WPS7341

Policy Research Working Paper 7341

How Much Could South Asia Benefit from Regional Electricity Cooperation and Trade?

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June 2015

Abstract

The South Asia region is lagging behind many regions in the world in regional electricity cooperation and trading, despite the huge anticipated benefits. This study uses an electricity planning model that produces optimal expansion of electricity generation capacities and transmission interconnections in the long-term to quantify the benefits of unrestricted cross-border electricity trade in the South Asia during 2015–40. The study finds that the unrestricted electricity trade provision would save US$226 billion (US$9 billion per year) of electricity supply costs over the period. The ratio of the present value of benefits, in the form of reduction of fuel costs, to the present value of increased costs due to generation and interconnection would be 5.3. The provision would reduce regional power sector carbon dioxide emissions by 8 percent, mainly because of substitution of coal-based generation with hydro-based generation, although regional emissions would be well above current levels absent other policy interventions. To achieve these benefits, the region is estimated to add 95,000 megawatts of new cross-border transmission interconnection capacity.

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How Much Could South Asia Benefit from Regional Electricity Cooperation and Trade?[1]

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Key Words: South Asia, Regional electricity cooperation, Cross-border electricity trade, Regional electricity market

JEL Classification: Q27, Q41

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[1] The study has benefitted enormously from input provided by a number of colleagues at the World Bank, including Anjum Ahmad, Julia Bucknall, Debabrata Chattopadhyay, Vivien Foster, M. Iqbal, Ashish Khanna, Richard Spencer, Rabin Shrestha, Jie Tang, and Salman Zaheer. We are also grateful to Fouzul Khan, K Ramanathan and other colleagues at TERI, Shankar Sharma, and Ashfaq Mahmood for their expert advice, and to numerous participants in various national level workshops in the region for their comments. The authors are grateful to AusAid for financial support.

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How Much Could South Asia Benefit from Regional Electricity Cooperation and Trade?

1. Introduction

The South Asia region (SAR) has for some time confronted several challenges affecting its national electricity systems.[3] Electricity supplies have not kept pace with demand growth, leading to long daily outages as well as frequent unplanned interruptions. These conditions impose hardships on households and businesses, and discourage new business investment in the economy (World Bank 2014). For example, Nepal faces load shedding up to 16 hours a day during the dry season. Although Nepal's current grid connected installed generation capacity stands around 700 MW, available capacity in the dry season decreases to one-third of installed capacity. In Pakistan, load shedding can stretch up to 8-10 hours a day. In India, the total electricity demand in fiscal year 2014-15 is expected to be 1,049 TWh against the projected supply of 995 TWh, which represents a shortage of 5 percent (CEA, 2015). Electricity demand also is growing rapidly, and the pace of growth will continue in the future. This implies a need for a rapid expansion of electricity supply systems in the region, both to mitigate current shortages and meet future demands.

Against this backdrop, one important question is the potential cost savings within the sector, and other benefits, from strengthening cross-border electricity cooperation and trade in the region. A number of studies (e.g. Rogers and Rowse, 1989; Bowen et al. 1999; Yu, 2003; Pineau et al. 2004 and Gnansounou et al. 2007) have reported several benefits of expanded cross-border electricity cooperation and trade, including establishment of regional electricity grids. In the context of South Asia, the potential benefits include, among others, (i) lower costs of electricity supply from better utilization of the region's primary energy endowments, especially the region's huge hydro resources; (ii) lower costs through economies of scale for new generation capacity through larger projects to serve more integrated systems; (iii) reduction of reliability costs through the provision of multiple links between system loads and cross-country generating resources, and through shared generation reserve margins; and (iv) reduction of environmental costs by increasing availability of cleaner sources of supply (hydro, solar, wind, natural gas), and reducing system balancing challenges with increased use of intermittent renewables (wind, solar). Lower electricity costs in turn would have positive economy-wide impacts (essentially, a positive productivity shock), but we do not attempt to assess that benefit here.

In terms of (i) and (ii) above, Nepal and Bhutan have massive hydropower potential that is only barely being utilized at present – especially in Nepal, where various estimates indicate a technically and economically feasible resource of over 40,000 MW. Northeast India also has huge hydro resources. Economic exploitation of these hydro resources requires access to larger regional markets for the electricity generated. With respect to (iii), Figure 1 illustrates how seasonal peaks in the different SAR countries do not coincide, implying a potential for cost-effectively meeting power demands across the year through cross-border trading of seasonal surpluses in different countries.

[3] In this paper we are concerned about the following countries: Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka.

Figure 1: Seasonal complementarity in power systems in South Asia – Monthly Electricity Load Profiles across South Asian Grids

	January	February	March	April	May	June	July	August	September	October	November	December
Bangladesh	Low	Low	Medium	High	High	High	Medium	Medium	Medium	Medium	Low	Low
India - North East	Medium	Low	Medium	Low	Low	Medium	High	High	Medium	High	High	Medium
Bhutan	High	High	Medium	Medium	Medium	Low	Low	Low	Low	Medium	Medium	High
India - East	Low	Medium	High	High	Medium	High	High	High	High	Medium	Low	Low
Nepal	High	High	Medium	Medium	Low	Low	Low	Low	Low	Medium	Medium	Medium
India - North	Medium	Medium	Low	Low	Medium	High	High	High	High	Medium	Low	Medium
India - West	High	High	High	Medium	Medium	Medium	Low	Low	Low	High	High	High
Pakistan	Low	Low	Medium	Medium	Medium	High	High	High	High	Medium	Medium	Medium
India - South	High	High	High	High	Medium	Low	Low	Medium	Medium	Medium	Low	Medium

Low Medium High

Sources: Authors' calculation based on CEA (2014) (India); Ali, Iqbal and Sharif (2013) (Pakistan); Kunwar (2014) (Nepal); Bangladesh Power Development Board (2013) (Bangladesh).

Despite these potential benefits, the South Asia region is lagging behind other regions that have established expanded cross-border interconnections and regional power exchange. These include the Greater Mekong Regional electricity interconnection,[4] the Southern African Power Pool (SAPP),[5] and the Central American Electrical Interconnection System (SIEPAC).[6] Major barriers in SAR have included limited cross-border transmission links; the presence of bottlenecks in the domestic energy infrastructure; poor operational efficiency, financial performance and creditworthiness of the utilities in the individual countries; and long standing political disputes (Singh et al, 2015). Regulatory reform and harmonization, reduction of trade-distorting inefficient national regulations, and cooperation to overcome domestic limits on institutional capacity are additional important components for more fully realizing the benefits of regionalizing electricity markets.

In this paper we assess the potential economic benefits of cross-border electricity cooperation and trade in South Asia over the longer-term, 2015 – 2040. We focus particularly on the possibilities with unlimited flow of power across borders in response to regional demands and investments in generation and transmission to cost-effectively meet those demands. To our knowledge, this is the first study that quantifies the benefits of full regional electricity trading in South Asia. Existing studies tend to qualitatively highlight the importance of regional electricity cooperation (Srivastava and Misra, 2007; SAARC, 2010; IRADe, 2013 and Rahman et al. 2013). Rahman et al. (2013) presents some quantitative analysis, but it focusses on already committed cross-border transmission links at sub-regional levels (Bangladesh, Bhutan, India, Nepal and Sri Lanka) and the analysis has a short-term perspective (until 2017).

The study uses a mixed-integer-programming based optimization approach that simulates least-cost plant dispatching and least-cost investments in generation capacity and interconnections to meet projected load in the region while satisfying technical, resource and other constraints. We first use the model to simulate expansion plans for each country separately, incorporating only existing as well as currently committed transmission interconnections. We compare this base case

[4] The Greater Mekong Sub-Region (GMS) was established in 1992 and its members include Cambodia, PDR Lao, Myanmar, Thailand, Vietnam, and the Yunnan Province of China. GMS relies mostly on bilateral trade agreements.
[5] Established in 1995, the members of SAPP include Angola, Botswana, Democratic Republic of the Congo, Lesotho, Mozambique, Malawi, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe. It manages energy trade within the umbrella of the Southern Africa Development Community (SADC).
[6] SIEPAC was set up in 1987, and its members include Panama, Costa Rica, Honduras, Nicaragua, El Salvador, and Guatemala.

to the results of a generation and transmission expansion plan for the region as whole. We also carry out several additional scenarios to examine the sensitivity of our analysis to different assumptions.

One important context-setting result from the base case is that total generation capacity in the region needs to increase by almost 750 GW (more than three times the current installed capacity) to meet rising national-level demands. Thus, large and costly investments will be needed to reduce shortages and respond to demand growth with or without an increase in cross-border cooperation and trade. In comparison to the base case, full regional cooperation would reduce total undiscounted electricity supply costs in the region by an average of more than US$9 billion per year over the time period studied. The gain mainly comes through the savings in operational costs. We find that the ratio of the present value of reduction of fuel costs, to the present value of increased costs for expanded generation and interconnection under full regional cooperation, is 5.3. Total CO_2 emissions for the entire region over the 2015-2040 period decline by 8% under full regional cooperation relative to the baseline, due mainly to substitution of coal based generation with hydro-based generation, although regional emissions in either case still would be well above current levels absent other policy interventions.

Section 2 of the paper briefly describes the modeling methodology we use, followed by the presentation of key parameter values and other assumptions in Section 3. Section 4 discusses key simulation results under full regional trading. This is followed by discussion of results from additional scenarios in Section 5. Key conclusions and implications are summarized in Section 6.

2. Methodology

The methodology used to assess the potential benefits of cross-border electricity cooperation and trade is based on a dynamic least-cost simulation model that identifies, for a given set of assumptions, the sequence of investments for expansion of generation and grid interconnection so that the power systems being studies meet a projected time profile of electricity demand with the lowest present value of cost. The costs included are for the new investments, fuel, and operation and maintenance. In addition, since we are concerned with the social cost of electricity system investment and operation, not just the direct financial cost, there is a representation in the model of the cost of unserved electricity demand while capacity investment "catches up" to meet demands. The model takes into account resource characteristics (e.g., potentials of hydro, solar, wind), technological characteristics (e.g., capacity limits, ramping time, provision of spinning reserves, capacity availability), and costs for fuels, capacity investments, and O&M. It facilitates an optimal trade-off between capacity expansion (investment) and operational costs of the system (including the cost of not serving the load). The model also can be used to reflect various environmental objectives, as we show in Section 5.

Our application of the model over the study horizon of 2015-2040 incorporates the following information specific to SAR:

- Electricity generation and grid-interconnection projects that are currently under construction or are committed to be built in the near future (including the CASA transmission line for bringing 1000 MW of power from Central Asia to Afghanistan and Pakistan).

- Potential additional transmission interconnections between national grids and the five regional grids in India.
- Existing policies, particularly related to renewable energy targets (though we do not include the Government of India's latest 2020 target of renewable energy).
- Unit costs in the region of various types of electricity generation technologies including coal/lignite, natural gas combined cycle and simple cycle gas turbine, diesel or other oil firing internal combustion engine, run of river and storage type hydro power, wind power, solar, biomass and nuclear power.
- Costs of electricity dispatching – fuel costs and variable operation and maintenance O&M) costs.
- Costs of maintaining electricity supply reliability standards (through an implicit target margin for capacity planning).

To represent the load duration curves (LDCs) for electricity demand, the model divides the year into six "seasons" and then looks within each season at seven different demand "blocks" corresponding to different degrees of capacity utilization (from low to peak, for that season). In meeting electricity demand, each country faces zonal "reliability constraints" which state that the firm capacity installed in the zone, plus firmly contracted imports minus firmly contracted exports, should be greater than the peak demand.[7] Candidates for new generation and transmission can be considered as discrete or continuous investment. For example, wind generators are relatively small, so wind expansion can be considered as a continuous investment decision, while big hydro projects are project-specific discrete decisions. Capital expenditures are allocated uniformly across the construction period (or lead time). If the economic life of the asset exceeds the optimization horizon, capital expenditures are scaled down to take into account the residual value of the investment.

The model chooses cost-minimizing combinations of building new power plants and strengthening the transmission network to more fully exploit existing generation capacities. In order to allow increased cross-border electricity trade, the model configures both additional transmission capacity between "zones" (national grids or, for India, regional-sub-grids), and the location and type of generation capacity increments. Power flows with increased cross-border electricity cooperation and trade are not limited to adjacent grids in the model. For example, if it is cheaper to supply power to the East India grid by developing new hydro generation capacity in the Northeast India grid and then transmitting that power across Bangladesh, perhaps with power sales to Bangladesh as well, the model will utilize that option – just as would actual power companies and traders in a well-organized regional market. Similarly, hydropower from Nepal could in principle flow through India to meet demand in Pakistan.[8]

To assess the potential gains from increased cross-border cooperation and trade, we start with a baseline scenario in which we assume no increased interconnections across countries beyond what are currently in place or are already committed to build. In this baseline, each country independently makes its own capacity investments (including increased internal grid connections,

[7] As noted, trade flows can move in different directions across seasons, with a particular area being an importer at one time and an exporter in another.
[8] A detailed technical description of the model is available at http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTRESEARCH/EXTPROGRAMS/EXTEAER/0,,contentMDK:22205467~menuPK:6477885~pagePK:64168182~piPK:64168060~theSitePK:5991650,00.html.

especially in India) to satisfy its projected demand profile.[9] We compare this baseline with a scenario that has a fully integrated regional system. In the model, we represent this as capacity investments and capacity utilization decisions made to minimize the present value of investment and operation costs across the region – as if the region were one power pool. While this is certainly not what one might expect right away with gradual increases in cross-border cooperation and trade in the near-to-medium term,[10] it does illustrate the potential benefits of cross-border trade and investment. It also illustrates the kinds of investments in both generation and transmission, and the nature of power flows, that increased cross-border cooperation and trade could engender.

We run two other cooperation scenarios for different sub-regions of SAR. The first sub-regional cooperation scenario focuses on the eastern part of South Asia – Bangladesh, Bhutan, India and Nepal. The second sub-regional cooperation scenario focuses on Afghanistan and Pakistan. As described further in Section 5, we also have looked at the base and full cooperation scenario under several different assumptions about model parameters. In particular, we have checked what happens to the model results if we assume the capacity investments currently in project pipelines are slowed and unserved demand takes longer to be reduced.

3. Data and Assumptions

The volume of data needed by this type of study is substantial. The key data items needed in this analysis include physical characteristics of existing as well as candidate power plants, economic data, system reliability data and load forecasts. The description of data items, their sources and various assumptions we made under each data category are briefly discussed below.

3.1 Physical characteristics of power plants and transmission interconnections (existing and candidate)

For the existing thermal electricity generation plants, information needed includes plant capacity, utilization factor, plant vintage, heat rate (or thermal efficiency) and heat and pollutant contents of the fuel. For hydro power plants information needed are type of plant (e.g., storage, run of river or pumped storage), capacity utilization rate by month or season as water discharge varies every month, especially in the case of run of river type hydropower plants. Resource availability information, in terms of capacity utilization, is also needed for other renewable sources such as solar, wind and biomass. For transmission interconnection, information needed are power flow capacity, voltage level and distance between interconnecting points. All information mentioned above are needed for all power plants and transmission interconnections that can be candidates for new addition during the planning horizon (2015 to 2040).

In Afghanistan, the list of existing as well as candidate power plants and their physical characteristics are taken from the power sector master plan prepared by the Asian Development Bank (ADB, 2013a) and a study commissioned by the Special Inspector General for Afghanistan Reconstruction in 2010 (SIGAR, 2010). All candidate hydropower plants in Afghanistan are assumed to be run of river type. In Bangladesh, the list of power plants and their physical

[9] This includes Nepal-India, Bangladesh-India, and Bhutan-India; it also includes the 1000MW for Afghanistan and Pakistan from Central Asia under the CASA project.

[10] It is what would emerge eventually from successful implementation of the SAARC's 2014 agreement on coordinated development of a regional power market.

characteristics are obtained from the official website of Bangladesh's national power utility, Bangladesh Power Development Board (BPDB, 2013), and the 2010 Power Sector Master Plan prepared by the Japan International Cooperation Agency and Tokyo Electric Power Company for the Ministry of Power, Energy and Mineral Resources (MPEMR, 2011). For Bhutan, physical characteristics of power plants are from the National Statistical Yearbook of Bhutan (NSB (2013) and Annual Reports of Druk Green Power Company Limited, Bhutan's national power company (DGPCL, 2013).

For Pakistan, physical characteristics of power plants are from an existing Power Sector Master Plan prepared by the SNC-Lavalin International Inc. in association with National Engineering Services Pakistan Limited for the National Transmission and Despatch Company Limited, Pakistan (NTDCL, 2011). The data are supplemented with information from an integrated energy plan 2009-2022 prepared by an energy expert group for the Economic Advisory Council, Ministry of Finance (EAC, 2009). Information on candidate hydropower projects are from a survey report prepared by Pakistan's Water and Power Development Authority (PWAPDA, 2011). Data for Sri Lanka are from the Central Electricity Boards' Long Term Generation Expansion Planning 2013-2032 prepared by for Government of Sri Lanka (CEB 2012). We tried to use the data from the existing electricity master plan, where available, to be consistent with countries national electricity expansion plan in the baseline. However, we did not force all aspects of the baseline in the master plan to apply in our study, as the underlying assumptions in the master plan might be different from ours.

In India, the list of all existing plants and their installed capacities, year of commissioning and fuel type were taken from various documents (CEA 2012a, 2012b, 2012c and 2012d) published by the Central Electricity Authority (CEA), a statutory organization under the Central Government that advises on matters relating to national electricity policy and plans. Supplemental information is taken from Energy Statistics published by India's Central Statistics Office (e.g., CSO, 2012).

In Nepal, information related to existing and planned plants is from annual reports of Nepal Electricity Authority, (e.g., NEA, 2013). Information related to candidate hydro power projects is critical for Nepal, as it is the main supplier of hydropower under the regional electricity trading scenario. Individual plant level information was obtained from various sources (MOE, 2010; detailed feasibility and pre-feasibility study reports of various hydropower projects). The aggregate capacity of these plants exceeds 31,000 MW. Another 2,000 MW, including large and small hydropower projects is under construction. Thus, existing, under construction and candidate power plants for which information is available at individual plant level add up to about 33,000 MW, 76% of the total potential identified as economically feasible in the country. We model the rest of the potential hydro capacity (run of the river and storage) as aggregated power plants with characteristics similar to the most expensive individually identified plants.

Since no information is available on the retirement of power plants, we assume no power plant already in operation will retire during the study period. If an existing power plant is too old to operate throughout the study horizon, it will be renovated. This is an optimistic assumption, but no alternative to this assumption is available in the absence of committed retirement dates for existing power plants.

Technology specific standard data are used for some aspects of candidate power plants for new capacity investment. For example, construction times of 4 years for coal, 3 years for CCGT, 2 years for GT, 6 years for nuclear, 1.5 for wind and PV and 4 years for hydro are assumed. Thermal efficiencies of power plants are assumed to be 37 to 40% for diesel engines, 38 to 39% for gas turbines, 36 to 40% for steam turbines, 54 to 56% for CCGT and 33% for nuclear. Plant availability factors are 90% for CCGT, diesel and gas turbine, 40 to 60% for hydro, 80% for biomass, 18 to 20% for solar, 27 to 30% for wind and 87 to 90% for nuclear.

3.2 Economic costs of generation capacity

Economic cost information for generation plants includes capital costs ($/kW) of each type of candidate power plants, non-fuel O&M costs, and economic lives of plant investments. While this type information ideally should be plant-specific, especially for large scale plants such as large hydropower projects, generalized information based on averages for a technology (e.g., capacity cost of combined cycle gas turbine) is used here. The summary of plant cost data is presented in Table 1. Differences across countries in these costs result in part from detailed consultations with technical experts in Bangladesh, India, Nepal, and Pakistan. For non-hydro renewable energy (i.e., solar and wind), we have carried out sensitivity analysis reducing their future capital costs. The economic life of a plant is assumed to be 30 years for steam turbine technology fired with coal or biomass; 20 years for solar, wind, gas turbine technologies and diesel fired internal combustion engines; 25 years for combined cycle gas turbine technology; 40 years for nuclear technology; and 50 years for hydropower plants.

3.3 Fuel prices

Projections of fuel prices were determined using various sources of information. For coal, we collected domestic coal prices in India and Pakistan and assumed that they would increase at the same rate the imported coal price increases. International price projections are available from International Energy Agency's 2013 World Energy Outlook (IEA, 2013), which we used to set the trend for imported coal prices in South Asian countries.[11] One important factor, often neglected in regional power system generation expansion planning, is the cost of transporting coal over a long distance from the mine or port. We account for transportation costs for all power plants considered in the study, albeit roughly. This is extremely important in a large country like India where some electricity grids (e.g., Eastern Electricity Grid of India) are endowed with fossil fuel reserves whereas others are not.

[11] The World Energy Outlook incorporates different scenarios. We have taken all of our fuel price projections from the current policy scenario, which reflects continuation of existing technology trends but no fundamental technological or policy transformation.

Table 1. Key economic data: capital and O&M costs power generation technology by type Capital costs (US$/kW)

Generation Technology	India	Bangladesh	Bhutan	Nepal	Pakistan	Af-ghanistan	Sri Lanka
Coal- supercritical (imported)	1770	1700			1770	1770	1770
Coal – Subcritical	1476	1476			1476	1476	
Coal – Ultra Supercritical	1966				1966	1966	1966
Diesel	1100-1200	1100-1200	1100-1200	1100-1200	1100-1200	1100-1200	1100-1200
Gas Turbine	392-907	392-907	392-907	392-907	392-907	392-907	392-907
Nuclear	4600	4060			4600		
Generic Hydro - ROR	1152		1152	(*)	(*)	(*)	1152
Hydro storage - Large	1800-1950	1800-2600	2364	1970-4496	(*)	(*)	2364
Small hydro	1800-2930	1800-2930	1800-2930	1800-2930	1800-2930	1800-2930	1800-2930
Wind	1900	2000	1900	1900	1900	1900	1900
Solar	2200	2350	2200	2200	2200	2200	2200
Combined Cycle	686	1160	686	686	686	686	686

The capital costs of biomass technology to be available by 2020 is $2800/kW; the cost is assumed to drop to $2600/kW by 2050. (*) No generic projects, all identified

Fixed O&M Costs (US$/kW)

Generation Technology	India	Bangladesh	Bhutan	Nepal	Pakistan	Afghanistan	Sri Lanka
Coal- supercritical (domestic)	22	39	22	22	22	22	22
Coal- supercritical (imported)	22	39	22	22	22	22	22
Coal – Subcritical	22	39	22	22	22	22	22
Coal – Ultra Supercritical	22	39	22	22	22	22	22
Diesel		30	13.7	13.7		13.7	13.7
Gas Turbine	17.6	17.6	17.6	17.6	17.6	17.6	17.6
Nuclear	116	40			116		
Generic Hydro ROR	29	40	23	38	26	62	55
Hydro storage large	29	40	23	38	26	62	55
Small hydro	29	40	23	38	26	62	55
Wind	21.5		21.5	23.5	21.5	21.5	21.5
Solar	19.6	24	19.6	19.6	19.6	19.6	19.6
Combined Cycle	14.7	30	14.7	14.7	14.7	14.7	14.7

The fixed O&M costs of biomass technology to be available by 2020 is $71.5/kW; the cost is assumed to drop to $69.6/kW by 2050. *Note and Source: These costs are compiled from various sources available in the region. Hydropower costs are based on available feasibility or pre-feasibility studies. Costs of wind and solar energy technologies are from International Energy Agency (IEA) and International Renewable Energy Agency (IRENA). Costs of thermal power technologies are based on latest bids of similar projects in a given country. In India, for example, they are either as per norms mentioned in different Regulations of CERC or on the basis recently built plants of the similar kind. Fixed O&M costs for all committed and candidate power plants are assumed as per the norms specified by national electricity authorities. In India, for example, they are compiled based on norms specified by the Central Electricity Regulatory Authority (CERC, 2009 and CERC, 2012).*

In order to incorporate transportation costs for fuels, we first find the distance through which imported coal needs to be transported once it is landed in a port. Table 2 presents the estimation of transportation costs a power plant would need to pay, on average, if it uses imported coal in Afghanistan, Bangladesh, India and Pakistan. According to Coal India Limited, the current transportation costs of coal using railway is Indian Rs. 5/per ton-per km. Using this figure in Table 2, we find that the price of imported coal varies from IRs. 22.5/tonne in Bangladesh to Irs. 100/tonne in Northern Grid of India to 117/tonne in Afghanistan. It would cost Irs. 71/tonne in Nepal and Irs. 96/tonne in Pakistan. As power plants using domestic coal tend to be sited near mines, we assume an average distance between mine to power plant 20 km; therefore we add Rs.100/tonne for transportation cost.

Table 2: Price of imported coal after transportation cost adjustments US$/Tonne)

Average Distance between port to load centers					
grid	Port	Load Center	Distance (km)	Transport cost (Rs./tonne)	
Northern grid	Hazira, Gujarat	Delhi	1200	6000	100
Western Grid	Hazira, Gujarat	Ahmedabad	300	1500	25
Southern Grid	Mangalore	Bangalore	360	1800	30
Eastern Grid	Haldia, Kolkota	Ranchi	380	1900	31.66667
North Eastern Grid	Chittagong, Bangladesh	Guhati, Assam	600	3000	50
Bangladesh	Chittagong, Bangladesh	Dhaka	270	1350	22.5
Nepal	Haldia, Kolkota	Birganj, Nepal	850	4250	70.83333
Pakistan	Karachi	Faisalabad	1150	5750	95.83333
Afghanistan	Karachi	Kabul	1400	7000	116.6667

For natural gas, we assumed that the regulated prices of domestic gas would increase gradually in order to fully converge with the price of LNG imports by 2040. For example, the average price of natural gas in Bangladesh is set at $4.20/mmbtu in 2015, we assume that it would increase gradually and reach $12.40/mmbtu in 2040 to be equal to the price of LNG imported by the country in that year. The projection of international LNG prices also comes from IEA (2013). The price of natural gas for electricity generation is a weighted average price of domestic gas and imported LNG. The share of imported LNG in Bangladesh would be very small, 2% of the total supply in 2020, but it would reach 70% by 2040 (Petrobangla, 2012). In Pakistan, prices of domestic gas and imported LNG are expected to be, respectively US$10/mmbtu and US$13.2/mmbtu in 2015. They will converge to US$12.40/mmbtu by 2040. The share of LNG in total gas supply is 42% in 2015, but it is projected to be 80% by 2040 (EAC, 2010). In India, the price evolution of domestic and gas and imported LNG are similar to those in Pakistan; the share of imported LNG is already 60% in India, which is expected to remain stable until 2040.

We have also incorporated the costs of LNG port facilities and transportation costs while delivering imported natural gas to the site of power plants. Based on the Gas Authority India Limited (GAIL) asking price of Rs. 73.5/MMBTU for 1400 km transmission line, gas transportation cost is estimated to be Rs. 0.0525 per Km per MMBTU. For petroleum products we have made use of projections from World Energy Outlook 2013 (IEA, 2013).

Finally, we have assumed a uniform 5% real discount rate for all countries. As is often the case, the choice of discount rate in this research was subject to various arguments. We initially selected a real discount rate of 8%, but were then advised that this rate was higher than what was typically used to evaluate social benefits and costs (e.g. from public investment) in at least some of our countries of interest. Since it is social benefits and costs, not private benefits and costs, that are relevant to our analysis, we updated our assumption to the lower 5% rate.[12]

3.4 Electricity Load Projections

Our electricity load projections are exogenously specified. While the price elasticity of demand for electricity certainly is not zero, assuming exogenously specified demands allowed us to utilize national load forecasts to the extent available. The electricity loads in 2013 were 5898MW for Afghanistan, 8,349MW for Bangladesh, 417MW for Bhutan, 159,177 MW for India, 1,185MW for Nepal, 24,989 MW for Pakistan and 2,451MW for Sri Lanka. National load forecasts are available in Bangladesh until 2030 (MPEMR, 2011), in Bhutan until 2020 (RGB, 2010), in India until 2022 (CEA, 2012e), in Nepal until 2027 (NEA, 2012) in Pakistan until 2030 (NTDCL, 2011) and in Sri Lanka until 2032 (CEB, 2012). The load forecast for Afghanistan is from ADB (2013a).

For the remaining period between the last year for which a national load forecast is available and 2040, we have projected the electricity load growth to be the same as the growth of per capita GDP. There is debate about the extent to which electricity demand growth will be faster than income growth for lower-income populations, or whether demand growth may start to slow down relative to income growth as incomes rise, especially in India. Our assumption is a simple compromise among these competing influences. One of our sensitivity analyses examines the implications of more rapid electricity demand growth.[13]

With these assumptions, loads are projected to grow annually at average rates of 4.6%, 6.6%, 1.7%, 5%, 6.2%, 6.1% and 4.5% in Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka, respectively during the 2013-2040 period. Total electricity load for the region as a whole will grow at an average rate of 5.2% annually during the 2013-2040 period. We assume the differences across demand blocks in each country remain the same as they are now.

4. Key Results – Baseline and Full Regional Trading Scenarios

The full regional trading scenario assumes that there would be unrestricted flow of power from any part of the region to any other parts as determined by the markets. The scenario assumes the entire South Asia region has a system of fully interconnected grids. Below we present results under this scenario as compared to the baseline scenario. In the baseline scenario, each country optimizes its power systems individually incorporating all existing policies including cross-border interconnections already connected. For example, the 1000 MW Central Asia South Asia (CASA) transmission interconnection is part of the baseline. Renewable energy targets are also the part of the baseline.

[12] The results with 8% were as might be expected: a decided switch in the mix of generation investments toward those with lower capital costs, including significantly less hydro investment.
[13] Slower demand growth had very limited impacts on the general findings.

To set a context for the results under full regional trading, Tables 3a through 3d present key findings from the baseline analysis.[14] Tables 3a and 3b show how generation capacity evolves out to 2040 without increased cross-border cooperation and trade. Total regional capacity would increase by 3.8 fold, from 276 GW in 2013 to 1,067 GW in 2040. More than 70% of the total regional capacity would be installed in India. Bangladesh, India, Pakistan and Sri Lanka would have large shares of coal in total electricity capacity. As of 2020, the share of coal-fired generation capacity in the total installed capacity would be 19%, 60%, 34% and 16%, respectively in those four countries. The corresponding shares in 2040 would be 67%, 58%, 45% and 37%. The systems in Afghanistan, Bhutan, and Nepal are dominated by expansion in hydro generation capacity.

Table 3a: Baseline Scenario Installed Capacity (GW)

	2020	2030	2040
Afghanistan	1.1	6.0	7.0
Bangladesh	27.2	48.7	67.8
Bhutan	6.9	14.7	14.8
India	387.2	586.5	783.9
Nepal	3.4	7.9	9.3
Pakistan	57.5	108.7	173.0
Sri Lanka	5.8	9.1	11.7
Total	489	782	1067

Table 3b: Baseline Installed Capacity Mix in 2020 and 2040 (%)

	Year	Diesel	Gas Turbine	Hydro	Solar	Coal	Wind	Combine Cycle	Biomass	Nuclear
Afghanistan	2020	19.2%	54.1%	24.6%	0.0%	0.0%	2.2%	0.0%	0.0%	0.0%
	2040	3.0%	8.5%	88.1%	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%
Bangladesh	2020	14.8%	9.2%	1.5%	17.3%	19.4%	0.4%	37.5%	0.0%	0.0%
	2040	5.9%	3.7%	0.6%	6.9%	66.8%	0.1%	15.0%	0.0%	0.9%
Bhutan	2020	0.1%	0.0%	99.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	2040	0.1%	0.0%	99.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
India	2020	0.3%	3.1%	15.5%	3.2%	59.9%	9.7%	3.8%	1.4%	3.0%
	2040	0.1%	6.9%	12.7%	2.6%	57.7%	9.3%	4.2%	2.9%	3.7%
Nepal	2020	1.6%	0.0%	97.8%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%
	2040	0.6%	0.0%	99.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
Pakistan	2020	0.8%	4.3%	29.8%	0.0%	34.3%	16.7%	10.7%	0.8%	2.6%
	2040	0.3%	1.6%	22.1%	0.0%	45.4%	20.0%	6.0%	0.3%	4.3%
Sri Lanka	2020	3.1%	10.7%	32.7%	1.5%	16.3%	17.8%	17.1%	0.8%	0.0%
	2040	0.8%	5.7%	17.6%	1.1%	37.1%	24.5%	12.3%	0.8%	0.0%
Total	2020	1.2%	3.7%	18.4%	3.6%	52.7%	9.9%	6.6%	1.2%	2.7%
	2040	0.6%	5.7%	15.9%	2.3%	54.3%	10.3%	5.1%	2.2%	3.4%

[14] All the baseline results are presented in Appendix A.

In the baseline, the expansion of grid interconnection mainly takes place within India. Cross-border interconnections between India-Bhutan and India-Nepal that are under construction or committed are implemented. In India most regional inter-grid connections are built by 2020; the connections that would expand in later periods of the study horizon are between northern and eastern grids and northern and western grids. These grids would be required to transmit coal fired generation from eastern and western grids to northern grids, where power demand is expected to increase the most and coal-fired generation is more expensive. This is because local coal resources there are limited, and imported coal carriers high transportation costs.

Table 3c: Baseline Scenario Changes in Grid Interconnection Capacity (MW)

	2020	2030	2040
Bangladesh to India East	500	500	500
Bhutan to India East	7,800	7,800	7,800
Central Asia to Afghanistan	3,138	3,138	3,138
India North to India East	6,278	16,202	26,078
India North to India West	7,187	26,987	40,742
Nepal to India East	1,050	1,050	1,050
Nepal to India North	75	75	75

The model results indicate that in the baseline, South Asia would spend 1,390 billion US$ for expanding electricity generation expansion during the 2015-2040 period, to add approximately 750 GW of electricity generation capacity. Already committed and planned inter-grid connection, especially within India, would require around 29 billion US$.

Table 3d: Baseline Scenario Undiscounted Cumulative Investment for 2015-2040 (Billion US$)

	Investment (Generation)	Investment (Interconnection)	Operation	Total
Afghanistan	16.36	0.18	0.47	17
Bangladesh	105.12	0.63	226.20	332
Bhutan	32.08	0.54	0.00	33
India	929.67	27.93	2,160.03	3118
Nepal	10.75	0.00	0.00	11
Pakistan	276.96	0.00	292.39	569
Sri Lanka	18.67	0.00	27.69	46
Total	1,390	29	2,707	4126

In the balance of this section, we present the results under the full regional trading scenario.

4.1 Installed Generation Capacity

The impacts of full regional interconnection on total installed capacity as compared to that under the baseline are presented in Figure 2. As can be seen from Figure 2a, Bangladesh and India will lower expansion of their installed capacity by 11 GW and 35 GW respectively from their baselines during the 2015-2040 period. Installed capacity of coal falls by 54 GW, wind by 7 GW, and gas turbine by 9 GW (see Figure 2b). These reductions in capacity are offset by hydro (52 GW from Nepal, 11 GW from India, 9 GW from Bhutan and 1.5 GW from Afghanistan) and combined cycle gas turbine from India (9 GW).

The primary reason for the expansion of hydro power capacity in Nepal is low cost hydro projects that allow replacing coal fired generation in the Northern Grid of India. This grid has the highest total electricity demand in India, and electricity demand in this grid increases by more than three times between 2015 and 2040. On the other hand, this grid has only limited supply of coal, the cheapest source for electricity generation. Utilization of imported coal would be expensive due mainly to coal transportation costs from the nearest port, which is 1200km away from the load center (Delhi). Therefore, Nepal's hydro, which is located within 400 km distance and relatively cheaper compared to other generation resources would be an attractive option to meet electricity demand in the Northern electricity grid of India.

Under regional cooperation and trade, total regional installed capacity would be modestly higher compared to the baseline – by about 5 GW. This is because the capacity factors of increased hydropower in Bhutan and Nepal would be lower compared to that of thermal power replaced in India and Bangladesh.

Figure 2a: Cumulative change in total installed capacity relative to regional cooperation and trade over the 2015-2040 period, by country (GW)

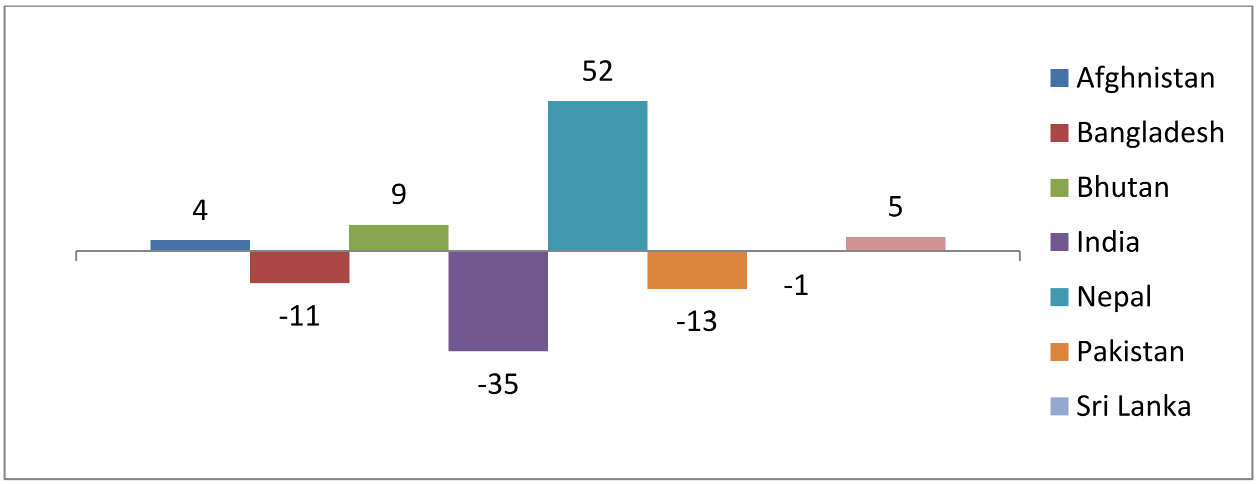
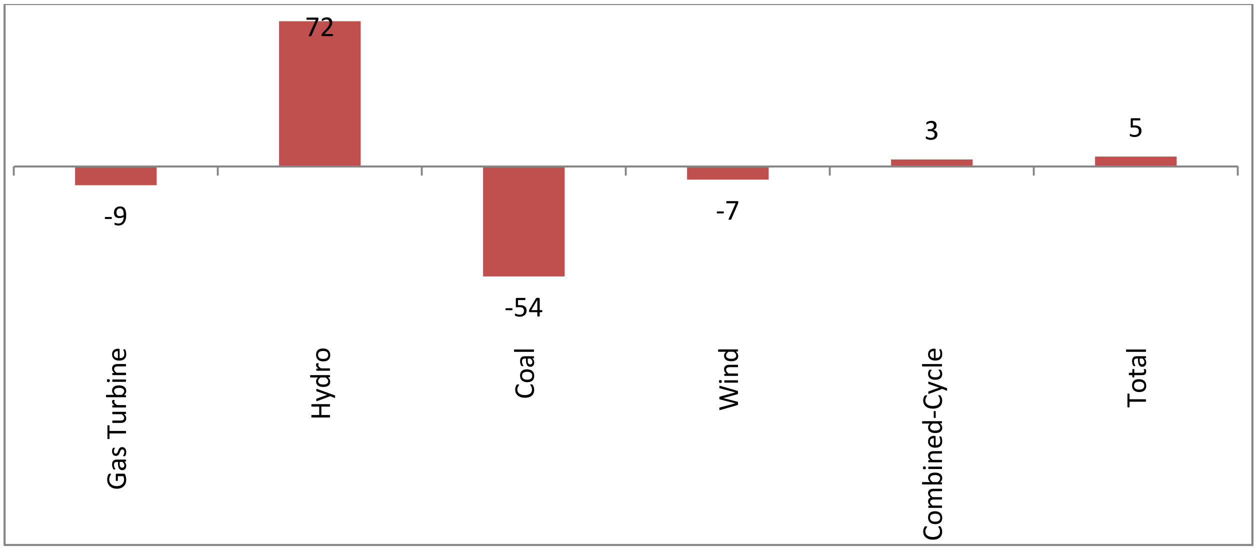


Figure 2b: Cumulative change in total installed capacity relative to baseline with regional cooperation and trade over the 2015-2040 period, by type of generation technology (GW)



Note: Electricity generation technologies not showing any change in their installed capacity as compared to that in the baseline scenario are not included in this graph.

4.2 Electricity Generation for 2015-2040 Period

Table 4 presents change in cumulative electricity generation from various types of power plants during the 2015-2040 period under regional electricity cooperation and trade. Also presented in the table are the changes expressed as percentages of corresponding generation in the baseline. Under full regional cooperation and trade, electricity generation from hydropower plants in Nepal and Bhutan substitutes for coal based generation in India and Bangladesh. Regional electricity trade would increase total electricity generation in Nepal and Bhutan during the 2015-2040 period by 7 and 2 times, respectively. Electricity generation in Afghanistan during the same period increases by 56%. These increases would replace 35%, 5% and 4% of the total electricity generation in Bangladesh, India and Pakistan, respectively. As with installed capacity, generation from coal fired plants would be substituted with mainly hydro and to some extent with gas combined cycle. Total coal based generation during the 2015-2040 period, which would be 56,648 TWh, drops by 9.4%. Electricity generation from hydropower plants that accounted for 12,865 TWh during the 2015-2040 in the baseline increases by 44% under the full regional trading scenario. Electricity generation from combined cycle power plants increases by 6%. Other generation that also gets replaced by hydro and combined cycle based generation incude diesel, wind and gas turbine based power plants. Note that to meet the domestic demand in the absence of regional trade, there was a huge expansion of wind power in India and Pakistan. In the baseline, wind generation increased by about 4 fold in India and about 34 fold in Pakistan between 2015 and 2040. Under regional trade, part of that wind power generation is replaced by hydro. In the region as a whole, wind power generation during the 2015-2040 period drops by 8.5% relative to the baseline.

Table 4: Changes in cumulative electricity generation for the 2015-2040 period from the baseline

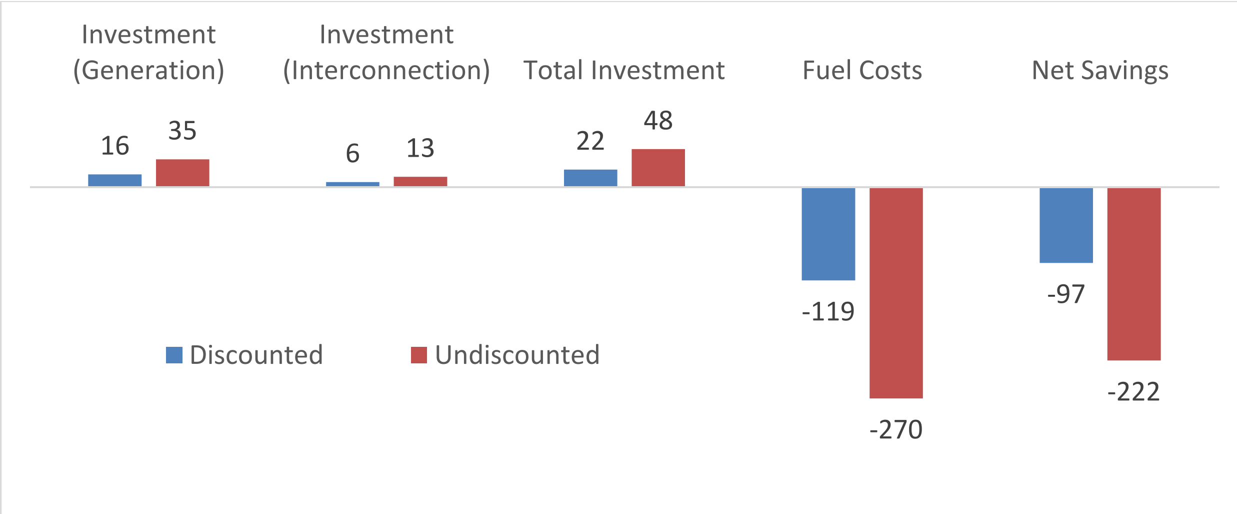
	Diesel	Gas Turbine	Hydro	Solar	Coal/Steam	Wind	Combined Cycle	Biomass	Nuclear	Total
Absolute generation (TWh) change from the baseline										
Afghanistan	0	0	190	0	0	82	0	0	0	271
Bangladesh	-8	0	0	1	-1,206	0	-331	0	0	-1,544
Bhutan	0	0	1,110	0	0	2	0	0	0	1,112
India	0	35	721	9	-3,799	-478	485	-47	-29	-3,103
Nepal	0	0	3,598	0	0	0	0	0	0	3,598
Pakistan	1	-41	-17	0	-332	-40	-16	0	15	-431
Sri Lanka	0	1	0	0	22	2	-19	0	0	6
Total	-7	-5	5,602	10	-5,315	-432	120	-47	-14	-90
% change from the baseline										
Afghanistan		-5.0	39.3			5156.7				55.7
Bangladesh	-67.6	-100.0	0.0	0.6	-35.2	0.0	-44.6		0.0	-34.8
Bhutan	-14.8		86.5							86.7
India	-66.6	74.8	10.6	1.3	-7.9	-13.0	54.2	-2.0	-0.7	-4.7
Nepal			605.7	5.2						605.0
Pakistan	7.3	-43.9	-0.5		-7.2	-3.3	-5.4	0.0	1.8	-4.0
Sri Lanka	0.0	4.5	0.0	0.0	6.1	1.3	-23.8	0.0		0.9
Total	-23.2	-3.4	43.5	1.1	-9.4	-8.5	5.9	-1.9	-0.3	-0.1

4.3 Electricity Supply Costs

The changes in cumulative electricity supply costs over 2015-2040 due to the full regional electricity cooperation and trade, relative to the baseline, are illustrated in Figure 3. As illustrated in the figure, regional trade in the power sector would lead to $222 billion in undiscounted net savings of power supply costs in the region during the 2015-2040 period. When discounted at the assumed 5% real discount rate, this net savings would be $97 billion in 2015 dollars. This is about 5% of the total electricity supply costs during the 2015-2040 period. The cost savings mainly come through the savings in operational costs, which fall by $270 billion US$, undiscounted, and $119 billion when discounted. At the same time, there would be a net increase in investment and fixed O&M costs for both expansion of generation capacity and transmission interconnections. The total regional investment (including fixed O&M costs) would be $48 billion, undiscounted and $22 billion, discounted. The ratio between the discounted benefits and costs stands at 5.34. This indicates the extent to which regional electricity cooperation is beneficial for the South Asia region as a whole.[15]

[15] In principle, it would be possible with the model to assess net benefits for individual countries using the shadow prices generated by the model's cost-minimization as representing competitive market prices. In practice, however, this turned out to be difficult to do, even if one accepted a competitive power market as the benchmark for calculating different countries' net benefits. This was due in part to the presence of congestion rents in a number of interconnections and demand blocks in the optimization. Further work is needed to assess different potential country-level distributions of regional benefits from trade. However, it seems clear that there are (infinitely) many distributions of generation and congestion rents such that all participants are better off than in the baseline. Which distributions might emerge will depend on the relative degree of market power of different supply sources, among other factors.

Figure 3: Change in cumulative costs from the baseline due to regional trade over the 2015-2040 period (Billion US$)



4.4 Cross-Border, Inter-Grid Transmission Links

The full regional cooperation that allows unrestricted flow of electric power would require 95 GW[16] of net additional transmission interconnection between the countries by 2040 (see Table 5 and Figure 4). The increased cross-border transmission interconnection capacities would however avoid 37 GW of interconnection that would have been built in the baseline to expand the interconnection of Northern India electricity grid with Eastern and Western India electricity grids. This is because it would be more economical for the Northern Electricity Grid of India to import hydropower from Nepal than coal based power from the Eastern and Western electricity girds of India. When this is accounted for, the net expansion of cross-grid interconnection would be around 59 GW.[17]

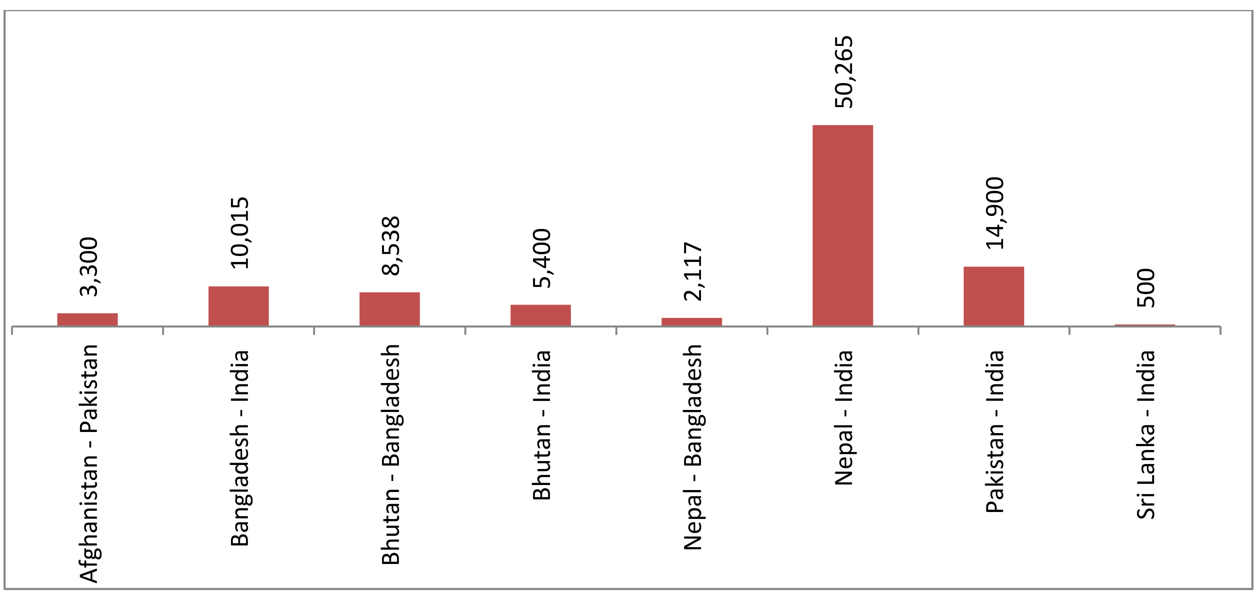
[16] Note that this number is different from the total number presented in Table 1, as this number does not account for the reduction in grid interconnections within India that would be avoided due to expanded cross-border electricity trading.

[17] Note the difference between 'cross-border' and 'cross-grid' interconnections. The former refers to the interconnection between countries, while the latter refers to the interconnections between grids, including regional electricity grids within India.

Table 5: Grid Interconnection Capacity by 2040 (Grid Level)

Grid- Interconnection	Capacity (MW)		Change in capacity from the baseline (MW)
	Baseline	Regional Grid	Regional Grid
Afghanistan - Pakistan	2,300	5,600	3,300
Bangladesh - India North East	0	9,115	9,115
Bangladesh - India East	500	1,400	900
Bhutan - India North East	0	3,600	3,600
Bhutan - Bangladesh	0	8,538	8,538
Bhutan - India East	7,800	9,600	1,800
India East - India South	5,238	5,238	0
India East - India North East	1,636	1,636	0
India East - India North	26,078	7,178	-18,900
India West - India North	41,656	23,304	-18,352
India West - India East	7,810	7,810	0
India South - India West	9,777	10,677	900
Nepal - Bangladesh	0	2,117	2,117
Nepal - India East	1,050	2,850	1,800
Nepal - India North	75	48,540	48,465
Pakistan - India North	0	10,100	10,100
Pakistan - India West	0	4,800	4,800
Sri Lanka - India South	0	500	500
Total	103,920	162,603	58,683

Figure 4: Change in cross-border transmission interconnection capacity from the baseline in 2040 (MW) due to the full regional trading



4.5 Inter-grid Power Flows

Table 6 presents changes from the baseline in cumulative flows of electric power across electricity grids and across country borders during the 2015-2040 period. The largest amount of electricity flow (3,566 TWh) goes from Nepal to the Northern Electricity Grid of India. As noted, this region is projected to have one of the fastest demand growth rates and is currently facing a huge shortage of electricity supply. The Northern Electricity Grid of India will import power from Nepal under the unrestricted cross-border trading scenario instead of from Eastern and Western grids of India, which would be case in the baseline.

More than 500 TWh of electricity (additional to that in the baseline) will flow from Bhutan to India (mostly to Eastern Electricity Grid) during the 2015-2040 period. Bangladesh imports around 1,800 TWh of electricity mostly from North East India and Bhutan. Pakistan imports from Western Grid of India and it exports to Northern Grid of India. Pakistan imports 348 TWh from Afghanistan during the 2015-2040 period.

Table 6: Change in the cumulative power flows between grids (countries) during the 2015-2040 period (TWh)

Transmission Interconnection	Flow of Electricity		
	Exports	Imports	Net Export
Afghanistan to Pakistan	348	-1	349
Bangladesh to India	126	1,124	-997
India North East	4	1,145	-1,141
India East	122	-21	144
Bhutan to Bangladesh	557	3	554
Bhutan to India	548	7	541
India North East	344	7	337
India East	204	0	204
India East to India South	200	-19	219
India North East to India East	-87	-23	-64
India North to India East	0	-1,641	1,641
India North to India West	0	-2,117	2,117
India West to India East	-7	7	-14
India West to India South	322	2	321
Nepal to Bangladesh	66	46	20
Nepal to India	3,528	28	3,500
India East	53	28	25
India North	3,475	0	3,475
Pakistan to India	300	397	-97
India North	282	67	214
India West	18	330	-312
Sri Lanka to India South	34	28	6

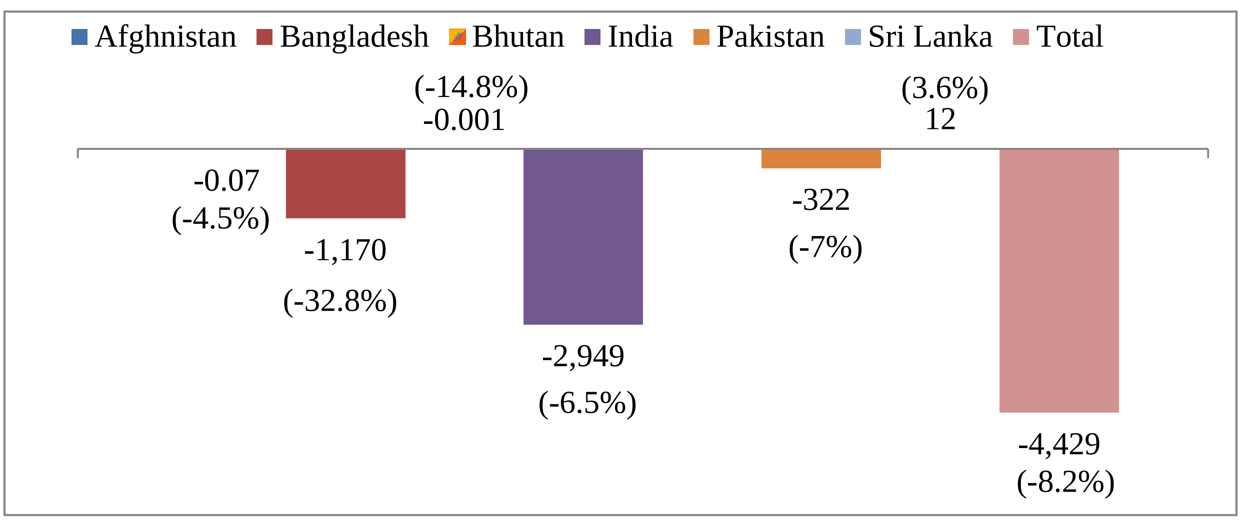
Regional coordination also would cause a huge change in inter-grid power flow within India relative to what would have happened in the baseline. While the flow of power from Eastern and Western grids to the Southern Grid increases, the flow from Eastern and Western Grids to Northern Grid drops by about a half. Note that the direction of flow could change hourly, daily or seasonally depending upon the difference in marginal costs of electricity production between any two neighboring grids. [18]

4.6 Power Sector CO_2 Emissions and Other Environmental Impacts

Since the regional trade allows a massive substitution away from coal based power generation in India, Pakistan and Bangladesh toward hydro power from Nepal, Bhutan and Afghanistan, regional CO_2 emissions from the power sector during the 2015-2040 period drop by 8% relative to the baseline. Figure 5 presents total CO_2 emissions from the power sector in the region. Although India accounts for two-thirds of the total power sector CO_2 emissions in the region, its percentage reduction accounts for 6.5%. In terms of percentage reduction, Bangladesh has the highest percentage, 32.8%. CO_2 reductions in Afghanistan and Bhutan come mainly through the substitution of their diesel based electricity generation with that produced from renewable sources.

The replacement of more than 50GW of coal-fired investment with hydro capacity under regional cooperation and trade also suggests substantial potential improvements in local air quality, since coal plants are major sources of fine particulates and other pollutants that cause damages to human health and the environment. How much air quality would improve depends not only on where the capacity substitution takes place (e.g. Northern India grid area versus elsewhere), but also on the pollution characteristics of the coal capacity avoided (e.g. modern supercritical new plants, repowered subcritical plants). Assessment of the magnitudes of air quality improvements is a topic for further research. Nevertheless, given the urgency of air quality problems in much of South Asia, the significant reductions in local pollutants from expanded regional trade is an important benefit to recognize.

Figure 5: Change in total CO_2 emissions due to the full regional trading over the 2015-2040 period, expressed in million tons and percentage



[18] The expanded grid size under regional cooperation and trade also makes introduction of intermittent renewable resources less complicated in terms of grid stability.

5. Other Scenarios

5.1 Results from parameter sensitivity analyses

We first present the results of four sensitivity analyses based on differences in certain key model parameters to investigate the robustness of the results under the full regional electricity trading scenario. These sensitivity analyses are:

Higher electricity demand growth (S1). This sensitivity analysis assumes that the future growth of electricity demand would be 1% higher in each year than projected in the baseline. In the baseline the average annual growth rate (AAGR) of electricity demand for the region as a whole during the 2015-2040 was assumed to be about 5.2%. The AAGR is increased to about 6.2% under this sensitivity analysis. In the baseline, the 2015-2040 period AAGR of Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka were respectively, 6.4%, 7.4%, 1.8%, 5.0%, 6.6%, 6.5% and 4.7%.

Increased coal prices (S2). Under this sensitivity analysis, it is assumed that the future growth of coal prices (in constant price expressed in 2011 US$) would be 1% higher in each year than assumed in the original analysis. Coal prices were assumed to grow at an average annual rate of 0.88% to reach $90.12/tons in 2035 from $75/tons in 2014. Under this sensitivity analysis, coal prices are assumed to grow by 1.88% per year and would reach $110.86/tons in 2035. Coal prices beyond 2035 are assumed to remain constant at the 2035 level. Note that coal prices would be different across grids once transportation costs are accounted for. The transportation costs are assumed to be same as in the original analysis.

Higher cost and lower availability of hydropower (S3). Under this sensitivity analysis the capital costs of hydropower plants are assumed to be 10% higher than that in the original analysis. This sensitivity analysis also assumes that the utilization of hydropower plants would be 10% lower than in the original analysis. The assumption of lower availability could be interpreted as representing for example the adverse effects on the water level in reservoirs or the water discharge in ROR plants due to future climate change.

Reduction of solar and wind costs (S4). This sensitivity analysis assumes that the costs of solar and wind power technologies will drop by 32% and 24% respectively by 2020. These drops are based on renewable energy costs projected by the International Energy Agency in its 2013 World Energy Outlook. In the original analysis, capital costs of solar PV and wind power were 2200/kW and 1,900/kW respectively.

The results of these sensitivity analyses are shown in Table 7 below. Table 7(a) shows that under the higher demand growth case (S1), the total installed capacity in the region of course also would increase relative to the original full-regional-trading analysis. However, the capacity increases vary widely, from 8.6% in Bangladesh to 642% in Nepal. Capacity already has been increased by 560% from the baseline in Nepal due to full regional trade under the original demand growth assumptions. The higher demand growth would cause Nepal's hydropower capacity to increase by 82 percentage points on top of that. The higher demand growth also brings back some growth in coal fired capacity which did not take place under the original full regional trading scenario, compared to the original baseline. Total installed capacity of coal fired power plants in the region decreased by 9.4% under the full regional trading scenario, relative to the baseline. Now it would increase by 23% under full regional trading to meet the higher demands, compared to the original parameterization.

The reduction in capital costs of solar and wind (S4) also has significant impacts on capacity addition and electricity generation. Total installed capacity of solar power under full regional trading almost doubles if its cost is assumed to decrease by 32%. Total wind capacity, which decreased by 6% from the baseline with full regional trading under the original assumption about demand growth, now increases by 26% under full regional trading if the capital costs of wind drops by 24%. The results of the sensitivity analyses for electricity generation are similar to those for installed capacity.

Turning to the sensitivity analysis results for costs (Table 7(b)), full regional trading caused a 4.8% ($97 billion) reduction in the present value of regional electricity supply cost relative to the baseline. If electricity demand growth rates increase by one percentage point, the total regional electricity supply cost under full regional trading increases by 18.6% relative to the original demand growth assumptions. However, if we compare regional trade to the no-additional-trading baseline with higher demand growth, full regional trading still leads to 4.5% net savings as compared to the baseline. With lower capital costs of wind and solar (S4), total cost under full regional trading drops by 6.5% relative to the original cost assumptions. If the lower wind and solar costs also are applied to the no-additional trading baseline, full regional trading leads to a 5% net savings compared to the baseline with lower renewable energy costs.

If the electricity demand growth in each country increases (S1), it would increase the installed interconnection capacity (Table 7(c)). A one percentage point increase in annual demand growth in each country would imply that cross-border interconnection capacity under full regional trading increases on net by 104GW relative to the baseline with increased demand growth. The comparable figure with the original demand growth assumptions was 95 MW.

The increased coal price (S2) would make electricity generation in India in particular more expensive, as coal remains the main fuel to generate electricity in the country. This leads to increased net exports of electricity from neighboring countries to India. When hydro availability decreases and cost of hydropower production increases (S3), the net exports of electricity from neighboring countries to India (as well as cross-border interconnection capacity) with full regional trading would be lower than in the full regional trading scenario with original hydro availability and cost assumptions. When solar and wind power production costs decrease (S4), it leads to Pakistan becoming a net exporter of electricity to India, whereas it is a net importer under the original cost assumptions for wind and solar.

Table 7: Results of parameter sensitivity analyses

(a) Percentage change in total installed capacity and cumulative generation relative to baseline

	Full Trading	Full trading with sensitivity				Full Trading	Full trading with sensitivity			
		S1	S2	S3	S4		S1	S2	S3	S4
	Total installed capacity in 2040					Cumulative generation during 2015-2040				
By country										
Afghanistan	50.9	51.7	50.9	48.7	175.4	55.7	59.1	60.6	40.4	92.4
Bangladesh	-16.7	8.6	-16.8	-15.2	-15.4	-34.8	-17.3	-35.6	-32.5	-35.7
Bhutan	61.6	62.2	62.2	62.2	63.2	86.7	87.0	86.9	71.2	87.1
India	-4.5	18.6	-5.8	-4.1	-1.6	-4.7	11.0	-5.3	-4.3	-5.3
Nepal	560	642	635	560	560	605	655	647	545	602
Pakistan	-7.6	19.8	-3.3	-4.6	-1.1	-4.0	18.8	-2.8	-2.3	-1.5
Sri Lanka	-4.4	19.2	1.3	-4.4	4.8	0.9	17.0	1.5	1.2	1.2
Total	0.5	24.4	0.9	1.3	4.7	-0.1	16.5	-0.2	-0.2	-0.1
By technology										
Diesel	0.0	0.0	0.0	0.0	0.0	-23.2	-7.4	-23.9	-18.6	-23.6
Gas Turbine	-15.4	43.7	-33.2	-19.6	-18.8	-3.4	-11.8	40.4	-14.5	14.3
Hydro	42.1	47.8	48.3	40.2	42.2	43.5	46.8	46.4	29.7	43.1
Solar	0.0	1.3	0.0	0.4	98.3	1.1	1.4	0.8	1.4	51.0
Coal	-9.4	23.1	-12.8	-7.9	-11.4	-9.4	11.8	-12.1	-7.2	-12.3
Wind	-5.9	4.8	5.4	-1.5	26.0	-8.5	6.5	1.6	-2.4	19.6
Combined Cycle	6.2	24.7	28.7	9.7	4.7	5.9	51.5	30.6	12.3	-0.8
Biomass	0.0	0.0	0.0	0.0	0.0	-1.9	-1.6	-1.8	-1.5	-3.2
Nuclear	0.0	0.0	0.0	0.0	0.0	-0.3	0.0	0.0	-0.1	-0.7

(b) Percentage change in discounted costs during the 2015-2040 period from the baseline

	Full Trading	Full trading with sensitivity analysis			
		S1	S2	S3	S4
Total investment (generation & interconnection)	3.5	30.3	4.9	7.7	5.1
Total fuel costs for power generation	-8.7	13.0	-2.6	-5.7	-11.9
Total electricity supply cost	-4.8	18.6	-0.2	-1.4	-6.5

(c) Change from the baseline in interconnection capacity and net electricity flow[@]

	Full Trading	Full trading with sensitivity				Full Trading	Full trading with sensitivity			
		S1	S2	S3	S4		S1	S2	S3	S4
	Total interconnection capacity in 2040 (GW)					Net cumulative electricity exports during 2015-2040 (TWh)				
Afghanistan to Pakistan	3.3	4.3	5.9	3.3	5.9	349	324	400	312	527
Bangladesh to India	10.0	9.7	10.4	9.4	10.0	-997	-963	-976	-950	-1,005
Bhutan to Bangladesh	8.5	8.4	8.6	7.4	8.7	554	568	568	505	577
Bhutan to India	5.4	5.5	5.4	5.4	5.4	541	518	529	396	523
Nepal to Bangladesh	2.1	4.2	2.7	1.7	2.2	20	39	61	12	28
Nepal to India	50.3	55.6	55.4	47.3	48.1	3,500	3,687	3,706	3,160	3,475
Pakistan to India	14.9	15.9	11.0	12.3	11.0	-97	384	90	67	355
Sri Lanka to India	0.5	0.5	0.5	0.5	0.5	6	4	10	9	9
Total	95.0	104.1	99.9	87.3	91.7	3,875	4,562	4,388	3,512	4,489

[@]*Since baseline value in most cases is zero, we used absolute change instead of percentage change.*

S1 *refers to the sensitivity case with high electricity demand,* ***S2*** *refers to sensitivity case with higher coal price,* ***S3*** *refers to the sensitivity case that assumes higher costs and lower availability of hydro and* ***S4*** *refers to the sensitivity with lower capital costs for solar and wind.*

5.2 Additional Scenarios

We also have analyzed out three additional sets of scenarios. These are as follows:

Sub-regional trading scenarios: Under this scheme unlimited electricity trade was assumed in two sub-regions within South Asia but there is no interconnection between these sub-regions. These sub-regions are: (i) Eastern sub-region and (ii) Western sub-region. The first includes Bangladesh, Bhutan, India and Nepal. The second sub-region is formed by Pakistan and Afghanistan.

Carbon pricing scenario: Under this scenario we introduce a carbon price applied uniformly across the region for all fossil fuels used for power generation in all South Asian countries. The purpose of this scenario is to examine how the carbon price stimulates renewable energy in the region in both the baseline and the full regional trading scenarios. The carbon price was assumed to be US\$10/tCO_2 starting from the year 2020, increasing to US\$20/tCO_2 in 2025 and US\$30/tCO_2 in 2030.

Scenario that incorporates physical infrastructure constraints in the short-term: This scenario incorporates potential physical infrastructure and institutional constraints in the short-term, until 2022. These constraints include, lack of port facility for importing coal in Bangladesh, lack of LNG regasification terminals in all LNG importing countries in South Asia, potential delays and cancellation of already planned or committed projects.

The **sub-regional trading scenarios** results are presented in Table 8. Under the full regional cooperation scenario, 35 GW (India) and 11 GW (Bangladesh) of thermal power (mainly coal based) is replaced with 9 GW and 52 GW of hydro from Bhutan and Nepal, respectively. Under the sub-regional cooperation within the eastern part of South Asia (Bangladesh, Bhutan, India and Nepal), India reduces capacity by an additional 5 GW relative to the baseline. Nepal installs 3 GW more hydro power generation capacity under the sub-regional scenario than that in the full regional scenario. The additional capacity saving in India could reflect that India was supplying capacity to Pakistan under the full regional trading scenario, which is not occurring by assumption in the sub-regional trading scenario. India may also have additional cost savings from importing electricity from Nepal in this case.

Under the full regional cooperation scenario, 13 GW of installed capacity was saved in Pakistan compared to the baseline (replaced by 4 GW of increased capacity in Afghanistan and other supplies coming from other parts of South Asia, including India). If expanded cross-border trading is just between Pakistan and Afghanistan, Pakistan needs to build 8 GW more capacity as compared to full regional trading scenario. Total installed capacity does not change in Afghanistan in this sub-regional scenario compared to that of full regional scenario. Total electricity generation under the sub-regional scenarios would be higher from the corresponding total under the full regional trading scenario.

Finally, GHG emissions under either of the sub-regional scenarios are larger for the sub-region compared to that under the full regional trading scenario. The additional economic efficiencies possible with full regional trading versus sub-regional outcomes also lead to slower GHG emissions growth.

Table 8: Sub-regional trading scenarios in eastern and western sub-regions of South Asia

(a) Eastern sub-region (Bangladesh, Bhutan, India and Nepal)

Country	Installed capacity 2040 (GW)		Cumulative generation for the 2015-2040 period (TWh)		GHG emissions (Million tons)	
	Change from		Change from		Change from	
	Baseline	Full trading	Baseline	Full trading	Baseline	Full trading
Afghanistan	0	-3.6	-2	-272.8	0	0
Bangladesh	-10	0.8	-1,518	25.7	-1,148	22
Bhutan	9	0.0	1,112	-0.6	0	0
India	-40	-4.8	-3,321	-217.9	-3,117	-168
Nepal	55	2.8	3,695	96.5	0	0
Pakistan	0	12.8	1	431.7	12	334
Sri Lanka	0	0.5	0	-6.2	0	-12
Total	13	8.6	-33	56.3	-4,253	175

(b) Western sub-region (Afghanistan and Pakistan)

Country	Installed capacity 2040 (GW)		Cumulative generation for the 2015-2040 period (TWh)		GHG emissions (Million tons)	
	Change from		Change from		Change from	
	Baseline	Full trading	Baseline	Full trading	Baseline	Full trading
Afghanistan	3.6	0.0	284.7	13.5	-0.1	0
Bangladesh	0.0	11.3	0.0	1,543.8	-3.2	1,167
Bhutan	0.0	-9.1	0.0	-1,112.3	0.0	0
India	0.0	35.1	0.6	3,103.5	-3.5	2,945
Nepal	0.0	-52.1	0.0	-3,598.1	0.0	0
Pakistan	-5.2	7.9	-366.7	64.2	-192.9	129
Sri Lanka	0.0	0.5	0.0	-6.2	0.0	-12
Total	-1.6	-6.5	-81.5	8.1	-199.6	4,229

(c) Change in Costs

Sub-regional trading Scenario	Undiscounted costs		Discounted costs	
	Change from		Change from	
	Baseline	Full trading	Baseline	Full trading
Change in Billion US$				
Eastern South Asia (Bangladesh, Bhutan, India, Nepal)	-204	22	-89	8
Western South Asia (Afghanistan and Pakistan)	-14	213	-4	93
Change in Percentage				
Eastern South Asia (Bangladesh, Bhutan, India, Nepal)	-4.9	0.6	-4.4	0.4
Western South Asia (Afghanistan and Pakistan)	-0.3	5.4	-0.2	2.4

(d) Change in cross-border transmission interconnection capacity and electricity flows with sub-regional trading instead of full regional trading

Cross-Border Interconnection	Cross-border transmission capacity by 2040 (GW)		Electricity exports for the 2015-2040 period (TWh)		Electricity imorts for the 2015-2040 period (TWh)	
	Eastern South Asia trading	Western South Asia trading	Eastern South Asia trading	Western South Asia trading	Eastern South Asia trading	Western South Asia trading
Afghanistan - Pakistan	-3	3	-349	20	1	1
Bangladesh - India	3	-10	90	-126	38	-1124
Bhutan - Bangladesh	0	-9	18	-557	0	-3
Bhutan - India	0	-5	-23	-548	-5	-7
Nepal - Bangladesh	0	-2	-17	-66	-26	-46
Nepal - India	3	-50	77	-3,528	-10	-28
Pakistan - India	-15	-15	-300	-300	-397	-397
Total	-12	-88	-505	-5,105	-400	-1,604

Table 8(c) presents a comparison of total regional electricity supply costs (net costs including both additional investment, and savings in fuel costs due to regional electricity trading) under the sub-regional trading scenario with that under (a) the baseline and (b) full regional trading. Sub-regional trading reduces total regional electricity supply costs compared to the baseline (4.9% reduction in net present value of the electricity supply costs due to Eastern South Asia sub-regional electricity trading, and 0.3% due to western South Asia sub-regional electricity trading). As expected, however, if electricity trade is limited to sub-regional levels, the reduction in electricity supply costs will be smaller than cost savings with full regional trading. The net present value of electricity supply costs under the Eastern South Asia sub-regional trading would be 0.4% higher compared to that in the full regional trading scenario. Similarly, the net present value of the electricity supply costs under the Western South Asia sub-regional trading would be 2.4% higher compared to that in the full regional trading scenario.

Table 8(d) presents the changes in cross-border interconnection capacity and electricity flows under the sub-regional trading scenarios compared to that in the full regional scenario. Under the Eastern sub-regional scenario, electricity trading as well as interconnection capacity between India and Bangladesh and between India and Nepal increases. This is because Nepal and Bangladesh partially offset the loss of trade between India and Pakistan that would have happened in the case of full regional scenario. The total interconnection capacity as well as cross-border electricity flows will drop under the sub-regional trading scenarios as compared to that under the full regional trading scenario.

Although the objective of this study is not to highlight the effects of carbon pricing in South Asian electricity systems, it is useful to examine the **sensitivity of regional electricity trade to**

imposition of a carbon price applied to fossil fuel inputs.[19] As noted, the carbon price was assumed to be US$10/t$CO_2$ starting from the year 2020, then increased to US$20/t$CO_2$ in 2025 and to US$30/t$CO_2$ in 2030. The results are presented in Tables 9 to 12. They are expressed in terms of both absolute deviation and percentage change from the baseline. For example, the numbers in "without electricity trading" columns refer to changes due to the carbon price from the baseline, where only limited trade of electricity already existing or committed by 2015 was considered. Similarly, the numbers in "with electricity trading" columns refer to change due to carbon price and full regional trading from the baseline.

The impacts of the carbon price on total installed capacity and total electricity generation are presented in Table 9(a) and (b). The results show that the assumed carbon price has significant impacts in electricity generation capacity in South Asia. More than 137 GW of coal fired electricity generation capacity (24% of the total installed coal capacity in 2040) would be replaced by low carbon or no carbon electricity generation technologies, even if cross-border electricity trade remained limited as in the baseline scenario. In the baseline, the carbon constraint would cause total wind and combined cycle power capacity to increase to 35% and 209% respectively. The carbon price would cause 16 GW of additional capacity in the region in the baseline from a situation in the absence of the carbon price. This is because wind power replaces coal fired electricity generation and the former has a much smaller capacity factor compared to the former, leading to a higher total installed capacity.

The carbon price would increase the total installed capacity in the region by 35 GW if it is implemented together with the full regional trading. This larger capacity addition due to the carbon price, compared to the 16 GW of additional capacity added in the absence of full regional trading, is a reflection of the fact that both carbon pricing and expanded regional power treading create incentives for investments in hydro and other renewable energy sources with lower capacity factor). However, this change is relatively small (only around 3% of the total increase in installed capacity) compared to the size of the regional electricity system (1,103 GW). Nevertheless, the impacts are especially high in Nepal, where the imposition of the carbon price would induce another 20 GW of hydropower capacity additions.

[19] Recall that our analysis treats final electricity demands as fixed, so our analysis of carbon price impacts does not account for a fall in demand as the electricity price increases with the carbon price. Accounting for demand effects would lessen somewhat the supply-side impacts that we present.

Table 9(a): Changes in the total installed capacity and electricity generation from the baseline due to the carbon price (by country)

Country	Installed capacity by 2040				Cumulative electricity generation for 2015-2040 period			
	Without electricity trading		With electricity trading		Without electricity trading		With electricity trading	
	GW	**%**	**GW**	**%**	**TWh**	**%**	**TWh**	**%**
Afghanistan	0.1	2.1	3.6	50.9	17	3.4	306	62.9
Bangladesh	0.0	0.0	-11.2	-16.5	-9	-0.2	-1,879	-42.4
Bhutan	0.0	0.0	9.3	63.2	1	0.1	1,117	87.1
India	10.4	1.3	-32.9	-4.2	-293	-0.4	-3,654	-5.5
Nepal	0.3	3.3	72.6	780.3	17	2.9	4,261	716.5
Pakistan	4.0	2.3	-7.3	-4.2	-11	-0.1	-324	-3.0
Sri Lanka	1.0	8.4	0.8	7.3	0	0.0	-9	-1.2
Total	15.8	1.5	35.0	3.3	-278	-0.3	-181	-0.2

Table 9(b): Changes in the total installed capacity and electricity generation from the baseline due to the carbon price (by generation sources)

Electricity generation type	Installed capacity by 2040				Cumulative electricity generation for 2015-2040 period			
	Without electricity trading		With electricity trading		Without electricity trading		With electricity trading	
	GW	**%**	**GW**	**%**	**TWh**	**%**	**TWh**	**%**
Diesel	0.0	0.0	0.0	0.0	-7	-23.6	-8	-25.7
Gas Turbine	-3.9	-6.4	-27.4	-45.1	31	20.1	68	43.9
Hydro	4.4	2.6	97.0	57.0	165	1.3	6,509	50.6
Solar	0.0	0.0	0.0	0.0	14	1.7	17	2.0
Coal	-137.2	-23.7	-146.5	-25.3	-9,917	-17.5	-11,858	-20.9
Wind	38.3	34.7	41.1	37.2	1,655	32.5	1,678	33.0
CC	114.3	208.7	70.8	129.3	7,679	380.7	3,320	164.6
Biomass	0.0	0.0	0.0	0.0	81	3.3	76	3.1
Nuclear	0.0	0.0	0.0	0.0	20	0.4	16	0.3

In the absence of a carbon price, the full trading scenario already induces investment in 61 GW of new hydropower capacity in the country, relative to the baseline. Under the carbon constraint scenario, almost the entire hydropower potential assessed to date (81 GW) would be exploited. Again, however, this capacity is only a small fraction (7%) of the total installed capacity of 1,103 GW needed by the region by 2040 under the full regional trading scenario.

The carbon price would substitute coal based generation with all other generation types – wind, hydro, combined cycle, biomass and nuclear. Under the baseline scenario, the carbon price would reduce coal based electricity generation by 18% during the 2015-2040 period. Coal based generation without expanded regional power trading is mainly replaced by combined cycle natural gas power generation. Electricity generation from the combined cycle plants would increase by almost four times due to the carbon price in the baseline scenario; electricity generation from wind would increase by 33 percent. With full regional trading, the imposition of the carbon price would further reduce the coal based generation over 2015-2040 – 21% versus the baseline, versus 18% in the absence of full regional electricity trading. Electricity generation from renewable energy sources (solar, wind and hydropower) due to the carbon price would be higher in the presence of full regional trading than in the absence full regional trading.

The carbon price would increase the electricity supply costs in the region (Table 10). While it would increase the total electricity supply costs by more than 31% in the absence of full regional trading scenario; the cost increment would be lower (23%) in the presence of the full regional electricity trading.

The impacts of carbon price on investment under the full trading scenario is the opposite of those under the baseline scenario. Total capital costs of generation under the baseline scenario decrease due to carbon price because of large-scale replacement of coal-fired capacity with combined cycle technology. However, under the full trading scenario, the replacement of coal fired capacity with combined cycle capacity is smaller compared to the baseline. Replacement of coal fired capacity with hydro and wind capacities is higher under the full trading scenario compared to the baseline scenario.

Table 10: Changes in discounted electricity supply costs from the baseline due to the carbon price

	Without electricity trading		With electricity trading	
	Billion US$	%	Billion US$	%
Total investment (2015-2040)	-31	-4.9	54	8.4
Total fuel costs (2015-2040)	663	48.4	415	30.3
Net electricity supply costs (net present value) for the 2015-2040 period	632	31.3	469	23.3

Turning to Table 11, we see that the carbon price would increase cross-border transmission interconnection capacity by more than 13 GW, mostly to transmit renewable electricity (hydro and wind). The additional capacity for transmission interconnection would be needed from Eastern Grid of India to Bangladesh, Bhutan, India North Eastern Grid, Nepal and Northern Grid of India. Similarly, transmission interconnection capacity needs to be added between Afghanistan and Pakistan and also between Nepal and India Northern Grid. The carbon price would, however, cause

India and Pakistan transmission interconnection to drop below what would have been built under full regional trading without the carbon price.

The carbon price would increase neighboring countries' electricity exports to India and decrease their electricity imports from India, as coal based power generation drops by a higher proportion in India given its coal intensity. Similar effects are observed for electricity trade between Bhutan and Bangladesh, and Nepal and Bangladesh; since Bangladesh's future power system will be more coal intensive than today, the carbon price would have a relative higher impact there. Similarly, the carbon price would cause Afghanistan to increase its electricity exports to Pakistan.

Table 11: Changes in cross-border transmission interconnection (GW) and power flow (TWh) due to carbon price

	Full regional trading without carbon constraint			Full regional trading with carbon constraint		
	Capacity	Exports	Imports	Capacity	Exports	Imports
Afghanistan to Pakistan	3.3	348	-1	5.9	422	-1
Bangladesh - India	10.0	126	1,124	11.2	149	1,274
Bhutan - Bangladesh	8.5	557	3	8.7	663	2
Bhutan - India	5.4	548	7	5.4	441	1
Nepal - Bangladesh	2.1	66	46	7.5	130	6
Nepal - India	50.3	3,528	28	58.0	4,039	-7
Pakistan to India	14.9	300	397	11.0	314	225
Sri Lanka to India	0.5	34	28	0.5	21	30
Total	95.0	5,507	1,632	108.2	6,179	1,531

Note that total exports include from total imports as South Asia region imports electricity from Central Asia but does not export. Capacity refers to total installed capacity in 2040; imports and exports represent cumulative values for the 2015-2040 period.

The carbon price would cause a 10% reduction of CO_2 emissions in the baseline during the 2015-2040 period (see Table 12). Under the full regional trading, the carbon price would cause 16% reduction of CO_2 emissions (or 6% additional reduction on top of what the carbon price alone could do in the absence of the full regional trading). Note that in the absence of the carbon price, the full regional trading scenario would cause 8% reduction of CO_2 emissions during the 2015-2040 period.

Table 12: Changes in power sector CO_2 emissions due to carbon price

Country	Cumulative CO_2 emissions from power generation for the 2015-2040 period			
	Without full regional trading		With full regional trading	
	Million tons	**%**	**Million tons**	**%**
Bangladesh	-277	-8	-1,580	-44
India	-4,419	-10	-6,332	-14
Pakistan	-756	-16	-850	-18
Sri Lanka	-58	-17	-53	-15
Total	-5,511	-10	-8,817	-16

Even if power projects are started for construction, delays in completion are common. For some technologies, **physical infrastructure constraints** (e.g., lack of port facility for importing coal in Bangladesh, lack of LNG regasification terminals in Pakistan, pipeline infrastructure in India) do not allow the least cost electricity planning to materialize. These constraints can be relaxed in the long term. However without incorporating these physical constraints, the electricity generation expansion plan could be optimistic. Therefore, our final sensitivity analysis assumes that large-scale power plants would have two additional years construction time (i.e., total plant completion time increases by 2 years); additional port facilities and LNG regasification plants will not be ready until 2021. This scenario also assumes that none of the large-scale hydropower plants would be commissioned before 2021. This scenario has, by design, significant impacts on installed capacity, electricity generation and costs and cross-border transmission capacity and power flow for the 2015-2021 period. During the entire study horizon (i.e., 2015-40 period), this scenario would see a 4% increase in total installed capacity by 2040 and more than 15% increase of total power supply costs in the region.

6. Conclusions

Afghanistan, Bhutan and Nepal all have the potential to cost-effectively supply electricity from hydroelectric resources in excess of their own demands, while Bangladesh, India and Pakistan are likely to become more dependent on higher-cost coal as well as natural gas to generate electricity. The countries of the South Asia region also have non coincident demand peaks across the year, implying gains from trade. Unfortunately, cross-border electricity transmission interconnections and electricity exchanges among South Asian countries have been very limited to date, implying that countries in the region may be missing significant opportunities for gains from trade through lower regional electricity supply costs. In particular, hydropower suppliers are losing economic opportunities if they could expand development of their resources through cross-border regional electricity trade and cooperation. Conversely, potential importers of lower-cost supplies (hydro or otherwise) lose the economic benefits from access to such sources of supply.

This study quantifies the potential economic benefits that the South Asia region could reap if the countries engage with full regional electricity trade and cooperation. A dynamic, perfect foresight, inter-temporal electricity planning model that optimizes the electricity generation and transmission interconnection systems for the period of 2015-2040 has been used to assess the potential benefits. The cooperation benefits reported by the model are direct sector-level gains from being able to efficiently develop and deploy generation and transmission assets at a regional level rather than country-by-country. These benefits include increased market access for lower-cost generation alternatives that can meet export as well as domestic electricity demands; and an ability to make shorter-term trades based on differences across the year when peak demands occur.

Under the baseline that assumes no further expansion of cross-border transmission interconnections than what already exist or are being constructed, the total generation capacity in the region would increase by almost 750 GW by 2040 (more than three times of the current installed capacity) to meet the electricity demands that is assumed to rise at an average rate of 5% over the 2015-2040 period. Regional electricity cooperation and trade would lead to notable reallocations of capacity investments across the region. Compared to the baseline, installed generation capacity would fall by 35 GW in India, 13 GW in Pakistan, and 11 GW in Bangladesh over the 2015-2040 period. Capacity would increase by 52GW and 9GW the generation capacities in Nepal and Bhutan respectively, and by 4 GW in Afghanistan, relative to the baseline. These reallocations reflect both major increases in hydro capacity relative to the baseline, and peak load sharing. Note that while the expansions of generation capacity in Nepal and Bhutan are many fold higher than their domestic demands by 2040 (36 times for Bhutan and 7 times for Nepal), they still represent only a small fraction (8%) of the total generation capacities required to be added in the region as a whole to meet the growing demand (with or without increased cooperation and trade). To realize the full-scale regional electricity trade, the region would need approximately 95 GW of net additional cross-border transmission interconnection capacities.

The modeling results indicate that the regional electricity cooperation and trade could reduce total undiscounted electricity supply costs in the region by US$222 billion, or more than US$9 billion per year over the time period studied, compared to the baseline. The gain mainly comes through the savings in operational costs, which would be (in undiscounted terms) $270 billion lower under regional cooperation. The present value of the fuel savings in the region as a whole would be $119 billion at a real discount rate of 5%. With that discount rate, the ratio of benefits in the form of reduction of fuel costs, to increased costs due to generation and interconnection, is 5.3. This also indicates that the economic benefits of full-scale regional electricity trade and cooperation is high. These direct net benefits from our partial equilibrium analysis do not include any economy-wide benefits from lower-cost electricity. They also do not include local environmental benefits or a monetized value of reduced CO_2 emissions.

The South Asia region's power generation trajectory in the baseline modeling analysis is dominated by coal, with more than 60 percent of the total electricity generation during 2015 – 2040 based on coal while 25 percent of total electricity generation would be from renewable sources (including hydro). The share of renewables electricity in total electricity generation during the 2015-2040 period expands to 31 percent under regional cooperation. Total CO_2 emissions for the entire region over the 2015-2040 period decline by 8% under regional cooperation relative to the baseline, due mainly to substitution of coal based generation with hydro-based generation, although regional emissions in either case still would be well above current levels absent other policy interventions.

A series of sensitivity analyses on a variety of assumptions, including coal prices, hydro cost/availability, and lower costs for wind and solar, indicates that the findings are robust. For example, if electricity demand grows more rapidly than as expected, costs rise – but the relative gains from regional cooperation are not significantly different. If there are delays in the completion of ongoing projects including non-delivery of large hydro, imported coal and natural gas projects by 2021, then total costs of power system expansion would increase by more than 15%. Finally, imposition of a hypothetical carbon price across the region acts as a major additional stimulus to hydro development as well as non-hydro renewables. Electricity costs rise in that case due to greater use of costlier and lower-capacity-factor generation sources as well as some additional increase in transmission interconnections.

Several important extensions of this analysis remain to be carried out. Aside from impacts on the local environment, already noted, it would be useful to identify the potential ways that regional gains could be distributed across different countries in the region. The optimization model generates shadow prices for constraints on both total generation capacity and transmission capacities along different interconnections. In principle we could use the shadow prices as busbar prices for generation and nodal prices for transmission in a perfectly competitive integrated regional power market. These prices in turn could be used to calculate total payments and receipts for power for the different countries, and thus the net gains from trade. We have not pursued that in this paper in part because the transmission system in the model is fairly simplified, and also because the assumption of perfectly competitive pricing in generation and transmission is a strong one. While it seems clear from the results that there exist multiple outcomes in which all countries are better off with regional cooperation and trade than without it, additional investigation of the sizes of these gains is warranted.

Another important and related question is the potential distributional impact of regional electricity cooperation and trade within countries. Suppose, for example, that Nepal were to apply marginal-cost pricing to power generation. With expanded production for exports, marginal costs and thus prices for generated electricity for domestic customers could rise, depending on how quickly up-front capital costs are rolled into rates and how strong are the economies of scale in hydro expansion. Further work on how rates can be designed to more broadly share the benefits of expanded export opportunities has a high priority.

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APPENDIX A: RESULTS FROM BASELINE SCENARIO

Installed Generation Capacity (GW)

- Coal would remain as the predominant energy resource to generate electricity in South Asia. It would account for more half of the total installed capacity in the region by 2040 because of its cost competitiveness as compared to other technologies to generate electricity;

Table A1a: Installed Capacity (GW)

	2020	2030	2040
Afghanistan	1.1	6.0	7.0
Bangladesh	27.2	48.7	67.8
Bhutan	6.9	14.7	14.8
India	387.2	586.5	783.9
Nepal	3.4	7.9	9.3
Pakistan	57.5	108.7	173.0
Sri Lanka	5.8	9.1	11.7
Total	489	782	1067

Table A1b: Installed Capacity Mix in 2020 and 2040 (%)

	Year	Diesel	Gas Turbine	Hydro	Solar	Coal	Wind	Combine Cycle	Biomass	Nuclear
Afghanistan	**2020**	19.2%	54.1%	24.6%	0.0%	0.0%	2.2%	0.0%	0.0%	0.0%
	2040	3.0%	8.5%	88.1%	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%
Bangladesh	**2020**	14.8%	9.2%	1.5%	17.3%	19.4%	0.4%	37.5%	0.0%	0.0%
	2040	5.9%	3.7%	0.6%	6.9%	66.8%	0.1%	15.0%	0.0%	0.9%
Bhutan	**2020**	0.1%	0.0%	99.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	2040	0.1%	0.0%	99.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
India	**2020**	0.3%	3.1%	15.5%	3.2%	59.9%	9.7%	3.8%	1.4%	3.0%
	2040	0.1%	6.9%	12.7%	2.6%	57.7%	9.3%	4.2%	2.9%	3.7%
Nepal	**2020**	1.6%	0.0%	97.8%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%
	2040	0.6%	0.0%	99.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
Pakistan	**2020**	0.8%	4.3%	29.8%	0.0%	34.3%	16.7%	10.7%	0.8%	2.6%
	2040	0.3%	1.6%	22.1%	0.0%	45.4%	20.0%	6.0%	0.3%	4.3%
Sri Lanka	**2020**	3.1%	10.7%	32.7%	1.5%	16.3%	17.8%	17.1%	0.8%	0.0%
	2040	0.8%	5.7%	17.6%	1.1%	37.1%	24.5%	12.3%	0.8%	0.0%
Total	**2020**	1.2%	3.7%	18.4%	3.6%	52.7%	9.9%	6.6%	1.2%	2.7%
	2040	0.6%	5.7%	15.9%	2.3%	54.3%	10.3%	5.1%	2.2%	3.4%

- All South Asian countries with exception of Afghanistan, Bhutan and Nepal would have large share of coal in total electricity generation. As of 2020, the share of coal-fired generation capacity in the total installed capacity would be 19%, 60%, 34% and 16%, respectively in Bangladesh, India, Pakistan and Sri Lanka. The corresponding shares in 2040 would be 67%, 58% 45% and 37% (see Table A1b).

- Total regional capacity would increase by 3.8 folds from 276 GW in 2013 to 1,067 GW in 2040. More than 70% of the total regional capacity would be installed in India.

Electricity Generation (TWh)

- Coal based generation would increase from 66% in 2020 to 71% by 2040 in the baseline;

- The share of coal-based generation would account for 92%, 75%, 64% and 57% in Bangladesh, India, Sri Lanka and Pakistan, respectively in 2040 under the baseline.

- Total regional generation would increase by 3.5 folds from 1,486 TWh in 2013 to 5,247 TWh in 2040.

Table A2a: Electricity Generation (TWh)

	2020	2030	2040
Afghanistan	1.4	26.3	31.7
Bangladesh	90.1	191.2	312.2
Bhutan	34.2	59.2	59.6
India	1,740.8	2,828.1	3,954.2
Nepal	15.0	27.3	36.5
Pakistan	207.2	442.7	808.6
Sri Lanka	19.0	30.6	44.4
Total	2,107.8	3,605.4	5,247.1

Table A2b: Electricity Generation Mix in 2020 and 2040 (%)

	Year	Diesel	Gas Turbine	Hydro	Solar	Coal	Wind	Combined Cycle	Biomass	Nuclear
Afghanistan	2020	0.0%	2.5%	92.6%	0.0%	0.0%	4.8%	0.0%	0.0%	0.0%
	2040	0.0%	0.0%	99.8%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%
Bangladesh	2020	0.3%	0.0%	1.6%	8.2%	30.3%	0.3%	59.4%	0.0%	0.0%
	2040	0.1%	0.0%	0.5%	2.4%	92.3%	0.1%	3.4%	0.0%	1.3%
Bhutan	2020	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	2040	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
India	2020	0.0%	0.1%	10.5%	1.1%	74.5%	5.9%	1.2%	2.1%	4.6%
	2040	0.0%	0.0%	8.3%	0.8%	74.5%	4.8%	2.2%	4.1%	5.4%
Nepal	2020	0.0%	0.0%	99.8%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
	2040	0.0%	0.0%	99.9%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Pakistan	2020	0.0%	2.3%	39.2%	0.0%	29.6%	12.7%	9.0%	1.6%	5.6%
	2040	0.0%	0.1%	21.8%	0.0%	57.1%	11.3%	2.1%	0.4%	7.2%
Sri Lanka	2020	0.0%	0.7%	19.1%	0.7%	33.6%	15.3%	29.0%	1.7%	0.0%
	2040	0.0%	0.0%	9.0%	0.4%	63.5%	18.5%	7.2%	1.5%	0.0%
Total	2020	0.0%	0.3%	15.2%	1.3%	66.0%	6.3%	4.7%	1.9%	4.3%
	2040	0.0%	0.0%	12.1%	0.7%	70.9%	5.5%	2.2%	3.1%	5.3%

Investment Requirement for Power Sector Development

- South Asia is projected to require 1,390 billion US$ for expanding electricity generation expansion during the 2015-2040 period (to add approximately 750 GW of electricity generation capacity). Already committed and planned inter-grid connection, especially within India would require around 29 billion US$.

- More than 67% of the total investment for electricity generation and 96% of grid interconnection expansion under the baseline would occur in India.

Table A3: Investment Requirement for the 2015-2040 Period (Billion US$, Undiscounted)

	Investment (Generation)	Investment (Interconnection)	Operation	Energy Not Served	Total
Afghanistan	16.36	0.18	0.47	0.61	18
Bangladesh	105.12	0.63	226.20	0.00	332
Bhutan	32.08	0.54	0.00	0.04	33
India	929.67	27.93	2,160.03	0.16	3118
Nepal	10.75	0.00	0.00	0.00	11
Pakistan	276.96	0.00	292.39	2.69	572
Sri Lanka	18.67	0.00	27.69	0.39	47
Total	1,390	29	2,707	4	4130

Transmission Interconnection Capacity (MW)

- In the baseline, the expansion of grid-interconnection occurs mostly within India. Cross-border interconnection are limited between India-Bhutan and India-Nepal, where transmission links under construction or committed will be implemented.

- In India most inter-grid connections will be built by 2020; the connections that would expand in later periods of the study horizon are between northern and eastern grids and northern and western grids. These grids would be required to transmit coal fired generations from eastern and western grids to northern grids, where power demand is expected to increase the highest and cheaper source of power generation (e.g., coal) is not available because local coal resources are limited and imported coal would be too expensive due to transportation costs.

Table A4: Power Flow: Grid Interconnection Capacity in the Baseline (MW)

	2020	2030	2040
Afghanistan to Pakistan	2,300	2,300	2,300
Bangladesh to India East	500	500	500
Bhutan to India East	7,800	7,800	7,800
Central Asia to Afghanistan	3,138	3,138	3,138
India East to India South	5,238	5,238	5,238
India North East to India East	1,636	1,636	1,636
India North to India East	6,278	16,202	26,078
India North to India West	7,187	26,987	40,742
India West to India East	7,810	7,810	7,810
India West to India South	9,777	9,777	9,777
Nepal to India East	1,050	1,050	1,050
Nepal to India North	75	75	75

<u>Power Flow (TWh)</u>

- In the baseline, a very limited cross-broader electricity trade is projected, except between Bhutan and India, the latter is planning to develop more than 10,000 MW of electricity generation capacity in the former.

- There would be a massive flow of inter-grid power flow between Indian electricity grids as Government of India is committed to strengthen inter-grid electricity flow by strengthening the inter-grid connection in the country.

Table A5: Power Flow

	2020	2030	2040
Afghanistan to Pakistan	8.2	11.9	10.0
Bangladesh to India East	-1.5	-1.4	1.1
Bhutan to India East	30.4	54.0	53.9
Central Asia to Afghanistan	17.4	3.6	4.8
India East to India South	23.5	11.7	-15.5
India North East to India East	-6.8	11.2	10.8
India North to India East	-36.3	-101.4	-217.2
India North to India West	-34.1	-175.5	-304.5
India West to India East	0.0	1.0	6.1
India West to India South	33.6	5.4	-3.3
Nepal to India East	4.3	5.8	2.8
Nepal to India North	0.4	0.5	0.3

CO_2 emissions (Million tons of CO_2)

- In the baseline, the power sector is projected to emit 1.4, 2.1 and 3.4 billion tons of CO2 emissions in 2020, 2030 and 2040 respectively. India, would obviously be the largest source in the region. However, India's share in the total regional CO_2 emission from the power sector would be declining (90% in 2020 to 78% in 2040). The share would be more than doubling in Pakistan during the 2020-2040 period (5% in 2020 to 13% in 2040). GHG emissions in Bangladesh would increase by almost five times.
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TableA6: CO_2 emissions from power generation (Million tons of CO_2)

	2020	2030	2040
Afghanistan	0	0	0
Bangladesh	58	161	265
Bhutan	0	0	0
India	1,263	1,856	2,667
Nepal	0	0	0
Pakistan	73	157	439
Sri Lanka	8	14	24
Total	1,401	2,188	3,395