impact is comparatively lower in nodes with a higher share of renewable energy in their generation mix. The highest electricity price is observed in Thailand, reaching $122 per MWh in 2030.

Under the complete decarbonization scenario in 2050, electricity prices (in \$/MWh) are projected as follows for the BIMSTEC region: Bangladesh (92.4), Bhutan (64.7), India North (77.7), India West (77.8), India South (82.4), India East (80.2), India Northeast (72.7), Nepal (64.7), Sri Lanka (81.5), Myanmar (75.7), and Thailand (84.1).

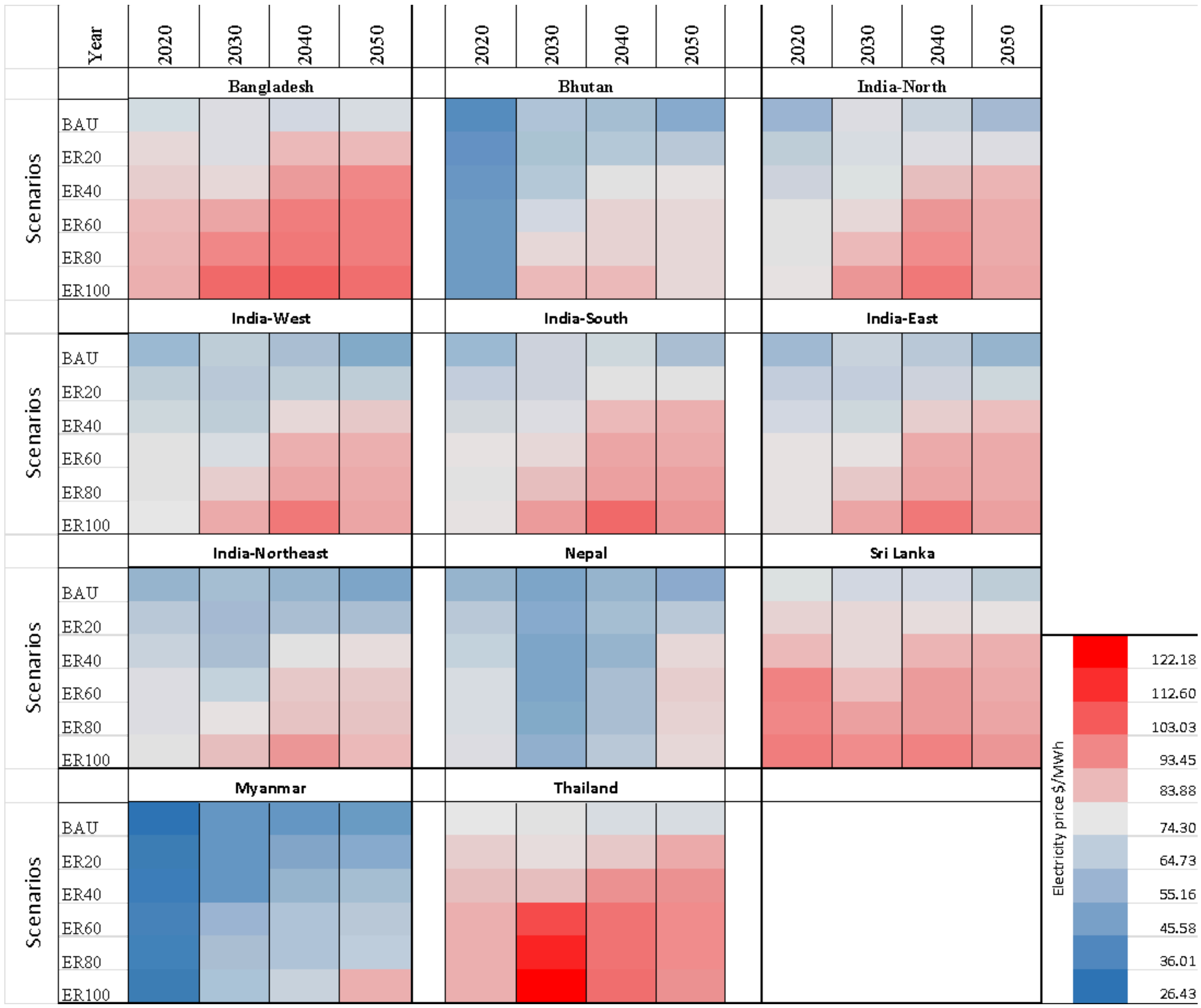

Figure 6: *Electricity price in different scenarios*

To achieve emission reduction targets, transitioning from the current fossil fuel-dominated power sector to renewable energy sources is imperative. However, this transition is capital-intensive and may not be naturally favored under existing market conditions. Introducing a carbon tax-levied per ton of CO_2 emitted - is an effective mechanism to incentivize emission reductions and facilitate the transition. The proposed model calculates a shadow price for each ton of CO_2 emitted, corresponding to the emission reduction targets set for various scenarios. This shadow price is utilized as the recommended carbon mitigation cost. **Figure 7** illustrates the carbon tax rates required under different scenarios to achieve the specified emission reduction goals. For the complete decarbonization of the power grid by 2050, the carbon mitigation cost reaches about a \$98.5 per ton of CO_2.

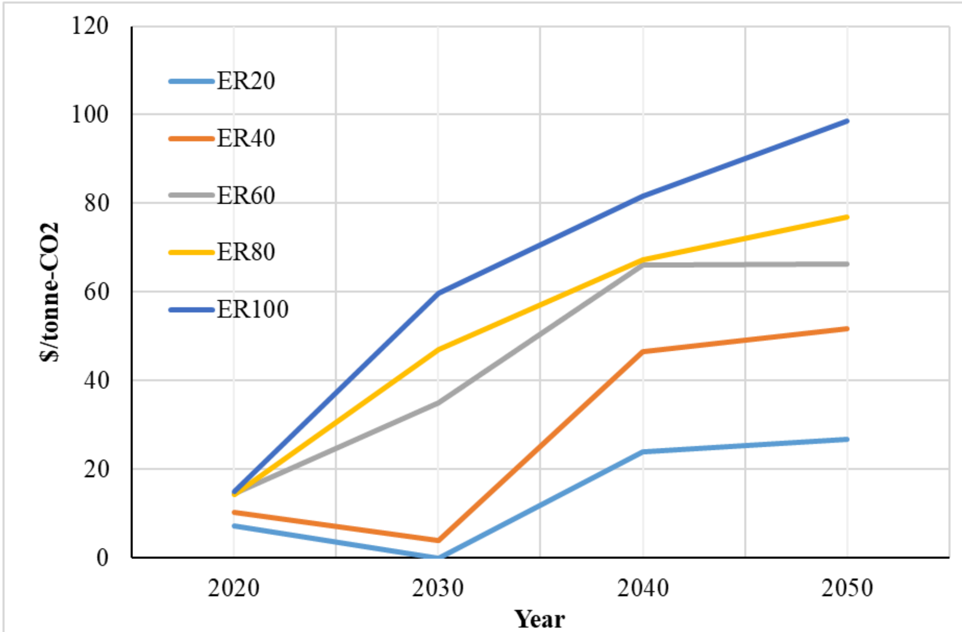

Figure 7: Cost of carbon mitigation in different years in considered scenarios

4. Conclusion

This study successfully achieved its objective by developing an integrated power grid model of BIMSTEC region and determined the carbon mitigation cost and corresponding electricity price required for decarbonizing the power system across various scenarios.

The optimization results show that as emission reduction targets become more stringent, the contribution of solar PV coupled with storage technologies increases substantially across most regions. This growth significantly reduces coal dependency in India, while the share of pumped hydropower and hydro storage expands notably in Bhutan, Nepal, and Northeast India. Power transmission between regional grids within India declines as emission reduction targets become stricter, while cross-border power trade increases, driven by the enhanced utilization of hydropower resources. Regions with a higher proportion of renewable energy in their generation mix like Nepal, Bhutan, experience comparatively smaller increases in electricity prices. To achieve complete decarbonization of the power grid by 2050, the carbon mitigation cost is approximately $98.5 per ton of CO_2. This study provides valuable insights for policymakers and researchers, supporting the sustainable energy transition in one of the world's most populous and economically significant regions.

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