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Cross-Border Electricity Cooperation in Southern Asia: Consequences and Benefits

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Abstract: This study analyzes the potential of cross-border electricity cooperation as an effective way to reduce the costs of renewable energy deployment in the South Asian region using a novel cooperation mechanism among countries. This paper studies the case of India, Bhutan, and Nepal. From the analysis, Bhutan and Nepal have a large under-exploited hydropower potential that presents a great opportunity for India's energy supply by developing cross-border electricity trading infrastructure and associated markets. For this, developing the infrastructure for power transmission and hydropower plants in each country is necessary to reduce investment in flexibility solutions, power system costs, and CO_2 emissions. According to a previous analysis, in Nepal's case, the Cross-Border Electricity Market (CBEM) development would increase Nepal's Gross Domestic Product (GDP) by up to 39%. India would also benefit from this mechanism. Using this energy trade mechanism, India's power generation needs would be reduced by 2% and CO_2 emissions would be reduced by 5.60% by 2045. The most important conclusions to highlight are that (i) there is an important opportunity to simultaneously enhance the economy sector in some undeveloped countries in the region when, at the same time, reducing carbon intensity in India; (ii) at the same time, there is a large barrier, as the analysis shows that despite these associated benefits there is a major risk in the lack of policy harmonization among all countries involved; and (iii) that one of the most important key aspects for success is the development of a coordinated regulation strategy. These results show the potential of CBEM systems in the region but also encourage researchers and policymakers worldwide to explore this mechanism as an effective way to enhance the decarbonization of power systems.

Keywords: carbon emission offsets; cross-border electricity trading; coal power plants; hydropower; India

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1. Introduction

Southeast Asia is rich in natural resources, such as coal and natural gas [1], and has a high solar and wind renewable energy potential [2]. In this sense, cross-border electricity cooperation can reduce renewable energy deployment costs by exploiting a cooperating partner's additional natural resource potential [3] and integrating higher shares of variable renewables, as the resulting power system would be larger [4]. Consequently, increased cross-border electricity trade, particularly in Bhutan, Bangladesh, India, and Nepal, among other South Asian nations, can help to make more suitable use of energy resources, bettering the region's energy security [5].

Cross-border grid and electricity market integration reduces the need to invest in flexibility solutions and reduces electricity system costs and CO_2 emissions [6]. In this regard, Southeast Asian countries call for enhancing power system resilience to appropriately prepare for increased penetration of renewable electricity [7] and to redesign electricity markets to reward flexibility and promote long-term investment [8]. Within South Asia, the sub-regions of Bangladesh, Bhutan, India, and Nepal are the first to exhibit a mutual effort in cross-border electricity trade (CBET) [9]. While the complementarity of supply and demand (S&D) in the four nations establishes a strong economic rationale for the expansion of energy trade [10], harmonization of policies among all countries is crucial, as poor or uncoordinated regulation can suppress cross-border electricity trade [11] and jeopardize potential public benefits [12].

So far, most hydropower plants (HPPs) in Bhutan have been established in close collaboration with the Indian government or with multilateral sovereign support [13]. Partnership in the hydropower sector between India and Bhutan is a genuine case of reciprocally advantageous cooperation [14]. Currently, Bhutan sells about 70% of the hydropower produced to India [15], generating export incomes for Bhutan and strengthening bilateral economic ties [14]. That said, as the agreements of several power plants expire in the coming years, Bhutan will be able to sell more power through the exchange platforms [16].

Background and Literature Review

This subsection analyzes the background of the problem and the previous research in this field.

Due in part to the inconsistency of hydropower [17], Nepal may have lost USD 11 billion in GDP value in nine years between 2008 and 2016 [18]. As a result, and to improve electricity transmission, the first 400 kV high-capacity Cross-Border Power Transmission Line (CBPTL) between India and Nepal was concluded in 2016, with financial support from the Indian government [19]. India currently exports around 700 MW to Nepal [20].

Figure 1 shows the breakdown of energy sources used specifically to generate electricity in several South Asian countries. India, Bangladesh, and Sri Lanka produce about 70% of their electricity from thermal generation (coal, oil, and gas), while Bhutan and Nepal produce most of their electricity (almost 100%) from hydropower. Finally, about half of the electricity produced in Myanmar comes from thermal generation, and the other half comes from hydropower.

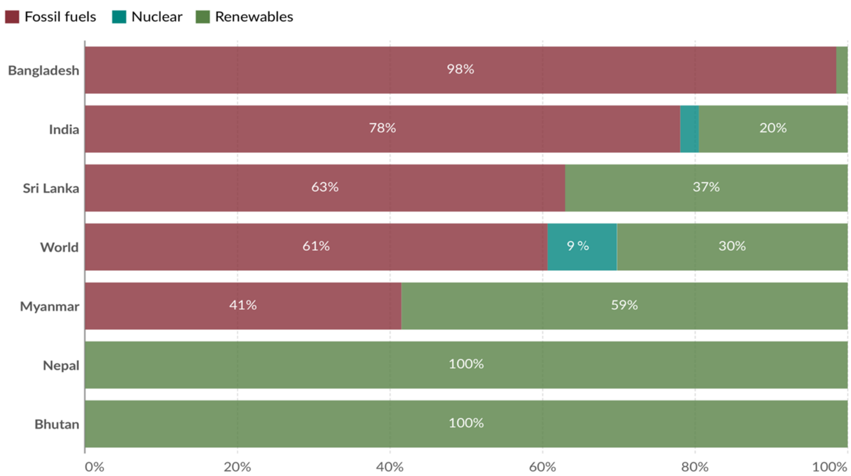

Figure 1. Share of electricity production by source in selected countries from South Asia. Data Source: Ember (2024); Energy Institute—Statistical Review of World Energy (2024). Source: https://ourworldindata.org/energy [21].

As Figure 2 shows, of the total installed capacity in the South Asian region, most of the contribution would come from India. As Timilsina et al. (2018) have pointed out in previous research [22], if cross-border transmission capacity is expanded to allow unrestricted electricity trade, the South Asian region would need an additional 743 GW of installed capacity by 2040. In this respect, although South Asia is blessed with a considerable hydropower potential (>350 gigawatts), barely 20% has been exploited to date [23].

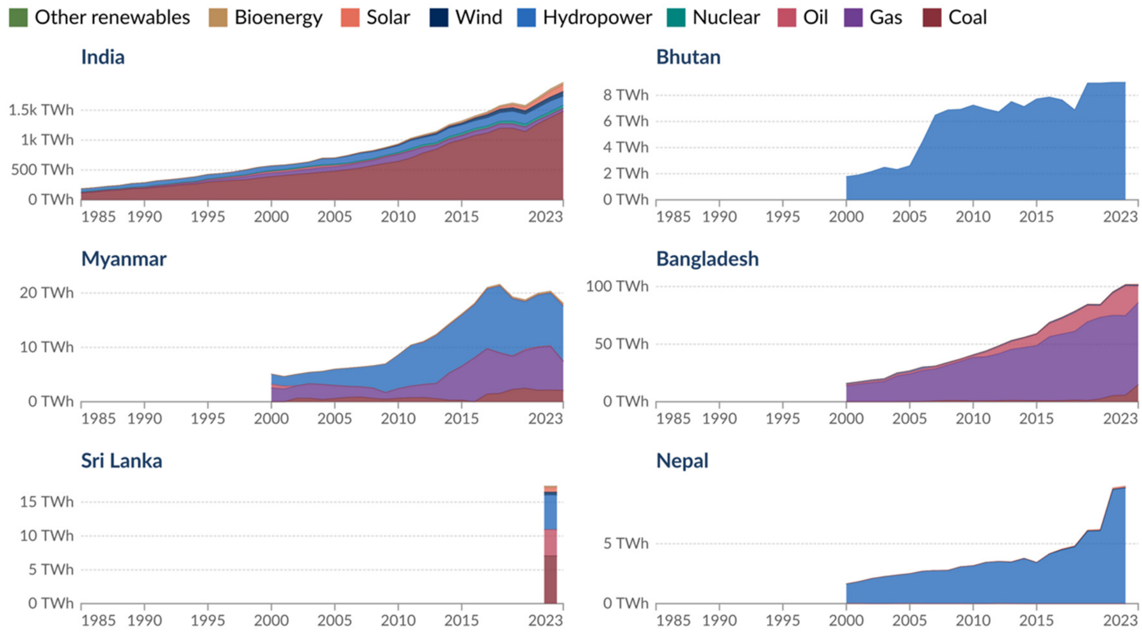

Figure 2. Electricity production by source in selected countries from South Asia. Data source: Ember (2024); Energy Institute—Statistical Review of World Energy (2024). Source: https://ourworldindata.org/energy [21].

In November 2014, aware of the need for multilateral cooperation on electricity, Bangladesh, Bhutan, India, Nepal, and Sri Lanka, among other South Asian countries, signed the Framework Agreement on Energy Cooperation [24]. This arrangement aimed to enable CBET on a discretional basis contingent on the signatory nations' Rules and Regulations (R&R) [25]. The fruitful energy cooperation between countries in the South Asian region has been demonstrated in recent years, especially during the #9pm9minute event in April 2020, where India's neighboring countries helped provide a fast ramp-up of their hydropower generation, thus helping to balance the grid during this critical 9 min period [26]. In this context, the overall objective of this research paper is to evaluate the impact of CBET in supporting the deployment and integration of renewable energy in India and its neighboring countries, thereby reducing greenhouse gas emissions from fossil fuel-fired power generation systems.

In the scientific literature, it is possible to find many research papers exploring the relationship between cross-border electricity trade and further integration of renewables. Among the most notable may be those carried out by Ahmed et al. (2017), who presented a feasibility study of high-voltage alternating current (AC) and high-voltage direct current (HVDC) transmission options for the Association of Southeast Asian Nations Power Grid interconnections [27]; those conducted by Boz et al. (2021), who provided empirical evidence to emphasize the crucial role of cross-border electricity trade in decreasing the use of fossil fuels in power industries and attaining higher electricity supply from solar and wind energy sources [28]; or the investigation conducted by Aryal and Dhaka, who presented surplus renewable generation as cross-border electricity trade potential to show how instrumental cross-border electricity trade can be to avoid renewable energy curtailment with case study of Nepal [29].

However, carbon emission offsets resulting from CBET in India and its neighboring countries have not been given the same attention, so a study that addresses them is necessary. An extensive review of the current literature [30–40] found that—even though there are plenty of different approaches—this paper contributes to the existing knowledge pool. This thorough literature review ensures the idea's originality.

This study is presented as follows: this Section 1 briefly introduced CBET to support the deployment and integration of renewable energy in India and its neighboring countries and reviewed the previous publications in this field; in Section 2, a structure to hold the theory of the analysis will be shown; in Section 3, a discussion on carbon emission offsets resulting from CBET in India and its neighboring countries is provided; in Section 4, conclusions will be presented. Finally, Appendix A will show the region's electricity production by source and country.

2. Analysis and Proposal of Cross-Border Electricity Trade Mechanism in South Asia

Electricity trade between India and Bangladesh, Nepal, and Bhutan is presently conducted through bilateral agreements [15] based mainly on government-to-government relations [41] outside the energy market economy [42], with a limited or minimal role for the private sector [41].

With rising incomes and living standards [43], India became the world's third-largest energy consumer in 2023, behind China and the United States [44]. According to the International Energy Agency (IEA), due to economic expansion, population, urbanization, and industrialization, India will see the largest increase in energy demand of all countries until 2040 [43]. Over the past few years, the energy sector in India has experienced a significant transformation, resulting in a redefined outlook for the sector [45]. In this regard, India's aim of reaching sufficient energy for its entire population has accelerated the nation's power capacity growth [46]. India currently has adequate generation capacity [47–50]. The installed renewable energy capacity in India amounts to 160.91 GW, representing 39.85% of the total available capacity in the country. Figure 2 shows electricity production by source in India, with more detail in Figure A1.

The following subsections describe the energy systems of South Asian countries that exchange or could exchange energy with India.

2.1. Bangladesh's Energy System and Its Relationship with India

As of January 2022, Bangladesh's total installed electricity generation capacity amounted to 22,066 MW [51]. Bangladesh's natural gas reserves are dwindling drastically, and in 2022, the electricity supply was rationed [52]. Bangladesh's power sector (which, for the time being, cannot meet electricity demand) imported a total of 1160 MW (or 5.54% of total demand) from India in 2019 [53]. Electricity production by source in Bangladesh can be seen in Figure 2 and in more detail in Figure A2.

On 11 January 2010, the Government of India signed a Memorandum of Understanding with the Government of Bangladesh to enhance bilateral cooperation in the power sector [54]. On 28 February 2012, the first power purchase agreement was signed to supply 250 MW from Indian power plants to Bangladesh [54]. Subsequently, in February 2013, the Bangladesh Power Development Board requested proposals to acquire 250 MW of electricity from Indian government-controlled power companies for three years [55]. On 10 September 2018, a second 500 MW high-voltage DC block was commissioned, expanding the electricity transfer capacity to 1000 MW. On 14 June 2021, a second 400 kV double-circuit line was likewise completed to reinforce the interconnection and enhance reliability [56]. Finally, on 11 August 2015, Adani Power Limited signed a Memorandum of Understanding with the Bangladesh Power Development Board to develop a 2 × 800 MW thermal power plant in India and supply all the power generated to the Bangladesh Power Development Board through a dedicated transmission line [57]. On April 2023, Bangladesh started to receive power from the Godda plant [58].

2.2. Bhutan's Energy System and Its Relationship with India

Bhutan has meaningful natural energy resources, including hydroelectric power [59]. Since its national electricity use is about 30%, the excess is delivered to India [59]. Nonetheless, from late November to March, its hydroelectric power production is small compared to the national energy requirements, which reach the highest point due to the need for regular calefaction throughout these cold winter months [59]. Therefore, energy is imported from India during the lean season for hydroelectricity generation to satisfy the increased demand [59]. As of 1 January 2022, Bhutan started purchasing electricity through the Indian day-ahead market to cover its needs during the dry season [60]. In 2008, measures were outlined to encourage Private Finance Initiatives (PFIs) and Foreign Direct Investments (FDIs) in Bhutan, expanding the favorable circumstances for further ventures in hydroelectric power proposals [61]. In 2009, Bhutan and India stated they would reach a goal of 10,000 MW of electricity production by 2020 [61]. Electricity production by source in Bhutan can be seen in Figure 2 and in more detail in Figure A3.

In the late 1960s, Bhutan began importing hydroelectric power generation from a hydroelectric power station in West Bengal, India [62]. The turning point in energy cooperation came in 1989 when the 336 MW Chukha hydropower plant came into operation, which was a major test in several aspects and determined the pace for a prospective collaboration [62]. With three-quarters of Chukha's total generation capacity exported to India, Bhutan became aware of the potentiality of hydroelectricity ventures along the way to earn further revenue [62]. Today, India has financed four hydroelectricity power ventures in Bhutan, totaling around 2.1 GW of hydropower [63]. Since 2003, there has been a spike in revenues generated by energy exports, substantially increasing revenues from Indian-assisted projects [62]. Hydropower generation has been the main area of commercial investment and the mainstay of Bhutan's development, currently contributing around 30% of its Gross Domestic Product (GDP) [64].

2.3. Nepal's Energy System and Its Relationship with India

Nepal is abundant in water resources, with one of the topmost hydroelectricity power potentials per unit of the population on Earth [65]. With roughly 1 GW of installed capacity, hydroelectricity power supplies virtually all of Nepal's national electricity consumption [66]. That said, while Nepal's topography is exceptional for hydroelectricity production, it introduces several challenges for power Transmission and Distribution (T&D) [67]. Hydroelectricity power infrastructure, the main source of electricity in Nepal, was severely damaged in the aftermath of the 2015 Gorkha earthquake sequence, resulting in a loss of 15% of the nation's electricity generation [68]. This earthquake damaged 14 [69] existing hydropower dams [70], totaling a capacity of 175 MW [71].

As of mid-April 2022, Nepal's installed electricity production capacity was 2191 megawatts [72] and is expected to reach 7300 MW by 2025 [73]. Because the highest electricity demand in 2023 was recorded at 2212 MW during peak hours [74], the country now has a surplus of power following the increase in total installed capacity [75]. Hydroelectricity has a prevalent function in Nepal's power grid. Presently, 96.2% of the installed capacity comes from hydroelectricity power plants, with 3.7% from thermal plants and 0.1% from solar plants [72]; Figure 2 shows Bangladesh's electricity production by source, with more detail in Figure A4.

Although power exchange between India and Nepal started in 1971 (by importing 5 MW from India to Nepal) [76], the first 400 kV cross-border transmission line between the two countries was only commissioned in 2016 [76]. By the agreements between Nepal and India, the Indian government authorized Nepal to trade electricity in the Indian market through a competitive tender. Nepal can currently export 364 MW of electricity produced by six hydroelectric projects. This will reduce Nepal's trade deficit with India and, concurrently, facilitate the management of the seasonal energy excess until Nepal's internal needs rise substantially [77].

2.4. Myanmar's Energy System and Its Relationship with India

Given its low electricity capacity and broad poverty, Myanmar has one of the lowest per capita energy consumption rates of all the Hindu Kush–Himalayan countries [78]. The country's total installed capacity is 6034 MW [78], of which 2496 MW comes from NG and 3262 MW from hydropower resources [79]. In September 2015, the World Bank approved a USD 400 million loan to support the Myanmar government's National Electrification Plan, which aims to achieve universal access to electricity by 2030 [80]. This is a demanding plan, given that in 2014, only one out of three rural populations had access to electricity [81], and per capita consumption stood at 232 kWh [82]. The electricity production by source in Myanmar can be seen in Figure 2 and in more detail in Figure A5. India currently exports a small amount of electricity to Myanmar (just 7 MW per year) but does not import power from Myanmar [83].

2.5. Sri Lanka's Energy System and Its Relationship with India

Planners of the Indian and Sri Lankan power systems and the research community have considered linking the two nations using a high-voltage direct current (HVDC) transmission link [84]. Establishing high-capacity transmission lines between India and Sri Lanka is in the planning/discussion phase at the time of writing [85]. Figure 2 shows the electricity production by source in Sri Lanka, more detail in Figure A6. During the pre-feasibility studies, several options for line routes and connection schemes were analyzed, and it was concluded that the interconnection would be achieved with 2 × 500 MW high-voltage DC terminals [86].

2.6. Proposal of Cross-Border Interconnectors in India for 2030–35

Figure 3 shows the proposed cross-border interconnection capacities for 2030–35 between India and its neighboring countries.

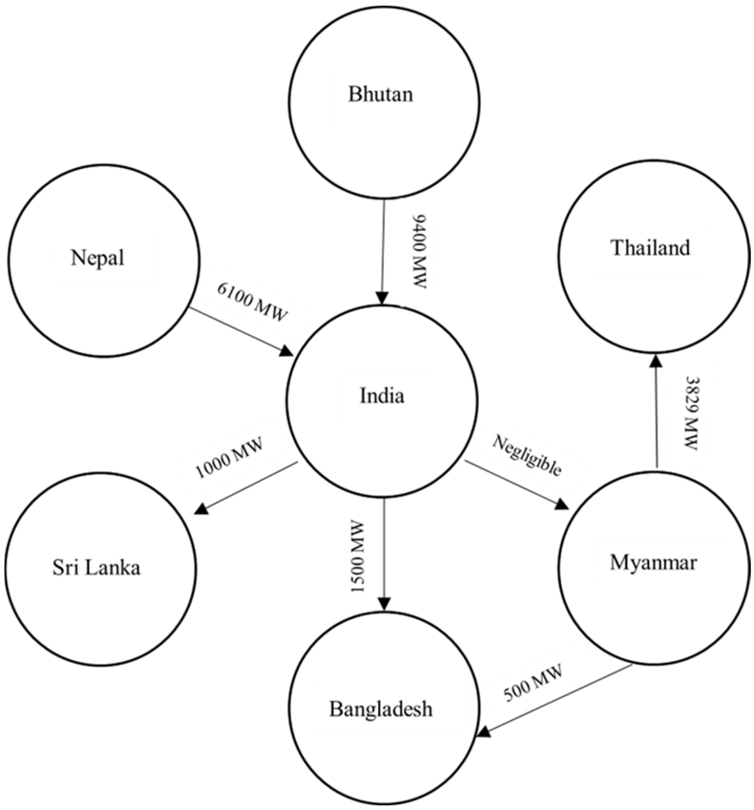

Figure 3. Proposed cross-border interconnection capacities for 2030–35 between India and its neighboring countries. Source: Adapted from [87].

Figure 3 presents a conceptual interstate power grid that could be considered an operational system that aggregates all the power generation sources and installed capacities using the presented interconnection systems. The power generation facilities and installed peak power for each generation source can be integrated as a whole system.

3. Discussion and Results

Burning fossil fuels such as coal and oil has elevated the atmospheric concentration of CO_2 [88] globally during the last century. By adding more CO_2 to the atmosphere, the natural greenhouse effect is supercharged, causing worldwide temperatures to increase. Global energy-related CO_2 emissions grew by 1.1% in 2023, increasing 410 million tonnes (Mt) to reach a new record high of 37.4 billion tonnes (Gt) [89], 50% above pre-industrial levels [90].

India plays a vital role in worldwide carbon reduction plans as it wants to produce 1.2 billion tons of coal by 2023–2024 [91] and expects its power plants to burn 8% more coal in the fiscal year [92]. India's dependence on coal will remain even in 2047, with a projected contribution of 42% to 50% to the energy mix [93]. India is inclined toward using its rich coal reserves because it supplies an inexpensive energy source and guarantees energy security [93]. India will continue to rely heavily on coal in the short to medium term [94]. In fact, in January 2023, India asked power companies not to decommission coal-fired plants until 2030 because of rising electricity demand, hardly two years after committing to phase out coal use [95]. By 2030, coal capacity in India is expected to reach 266 GW [96]. Therefore, India will not see a transition from coal in the foreseeable future, and coal is expected to play a major role until 2040 and beyond [97]. Figure 4 shows that India was, in 2022, with 1.85 billion tonnes, the second largest emitter of CO_2 from coal globally, behind only China.

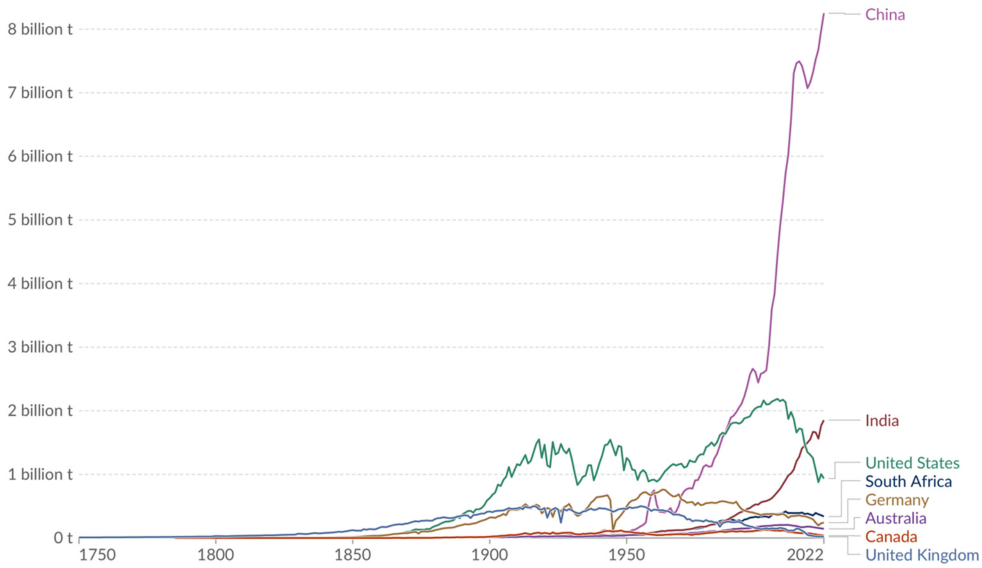

Figure 4. Annual CO_2 emissions from coal. Data source: Global Carbon Budget (2023). Source: https://ourworldindata.org/co2-and-greenhouse-gas-emissions [98].

Figure 4 is based on theoretical and experimental data; increasing the efficiency of coal-fired power plants reduces CO_2 emissions per MWh generated. In India, the average efficiency of units is 35%, compared to a leading efficiency of 47.5% [96]. Therefore, there is great potential to reduce CO_2 emissions from India's coal plants using a combined strategy that includes decommissioning or modernizing older plants and building new efficient ones [96]. As an alternative and complementary solution to decarbonize the Indian power mix, the interconnection with low-emission power systems can be an effective solution that can also be applied in similar scenarios worldwide.

The neighboring countries, mainly Bhutan and Nepal, are almost carbon-free as these countries rely mainly on hydropower systems, as shown in Figure 1. Interconnection systems have been developed in recent years, and one of the most important milestones was achieved in 2013 when the power systems of India and Bangladesh were interconnected through a high-voltage direct current line. This HVDV link can support the export of electricity of up to 500 MW between India and Bangladesh, depending on the negotiated and market-based price [41]. To make the connection between the transmission grids of the two countries, the project consisted of the installation of more than 100 km of 400 kV double-circuit transmission line between the Baharampur (India) and Bheramara (Bangladesh) power substations [48]. In addition, a 100 MW link (eastern interconnection) from Tripura's state grid in Suryamaninagar to South Comilla in Bangladesh via a 400 kV radial-mode transmission line was commissioned in 2016 [49]. As far as Nepal is concerned, India has been marginally exporting power to Nepal in radial mode at 33 kV and 132 kV from the Indian states of Bihar and Uttar Pradesh [50]. Finally, trade between India and Nepal began in August 2018, when a 400 kV transmission line from Dhalkebar (Nepal) to Muzaffarnagar (India) was loaded at 220 kV [15].

Based on existing data, Table 1 summarizes the current and proposed bilateral energy trade and interconnections between India and its neighboring countries. It should be noted that because the energy exchanged and forecast between India and Myanmar is negligible, it has not been included in Table 1.

Table 1. Existing and proposed cross-border interconnectors in India. Self-made from [50].

Interconnections	Power Export/Import	Capacity, MW	Approximate Cost (USD Million)	References
India–Bhutan (400 kV)	Hydropower export to India	2100	140–160	[50]
India–Bangladesh, 400 HVDC (West Connection)	Power Exchange between Bangladesh and India	500–1000	190–250	
India–Bangladesh, 400 HVDC (East Connection)	Power Exchange between Bangladesh and India	100–500	164	
India–Nepal, 400 kV	Power Exchange between Nepal and India	500	186	
India–Sri Lanka (400 HVDC)	Power Export to Sri Lanka (submerged sea cable under discussion)	500–1000	650	

For this scenario and considering all the previous research, this analysis studies the potential of CBET as an effective way to reduce the carbon intensity of the Indian power system and studies the potential as a solution to be applied in countries with different generation mixes that can effectively contribute as a whole system to ensure that the combined carbon emissions are reduced. India mainly relies on coal plants for power generation, representing up to 74% of electrical generation in 2020, and this is planned to be up to 50% by 2030. This fact does not imply a reduction in coal power capacity as this is associated with an increase in energy demand and increasing peak coal capacity of 38 GW, making the total coal capacity 266 GW (2030). The Indian economy is expanding, and its coal-fired plants are a secure generation source and one of the most affordable, combining dispatchability capacities. This generation matrix makes it difficult to reduce CO_2 emissions without large investment plans to modernize the existing coal plants and invest in more efficient systems. The most available technology for this purpose is supercritical (SC) or ultra-supercritical (USC) coal-fired plants that can raise efficiency by 40% and 43%, respectively [98,99]. Considering a Business-as-Usual scenario (BAE), Indian energy consumption is expected to increase in the coming years, and the external energy dependency is likely to reach up to 61% by 2047 from a previous reference of 31% in 2012.

All the countries rely mainly on fossil fuels (based on 2019 available data); coal represents 48% of the electrical capacity, natural gas 14%, and oil and diesel represent 8.2%, and the renewable energy capacity is 20%. Hydro capacity is 13%. The hydropower capacity for the whole region represents an opportunity in conjunction with power transmission lines because it allows India to develop a novel decarbonization strategy using the remote use of renewable hydro energy. This solution can contribute to the required energy supply for increasing demand in the coming years and decades and provides additional benefits for India and neighboring countries.

3.1. Energy Resources in the Region and CBET Potential

This section presents a proposed first-stage calculation of the mechanism's potential using previous research data.

Several previous research studies have examined the region's energy potential. This analysis focuses on the decarbonization potential through hydro-generated electricity trade using Cross-Border Power Transmission Lines (CBPTLs). The hydro energy potential for the countries is detailed in Table 2.

Table 2. Hydro energy potential in the region. Source: [50].

Country	Hydro Energy Potential (GW)	Present Capacity, MW	Approximate Cost (USD Million)	References
Bangladesh	0.3	0.2	140–160	[50]
Bhutan	23.8	2.3	190–250	
India	145	45.4	164	
Myanmar	100	3.3	186	
Nepal	42	1.1	650	
Sri Lanka	2	1.4		
Thailand	15.2	3.5		
Total	328	57.2		

The hydro potential in this region is underutilized, with a remaining potential of up to 328 GW of new hydroelectric potential (Table 3). While, in most hydro potential-rich countries, the demand is low, especially in Myanmar (100 GW), Nepal (42 GW), and Bhutan (23.8 GW), India's energy demand is greater and is projected to greatly increase during the coming years. Using the data presented in previous research [50,100], a preliminary approach to the potential in the region and the available capacity is calculated. Under this scenario, it is necessary to develop a regional development strategy as the only chance to optimally use the large potential in the region; under this scenario, the objectives can only be achieved by a large increase in the CBET mechanism and associated systems (Figure 5a,b). The lack of a previous regional strategy and, therefore, of cooperation has caused the installed hydro peak power to remain as low as 57 GW, representing less than 17% of the total potential. The Indian energy mix, mainly based on coal, as stated before, has greatly benefited from reducing CO_2 emissions per kWh during the past year by importing hydro-based energy from neighboring countries [50,100].

Table 3. Hydro energy potential development capacity.

Country	Hydro Energy Potential (GW)	Present Capacity MW	Potential Use (%)	Available Capacity (GW)	Available Capacity (%)
Bangladesh	0.3	0.2	67%	0.1	50%
Bhutan	23.8	2.3	10%	21.5	935%
India	145	45.4	31%	99.6	219%
Myanmar	100	3.3	3%	96.7	2930%
Nepal	42	1.1	3%	40.9	3718%
Sri Lanka	2	1.4	70%	0.6	43%
Thailand	15.2	3.5	23%	11.7	334%
Bhutan + Nepal	65.8	3.4	5%	62.4	1835%
Total	328	57.2	17%	270.8	473%

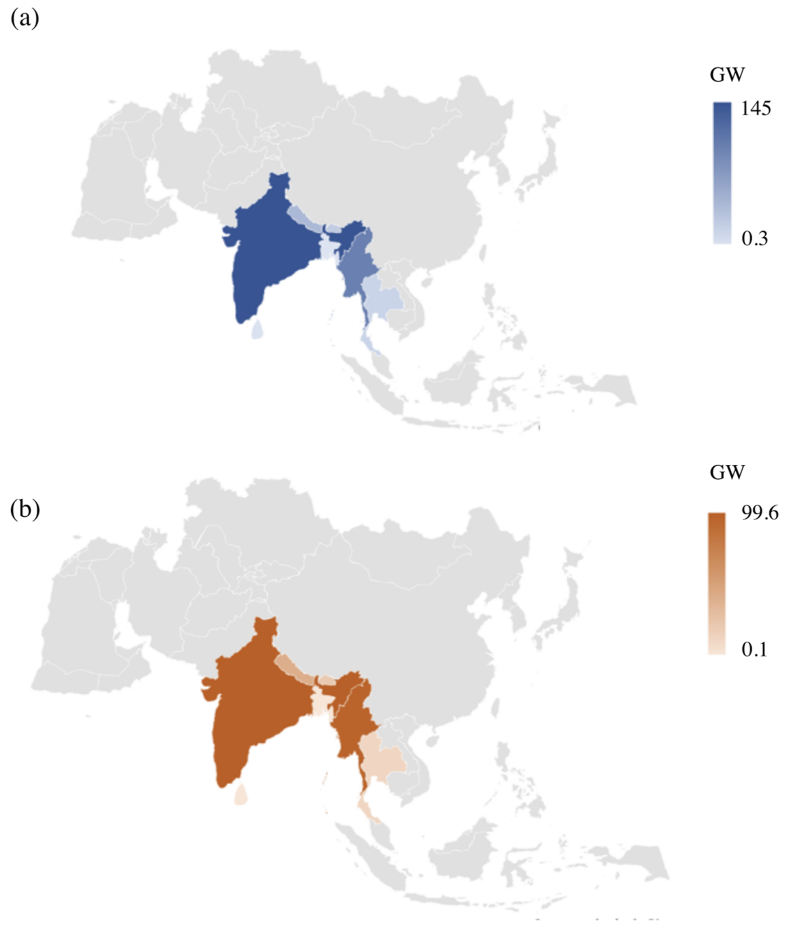

Figure 5. Hydropower capacity: (**a**) total hydro capacity (GW) and (**b**) available hydro energy potential (GW).

3.2. *CBET Potential for India, Bhutan, and Nepal*

Nepal and Bhutan are the countries with the larger hydro energy potential and opportunities to export energy to India. Nepal and Bhutan are the poorest countries in the region, and energy trade represents a great opportunity to increase their GDP, create new hydro plant maintenance and operation jobs, and reduce India's carbon intensity, among others. The interconnection and development of CBET systems can also increase the power grid stability in both countries using interconnection with coal and gas plants. Several regional characteristics greatly benefit the energy trade potential, enhancing global energy system operation and encouraging energy supply security. Despite this, there are several significant risks and challenges to be addressed. The following subsections analyze the benefits, risks, and challenges, respectively.

3.2.1. Economic, Technical, Social, and Environmental Benefits

The development of the proposed CBET mechanism will ensure several benefits for the involved countries from an economic, technical, social, and environmental point of view.

During the last few years, Bhutan has benefited from energy imports from India, based on coal or gas power plants in dry months. Nepal has avoided outages through this importing strategy. These countries can benefit from the power system characteristics listed below in Table 4. At the same time, as presented in previous sections, Nepal and Bhutan are the countries with the largest hydro energy potential and exporting energy opportunities to India. These two countries are the poorest countries in the region, and energy trade represents a great opportunity to increase their GDP and create new hydro plants. Moreover, deploying this solution can create great synergy with other renewable sources (wind, solar) and include energy storage to ensure maximum coordination and grid resilience. The combination of this renewable energy and storage mix could enhance feasibility.

As a conclusion of the previous analysis, it is shown that the CBET presents a high potential in the region and associated benefits that can enhance renewable energy share and improve the economic, technical, and social aspects, mainly in Nepal and Bhutan, as net exporters of power. Nepal has experienced high growth in the last few years but is still one of the poorest countries in the world despite it. Nepal ranks 165th in global nominal GDP per capita. If the value is studied for individuals, it occupies 162nd place in global GDP/per capita Purchasing Power Parity (PPP). Bhutan is in a better situation, but despite this, it occupies 178th in nominal GDP and 166th in PPP. Both countries focus on primary sectors, mainly agriculture and forestry, and tourism is increasingly important in these countries, especially Nepal. Both countries are extremely dependent on India's trade and financial assistance. The development of hydro resources enhances the possibility of creating new economic activity with many associated benefits throughout the whole life cycle, as presented in Table 3. India will also benefit from this economic activity, and the power sector and the whole grid will improve their global indicators, as presented in previous sections [101].

Particular analysis has been carried out for the case study of Nepal. CBET's existing data show that Nepal's exports are 38 GWh/year, with a current hydropower capacity of 1.1 GW (Table 3). Considering a case study of the development of available and economically feasible capacity of 82% by 2045, the peak power would be up to 34.5 GW, with the development of new 33.4 GW hydro plants. Under this scenario, the energy exports will reach up to 115,000 GWh/year, and this activity would increase the GDP of Nepal by up to 39%. India would also benefit from this mechanism as the internal energy generation demand will be reduced by 2% (considering the energy demand scenarios forecast and the fact that the Indian demand is much higher than Nepal's export capacity). The CO_2 emissions will be reduced by 5.60%. The inner peak load and technical synergies will enhance the reduction in peak power capacity requirements in India up to 75 GW, with the associated benefits in terms of investment, operational costs, and fossil fuel requirements. Table 4 below summarizes the most important aspects and their associated benefits.

A detailed review of previous research shows that no specific analysis exists for Bhutan, but in this study, a basic analysis of this capacity and its impacts is performed. Considering the available capacity in Bhutan and a similar development of up to 82%, the installed capacity in 2045 would reach 19.5 GW. It is important to note that several international organisms have reported that the hydro capacity could exceed these values. For example, the International Hydropower Association remarks that Bhutan's hydropower potential is about 30 GW, of which 23.76 GW is economically feasible. This could raise to higher values in the coming years due to rising energy and CO_2 emission costs, which would improve the economic feasibility of these plants. Under a 19.5 GW development scenario, the exports to India would reach up to 65 GWh/year, contribute to 1.1% of India's power demand, reduce carbon emissions by up to 3.2%, and increase the peak power requirements by 42 GW. This scenario differs from other energy resource exports since the power source remains the country itself and can be considered renewable, considering that the climatic conditions (available water) remain stable, providing an additional benefit of internal energy security.

Table 4. Economic, technical, social, and environmental benefits associated with CBET.

Aspects	Type of Benefit, Cause, and Associated Benefits to CBET		Capacity, MW	Approximate Cost (USD Million)	References
Seasonal variance	Technical Environmental	Dry season discrepancy: hydro exports to India in rainy seasons and thermally generated energy imports in dry seasons	2100	140–160	Self elaboration from [50,87]
Energy resource sharing	Economic Technical Environmental	Cross-border sharing of both renewable and non-renewable resources enables a more diversified mix and enhances energy transition	500–1000	190–250	
Environmental benefits at a local and global scale	Environmental	Carbon intensity reduction in India (and consequently in the whole region) has an impact worldwide	100–500	164	
Renewable energy promotion	Economic Technical Environmental	Increase in renewable energy share in the region using underused hydro resources	500	186	
Peak curve flattening	Economic Technical Environmental	Different peak curve schemes and hourly differences enhance the flattening of the global peak curve and promote energy share using the CBET mechanism			
Grid resilience	Economic Technical	Enhanced resilience using a larger grid structure and distributed energy resources. Improved both economic and technical resilience in comparison with base case			
Improve electricity access	Economic Social	Improvement in electricity access, especially in the poorest regions of Nepal and Bhutan, with the associated benefits (economic, social, healthcare, education, etc.)			
Increased GDP and alternative economic activity	Economic Social	Creating a new economic sector in Bhutan and Nepal is focused on clean energy generation. This improves GDP and promotes economic activity in all the phases (construction, operation and maintenance, etc.)	500–1000	650	

3.2.2. Barriers and Risks

Despite the several associated benefits of the proposed CEBT mechanism, many barriers can make it impossible to achieve the required objectives. Based on the present analysis and previous analyses of the power system in the regions [50] and the policy situation [79], the most important risks and associated requirements, as concluded for the literature review and the author's analysis, are listed in Table 5.

Table 5. Barriers to CBET development in India, Nepal, and Bhutan and proposed measures.

Risk	Required Action	References
Lack of energy infrastructure	Development of CBET power lines and internal infrastructures to ensure reliable power export.	Authors' own elaboration from research analysis and previous data in [50,87]
Uncooperative energy planning	Work on interregional energy planning that includes CBET and hydro-generated power as key actors.	
Fund risk	Alternative financing methods with a focus on public/private cooperation.	
Lack of official organisms	Create an organism to effectively tackle and develop the whole project.	
Different regulatory frames	Working on an "Open Access" power infrastructure that makes it feasible for all involved actors to effectively integrate their regulation.	
Different policy strategies	Develop an energy strategy for the region rather than for each country, focusing on energy security, energy infrastructure, and renewable energy.	
Resilient power grid	Create a resilient power grid in each country and the required interconnections using HDVC/HVAC systems.	
Different power market system and operation	Development of a common power market system to enable a CBET exporting mechanism with a harmonized strategy and operational scheme.	

Therefore, as a general conclusion about the benefits, it is important to remark that, despite the great opportunity to improve the power systems of the involved countries and, at the same time, enhance renewable energy-driven generation and improve life conditions, especially of the poorest countries in the region, several risks endanger the whole project and great efforts must be made to ensure its feasibility. It is important to remark that private–public partnerships could be a key aspect to tackle the financing barriers and drive the proposed roadmap. The findings of this research can be used by policymakers and technicians involved in the region as a reference scheme for future actions and, at the same time, endorse the development of similar analysis and solutions worldwide as it is shown that interregional collaboration in power generation, transmission, and management can enhance the road to the net zero scenario while, at the same time, achieving environmental, social and economic benefits. It is important to note that a major risk is the lack of harmonization of policies among all involved countries, with the development of coordinated regulation and strategies being a key aspect to ensure feasibility.

4. Conclusions and Policy Implications

An analysis of the previous publications on South Asia's natural and power sources shows that South Asia has vast potential, including non-renewables such as coal and natural gas, and high solar, hydro, and wind renewable energy potential. This study presents a detailed review of the background of the region. It mainly analyzes the potential of cross-border cooperation for electricity as an effective way to reduce the costs of renewable energy deployment by exploiting the additional natural resource potential of a cooperating partner, particularly in the case of India, Bhutan, and Nepal. The analysis shows that these two countries have a large under-exploited hydro potential of up to 62 GW, detected as being economically feasible. Using the development of a CBET infrastructure and associated markets, these countries may contribute to reducing India's dependence on fossil fuels, requiring peak power, and, on the other hand, creating a new economic activity model for these regions.

Developing the required infrastructures for power transport and the hydro plants in each country can reduce the investment in flexibility solutions, electricity system costs, and CO_2 emissions, enhancing energy security, resilience, and economic performance. This interregional energy scenario enables sharing renewable energy resources and benefits from different climates, peak load curves, and pricing in each country.

The analysis results show that in Nepal, the development of the CBET market would increase the GDP by up to 39%. India would also benefit from this mechanism as the energy generation requirements in India would be reduced by 2%, and the CO_2 emissions would be reduced by 5.60%. Similar benefits can be achieved in the case of Bhutan, and the strategy can be used in neighboring countries, which is the most important advantage for Nepal and Bhutan with their high hydro potential.

Despite this, several risks must be tackled to develop the proposed mechanism. A major risk is the lack of harmonization of policies among all involved countries, with the development of coordinated regulation and strategy a key aspect to ensure feasibility. The most important findings can be used by policymakers and technicians involved in the region as a guideline and scheme for future actions and also endorse researchers to develop similar analyses and solutions worldwide as it is shown that interregional collaboration in power generation, transmission, and management can enhance the road to the net zero scenario while, at the same time, achieving environmental, social and economic benefits. The results can be applied in any other region worldwide, showing the potential of CBET systems as an effective way to enhance power system decarbonization, improve resilience, and simultaneously accelerate the transition to a net zero power system.

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Nomenclature

AC	Alternating Current
BAE	Business as Usual
CBEM	Cross-Border Electricity Market
CBPTL	Cross-Border Power Transmission Line
CBET	Cross-Border Electricity Trade
CO_2	Carbon Dioxide
DC	Direct Current
FDI	Foreign Direct Investment
GDP	Gross Domestic Product

HPPs	Hydropower Plants
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
IEA	International Energy Agency
NG	Natural Gas
PFI	Private Finance Initiative
PPP	Power Purchase Parity
R&R	Rules and Regulations
S&D	Supply and Demand
SC	Supercritical
T&D	Transmission and Distribution
USC	Ultra Supercritical

Appendix A. Electricity Production by Source and Country

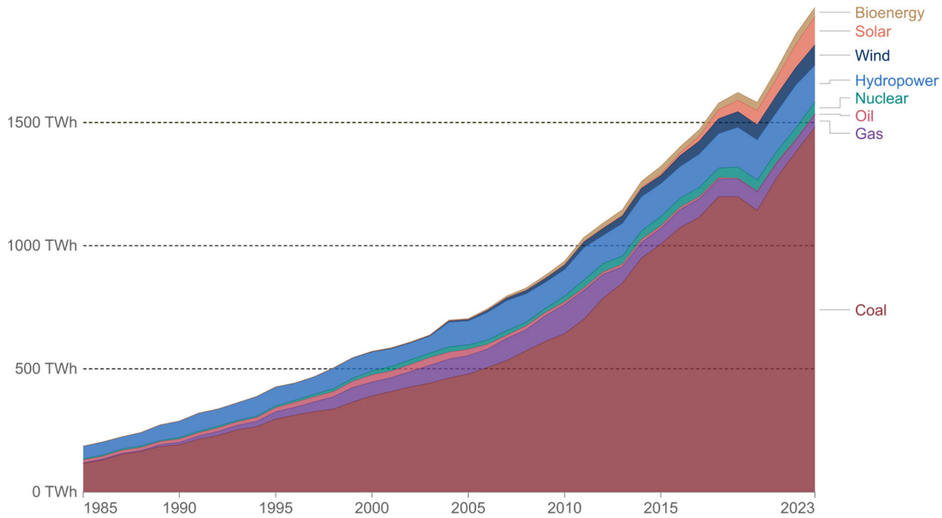

Figure A1. Electricity production by source in India. Data source: Ember (2024); Energy Institute—Statistical Review of World Energy (2024). Source: https://ourworldindata.org/energy [21].

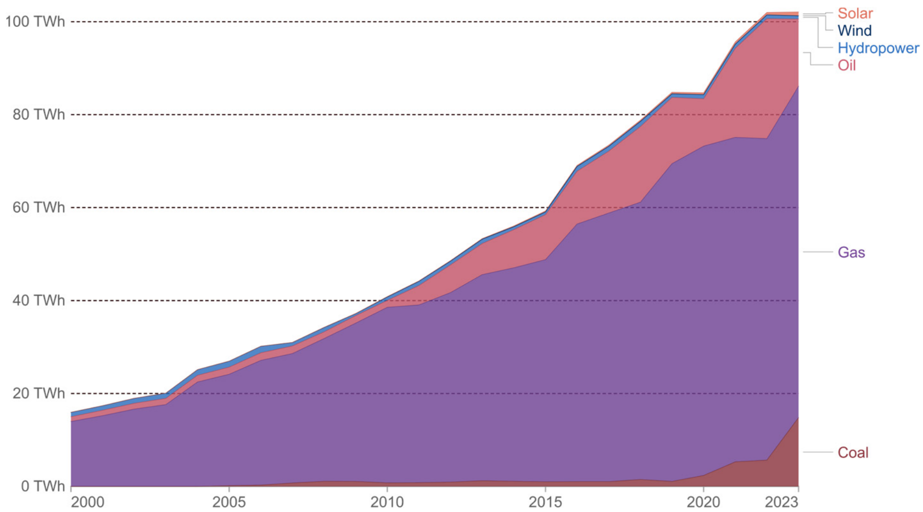

Figure A2. Electricity production by source in Bangladesh. Data source: Ember (2024); Energy Institute—Statistical Review of World Energy (2024). Source: https://ourworldindata.org/energy [21].

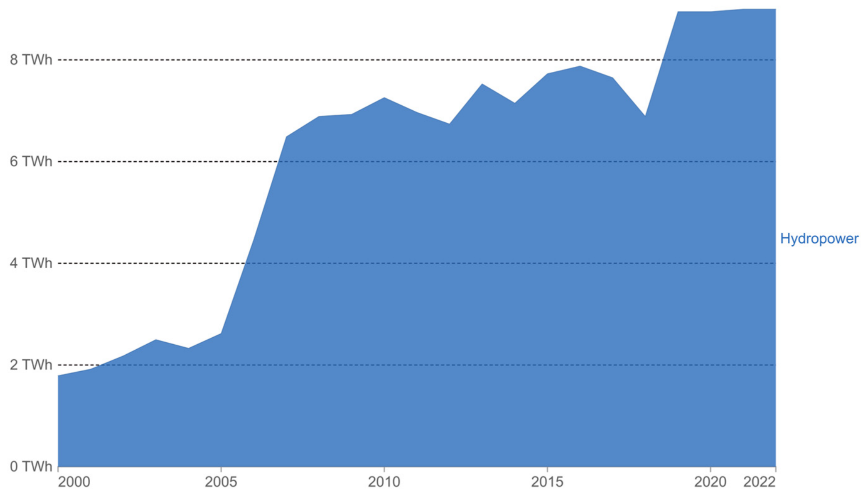

Figure A3. Electricity production by source in Bhutan. Data source: Ember (2024); Energy Institute—Statistical Review of World Energy (2024). Source: https://ourworldindata.org/energy [21].

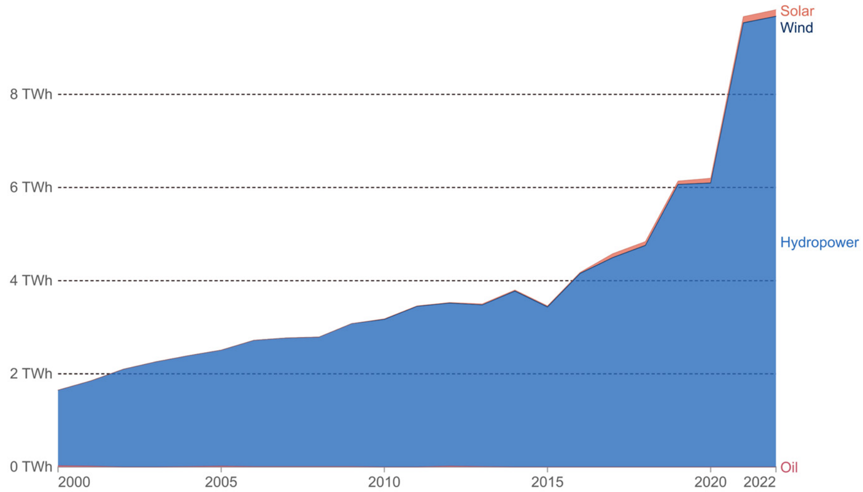

Figure A4. Electricity production by source in Nepal. Data source: Ember (2024); Energy Institute—Statistical Review of World Energy (2024). Source: https://ourworldindata.org/energy [21].

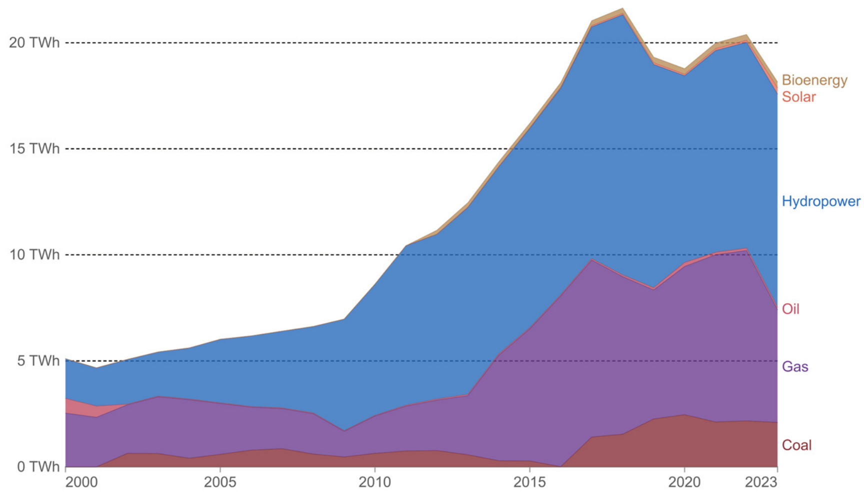

Figure A5. Electricity production by source in Myanmar. Data source: Ember (2024); Energy Institute—Statistical Review of World Energy (2024). Source: https://ourworldindata.org/energy [21].

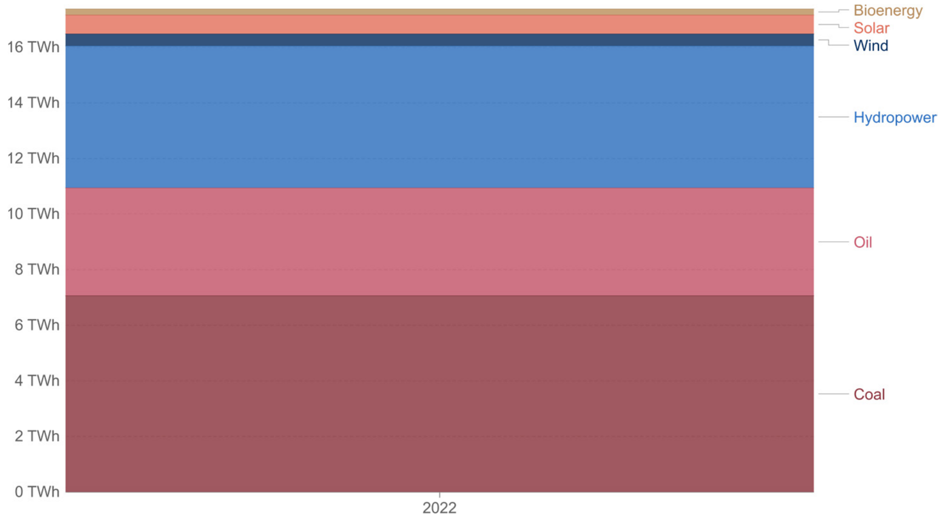

Figure A6. Electricity production by source in Sri Lanka. Data source: Ember (2024); Energy Institute—Statistical Review of World Energy (2024). Source: https://ourworldindata.org/energy [21].

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