Impacts of CO_2 emission constraints on penetration of solar PV in the Bangladesh power sector

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Abstract: This paper examines the impacts of CO_2 emission reduction targets and carbon tax on future technologies selection especially solar PV and energy use in Bangladesh power sector during 2005-2035. It also examines the co-benefits of energy security of the country. The analyses are based on a long-term energy system optimization model of Bangladesh using the MARKAL framework. The results of the study show that on a base **scenario**, power generated from solar PV is not yet competitive with that of fossil fuel-based power plants. Alternative **policy scenarios** on CO_2 emission constraints reduce the burden of imported fuel, improve energy security and reduce environmental impacts. The results show that the introduction of the CO_2 emission reduction targets and carbon tax directly affect the shift of technologies from high carbon content fossil-based to low carbon content fossil-based and clean solar PV technologies compared to the base scenario. The cumulative net energy imports during 2005-2035 would be reduced in the range of 33-61% compared to the base scenario. The total primary energy requirement would be reduced in the range of 4.5-22.37% and the primary energy supply system would be diversified. Solar PV plays an important role in achieving reasonable energy security.

Keywords: *Solar PV, CO_2 emission, MARKAL Model, Bangladesh Power Sector*

1. Introduction

The future economic development of Bangladesh is likely to result in a rapid growth in the demand for energy with accompanying shortages and problems. The country has been facing a severe power crisis for about a d ecade. Known reserves (e.g., natural gas and coal) of commercial primary energy sources in Bangladesh are limited in comparison to the development needs of the country [1]. Power generation in the country is almost entirely dependent on f ossil fuels, mainly natural gas that accounted for 81% of the total installed electricity generation capacity (5,719 MW) in 2009 [2]. Only about 42% of total population has been connected to electricity [3], with vast majority being deprived of a power supply. The government of Bangladesh has declared that it aims to provide electricity for all by the year 2020, although at present there is high unsatisfied demand for energy, which is growing by more than 8% annually [4, 5]. Coal is expected to be the main fuel for electricity generation. The government of Bangladesh has planned to generate 2,900 MW power from coal in the next 5 years [1], although coal power has adverse environmental effects and coal reserves are limited. The government has also focused on furnace-oil-based peaking power plants. As a result, the share of CO_2 emissions coming from fossil-fuel-based power plants in the national CO_2 inventory is expected to grow, and there is a growing dependency on imported fossil fuels for power generation. On the other hand, technical potential of grid-commented renewable energy technologies specifically solar PV to generate electricity is relatively very high in Bangladesh that is 10 times higher than present generation capacity [3]. Increasing the use of fossil fuels to meet the growing worldwide electricity demand, especially in developing countries, not only counteracts the need to prevent climate change globally but also has negative environmental effects locally. In Bangladesh, the power sector alone contributes 40% of the total CO_2 emissions [6, 7]. CO_2 is the principal greenhouse gas (GHG), produced mainly from the combustion of fossil fuels. Improved efficiency in the use of fossil fuels and increased use of renewable energy sources are among the most promising options for reducing CO_2 emission [8]. In this case, it is necessary to develop and promote alternative energy sources that ensure energy security of Bangladesh without increasing environmental impacts. Since developing countries are not obliged to reduce GHG emissions, studies in evaluating the impacts or co-benefits of GHG mitigation policies in developing countries are lacking [9]. For a developing country like Bangladesh, the evaluation of the impacts of GHG mitigation policies in the power sector would provide a basis for more comprehensive technological choice, and economic and environmental analysis. Such an evaluation would also support climate change mitigation policies aimed on sustainable power-sector development as part of the efforts to address the climate change issues identified in the United Nations Framework Convention on Climate Change (UNFCCC) which Bangladesh has already ratified.

This study examines the future technologies selection applying CO_2 emission reduction targets and carbon tax in the Bangladesh power sector during 2005-2035. This study also analyzes the co-benefits on energy security of the country from the CO_2 emission constraints. A bottom-up least cost energy system optimization model of Bangladesh was developed on the market allocation (MARKAL) modeling framework and the following scenarios were considered:

1) Base scenario: It presumes a continuation of current energy and economic dynamics and provides a reference for comparing impacts of future policies.
2) 10% CO_2 emission reduction scenario (hereafter referred as "CO210"): It evaluates the effects of CO_2 emission reduction in the entire energy-supply system. The CO210 is the 'what if' scenario, in which a cumulative reduction of not less than 10% of the cumulative CO_2 emission during the planning horizon in the base scenario is desired, all other things remaining the same as in the base scenario.
3) 20% CO_2 emission reduction scenario (hereafter referred as "CO220"): The CO220 scenario is defined similarly for cumulative reduction in CO_2 emission of not less than 20% from the base scenario.
4) 2500 Taka/ton (1 USD = 70 Bangladeshi Taka) carbon tax scenario (hereafter referred as "CT2500"): The CT2500 is the 'what if' scenario, in which a carbon tax of 2500 Taka/ton is applied during the planning horizon in the base scenario.

2. MARKAL methodology

The MARKAL model mainly consists of the description of a large set of energy technologies, linked together by energy flows, jointly forming a reference energy system. The reference energy system is the structural backbone of MARKAL for any particular energy system and its great advantage is that it gives a graphic idea of the nature of the system. Another important characteristic of MARKAL is that it is driven by a set of demands for energy services. The feasible solutions are obtained only if all specified end-use demands for energy for all the periods are satisfied. The user exogenously supplies these demands in the model. Once the reference energy system has been specified, the model generates a set of equations that hold the system together. In addition, the MARKAL model possesses a clearly defined objective, which is usually chosen to be the long-term discounted cost of the energy system. The objective is optimized by running the model, which means that configuration of the reference energy system, is dynamically adjusted by MARKAL in such a way that all MARKAL equations are satisfied and the long-term discounted system cost is minimized. In this process the model computes a partial equilibrium of the energy system at all intermediate stages in all aspects e.g. flow conservation, demand satisfaction, capacity transfer, capacity utilization, source capacity, growth constraints, emission and other constraints.

3. The MARKAL Bangladesh model

3.1. *Reference energy system of Bangladesh power sector*

For the purpose of this study, MARKAL-Bangladesh was developed. A major part of the work was to develop input parameter values. In MARKAL, the reference energy system is the first step towards building a model of the Bangladesh power sector (Fig. 1). The reference energy system represents the activities and technologies of an energy system, depicting energy demands, energy conversion technologies, fuel mixes, and the resources required to satisfy energy service demands [10]. The reference energy system is able to allocate energy sources for a given sectoral demand depending upon the efficiencies and other losses from the energy conversion device. The system does not provide any information about economics of a solution neither about the cost to the national economy for providing the energy supply. An optimized energy system can be obtained from the MARKAL model.

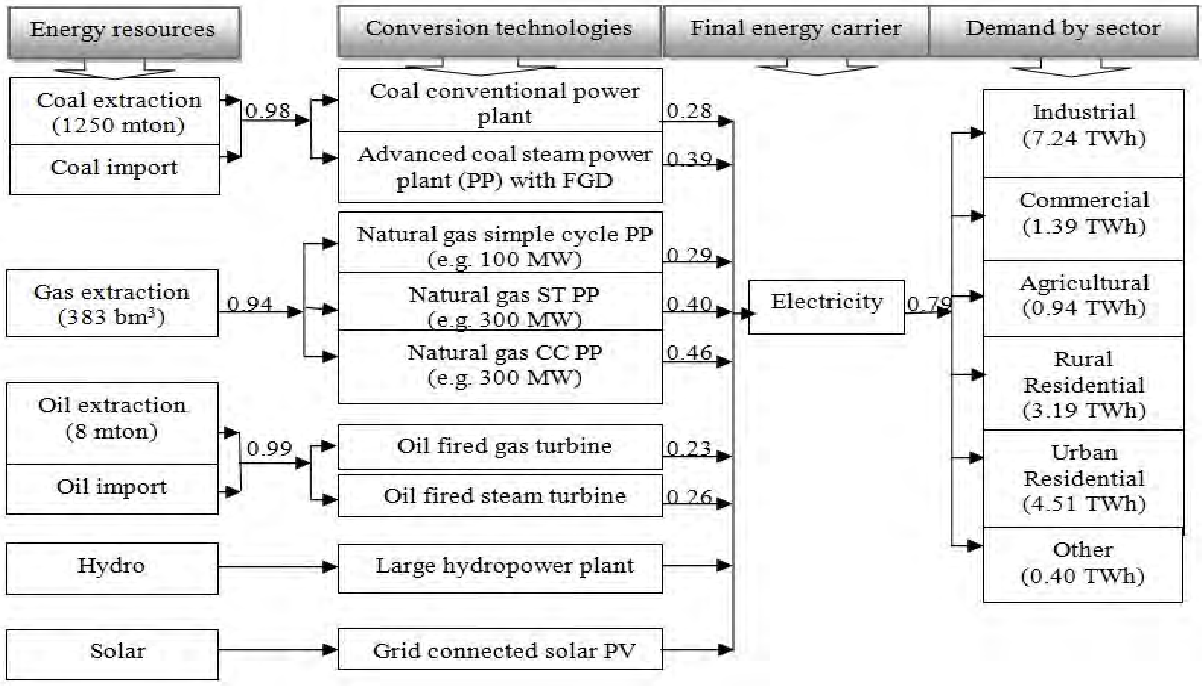

Fig 1. Simplified reference energy system of Bangladesh power sector
(Values shown indicate proven reserves, conversion & transmission efficiency, and demand in 2005)
(CC refers combined cycle, FGD refers flue gas desulphurization, mton refers million ton and bm^3 *refers billion* m^3*)*

3.2. *Energy resources and emissions*

The model requires that the cost of all primary energy sources be defined along with constraints on their availability. It is provided supply cost estimates and upper bounds on resource availability for fossil fuels and the maximum rates of introduction of solar PV and hydro are given in [1]. A limit on imported coal is not considered here. In mined coal, the average sulfur content is 0.57% and carbon 46.2% [11]. These values form the basis of the calculated emission coefficients used in this study. The IPCC (1996a) database is used for the CO_2 emission of imported coal. Due to different carbon content percentages in different gas fields in Bangladesh, the IPCC (1996a) emission factor is used in the model. CO_2 and SO_2 emission factors are calculated separately for diesel, kerosene and fuel oil products based on the IPCC workbook [12] and IPCC reference manual [13].

3.3. Energy demand

In 1994, the total electrical energy demand was 9.63 TWh and had increased to 17.64 TWh in 2005 [14]. The Long-range Energy Alternatives Planning (LEAP) tool was examined to form demand scenarios according to the trend of gross domestic product (GDP) growth rates (5.5%, 6.8% and 8%) and the nature of the energy sector itself, and taking into consideration broader factors, e.g., population, households, urbanization and other influencing factors for the time span 2005 to 2035. It is worth mentioning here that the actual GDP growth rate in Bangladesh is neither low nor high and therefore, in this study, the demand projection is based on a GDP growth rate of 6.8% is given in [15].

3.4. Conversion technologies[1]

The characteristics of all technologies must be provided to the model. Conversion technologies convert primary energy into final energy carriers. The model requires users to create detailed profiles for two sets of energy conversion technologies: one for converting primary into final energy carriers, and one for converting final energy carriers into energy services. A reasonably representative set of conversion technologies is developed, which includes a total of 9 distinct conversion technology types (coal steam conventional, advanced coal flue gas desulphurization (FGD) 300 M W, fuel oil-based steam, fuel oil-based gas turbine, gas-based simple cycle (SC) and steam turbine (ST), gas-based combined cycle (CC, hydro and solar PV). Other renewable energy technologies are not considered due to their limited technical potential to generate electricity [3]. For each of the technology types, values are specified for energy input per unit energy output (efficiency), capital cost, fixed and variable operation and maintenance costs, NO_2 and SO_2 emissions per unit of energy output, and the first year in which the technology was introduced**.** All costs are in Bangladesh Taka (1 USD = 70 Taka). The characteristics are performance and cost level inputs to the model for 2005-2035. For most of the technologies, the performance and cost levels are assumed to be constant over the whole analysis period except for solar PV, where the investment cost is expected to decrease by 3% annually [16] due to technological learning effects on solar PV cost after introduction in 2010. The model determines the capacity level for any technology. In this modeling, the most reliable studies are selected and evaluated to yield as consistent a set of cost data as possible.

3.5. Generic details

Besides the technical and financial parameters related to different stages of reference energy system of the Bangladesh power sector, the other parameters, assumptions and boundaries are also required by MARKAL which are discussed in [1].

4. Results

Under the base scenario, the total generation capacity is expected to increase from 5.56 GW in 2005 to 50.85 GW in 2035, i.e., at an average growth rate of 7.6 %. At the same time, the generation structure changes significantly. The share of gas-fired power plants reduces from 86% (4.83 GW) in 2005 to 37.4% (19.04 GW) in 2035 in total capacity, whereas the increase in the capacity of coal-based power plants 0.25 GW in 2010 to 30.75 GW in 2035 (60.4% of total capacity) is extremely high. It is observed that coal is the dominant electricity generation technology in base scenario. In the base scenario, the advanced coal flue gas desulphurization (FGD) produces 32% of electricity in 2015 and 91% in 2035, due to unused capacity of oil-

[1] Cost data, technology selection and technology specification data mainly based on Bangladesh Power Sector Master Plan, Bangladesh Power Development Board and Ministry of Power, Energy and Mineral Resources.

based power plants and limited gas is mainly used in the early period (2005-2025). Hydro capacity reaches its allowed upper limit in the base scenario. Solar photovoltaic (PV) is not selected in the base scenario due to its high investment cost and low efficiency.

The switch from gas- to coal-based power plants leads to a strong increase in coal consumption (178 PJ in 2015 to 1913 PJ in 2035), i.e., at an average growth rate of 26%. This rate is higher than the domestic availability. Thus, the country would need to import energy resources such as coal from 2025 onwards to meet the required demand. The proportion of imported coal in the total fossil fuel consumption would increase substantially from 16% (187 PJ) in 2025 to 57% (1178 PJ) in 2035. This deficiency would have adverse impacts on the country's balance of payments and the availability of foreign currency resources.

The introduction of the CO_2 emission reduction targets and carbon tax scenarios (the CO_2 emission reduction of 10%, 20% and carbon tax 2500 Taka/ton are referred to hereafter as CO210, CO220 and CT2500, respectively) directly affects the shift of technologies from high carbon content fossil-based to low carbon content fossil-based and clean renewable energy-based solar PV technologies. As a result of emission constraints, power generation based on solar PV is introduced and its generation capacity gradually increases during 2010–2035. Compared to the base scenario, 15.12 GW, 34.92 GW and 40.62 GW solar PV-based generation capacities are additionally selected in 2035 in the CO210, CO220 and CT2500 scenarios, respectively. Solar PV generation starts with a capacity of 0.02 GW, 0.05 GW and 0.06 GW in 2010 in the CO210, CO220 and CT2500 scenarios, respectively and grows at a rate of 29.5% per year. The total generation capacity is expected to increase from 5.56 GW in 2005 to 65.72 GW, 86.15 GW and 91.23 GW in 2035 in the CO210, CO220 and CT2500 scenarios, respectively (Fig. 2). The generation capacity is relatively higher in the CO_2 emission constraint scenarios than in the base scenario due to implementation of a higher solar PV capacity, which generates electricity only during the day.

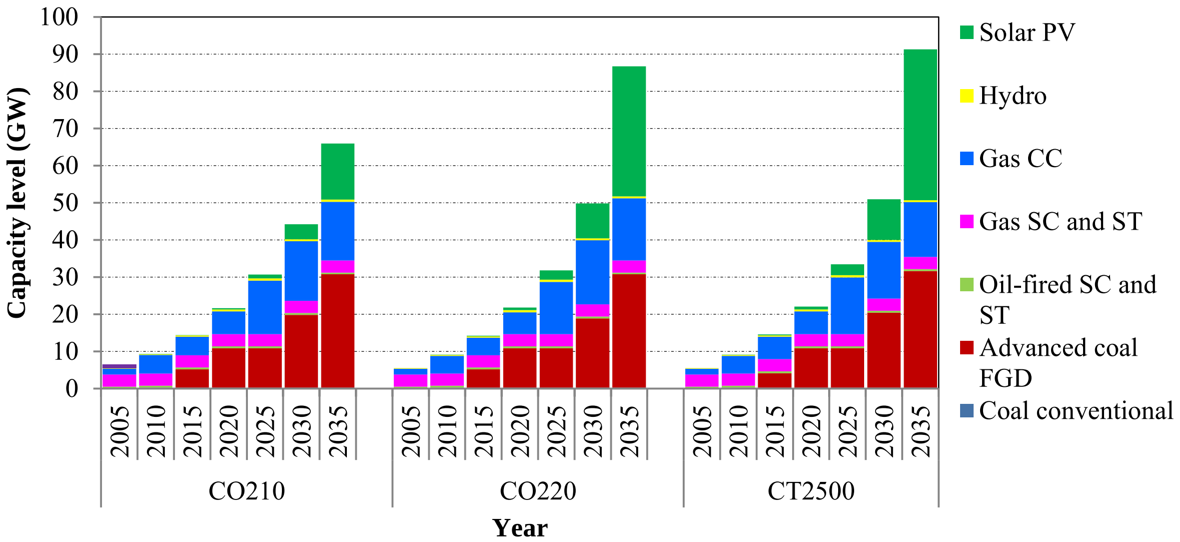

Fig 2. Technology capacity level in all CO_2 constraint scenarios

Gas-based combined cycle (CC) power plant capacity increases significantly in the later period (2020-2030) in all alternate scenarios compared to the base scenario. The model reveals that the least-cost solution is to use the limited gas reserves in the mid-term period, although the gas-based CC plants are mostly unused in the end period (2035). That is why the power generation capacity based on coal FGD decreases significantly in the later period (2025-2030) in the CO_2 emission constraint scenarios compared to the base scenario. Due to high oil prices, oil-based power plants do not receive higher allocation in the CO_2 emission reduction targets and carbon tax scenarios. Gas-based simple cycle (SC) and steam turbine (ST) plants, coal conventional also do not get more allocation in the alternate scenarios. The capacity levels of hydro are the same in all scenarios. Coal FGD maintains the almost same capacity level in 2035 i n all scenarios as gas resource is limited. Fossil fuel-based technologies would be required, as solar PV technology cannot cater for the entire future energy demand. The learning cost for solar PV enhances competitiveness of the technologies and leads to a higher rate of implementation of this technology in the analysis period.

To summarize the extensive results generated for each of the CO_2 emission reduction target and carbon tax scenarios by the MARKAL-Bangladesh model, the primary energy mix in 2035 is selected as the principal metric (Fig. 3). This provides a good indication of the types of choices made by the model to meet the various CO_2 emission constraints applied. The colored bars (except yellow in the middle) provide the breakdown of primary energy use for the base scenario in 2005 and all scenarios in 2035. The numbers above each bar indicate the total and percentage of the cumulative imported coal and the total cumulative and percentage of CO_2 emission reduction compared to the base scenario during the study period. Oil is not indicated, as it is not selected for power generation during the study period. The center yellow bar in the three scenarios on t he right in this figure shows the change in cumulative total system cost relative to the base scenario. Due to the large uncertainties in this kind of analysis, the percentage change in system cost between the various scenarios as the measure of the cost impact of the changes imposed by each scenario is applied. The system cost for the base scenario is the reference cost in all cost comparisons.

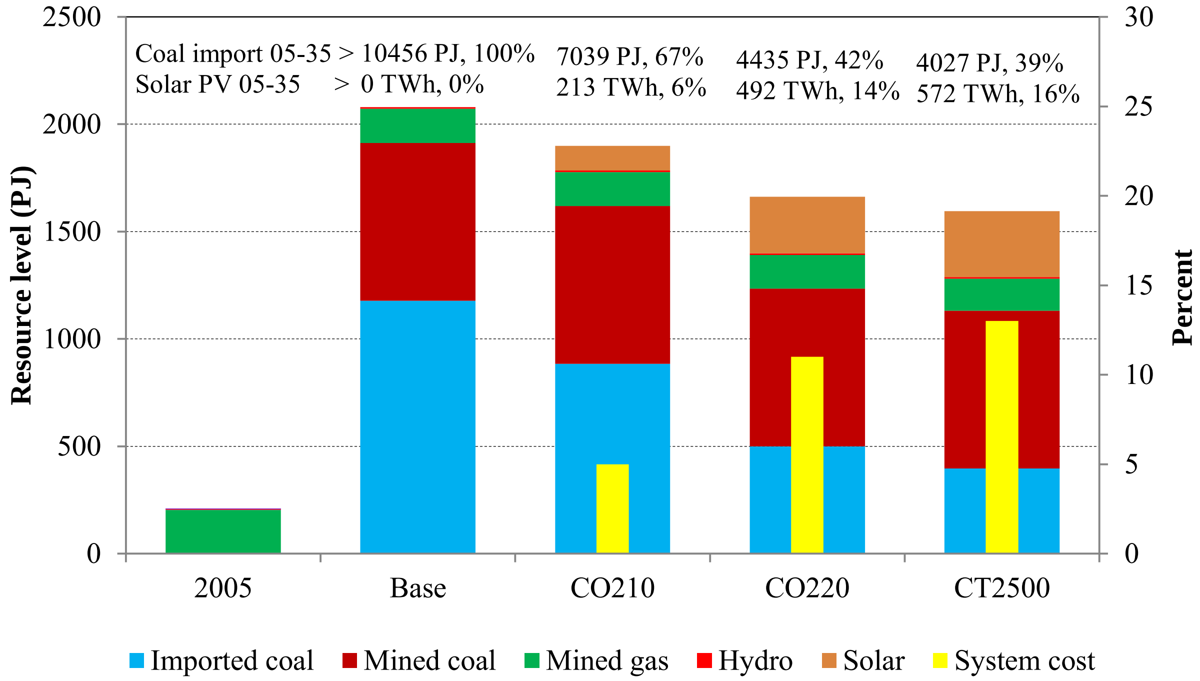

Fig 3. Primary energy mix in 2035 in all scenarios and percentage change in cumulative (2005-2035) system cost. Also indicated are the energy mix in 2005, the cumulative total and percentage of total imported coal, and the total electricity generation from solar PV.

CO_2 emission constraints have positive impacts on the energy security of the country. The energy security issue is analyzed in terms of changes in net energy import dependency and diversification of energy resources resulting from the selected CO_2 emission reduction targets and carbon tax. The CO210 scenario allowed a reduction in imported coal use of about 33% contributing an only 5% increase in system cost during 2005-2035. Import dependency reduces by 58%, and 61% in CO220 and CT2500 scenarios, respectively, compared to the base scenario during the study period, but led to an increase in the total system cost of 11% and 13%. Alternatively, import dependency based on the base scenario value 100%, drops to 67%, 42%, and 39% in the CO210, CO220 and CT2500 scenarios, respectively.

A reduction in the total primary energy requirement is another co-benefit of the CO_2 emission constraints. It is revealed that the total primary energy supply reduces by about 4.6%, 9.4% and 10.8% in the CO210, CO220 and CT2500 scenarios, respectively, during 2005-2035 as compared to the total primary energy supply in the base scenario due to efficient technology selection by the model. In the base scenario, primary energy use in 2035 is expected to be 2079 PJ, and reduces to 1595 PJ in the CT2500 scenario. Gas is the dominant energy source in 2005, and coal is dominant in all scenarios in 2035. Coal imports decrease from 1178 PJ in the base scenario to 884, 499 a nd 396 PJ (25%, 58% and 65%) in the CO210, CO220 and CT2500 scenarios in 2035, respectively. Solar energy use increases by 114 PJ, 263 PJ and 306 PJ in 2035 in the CO210, CO220 and CT2500 scenarios, respectively. In the base scenario, the expected electricity generation from solar PV is 0 TWh between 2005 and 2035; it is expected to increase by 213 TWh, 492 TWh and 572 TWh in the CO210, CO220 and CT2500 scenarios, respectively, during the study period.

5. Conclusions

This paper has analyzed the effects of selected CO_2 emission reduction targets and carbon tax on environmental emissions as well as energy technology and resource mix using the MARKAL model for Bangladesh power sector. It is observed that coal is the dominant electricity generation technology in all scenarios in the later period (2020-2035). In the later period, advanced coal FGD trends to be the first choice for Bangladesh. The introduction of the CO_2 emission constraints directly affects the shift of technologies from high carbon content fossil-based to low carbon content efficient fossil-based and clean solar PV-based technologies. Solar PV is an attractive technology in almost all alternate scenarios. It becomes more and more attractive with introduction of higher carbon tax and higher CO_2 emission reduction target.

The analysis results show that the degree of diversification in the total energy requirement would increase with the applied CO_2 emission constraints. The primary energy supply system would diversify from the one dominated by coal in the later period (2020-2035) to that involving a greater use of solar energy and gas under the selected emission reduction targets and carbon tax scenarios. The analysis results show that the primary energy requirement would decrease in the alternate scenarios. This would enhance the country's energy security.

Furthermore, the results show that the increase in total system cost for reduction of cumulative CO_2 emissions over the study period is around 543 Taka/ton, 603 Taka/ton and 615 Taka/ton in the CO210, CO220 and CT2500 scenarios, respectively. These costs are much lower than those in developed countries, as the solar-PV-based power generation is relatively much cheaper in Bangladesh. It could thus be attractive for developed countries to invest in solar PV to generate electricity in Bangladesh to reduce their committed CO_2 emissions defined in the Kyoto Protocol through the "clean development mechanism (CDM)".

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