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環境

Physics-Constrained Deep Learning for Reliable Solar Energy Projections: Transforming Africa's Renewable Energy Planning

TECHNOLOGY SHOWCASE

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■ Introduction

Africa possesses exceptional solar resources, receiving an annual average of 2,119 kWh/m² of solar radiation—significantly exceeding most global regions—positioning the continent strategically for renewable energy transition [1]. However, over 600 million people across Africa lack electricity access, while climate models exhibit systematic biases in simulating surface solar radiation, creating substantial uncertainties for long-term infrastructure planning [2]. These biases stem from inadequate representation of cloud-radiation interactions, aerosol transport mechanisms, and land-atmosphere feedback. CMIP6 models systematically overestimate global mean surface solar radiation while showing considerable variation in aerosol treatment across Africa's diverse climate regimes. Such limitations significantly undermine solar resource assessments for energy planning, potentially leading to suboptimal investment decisions for infrastructure with typical 25-30-year lifespans.

■ Research Activity

1. Data

The Surface Solar Radiation Data Set - Heliosat (SARAH) Edition 2.1 for the historical period (1983-2017) was used as observation. We utilized 19 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) that provide both historical simulations (1983-2014) and future projections under four Shared Socioeconomic Pathway scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). From each model, three key variables were extracted: surface downward solar radiation (Rs), total cloud cover (TCC), and clear-sky surface downward solar radiation (rsdscs)

2. Methods

Physics-Constrained Deep Learning Framework - In this study we developed a three-stage physics-constrained deep learning approach integrating radiative transfer physics within neural network architectures. Stage 1 applies cloud-weighted atmospheric nudging, leveraging observational accuracy where model uncertainty is highest based on total cloud cover as the primary modulator of surface radiation. Stage 2 employs Fourier spectral correction through frequency domain manipulation, preserving the model's natural amplitude spectrum while incorporating observational phase patterns for spatial organization. Stage 3 utilizes multi-branch convolutional neural networks processing Rs, rsdscs, and TCC through identical CNN branches with embedded physical constraints ensuring corrections remain within bounds: $0 \leq Rs,final \leq$ min(rsdscs).

■ Contribution of the study

This study develops a physics-constrained bias correction framework for solar radiation over Africa, identifying regions with reliable solar resources to support optimal renewable energy infrastructure planning and accelerate the continent's energy transition. **Energy Sector:** This research provides accurate long-term solar resource projections enabling optimal photovoltaic plant siting, capacity planning, and performance forecasting. The framework quantifies regional and seasonal variations in solar availability under climate change, supporting investment decisions for infrastructure with 25-30 year lifespans as Africa's installed capacity continues growing from 2.5 GW (2016) to over 10 GW (2023). **Policy and Investment Sectors:** Evidence-based intelligence for national renewable energy policies and risk-adjusted frameworks for multi-billion dollar solar infrastructure investments. The uncertainty quantification (model: 51%, variability: 49%, scenario: 2-4%) enables informed decision-making for governments and financial institutions supporting Africa's electrification goals.

Refrences [1]

IEA (2022). Africa Energy Outlook 2022. International Energy Agency, Paris.

[2] Wild, M. (2020). The global energy balance: A review of CMIP6 radiation biases. Climate Dynamics, 55, 1217-1237.

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