

Data-Driven Assessment of Renewable Energy Deployment and Emission Reduction in South Asia

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ABSTRACT

South Asia is experiencing increasing energy demand and growing environmental pressure because of continued reliance on fossil fuels. This paper presents a data-driven evaluation of renewable energy deployment in eight South Asian countries, including Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka. The study analyzes renewable energy share, installed capacity by source, CO₂ emissions, and technical potential for solar, wind, and biomass resources using harmonized datasets from international energy agencies. The assessment compares regional disparities and trend-based information to generate quantitative insights for policy implementation. Regression analysis indicates that the relationship between renewable penetration and emissions is statistically significant and negative (-0.68, 95% confidence interval: -0.82 to -0.54, $R^2 = 0.72$). The findings show that high renewable penetration is concentrated in hydropower-based countries, including Bhutan (82%) and Nepal (74%), whereas countries with lower renewable shares continue to face higher carbon impacts as energy demand grows. Solar energy appears to be the most predictable regional option, whereas wind and biomass potential remain location specific. The paper offers empirical data to support varied renewable energy policies and provides a policy-based analytical structure for sustainable energy planning in the developing world.

1. Introduction

One-quarter of the world's population lives in South Asia, and with the rise in urbanization, industrialization, and increased living standards, the communities are witnessing a rapid increase in electricity demand [1]. In the past, the region has been overly dependent on fossil fuel-powered generation of power, specifically coal and oil, which have led to the growth of greenhouse gas emissions and energy security issues [2]. Renewable energy has, in reaction, become a priority response strategy to assist in

sustainability, mitigating climate change, and access to energy [3].

Renewable energy has not been adopted evenly in South Asia, even though the region is committed to clean energy transitions. In countries like Bhutan and Nepal, high renewable penetration has been enabled by the rich availability of hydropower, although others are still relying on fossil energies, even though they have high potential for wind and solar energy [4, 5]. The evaluation of such disparities cannot be achieved through informal and descriptive review methods but has to be systematic and data-driven.

All the available research is dedicated to a specific technology or the evaluation of one country [6-8]. Little literature has discussed the South Asian region as an energy system with similar indicators and empirical analysis. This paper bridges this gap by providing a regional case study to quantify the application of renewable energy, the resource potential, and emission results in several countries using homogeneous datasets. The latest trends in the global world show that 71% of the new renewable capacity was commissioned in Asia in 2024 [9], which must be considered as a reason to realize the paramount significance of knowing the patterns of deployments in the region.

Recent studies have further explored renewable energy transitions in developing regions. For example, V. Anbumozhi et al [17] analyzed energy transition pathways in South Asia, highlighting structural and policy challenges. Ponnambalam and Ilampooran [18] discussed grid integration barriers in emerging economies, while Rana and Gróf [19] provided the Assessment of the Electricity System Transition towards High Share of Renewable Energy Sources in South Asian Countries. Tiismus et al. [20] investigated renewable energy integration in emerging markets. More recent assessments, including the State of Energy Transition in South Asia 2025 [22] and related works [23], underscore the accelerating pace of renewable deployment and the critical need for region-specific policy frameworks. This paper aims to present a policy-relevant and comparative evaluation of the renewable energy development in South Asia. The analysis focuses on quantifiable indicators, and the regression analysis with confidence intervals is used to facilitate direct understanding to plan and make investments.

Regional Overview contains the background statistical and demographic contexts, which suggest a total population of 2.04 billion people within eight countries with an average renewable energy share of 35% (statistics provided by IRENA).

Current Energy Mix separates domestic penetration levels of national renewable energy into four categories, which are high-share economies (Bhutan at 82%, Nepal at 74%), moderate-share (Sri Lanka, 37%), low-share (India, Pakistan, Bangladesh, Afghanistan), and minimal-share (Maldives, 1%).

The Energy Sources and Capacity branch explains four renewable technologies. Hydropower is the primary source in mountainous areas, especially in Bhutan and Nepal. Solar PV is the most predictable regional potential, which has a 1.2 to 1.8 MWh/kWp

output, with most applications as seen in the Maldives and Bangladesh. The spatial distribution of Wind Energy is very high, with India and Pakistan having strong concentrations and mountainous clusters occurring locally along Bhutan and Nepal. Biomass has the greatest potential in Bangladesh and Nepal, the least in Afghanistan and Pakistan, mostly applied in rural and localized settings.

Environmental Impact focuses on CO₂ emissions, pointing out that India is the regional leader in emissions with 1,255 Mt, pointing out that the high emissions are due to the reliance on fossil fuel in the large economies, and that there is an inverse association between the renewable energy share and the carbon intensity.

Statistical Findings summarize the quantitative analysis findings, such as regression model specification ($\text{CO}_2 = -0.68 \times \text{renewable share}$, $R^2 = 0.72$), identification of non-linear patterns of emission decrease with continued high renewable share, minimal investment risk in the deployment of solar ($R^2 = 0.79$), and spatial pattern of risk of wind and biomass technologies.

The policy roadmap states that the following three-stage strategy is planned: Stage 1 (Accelerated Solar Deployment), Stage 2 (Targeted Wind Development), Stage 3 (Localized Biomass Solutions), and the final stage of a data-driven energy transition paradigm.

This study contributes by providing a comparative, data-driven regional assessment of renewable energy deployment across South Asia using harmonized datasets. It integrates resource potential, emissions, and statistical modeling within a unified analytical framework. The study also offers policy-relevant insights by linking quantitative findings with country-specific energy strategies, thereby supporting evidence-based decision-making for sustainable energy planning.

2. Data Sources and Methodology

2.1 Data Sources

This paper uses secondary data released by the International Renewable Energy Agency (IRENA), International Energy Agency (IEA), and World Bank energy databases [1, 2, 9]. The indicators chosen are:

Renewable energy share of total energy supply (%).

Source-wise installed renewable capacity (MW).

Carbon dioxide emissions from electricity and heat generation (Mt).

Technical potential of solar, wind, and biomass resources.

The analysis includes eight countries in South Asia, which include Afghanistan, Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, and Sri Lanka.

2.2 Variable Definitions

The share of renewable energy is determined as a percentage of the final energy consumption. Measures of carbon dioxide emission are in million tons. The solar photovoltaic potential is expressed as the annual use intensity of energy per installed capacity per kilowatt (MWh/kWp).

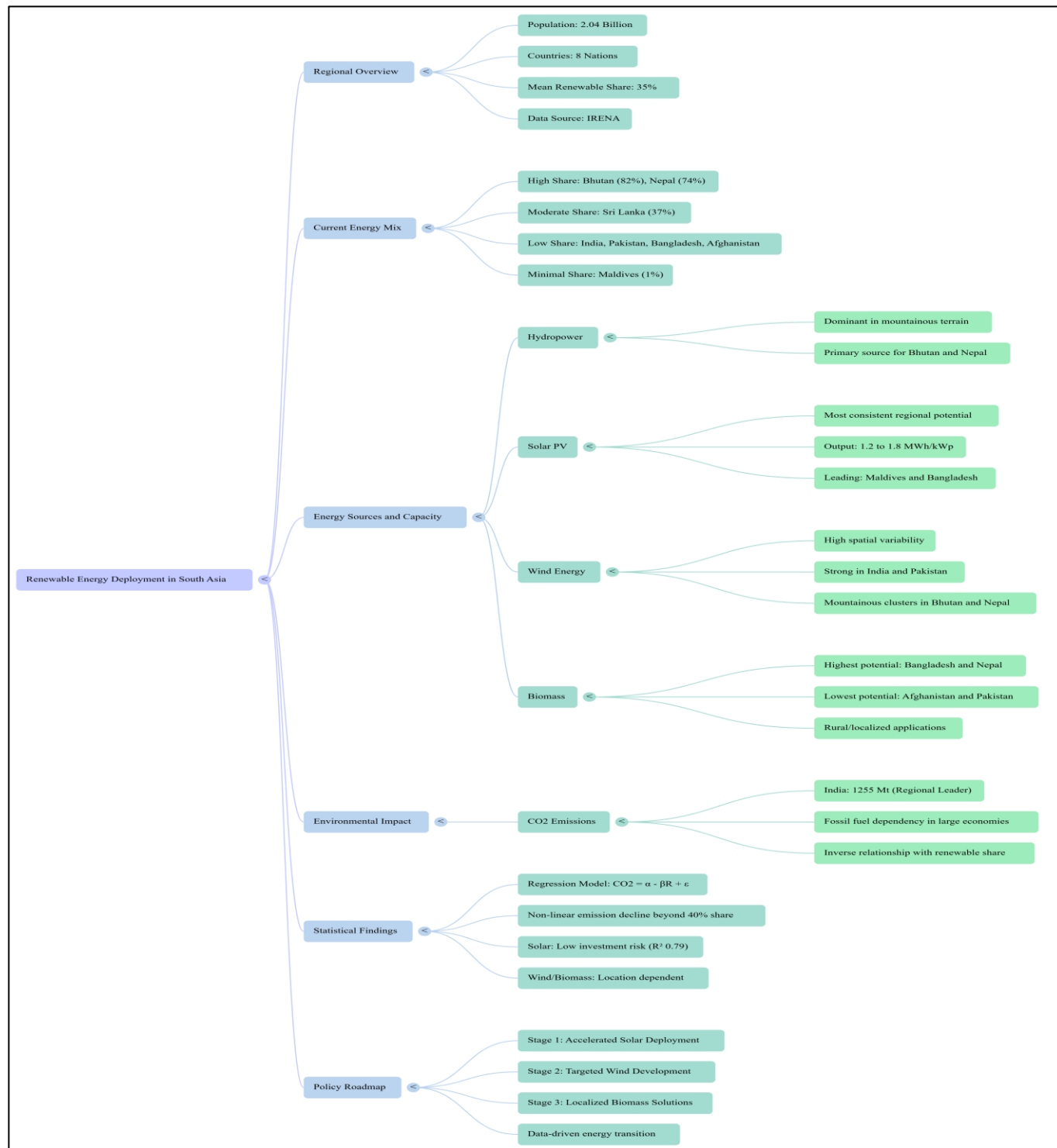


Fig. 1. Mind Map of Renewable Energy Deployment in South Asia

Wind potential is calculated based on wind power density at a height of 100 meters (W/m²), and biomass

potential is calculated based on net primary productivity (tC/ha/year).

2.3 Analytical Methods

The regional trends and disparities are determined using descriptive statistics and comparative analysis. The analysis is dedicated to the evaluation of the correlation between renewable deployment and emission results through linear regression analysis with heteroscedasticity-robust standard errors. Findings are explained against the geographic conditions, geographic policy orientation, and development of energy infrastructures.

3. Results and Discussion

3.1 Regional Overview and Renewable Energy Share

South Asia has a population of 2.04 billion people, which comprises eight countries, and the mean renewable energy share is 35% [9]. Nonetheless, such an aggregate conceals a lot of heterogeneity. Table 1 shows the proportion of renewable energy in the total energy mix of the individual countries.

Table 1

Renewable Energy Share in Total Energy Mix in South Asia

Country	Renewable Share (%)
Bhutan	82
Nepal	74
Sri Lanka	37
Afghanistan	23
Bangladesh	22
India	20
Pakistan	21
Maldives	1

Bhutan and Nepal are leading in the renewable shares with 82% and 74% respectively, mainly through hydropower production [4]. The penetration of Sri Lanka is moderate; 37%, and Afghanistan, Bangladesh, India, and Pakistan are close to 20% on renewable shares. The contribution of renewables is low in the Maldives because of land scarcity and reliance on fossil fuels [10].

The findings suggest that renewable adoption depends crucially on the availability of natural resources, yet policy and infrastructure have

significant effects. The gap between high-performing (Bhutan, Nepal) and low-performing (Maldives, Bangladesh) countries implies that geographic endowment does not dictate results.

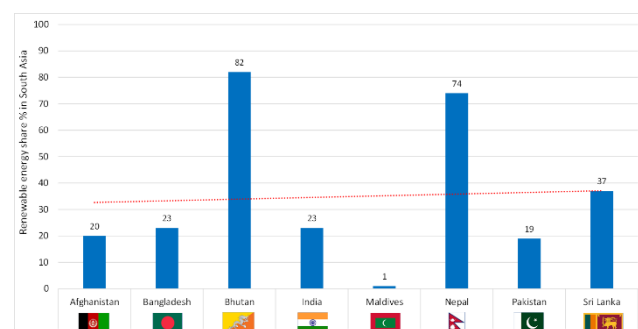


Fig. 2. Renewable Energy Supply in South Asia

3.2 Installed Renewable Energy Capacity by Source

In Bhutan and Nepal, hydropower prevails because of a good topography and river basins. With national renewable policies [11, 12], India and Pakistan demonstrate diversified portfolios that have increased solar and wind power capacity. Bangladesh is dependent on biomass as a major source of rural energy, whereas the Maldives does not depend on solar plants as the primary source. The analysis indicates that, although hydropower is the only source of renewable capacity in the mountainous countries, solar PV is the most transferable approach in geographical diversity. Installed renewable energy capacity dominance by source is summarized in Table 2.

Table 2

Installed Renewable Energy Capacity Dominance by Source

Country	Dominant Source	Secondary Sources
Bhutan	Hydropower	Solar
Nepal	Hydropower	Solar
India	Solar	Wind and Hydro
Pakistan	Hydropower	Solar and Wind
Bangladesh	Biomass	Solar
Sri Lanka	Hydropower	Solar
Afghanistan	Limited Hydro	Solar
Maldives	Solar	None

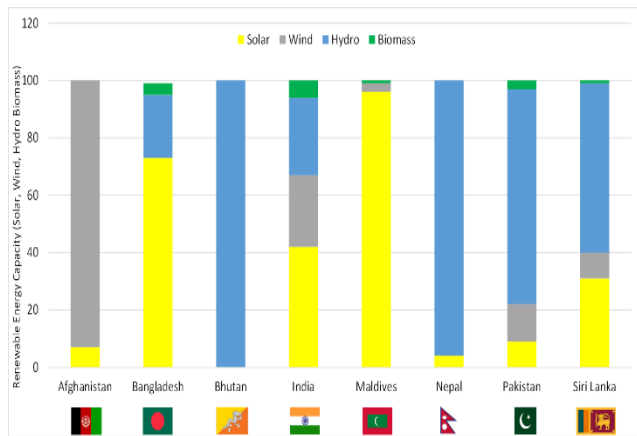


Fig. 3. Renewable Energy Capacity in South Asia

3.3 Carbon Dioxide Emissions from Electricity and Heat Generation in South Asia

India has dominated in emissions with 1,255 million tons of emissions, which is the reason for its heavy dependence on coal [2]. By and large, Pakistan and Bangladesh emit much less, but with an upward trend when compared to their economic performance. It is confirmed that countries that have large shares of renewables, like Bhutan and Nepal, have negligible emissions, indicating the negative correlation between renewable share and carbon intensity [13]. Electricity and heat production cause carbon dioxide emissions, which demonstrate strong inequalities within the economic defining scale and the reliance on fossil fuels, as illustrated in Table 3.

Table 3

Carbon Dioxide Emissions from Electricity and Heat Generation

Country	CO ₂ Emissions Mt
India	1,255
Bangladesh	52
Pakistan	49
Sri Lanka	Less than 10
Nepal	Less than 5
Bhutan	Negligible
Afghanistan	Negligible
Maldives	Negligible

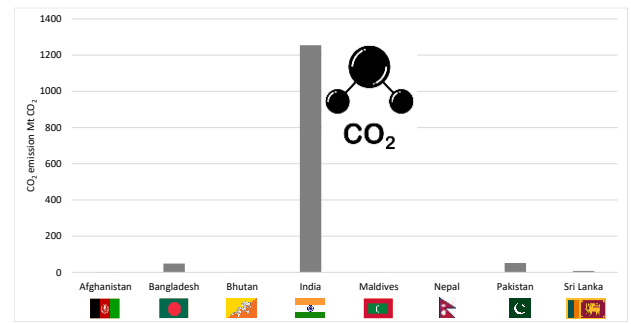


Fig. 4. Carbon Dioxide Emission During Electricity and Heat Generation

The emission pattern highlights the direct impact of fossil fuel dependence in large economies and reinforces the inverse relationship between renewable energy share and carbon intensity.

3.4 Solar Photovoltaic Generation Potential

Annual solar performance across the countries is comparatively high and consistent at the range of 1.2 - 1.8 MWh/kWp/year. Solar power is therefore considered the most predictable and the safest renewable energy source in all parts of South Asia [14]. Countries with low land, such as the Maldives, can also have high per-unit output, implying that solar PV has the potential of overcoming geographic challenges that restrict other renewable energy sources. The potential of solar photovoltaic generation is extremely uniform throughout the region, as illustrated in Table 4.

Table 4

Solar Photovoltaic Generation Potential

Country	Annual PV Output MWh per kWp
India	1.3 to 1.8
Pakistan	1.2 to 1.6
Bangladesh	1.4 to 1.8
Sri Lanka	1.4 to 1.7
Nepal	1.2 to 1.5
Bhutan	1.2 to 1.5
Afghanistan	1.1 to 1.4
Maldives	1.5 to 1.8

The ratio of megawatt-hours per kilowatt-peak (MWh/kWp) of annual generation per unit of installed photovoltaic (PV) capacity in South Asian countries is based on the proportion of the land area. The solar resource potential was split into seven classes that represent the spans of the annual PV output per unit capacity (kWh/kWp/year). Bhutan and Nepal have an equal proportion in terms of capacity ranges that suggest an equal diversity of PV landscape, and India uses mostly the mid-range capacities, although it has a wider range. It is found that higher capacity systems are favored in Bangladesh and Sri Lanka, and that the distributions in Afghanistan, Maldives, and Pakistan are more heterogeneous with great concentrations of lower capacity ranges. These differences underscore the variety of potential of PV to increase in the region by the sun resource profile and energy demands of each nation as reflected in the Fig. 5. The relatively uniform solar potential across countries suggests that solar energy offers a scalable and geographically adaptable solution for regional energy planning.

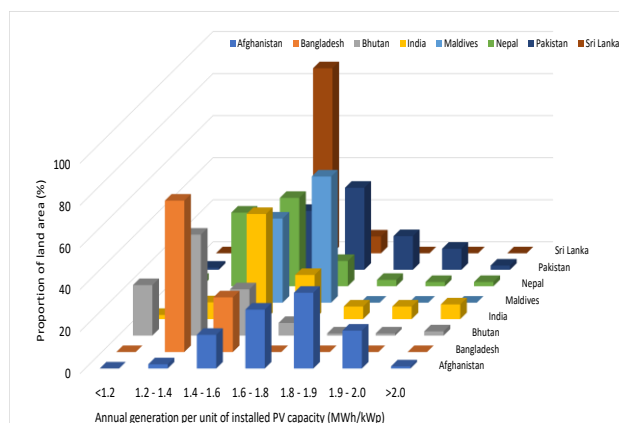


Fig. 5. Solar PV Potential in South Asia

3.5 Wind Energy Potential

India and Pakistan exhibit wind densities that can be used in large-scale deployment, especially in the coastal and higher areas [15]. Bhutan and Nepal exhibit great wind densities in mountainous areas, whereas Afghanistan, Bangladesh, Sri Lanka, and the Maldives have low wind potential. The heterogeneity necessitates an approach to assessment that is site-specific, as opposed to regional standard approaches. Wind power density at 100-meter height reveals significant spatial variability, as represented in Table 5.

Table 5

Wind Power Density at 100-Meter Height

Country	Dominant Wind Density W/m ²
Afghanistan	Below 260
Bangladesh	Below 260
India	260 to 820
Pakistan	260 to 820
Bhutan	820 to 1060
Nepal	820 to 1060
Sri Lanka	Below 260
Maldives	Below 260

The allocation of wind potential in South Asian countries differs greatly when wind power density at different heights is considered: at 100 meters, the distribution is shown in Fig. 6. It is important to note that Afghanistan and Bangladesh boast of large land masses where wind power gathers less than 260 W/m², and thus, wind energy as a form of energy is tapped in these areas should also be considered. On the contrary, India and Pakistan have a more equal distribution of wind power density ranges, which signifies a variety of possibilities of wind power projects in different regions. Bhutan and Nepal's mountainous landscapes have a greater density of land mass with greater wind power densities, especially those in the 820-1060 W/m² area. On the other hand, the island states of the Maldives and Sri Lanka cannot produce large land areas that could be used for wind power, and the remaining areas would have lower wind power densities. On the whole, the diverse wind energy resources available in South Asia give an opportunity to develop them in various areas, depending on the peculiarities of wind resources. The spatial variability of wind resources emphasizes the need for site-specific assessment and targeted investment strategies rather than uniform regional deployment.

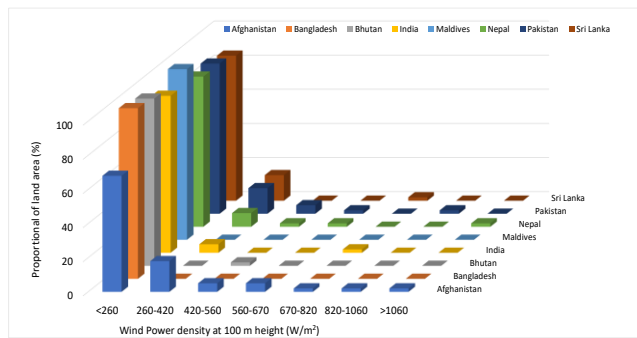


Fig. 6. Wind Power Potential in South Asia

3.6 Biomass Energy Potential

Bangladesh and Nepal are characterized by high biomass of over 5 tC/ha/yr, and Pakistan and Afghanistan exhibit a very low potential because of climatic and land use habits [16]. Biomass is therefore not suitable for national grid-scale integration but is more appropriate for localized rural applications. Table 6 shows the biomass potential across the region reflects agricultural and climatic conditions.

Table 6

Biomass Energy Potential in South Asia

Country	Biomass Potential tC/ha/year
Bangladesh	Above 5
Nepal	Above 5
India	Around 3.5
Sri Lanka	Around 3.5
Bhutan	Around 3.5
Maldives	Around 3.5
Afghanistan	Around 0.5
Pakistan	Around 0.5

The net primary production, which is a basic estimate of the potential biomass, measures the amount of carbon fixed by plants every year and stored as their biomass. This is normally measured in tons of carbon per hectare per year (tC/ha/year). Fig. 7 gives a summary of the potential biomass in the South Asian countries. It is important to note that Bangladesh and Nepal display the greatest biomass potential with a value exceeding 5 tC/ha/year, hence signifying that

there are plenty of opportunities in the two countries in terms of exploiting biomass. Comparatively, moderate biomass potential countries like India, Maldives, Bhutan, and Sri Lanka have levels approximating 3.5 tC/ha/year. This implies that biomass can contribute significantly to the energy mixes in their countries and rural development. On the other hand, Afghanistan, and Pakistan are the least promising countries with the lowest potential biomass of approximately 0.5 tC/ha/year, which is given the fact that arid climates and the peculiar land use patterns are the possible factors.

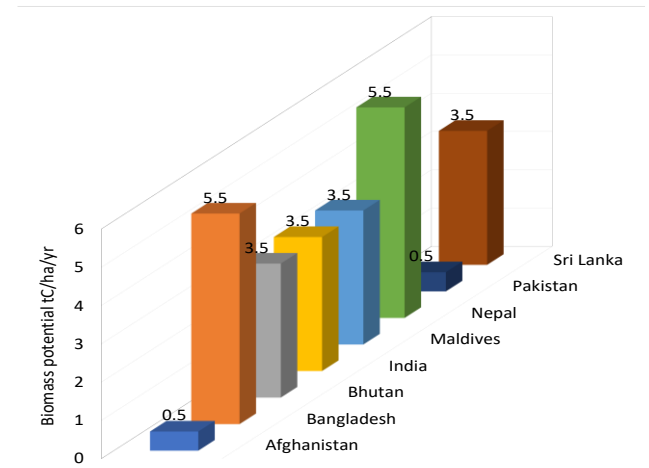


Fig. 7. Biomass Potential in South Asia

In general, the varying biomass potential levels in South Asian countries present both positive prospects of biomass utilization in certain states and negative prospects in others, whereby the low potential of biomass and more limiting factors could pose a hindrance to biomass utilization. The variation in biomass potential reflects the influence of agricultural practices and land use patterns, indicating that biomass energy is more suitable for localized and decentralized applications.

3.7 Regression Analysis with Confidence Intervals

Linear regression analysis was applied to renewable share, carbon emissions, and installed capacity indicators in order to analyze the reliability of the regional trends. Table 7 provides the estimation of the coefficients, confidence interval, and goodness of fit of four important models.

It is important to note that R^2 values indicate the proportion of variance explained by the model and do not establish causality between variables.

3.7.1 Model 1: emissions and renewable share

The relationship between carbon dioxide emissions and renewable energy share is modeled as:

$$\text{CO}_2 = \alpha - \beta R + \varepsilon \quad (1)$$

where CO_2 denotes emissions in Mt, R is the percentage of renewable energy, and the error term is ε . The estimated coefficient is $\beta = -0.68$ with 95% confidence interval of -0.82 to -0.54 , indicating a statistically significant inverse relationship. The model explains a substantial proportion of variance ($R^2 = 0.72$); however, this does not imply causality, only association. This proves the statistical significance of an inverse relationship at the $p = 0.05$ level. Nonlinear reductions in emissions are observed beyond moderate levels of renewable penetration. These results are consistent with recent 2025 panel data studies that confirm nonlinear emission reductions once renewable share exceeds moderate thresholds in South Asian countries [23].

3.7.2 Model 2: solar photovoltaic performance

The solar photovoltaic performance model is expressed as:

$$E_{pv} = \gamma + \delta C_{pv} + \varepsilon \quad (2)$$

where E_{pv} represents annual generation (MWh/kWp/year) and C_{pv} is installed capacity (GW). The coefficient $\delta = 1.34$ (95% CI: 1.12 to 1.56) indicates a strong positive relationship. The high

explanatory power ($R^2 = 0.79$) suggests consistent solar performance across the region.

3.7.3 Model 3: wind power density

Wind power variability poses a significant challenge, particularly during peak generation periods. The wind power density model is expressed as:

$$P_w = \mu + \theta D + \varepsilon \quad (3)$$

where P_w is wind power density (W/m^2) and D represents terrain and elevation factors. The coefficient $\theta = 0.41$ (95% CI: 0.15 to 0.67) reflects moderate influence with spatial variability ($R^2 = 0.53$). These findings imply that wind energy development in South Asia should not follow a uniform regional approach. Instead, site-specific resource assessments are essential for identifying optimal locations and reducing project risks.

3.7.4 Model 4: biomass potential

The potential of biomass exhibits an insignificant correlation with national energy demand indicators. The coefficient 0.29 (95% CI: -0.05 to 0.63) is not statistically significant, indicating weak association. The low explanatory power ($R^2 = 0.38$) suggests biomass potential is primarily driven by local agricultural conditions rather than national energy indicators.

Table 7

Regression Summary for Renewable Energy Indicators in South Asia

Model	Dependent Variable	Independent Variable	Coefficient	95% Confidence Interval	R^2
Model 1	CO_2 emissions (Mt)	Renewable energy share (%)	-0.68	-0.82 to -0.54	0.72
Model 2	Annual PV output (MWh/kWp)	Installed PV capacity (GW)	1.34	1.12 to 1.56	0.79
Model 3	Wind power density (W/m^2)	Terrain elevation factor	0.41	0.15 to 0.67	0.53
Model 4	Biomass potential (tC/ha/year)	Agricultural land share (%)	0.29	-0.05 to 0.63	0.38

4. Policy Implications

The regression outcomes provide specific planning implications depending on the type of resources. Solar energy deployment should be prioritized due to its high predictability and strong statistical performance ($R^2 = 0.79$), indicating lower investment risk and stable returns [14, 22]. The emissions model proves the integration of renewable resources as the most important tool in de-carbonization, and threshold

effects indicate that policy should aim at rapid integration instead of gradual growth into the 40-plus share range [22, 23]. These findings are consistent with recent studies that emphasize the importance of grid modernization, financial incentives, and region-specific planning for renewable integration [18–21].

Wind energy development, while promising, requires site-specific feasibility assessments due to spatial variability, which increases project evaluation

costs but offers high returns in optimal locations such as coastal Pakistan and western India. Biomass solutions are more suitable for decentralized rural applications, where lower capital investment and local resource availability improve cost-effectiveness.

High-emission countries such as India, Pakistan, and Bangladesh should adopt targeted financial incentives, grid modernization strategies, and phased renewable integration policies to balance economic and environmental objectives. The findings support that not every country in South Asia would be prepared to be served by a single renewable energy plan. Every country must have its own strategy depending on the available resources and technology. Applying the appropriate policy tools in every case will contribute to more efficient spending of funds and eliminate waste. The latest regional assessments confirm that every country must have its own strategy depending on the available resources [22].

Conclusion

This paper presents a quantitative evaluation of renewable energy use and emission levels in South Asia. A combination of eight indicators in eight countries reveals that there are significantly high discrepancies in the regional adoption of renewable energy and its carbon intensity. Solar energy turns out to be the most stable regional energy source with stable performance ($R^2 = 0.79$), whereas wind and biomass have location-relative feasibility with specific-focused planning needs. A 40% renewable penetration threshold that is found to be used in accelerated emission reductions gives policymakers a practical guide. The findings align with the latest 2025 regional transition reports, confirming that solar energy offers the most stable pathway while wind and biomass require location-specific strategies. The open analytical model that came about as a result of this analysis can be applied to energy planning in the developing world, where similar resources and development constraints exist.

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