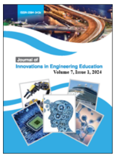

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Cost allocation for cross-border transmission lines in the BBIN sub-region using Game theory

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Abstract

The BBIN sub-region - Bangladesh, Bhutan, India, and Nepal - are witnessing a significant surge in electricity demand, accompanied by an uneven distribution of resources and consumption patterns across the region. Optimizing the unevenly distributed energy resources through a harmonized generation mix, tailored to the distinct load patterns and demands of individual nations, creates opportunities for enhanced electricity trade through multilateral cooperation. To facilitate this, the region has been conceptualized into four nodes connected by five interconnections: Bangladesh-Bhutan, Bangladesh-India, Bangladesh-Nepal, Bhutan-India, and India. While electricity trade has existed historically, a systematic approach to allocating the costs of cross-border transmission infrastructure has not been adopted. This study quantifies the benefits of regional electricity trade and proposes cost-sharing mechanisms using methodologies rooted in Game Theory, particularly the Shapley Value, alongside cooperative game theory, to ensure equitable cost distribution. A dynamic optimal power generation mix model reveals that the grand coalition - where all nations cooperate - is the most efficient configuration. In this scenario, India incurs the highest transmission line cost, reflective of its substantial size and electricity demand.

1. Introduction

Climate change has emerged as a critical global concern, prompting collaborative international efforts to mitigate its impacts [1]. The Paris Agreement, involving numerous nations, was established to limit the increase in global temperatures to below 1.5°C above pre-industrial levels [2] . This has led to the formulation of various policies aimed at reducing greenhouse gas emissions through a transition to clean energy sources. Among these efforts, decarbonizing the transportation and electricity sectors has become a priority, driving extensive research and innovation in these fields [3] .

The energy resource endowments within the BBIN (Bangladesh, Bhutan, India, and Nepal) sub-region are both limited and unevenly distributed [4]. India, for instance, possesses abundant coal reserves but faces constraints in oil availability [5] . Similarly, Bangladesh, along with northeastern India, has limited deposits of natural gas [6] . In contrast, hydro resources are predominantly concentrated in Nepal, Bhutan, and the northeastern regions of India [7], highlighting the geographical disparities in resource distribution within the region.

The power sector within the BBIN region faces significant challenges, including frequent supply disruptions, substantial transmission and distribution losses, and intermittent power outages [4] . Seasonal variations in demand and resource availability across these countries underscore the potential for regional energy cooperation, fostering electricity trade from surplus regions to those with deficits [8] . For instance, Bangladesh has historically relied heavily on subsidized indigenous natural gas to meet its electricity needs [9]. However, current consumption trends indicate that Bangladesh's natural gas reserves may be exhausted within the next decade [10].

The BBIN region's vast yet scattered hydroelectric potential, estimated at 219 GW [4], presents both opportunities and challenges for developing a regional power

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grid. Cross-border electricity trading, currently operating under government-to-government agreements, plays a pivotal role in addressing these challenges. Bhutan, for example, has been exporting 1.5 GW of surplus electricity to West Bengal, India, since their power trade agreement in 1974 [4] . With India's technical and financial assistance, approximately 11 GW of hydropower and associated cross-border transmission line projects are under development [11] . Similarly, a bilateral agreement between India and Nepal, also established in 1974, enables seasonal power exchange: Nepal imports electricity from India during the dry season and exports surplus electricity during the wet season[12]. In 2010, Bangladesh and India signed a memorandum of understanding to facilitate electricity exchange through cross-border connectivity, with India currently exporting 1.16 GW to Bangladesh. In 2018, Nepal and Bangladesh signed a memorandum of understanding to trade electricity through transmission lines traversing India, enabling Nepal to export surplus hydroelectricity to Bangladesh [13] . Recently, Nepal, India, and Bangladesh have signed a trilateral agreement facilitating the trade of 40 megawatts of electricity. Bangladesh will import the electricity from Nepal via Indian transmission infrastructure, bridging the territorial gap between Nepal and Bangladesh. In response to growing electricity demand, Bangladesh is actively seeking power trading partnerships with Bhutan.

These agreements underscore the strategic importance of regional cooperation in addressing energy challenges within the BBIN region. Ref. [4] identifies potential interconnections based on existing, planned, and under-construction transmission lines between the countries. However, the equitable sharing of costs for developing cross-border energy infrastructure remains a significant challenge, largely due to the lack of centralized coordination or regulatory frameworks. The veto power held by each country over cross-border interconnection projects further emphasizes the necessity of fair cost and benefit allocation to ensure sustained regional collaboration. Despite its importance, this issue has received limited attention in the context of cross-border power systems in the BBIN sub-region.

The Shapley value, a foundational concept in cooperative game theory, has been widely utilized in the allocation of transmission network costs in various regions. Its application has demonstrated significant effectiveness in aligning cost distribution with social welfare enhancements, as evidenced by studies such as [14],[15],[16],[17],and [18]. For instance, [18] employed the Shapley value to allocate the costs associated with transmission network expansion, highlighting its utility in ensuring equitable cost distribution. Similarly, a study [19] proposed a refined methodology to classify transmission capacity costs, further underscoring the Shapley value's versatility in addressing complex cost allocation challenges within energy systems. Studies such as [20] have examined inter-regional compensation mechanisms for investment cost recovery, while others, like [17], have applied the Shapley value method to allocate fixed network costs among market participants.

Previous studies in the BBIN sub-region have primarily concentrated on optimizing power generation capacity and the generation mix. For instance, the energy sector's status and future prospects have been reviewed with high spatio-temporal resolution in Ref. [21]. A high-resolution capacity expansion model was employed to explore pathways for decarbonizing the power grid across the BBIN region [21]. Another study utilized a spatially disaggregated capacity expansion model to analyze the dynamics of the regional power sector [22]. While these analyses have extensively examined the power sector, including cost optimization over the study periods, a significant gap remains in addressing the equitable allocation of costs for cross-border infrastructure, such as transmission lines, based on the benefits accrued by individual countries. This oversight underscores the necessity for further research to establish fair cost allocation mechanisms for cross-border power transmission lines, thereby enhancing the understanding of their implications for regional energy cooperation and integration.

This research seeks to address the critical gap in cross-border power transmission cost allocation within the BBIN region by employing Cooperative Game Theory. Specifically, it aims to develop a comprehensive power generation mix model for the BBIN countries, systematically evaluating generation costs for individual nations, coalitions, and the grand coalition. By leveraging the Shapley value, the study ensures an equitable distribution of costs, promoting fairness in regional collaboration. Furthermore, the research endeavors to conceptualize the BBIN region as a unified entity for the equitable allocation of generation costs, thereby advancing a more integrated and sustainable framework for regional energy cooperation.

2. Research methods

2.1. Model development

The foundational structure of the integrated model developed for this analysis is illustrated in Figure 1. The capacity expansion model is constrained by various technical parameters, and utilizes linear programming techniques with the objective of minimizing costs. Key drivers for power system expansion include electricity demand growth, resource limitations, technology costs, and policy frameworks. The model uses 2020 as the

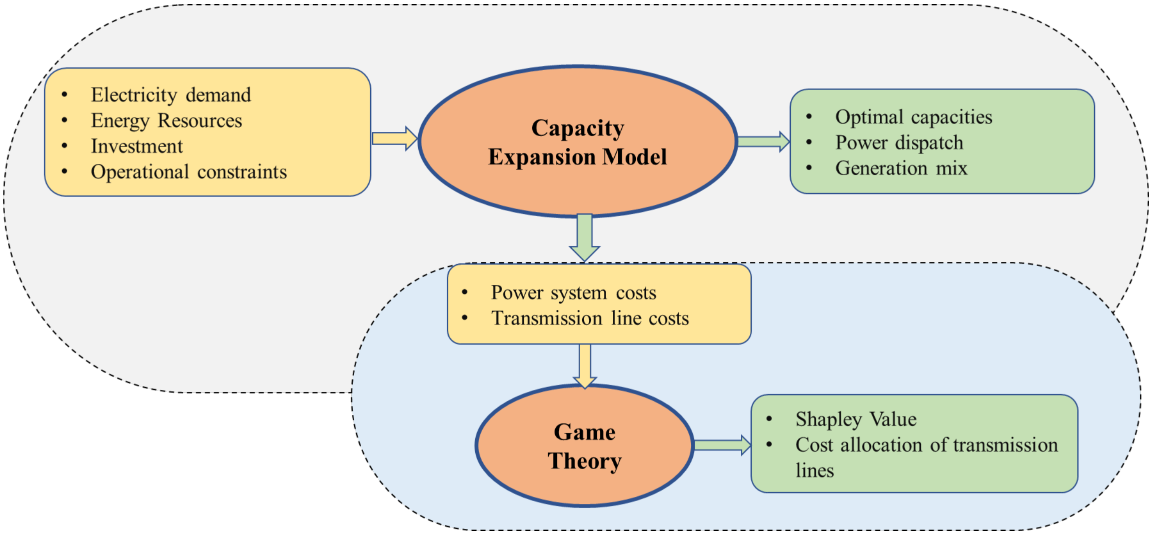

Figure 1: Basic structure of the model

base year and conducts optimization at six intervals, each representing five-year increments, with an hourly resolution for each year, spanning until 2050.

The model optimizes the power generation shares across three types of hydropower plants (Run-of-River, Pondage Run-of-River, and Storage), five types of thermal power plants (Nuclear, Coal, Coal with CCS, Natural Gas, and Biomass), two forms of intermittent renewables (Solar PV and Wind), and the charging/discharging operations of three storage technologies (Pumped hydro, NaS battery, and Hydrogen Systems) throughout the study period. Additionally, it incorporates bulk power transfer between nodes via five transmission lines. The detailed mathematical formulations of the capacity expansion model based on the large-scale linear programming is presented in the paper [21].

The model identifies the optimal power generation mix to meet electricity demand based on an exogenously defined load curve. By optimizing the entire system rather than focusing on individual technologies, the model evaluates supply flexibility and storage options. Simulation results are analyzed to assess key outputs, including the optimal technology mix, generation mix, system costs, emissions, and electricity prices. These results, generated under various scenarios, inform the calculation of the Shapley Value through cooperative game theory, which is then used to determine equitable cost allocation for transmission lines.

2.2. Model input

The entire BBIN sub-region is divided into 4 nodes namely Bangladesh (BD), Bhutan (BT), India (IN) and Nepal (NP). The model utilizes electricity demand data for the year 2020 as the baseline, sourced from various governmental publications. Hourly electricity demand for Bangladesh was derived from daily generation reports [23], while Bhutan's hourly demand was estimated based on available data [24]. For India, hourly demand was calculated using daily energy requirements [25][26], supplemented by typical state-level load curves, which were aggregated to represent India as a single node. These estimates were subsequently validated against data provided by regional load dispatch centers in India. In the case of Nepal, demand data were obtained directly from the Load Dispatch Center of the Nepal Electricity Authority (NEA). More information on resource inputs, technical parameters on operational characteristics of power plants, storage technologies, transmission lines and their costs is available in Ref. [21]. The total 5 interconnections assumed in the model is shown in Figure 2.

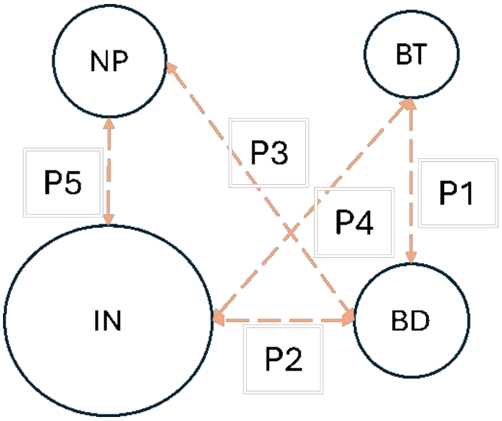

Figure 2: Illustration of interconnections assumed in the model

2.3. Scenario formation

For the subsequent analysis, various scenarios were developed to evaluate the implications of different levels of cooperation among the BBIN countries. These scenarios provide a framework for assessing the impacts of incremental cooperation on regional energy dynamics and are categorized as follows, with their specific combinations and sequence.

- No Cooperation: Absence of any collaborative efforts among the countries.
- Bilateral Cooperation: Collaboration between two countries.
- Trilateral Cooperation: Partnership among three countries.
- Full Regional Cooperation: Comprehensive collaboration involving all four countries.

3. Result and discussion

The model was executed across fifteen distinct combinations to evaluate its performance under varying conditions using IBM CPLEX Optimization Studio version 12.5. Simulations were executed on a Microsoft Windows Server 2016 system equipped with 768 GB of memory and an Intel Xeon E5-2687Wv4 processor, featuring 24 cores operating at 3.0 GHz and capable of running 48 threads concurrently.

3.1. Capacity and generation mix

The optimal results were achieved without imposing restrictions on emissions. Consequently, it is observed that coal maintains a consistent presence in both the capacity mix and the generation mix in complete coalition scenario, as depicted in Figure 3 and Figure 4. Furthermore, the share of wind energy is projected to increase significantly in the coming years, accompanied by the integration of hydrogen storage systems. The total installed capacity is expected to surpass 1600 GW, with energy demand anticipated to nearly triple from the levels observed in 2020 by the year 2050.

3.2. Coalitions and Shapely value

The simulation was conducted using 15 distinct combinations. Table 1 presents the optimal results for power system costs computed under these scenarios, including the costs associated with no cooperation among countries, bilateral cooperation, trilateral cooperation, and full cooperation. The results indicate that power system costs decrease as the level of cooperation increases, with the lowest costs observed in the case of the grand coalition.

Based on the optimal power system costs derived from 15 distinct coalitions, the Shapley value for each region

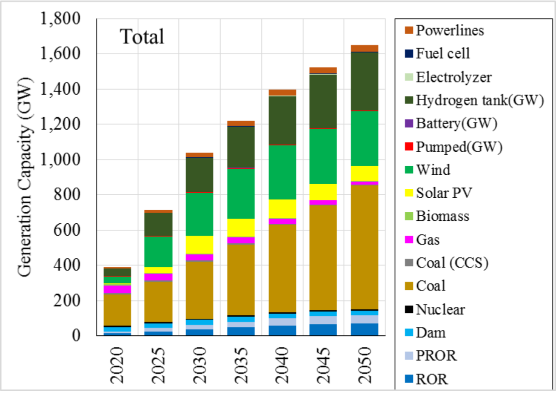

Figure 3: Transition of optimal capacity mix generated from the model in complete coalition scenario.

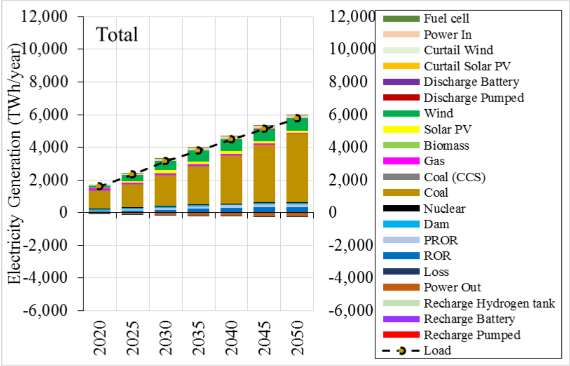

Figure 4: Transition of optimal capacity mix generated from the model in complete coalition scenario.

Table 1: Optimal power system cost computed in 15 different combinations

Collaboration	Coalitions	Cost (Billions USD)
No cooperation	BD	184.01
	BT	11.17
	IN	1565.10
	NP	25.30
Bilateral cooperation	BD, BT	174.79
	BD, IN	1713.76
	BD, NP	188.60
	BT, IN	1560.43
	BT, NP	26.40
	IN, NP	1572.98
Trilateral cooperation	BD, BT, IN	1686.40
	BD, BT, NP	179.77
	BD, IN, NP	1713.76
	BT, IN, NP	1569.81
Full cooperation	BD, BT, IN, NP	1708.22

was calculated using 24 different sequences of forming the grand coalition, as shown in Table 2. The calculation of the Shapley value involves dividing the marginal contribution of each interconnection in a given country by the total marginal contribution of the interconnection to the entire system. Given that India represents the largest economy in the region, a substantial portion of the contribution is allocated to India. The Shapely value for Bangladesh, Bhutan, India and Nepal is calculated to be 0.09, -0.0007, 0.9014 and 0.0089 respectively.

Table 2: Marginal cost (in billion USD) and calculations of Shapely value

S.N.	**Bangladesh**	**Bhutan**	**India**	**Nepal**
1	184.01	-9.22	1511.6	21.82
2	184.01	-9.22	1528.5	4.98
3	184.01	-27.36	1529.8	21.82
4	184.01	-5.54	1529.8	0
5	184.01	4.59	1525.2	-5.54
6	184.01	-9.22	1511.6	21.82
7	163.62	11.17	1511.6	21.82
8	163.62	11.17	1528.5	4.98
9	125.97	11.17	1549.3	21.82
10	138.41	11.17	1549.3	9.38
11	138.41	11.17	1543.4	15.23
12	153.37	11.17	1528.5	15.23
13	148.66	-5.54	1565.1	0
14	148.66	-27.36	1565.1	21.82
15	129.07	4.67	1565.1	9.38
16	125.97	4.67	1565.1	12.48
17	140.78	-5.54	1565.1	7.88
18	132.07	3.17	1565.1	7.88
19	163.3	-8.83	1528.5	25.3
20	163.3	-5.54	1525.2	25.3
21	153.37	1.1	1528.5	25.3
22	138.41	1.1	1543.4	25.3
23	140.78	-5.54	1547.7	25.3
24	132.07	3.17	1547.7	25.3
Mean	154.33	-1.23	1539.9	15.19
Shapely value	0.09	-0.0007	0.9014	0.0089

3.3. Transmission line cost allocation

The Shapley value is employed to derive fair allocation values for each country. These allocations, as discussed in the previous section, provide a framework for distributing the total generation cost among the participating countries. Additionally, the fair allocation ratios determined by the Shapley value are applied to allocate the investment costs of transmission lines equitably. This approach identifies the proportion of the total investment cost each country should contribute. The allocation process adheres to two principles: first, a transmission line should be geographically proximate to the country contributing to its investment, and second, a country should derive benefits from power exports through the lines it helps finance. The total cost of each transmission line from 2020 to 2050 is calculated as a model output and is presented Table 3 along with the transmission costs allocated to each country for each respective transmission line.

4. Conclusion

The optimal power system costs, derived from the multi-region capacity expansion model, were utilized to evaluate the fair cost allocation of cross-border transmission lines using the principles of Cooperative Game Theory and the Shapley value. The model was executed under various scenarios, generating power system costs for 15 coalitions, after which the Shapley value was calculated.

The analysis reveals that the Shapley value is highest for India (0.9014) and lowest for Bhutan (-0.0007), indicating that India is the primary beneficiary of the cooperation. The computed Shapley values applied to fairly allocate the costs of cross-border transmission lines among the BBIN sub-regions, assuming they operate as a unified entity. The results demonstrate that the formation of a grand coalition, where all countries cooperate, leads to a significant reduction in power system costs. Given India's higher Shapley value, it is expected to contribute the largest share of the investment, while Bhutan, with a negligible or negative Shapley value, is not required to bear any costs.

In real-world scenarios, the allocation of transmission line costs among BBIN countries must ensure fairness and stability. For instance, India's disproportionate contribution to the Bangladesh-Bhutan interconnection may result in dissatisfaction and an unstable coalition. In cooperative game theory, stability requires allocations that satisfy all participants. However, this research does not account for the stability of players, potentially leaving third-party countries dissatisfied. Future work could address this limitation by incorporating the concept of the nucleolus to enhance coalition stability.

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Table 3: Fair cost (in million USD) allocation for cross-border transmission lines calculated using Shapely value

Interconnections	**BD-BT**	**BD-IN**	**BD-NP**	**BT-IN**	**IN-NP**	**Total**
Bangladesh	62.38	166.00	51.79	31.17	70.58	381.92
Bhutan	0.00	0.00	0.00	0.00	0.00	0.00
India	622.47	1656.33	516.74	310.97	704.3	3810.81
Nepal	6.14	16.34	5.10	3.07	6.95	37.60
Total	690.5	1837.35	573.22	344.96	781.27	4227.3

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