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Impacts of Climate Change on the Generation Potential of Solar and Wind Energy Systems in India#

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ABSTRACT

Low-carbon energy sources like wind and solar are essential for decarbonizing the electricity sector. In addition, the cost of electricity generated from these sources has plummeted over the last decade. Therefore, these energy sources are poised to take a significant share of the total installed capacity soon. However, they are susceptible to the impacts of climate change as their generation potential depends on the weather conditions. Estimating the installed capacity requirements of solar and wind energy to decarbonize the power sector without accounting for these possible changes in generation potential could lead to missing out on the set climate goals and meeting future electricity demand. This study evaluates the effect of climate change on the generation potential of wind and solar energy systems in India for two future periods, 2050 and 2070, under two climate scenarios or Shared Socioeconomic Pathway (SSP): SSP245 and SSP585. Almost all regions show a decrease, and most regions show a significant decline (>5%) in the generation potential of solar Photovoltaic (PV) as compared to 2010 levels under both climate scenarios and future periods. The changes in the generation potential of wind energy are more significant (>10%), and the majority of regions show a decline in generation potential. Southwestern and central regions show an increase in wind generation potential for 2070 as compared to 2050 levels under the SSP245 scenario and the SSP585 scenario, respectively.

Keywords: Variable Renewables, Solar, Wind, Climate Change, CMIP6 Climate models, Generation Potential

NOMENCLATURE

Abbreviations	
PV	Photovoltaic
VRE	Variable Renewable Energy
CMIP6	Coupled Model Intercomparison Project–6
GCM	Global Circulation Model
SSP	Shared Socioeconomic Pathway
GHI	Global Horizontal Irradiance

1. INTRODUCTION

Deep decarbonization of the electricity sector is crucial to achieving India's long-term goal of reaching net-zero emissions by 2070. Variable Renewable Energy (VRE) sources like solar and wind are low-carbon alternatives to conventional energy sources and are best suited for this task. On the other hand, the cost of solar PV panels has plummeted over the last decade, and solar energy is now the cheapest source of electricity [1]. With the present need for low-carbon alternatives and reduced cost, the installation of utility-scale solar PV has increased from a mere 3 GW in 2014 to more than 82 GW by March 2024 in India [2]. Wind energy technologies saw a similar growth to solar PV, and their installation capacity has more than doubled in the last decade [2–3]. This trend will likely continue, and the installed capacity share of solar PV and wind energy technologies will become significant. As per the estimates of the Central Electricity Authority of India, combined solar PV and wind energy are likely to constitute more than 50% of the installed capacity required by 2029–30 [4].

The installed capacity required for meeting future demand and the set climate goals is estimated using a capacity expansion model. It requires input parameters, including techno-economic parameters of various energy sources, demand data, transmission network topology and capacity factor of renewable energy sources for future periods. Here, the capacity factors of solar PV and wind energy for future periods are assumed to remain

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the same as those of the present period. However, VRE technologies are susceptible to the impacts of climate change as their generation potential depends on the weather parameters. Thus, the estimated installed capacity requirements need to be revised to meet the set climate goals. Moreover, with VRE poised to take a significant share of installed capacity in the future, a small percentage change in generation potential can significantly affect the country's capacity to meet the electricity demand. Therefore, it is essential to assess the expected changes in the generation potential of VRE technologies for future periods.

Gernaat et al. studied the impacts of climate change on different renewable energy sources using Coupled Model Intercomparison Project (CMIP6) climate models. They estimated an increase in wind energy potential (<10%) and a decrease in solar PV potential (>-10%) under the SSP2-RCP6.0 scenario for the period 2071–2100 for India [5]. Liu et al. studied the climate change impacts on the demand and supply of global wind and solar energy systems. They estimated an increase in wind potential (10–15%) and solar PV potential (0–5%) under the SSP245 scenario for the period 2071–2100 for Southeast Asia [6]. However, these studies have failed to capture the variations in generation potential for different future periods and climate scenarios for various regions within India. The changes in generation potential across different regions are essential in estimating the installed capacity requirements for meeting the country's climate goals. Therefore, this study aims to fill this research gap by studying the impacts of climate change on wind and solar PV generation potential for two future periods under two climate scenarios for different regions within India.

2. METHODOLOGY

This study used the output data of EC-Earth3, a CMIP6 Global Circulation Model (GCM) model with a high spatial resolution of 0.703125° latitude and 0.703125° longitude and temporal resolution of the daily mean. We obtained the data for three weather parameters, including temperature, wind speed and solar irradiance, under two scenarios: SSP245 and SSP585, for two future periods: 2050 (representing the period 2041–2060) and 2070 (2061–2080). For the base period climate, we obtained data for 2010 (2001–2020) from the 'historical' scenario simulations, but these simulations terminate in 2014. Therefore, we obtained the data from the SSP scenarios for the rest of the six years (2015–2020). Thus, to estimate the changes in generation levels, we compared the SSP scenario's data for future periods with the 'historical' and their respective SSP scenario's base period data. We assessed the changes in solar PV and wind generation levels for each scenario by estimating the generation values of the typical year of both future and base period, which is representative of typical weather conditions for the 20-year period at a particular location. The following sections explain the methodology involved in the calculation of the generation potential of solar PV and wind energy systems.

2.1 Wind Energy Generation

The generation potential of wind turbines (E_{wind}) is a function of instantaneous wind speed (U), air density (ρ) and area of the blades (A) as shown in Eq. 1. Wind power varies with the cube of wind speed when U is higher than the cut-in speed U_{min} and lower than the rated speed U_c. Beyond U_c, wind power is proportional to the cube of U_c up until the wind speed reaches cut-out speed U_{max}. For wind speeds higher than U_{max} or lower than U_{min}, wind energy generation is zero. We set the values for U_{min}, U_c and U_{max} as 4 m s^{-1}, 13.5 m s^{-1} and 25 m s^{-1} respectively [6].

$$E_{wind} = \begin{cases} 0, & U < U_{min} \ or \ U > U_{max} \\ \frac{1}{2}\rho A U^3, & U_{min} \le U \le U_c \\ \frac{1}{2}\rho A U_c^3, & U_c < U \le U_{max} \end{cases} \quad (1)$$

To estimate the wind energy generation using the daily mean data of wind speed obtained from the GCMs, we assumed the instantaneous wind speed to follow a two-parameter Weibull distribution, as shown in Eq. 2 [7].

$$p(U) = \frac{k}{\lambda}\left(\frac{U}{\lambda}\right)^{k-1} exp\left[-\left(\frac{U}{\lambda}\right)^k\right] \quad (2)$$

The shape parameter k is set as two per the recommended range [8]. The scale parameter λ is a function of mean wind speed $\overline{U}$ and k as shown in Eq. 3, where $\Gamma()$ is the gamma function.

$$\lambda = \frac{\overline{U}}{\Gamma(1 + 1/k)} \quad (3)$$

Assuming the swept area of wind blades and air density to be constant, we can derive the equation of wind energy generation as Eq. 4, where $m = (U/\lambda)^2$. Substituting Eq. 3 in Eq. 4, we obtained the total wind energy generation for the typical year of the study periods under different scenarios.

$$\int_4^{25} E_{wind}(U)\, p(U) dU = \frac{1}{2}\rho A \left(\lambda^3 \int_{\left(\frac{4}{\lambda}\right)^2}^{\left(\frac{13.5}{\lambda}\right)^2} m^{3/2} e^{-m} dm + (13.5^3)\left[e^{-\left(\frac{13.5}{\lambda}\right)^2} - e^{-\left(\frac{25}{\lambda}\right)^2} \right] \right) \quad (4)$$

The wind speed data obtained from the GCMs represent wind speed levels at 10m height from the surface. We estimated the wind speed at 102m [9], the hub height of Siemens Gamesa SG126 2.5 MW wind turbine, using the logarithmic law as shown in Eq. 5, where α is usually approximated as 1/7 [6].

$$\frac{\overline{U}_{102}}{\overline{U}_{10}} = \left(\frac{102}{10}\right)^{\alpha} \quad (5)$$

2.2 Solar Energy Generation

The generation potential of solar PV (E_{PV}) is a function of total solar irradiance incident on the panel (I), area of the PV panel (a), performance ratio accounting for the difference in performance under standard test conditions and actual outputs of the panels (PR), and the efficiency of PV panels (η_{PV}) as shown in Eq. 6 [5].

$$E_{PV} = I \times a \times PR \times \eta_{PV} \quad (6)$$

We require Global Horizontal Irradiance (GHI) data at an hourly resolution to estimate the solar PV generation of an arbitrarily tilted panel. Then, we can employ models like Perez or BRL to decompose the GHI into its constituents and estimate the total solar irradiance incident on the tilted panel. However, the climate data obtained from GCMs are of daily resolution. Therefore, we estimated the generation potential of panels with zero tilt, where the total irradiance incident on the panel is the GHI.

The panel area is set as 1m^2, and the performance ratio is assumed to be 0.85 [5]. The panel efficiency (η_{Panel}) given by Eq. 7 is a function of γ, which is the efficiency response of standard monocrystalline silicon solar panel (0.005 ˚C^{-1}), T_{STC} which is the reference temperature (25 ˚C) and T which is the corrected temperature.

$$\eta_{PV} = \eta_{Panel} \times (1 + \gamma(T - T_{STC})) \quad (7)$$

Corrected temperature T considers the effects of different climate parameters, including temperature, wind speed and solar irradiance, as given by Eq. 8.

$$T = c_1 + c_2 \times T_a + c_3 \times I + c_4 \times V \quad (8)$$

Where c_1 is 4.3 ˚C, c_2 is 0.943, T_a is the ambient surface air temperature (˚C), c_3 is 0.028 (˚C m^2 W^{-1}), I is the total solar irradiance incident on the panel (kW m^{-2}), c_4 is -1.528 (˚C s m^{-1}) and V is the surface wind speed (m s^{-1}) [5]. Other factors like the packing factor and available area for PV panels are assumed to be constant. Our analysis does not consider them since we focus on the climate impacts.

3. RESULTS

Figure 1 shows the percentage change in the annual generation potential of solar PV for different regions in India under SSP245 and SSP585 scenarios for 2050 and 2070. Almost all regions show a decrease (0% to - 10%), and most regions show a significant decline (-5% to -10%) in generation potential under both climate scenarios and future periods compared to the 2010 levels. Under the SSP585 scenario, there is a decrease in generation potential of about 2.5% compared to the SSP245 scenario for both periods, as expected, since the emission levels are higher and thereby, the ambient temperature levels will be higher in the SSP585 scenario, which negatively affects the generation potential of solar PV generation. In 2070, there will be a slight increase in generation potential for central India under both scenarios. This can be due to the increase in wind speed, which is discussed in the next paragraph.

Figure 2 shows the percentage change in annual generation potential of wind energy for different regions in India under SSP245 and SSP585 scenarios for 2050 and 2070. The majority of the areas show a decrease (0% to - 20%) in generation potential under both climate scenarios and future periods compared to the 2010 levels. In 2070, under both scenarios, there will be a slight increase in generation potential for most regions. This can positively influence solar PV generation, as seen in Figure 1. The regions where an increase in generation potential can be seen are quite different under both scenarios. Under the SSP585 scenario, Central India shows an increase in potential, whereas under the SSP245 scenario, Southwestern regions show an increase in potential.

4. CONCLUSIONS

This study investigated the impacts of climate change on the generation potential of solar PV and wind energy technologies. The results indicate a significant change in generation potential for wind energy (>10%) and moderate change in solar PV (>5%) generation in the

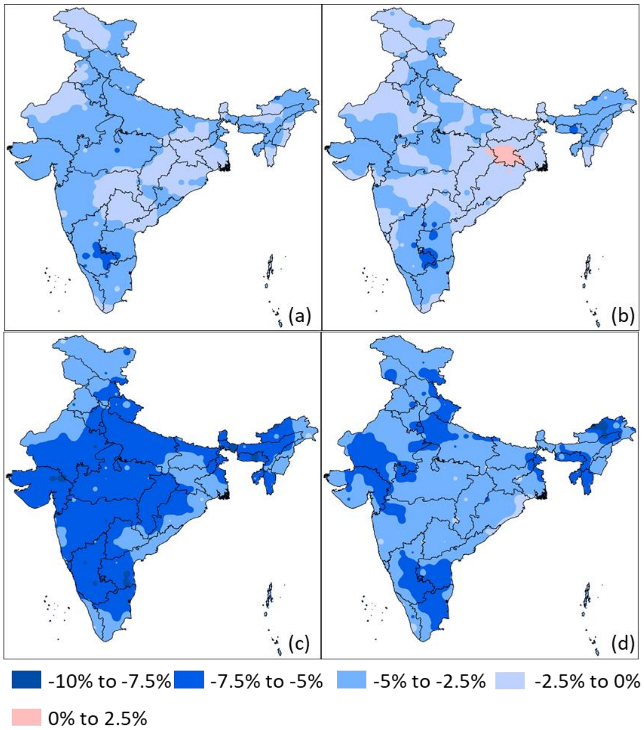

Fig. 1 Percentage change in annual solar PV energy under the SSP245 scenario for 2050 (a) and for 2070 (b) and under the SSP585 scenario for 2050 (c) and for 2070 (d) compared to the 2010 period.

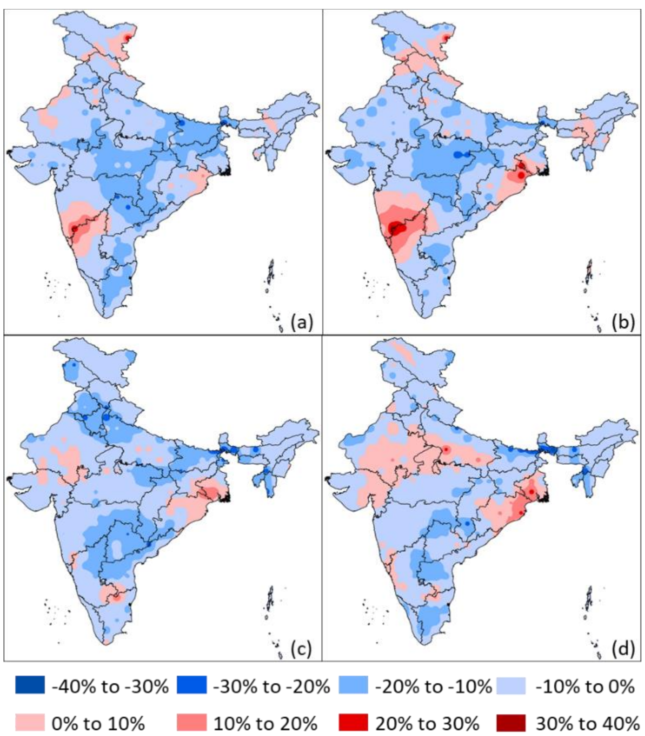

Fig. 2 Percentage change in annual wind energy generation under the SSP245 scenario for 2050 (a) and for 2070 (b) and under the SSP585 scenario for 2050 (c) and for 2070 (d) compared to the 2010

majority of the regions within India for both future periods under both climate scenarios. Thus, assuming the capacity factors for future periods to remain the same as those of the present period will result in the erroneous estimation of the installed capacity required for meeting future demand and set climate goals. Therefore, it is crucial to capture these changes in generation potential due to climate impacts and estimate the appropriate capacity factors of solar and wind energy systems for future periods.

REFERENCE

[1] Renewable power remains cost-competitive amid fossil fuel crisis. (2024, July 13). Retrieved from https://www.irena.org/news/pressreleases/2022/Jul/Renewable-Power-Remains-Cost-Competitive-amid-Fossil-Fuel-Crisis

[2]Year Wise Achievements. Ministry of New and Renewable Energy India. (2024, August 18). Retrieved from https://mnre.gov.in/year-wise-achievement/

[3] Wind Power Costs Reduced Dramatically. (2024, September 20). Retrieved from https://energyanalysis.lbl.gov/news/wind-power-costs-reduced-dramatically

[4] Report on Optimal Generation Capacity Mix for 2029–30 Version 2.0. (2024, April 20). Retrieved from https://cea.nic.in/wp-content/uploads/irp/2023/05/Optimal_mix_report__2029_30_Version_2.0__For_Uploading.pdf

[5] Gernaat, D. E., de Boer, H. S., Daioglou, V., Yalew, S. G., Müller, C., & van Vuuren, D. P. (2021). Climate change impacts on renewable energy supply. *Nature Climate Change*, *11*(2), 119-125.

[6] Liu, L., He, G., Wu, M., Liu, G., Zhang, H., Chen, Y., ... & Li, S. (2023). Climate change impacts on planned supply–demand match in global wind and solar energy systems. *Nature Energy*, *8*(8), 870-880.

[7] Pryor, S. C., Barthelmie, R. J., Bukovsky, M. S., Leung, L. R., & Sakaguchi, K. (2020). Climate change impacts on wind power generation. *Nature Reviews Earth & Environment*, *1*(12), 627-643.

[8] Pryor, S. C., Nielsen, M., Barthelmie, R. J., & Mann, J. (2004). Can satellite sampling of offshore wind speeds realistically represent wind speed distributions? Part II: Quantifying uncertainties associated with distribution fitting methods. *Journal of Applied Meteorology and Climatology*, *43*(5), 739-750.

[9] Gamesa G126-2.5 MW. (2024, August 18) Retrieved from https://en.wind-turbine-models.com/turbines/1286-gamesa-g126-2.5mw#datasheet