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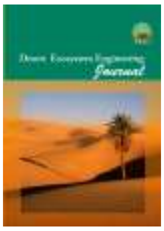

Assessing the Impacts of Climate Change on the Potential and Sustainability of Offshore Wind Energy in the Persian Gulf

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Extend abstract

Introduction

Global atmospheric warming is fundamentally altering atmospheric circulation patterns, which directly influence wind regimes and their associated variability. Consequently, climate change is anticipated to exert a significant impact on future wind characteristics and, by extension, the reliability of wind energy resources. Given that wind power density is highly sensitive to wind velocity, even marginal shifts in wind speed can substantially affect offshore wind energy generation. Despite the rising global prominence of offshore wind energy, the specific impacts of climate change on power density and energy potential within the Persian Gulf have received limited academic attention. To address this research gap, the present study evaluates the impacts of climate change on offshore wind energy potential in the coastal region of Bushehr, situated in the northern Persian Gulf, under various projected climate scenarios.

Materials and Methods

This study aims to assess the clean energy generation potential of offshore wind turbines along the Bushehr coastline and to project future energy extraction capacity under CMIP6 climate scenarios. Historical wind speed data (1980–2024) were retrieved from the Bushehr coastal meteorological station. Future wind patterns for the 2025–2050 period were simulated using the CESM2 global climate model under SSP2-4.5, SSP3-7.0, and SSP5-8.5 forcing scenarios. To characterize wind speed distribution, wind power density (WPD), and energy potential for both historical and future periods, the Weibull distribution function—characterized by its shape (k) and scale (c) parameters—was applied. WPD was computed at the turbine hub height, and annual electricity generation potential was estimated based on the deployment of 5 MW offshore wind turbines. Furthermore, the InVEST offshore wind energy model was utilized to evaluate energy production capacity, socio-economic indicators, and carbon offset potential under both baseline and projected climate conditions.

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Results

Analysis of wind speed anomalies in the coastal regions of Bushehr revealed a transition from predominantly negative anomalies during 1980–2000 to positive anomalies post-2000, indicating a trend toward intensification of wind conditions in recent decades, with peak anomalies observed during 2010–2015. Climate projections suggest that rising air temperatures will likely intensify offshore wind speeds across the Persian Gulf. Relative to the baseline period (1980–2024), mean wind speed is projected to increase from 5.78 m/s to 6.1, 6.3, and 6.7 m/s under the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively, representing growth rates of approximately 6%, 8%, and 14%.

Consistent with these shifts, wind power density (WPD) is projected to experience substantial growth under future climate conditions. Compared to the baseline, WPD is expected to rise by approximately 20%, 23%, and 27% under the respective SSP scenarios. Incorporating bathymetric constraints and turbine installation costs, our findings indicate that a single 5 MW offshore turbine, which generates approximately 17.79 GWh/year under baseline conditions, could see its energy output increase by 13% to 21% depending on the climate pathway. Similarly, a 20-turbine wind farm, currently capable of generating ~355 GWh/year, is projected to experience a capacity increase of 13% to 22%. Finally, the Levelized Cost of Energy (LCOE), estimated at 0.015 USD/kWh in the baseline period, is projected to decline to approximately 0.011, 0.010, and 0.013 USD/kWh under the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively, highlighting the enhanced economic viability of offshore wind energy in the region under future climate projections.

Discussion and Conclusion

Offshore wind energy has experienced rapid global expansion, driven by superior wind resource availability and proximity to coastal demand centers. This study demonstrates that the Bushehr coastal region possesses significant offshore wind energy potential, which is projected to persist—and potentially enhance—under evolving climate conditions. Our findings indicate that anticipated increases in wind speed and power density will likely bolster energy generation capacity, thereby improving the economic feasibility of offshore wind projects in the region. The results further suggest that deploying twenty 5 MW offshore turbines within 15 km of the Bushehr coastline could generate approximately 355 GWh/year of clean electricity, effectively offsetting nearly 0.24 million tons of carbon emissions annually. Compared to fossil-fuel-based power generation in Iran, this transition offers substantial environmental benefits. Furthermore, our uncertainty analysis, utilizing Monte Carlo simulations, reveals notable variability in the Levelized Cost of Energy (LCOE). Complementary tornado analysis identifies wind speed as the most influential driver of LCOE, underscoring the critical importance of accurate wind resource assessment for project economics. Overall, these findings highlight the immense potential of the Bushehr coastline as a strategic hub for sustainable offshore wind development, providing a robust pathway for diversifying Iran's energy portfolio while mitigating climate-related risks.

Keywords: Bushehr; Climate Change; Offshore Wind Energy; Turbine; Wind Power Density; Weibull Distribution.