Solar Radiation Modelling in Different Climate Zones of Morocco: Resource Assessment, and Agricultural Applications

DOCTORAL (Ph.D.) DISSERTATION

By: Mendyl Abderrahmane

ELTE
EÖTVÖS LORÁND
UNIVERSITY

EÖTVÖS LORÁND UNIVERSITY
FACULTY OF SCIENCES

Doctoral School of Environmental Sciences
Prof. Dr. Tamás Turányi
Institute Of Geography and Earth Sciences
Department of Meteorology

Supervisor:

Associate Professor Dr. Habil. Tamás Weidinger

Eötvös Loránd University, Institute of Geography and Earth Sciences,
Faculty of Sciences, Department of Meteorology

BUDAPEST

2024

DOI: 10.15476/ELTE.2024.169

1. Introduction

Solar radiation (SR), emitted by the sun, plays a crucial role in various natural processes (Keller & Costa, 2011). It affects the energy balances of numerous physical, chemical, and biological phenomena on Earth's surface (Beer et al., 2010). Changes in solar radiation levels have notable consequences on heat distribution, the water cycle, ecosystems, and climate patterns. Importantly, solar energy presents a cleaner alternative to conventional energy sources like fossil fuels, emitting considerably less pollution. It stands as the most abundant renewable energy resource globally and is utilized commercially through large-scale solar power plants (Panwar et al., 2011). Therefore, accurately measuring and understanding the spatial and temporal variations of solar radiation are essential for meteorological, hydrological, and energy-related endeavours.

The rising energy demand, energy security concerns, and the need to fight climate change have pushed renewable energy to the forefront of the global energy scene. Notably, wind and solar photovoltaic (PV) systems have experienced significant growth since 2010. However, despite advancements, renewable energy penetration remains relatively low. Many nations, including the European Union (EU), have set ambitious targets to transition to cleaner energy sources. Morocco declared at the Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UN-FCCC) that it intends to increase its renewable energy capacity to 52% (20% solar, 20% wind, and 12% hydro) by 2030. Between 2018 and 2030, the country expects to install around 10 GW of renewable energy (RE) volume (4.5 GW of solar, 4.2 GW of wind, and 1.3 GW of hydroelectric) (NDC Partnership, 2021). These targets are vital for achieving broader climate goals, such as reducing greenhouse gas emissions. Moreover, the United Nations aims to create millions of jobs in renewable energy and energy efficiency, highlighting the global focus on transitioning away from fossil fuels. As countries increasingly integrate renewable energy sources into their energy mix, accurate forecasting of solar radiation becomes essential for optimizing solar power generation and addressing intermittency challenges. However, accurately estimating solar energy resources remains a complex task due to various factors, necessitating the use of diverse methodologies, including machine learning, to enhance accuracy, particularly in regions with variable weather conditions.

2. Research Objectives

1. Evaluate, and calibrate, then validate six different clear sky models for hourly global horizontal irradiance (GHI) across various regions of Morocco, leveraging satellite-derived datasets and the Pvlib Python module (Holmgren et al., 2018) to enhance the accuracy of solar radiation estimation. Assess the accuracy of the clear sky models using quantitative statistical indicators to identify trends of overestimation or underestimation across different sites in Morocco (Mendyl et al., 2022).

2. Investigate the efficacy of three machine learning models for hourly solar radiation forecasts under all sky conditions. Compare the advantages and disadvantages of each machine learning model and explore aggregation techniques to improve forecast accuracy. Develop and evaluate the Sugeno Lambda-measure and Sugeno Integral (SLSM) model by integrating outputs from multilayer artificial neural networks (MLANN) long short-term memory (LSTM), and support vector machine (SVM) to enhance solar radiation forecast accuracy. Quantify the effectiveness of the SLSM model and demonstrate its impact on forecast accuracy (Mendyl et al., 2024) are also important goals of the research.

3. Investigate practical applications of solar energy by constructing an innovative absorber for indirect solar drying in a solar air collector, utilizing corrugated aluminium plates to optimize airflow during the drying process. Study the drying process of two varieties of bananas, one native to Morocco and one from another region (imported bananas), using the solar air collector to assess its performance in moisture elimination. Provide insights into the practical utilization of solar energy in agricultural processes, contributing to the effective deployment of solar energy systems in Morocco and enhancing sustainability (Mendyl et al., 2023).

3. Methodology

The methodology employed in these research exhibits a systematic and comprehensive approach to solar radiation modelling for short term GR forecast and for practical application of solar energy through the optimisation of drying process of bananas.

In the first study (Mendyl et al., 2022), the process began with downloading ERA5 hourly fractional cloud cover data to assess cloud coverage in different locations. By aggregating the hourly data into daily values, clear-sky days were identified as those with zero cloud cover. Then, I calibrated the clear sky models using Python programme and validated the results against the hourly McClear clear sky model. This validation focused on time intervals with zenith angles less than 90 degrees, representing the period between sunrise and sunset.

The second study (Mendyl et al., 2024) focused on a diverse array of meteorological parameters crucial for solar radiation prediction. Leveraging data from sources like NASA POWER and SOLCAST, the study meticulously pre-processed the collected data, ensuring its readiness for subsequent analysis. I trained three distinct models LSTM, MLANN, and SVM. This training process involved a meticulous selection of architectures, training functions, and algorithms, tailored to the unique requirements of solar radiation prediction. The computational was carried out on a well-equipped laptop, facilitating efficient model training.

Following model training, I subjected their respective models to rigorous testing using separate test datasets. This evaluation phase aimed to gauge the models' performance in accurately forecasting solar radiation levels, a critical aspect for solar energy system planning and performance assessment as in our last publication (Ammari et al., 2024).

Throughout these studies, I meticulously paid attention to data transparency and reproducibility. This included careful division of datasets into training and test sets, coupled with the provision of detailed statistical information.

Through the drying process of bananas (Mendyl et al., 2023), I utilized an indirect air solar dryer, specifically designed for solar drying of agricultural products. This solar air dryer, constructed step by step at the Laboratory of Solar Energies and the Environment at the University of Mohammed V, Rabat, Morocco, supported by The Institute for Solar Energy and New Energies Research (IRESEN). All equipment was strategically placed on the roof of the annex, situated in Rabat, Morocco, to maximize solar radiation absorption for our drying experiment as I monitored the drying process.

4. Theses of the dissertation

Based on the combined evaluation of the results achieved by the methods used during my doctoral research, I came to the results and findings summarized in the following theses:

A). Based on the calibration and validation of global horizontal irradiance of six clear sky models against the McClear clear sky model as the reference, it was observed that the developed models demonstrated different performance across various regions, showcasing their reliability in estimating solar radiation under clear sky conditions (Mendyl et al., 2022).

Here's a breakdown of the key findings:

1. My analysis of various meteorological parameters across different latitudinal sites revealed a significant impact on model performance. Despite the variations in model performance concerning humidity content, clear-sky days, and annual water vapor content, distinct differences were observed between polar and equatorial region.

2. I found Tantan as an outlier with a mean bias overestimation in solar radiation measurements, contrasting with the underestimations in other cities. This is due to Tantan's lower latitude (28.437° N) resulting in higher solar radiation and its Tropical and Subtropical Desert Climate (Bwh) with high temperatures and low precipitation.
3. Fes and Tangier exhibited similar solar radiation results due to their nearly identical latitudes, which result in comparable solar radiation levels. Both cities also share a Mediterranean climate, leading to consistent weather patterns that similarly influence solar radiation in both locations.
4. The Bird model's has poor performance in Tantan due to its sensitivity to local atmospheric conditions and Tantan's unique environmental characteristics. The model's sensitivity to aerosol optical depth AOD means that inaccurate AOD values for Tantan result in overestimations of solar radiation, compromising the model's accuracy.
5. The Adnot–Bourges–Campana–Gicquel (ABCG) and Berger–Duffie (BDD) models consistently underestimate high solar radiation levels due to their simplified approaches, which failing to capture atmospheric variability and nonlinear relationships, they overlook complex atmospheric factors like aerosols and humidity during of high radiation, leading to inaccuracies.
6. The coefficient of determination (R^2) further emphasized the latitude's influence, with higher R^2 values observed at Tangier compared to Tantan, suggesting latitude-specific preferences for clear sky models.
7. Evaluation metrics such as relative Mean Absolute Error (rMAE) and relative Root Mean Square Error (rRMSE) indicated that complex models outperformed simple clear sky models. Specifically, the ABCG model showed satisfactory performance at low latitudes but performed poorly at high latitudes.
8. I found that SOLCAST performs well in Mediterranean climates and moderately humid environments, it requires enhancements to accurately predict solar radiation in high-altitude and extremely dry or humid conditions.
9. Despite the overall reliability of the McClear model, potential biases were identified, emphasizing the need for continuous validation, particularly with reference observation data.
10. I noticed the limitations regarding aerosol data interpolation and monthly averages for ozone highlighted the necessity for high spatial and temporal resolution inputs for accurate model assessment.

B). Based on the study of enhancing solar radiation forecasting in diverse Moroccan climate zones using machine learning models with the Sugeno Integral aggregation model, it was found that the integrated approach improved forecast accuracy, demonstrating its potential to effectively predict solar radiation in varying climatic conditions across Morocco (Mendyl et al., 2024).

Here's a breakdown of the key findings:

1. Evaluation utilizing Taylor diagrams, violin plots, and error criteria (RMSE, MAE, R^2) revealed that LSTM exhibited the best performance in predicting observed values surpassing SVM and MLANN.
2. I verified that the advantage of LSTM lies in its integration with the learn-and-forget structure and optimization techniques, resulting in predictions with reduced error despite its complex structure with hyperparameters.

3. I confirmed the robustness of LSTM's performance through Kruskal–Wallis (KW) tests, indicating the stability of the suggested LSTM model at a 95% confidence level, with the distributions of predicted and actual models found to be identical.
4. I found that the performance of SVM was low in Tantan during the training phase, while it showed reasonable satiability performance during the testing phase. The data associated with Marrakech and Agadir shown less satiability performances.
5. I found that the MLANN model overestimates solar radiation in Fes due to the climatological aspects of the recorded data, specifically extreme weather conditions that introduce outliers, significantly impacting the model's results.
6. I found that prediction accuracy could be significantly enhanced by integrating model outputs using aggregation techniques.
7. I realised that my new proposed hybrid model named SLSM, which combines LSTM, SVM, and MLANN predictions with Sugeno λ-measure and Sugeno integral, demonstrated improved prediction accuracy, reducing irregularities associated with SR data.
8. The results validate the applicability and reliability of the SLSM and LSTM model as an alternative for SR prediction in Morocco's tropical and subtropical desert climate zones.

C). The study presents an innovative absorber design for a solar air collector used in an indirect solar dryer through the drying process of bananas, these findings facilitated a deeper understanding of drying effectiveness and identified areas for performance improvement, emphasizing the importance of temperature control, heat conservation, treatment methods for agricultural products, and heat storage mechanisms for nocturnal temperature drops in optimizing drying processes. Monitoring moisture content emerged as crucial for enhancing dryer efficiency and ensuring food meets optimal standards for presentation. (Mendyl et al., 2023).

Here's a breakdown of the key findings:

1. I established that humid air entering the drying chamber at night led to a dip in temperature, which increased humidity and extended the drying time for the product.
2. I realised that there was a significant weight reduction from 150 grams to 48 grams and a decrease in moisture content from 78% to 28.1%.
3. I found that fluctuating weather conditions during the day also affected the drying temperature unfavourably, requiring adjustments to maintain ideal drying conditions.
4. A drying temperature of 55 °C was found to produce superior quality banana slices, with reduced bulk, improved flavour, decreased water activity, and reduced dehydration time and energy usage.
5. I established that the viscosity of bananas increases during the drying process, particularly in the morning, due to sugar adhering to pores as water migrates towards them. Even at the final stages of drying, noticeable viscosity remains due to sugar retention.

5. Conclusion

The research aims to advance understanding and application of solar radiation estimation and forecasting, particularly in Moroccan contexts, with the overarching goal of promoting safe and sustainable integration of solar energy. The main contribution of this research is focusing on implementation and analysis of models while acknowledging potential limitations that could guide future research directions.

In the initial phase, the study focused on estimating global horizontal irradiance (GHI) using clear sky models. By evaluating and calibrating six models across diverse Moroccan sites, both complex and simple models were compared, providing insights into their effectiveness. Validation against established models and satellite-based datasets ensured robust analysis, guiding the selection of suitable models for different climate zones and future estimation efforts.

The second phase employed machine learning models for solar radiation forecasting under varying sky conditions. Comparison of three models—support vector machine regression (SVMR), long short-term memory (LSTM), and multilayer artificial neural networks (MLANN) highlighted their stability. The proposed SLSM model, integrating outputs from these models, demonstrated a significant increase in accuracy, offering insights into the strengths and weaknesses of each approach.

The final phase explored the practical applications by constructing a solar air collector for indirect solar drying. The design, featuring an absorber made of corrugated aluminum plates, optimized airflow during drying. Experimental studies evaluated the solar dryer's performance in removing moisture from two banana varieties, showcasing the potential of solar energy in agricultural processes, and providing valuable insights for efficient solar dryer utilization.

References:

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., et al. (2010). Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate. Science, 329 (5993), 834–838. https://doi.org/10.1126/science.1184984.

Holmgren, W. F., Hansen, C. W., & Mikofski, M. A. (2018). pvlib python: A python package for modeling solar energy systems. Journal of Open-Source Software, 3(29), 884. https://doi.org/10.21105/joss.00884

Keller, B., & Costa, A. M. S. (2011). A Matlab GUI for calculating the solar radiation and shading of surfaces on the earth. Computers & Applications in Engineering Education, 19, 161–170. https://doi.org/10.1002/cae.20301.

NDC Partnership. (2021). Morocco Submits Enhanced NDC, Raising Ambition to 45.5 Percent by 2030. Retrieved from https://ndcpartnership.org/news/morocco-submits-enhanced-ndc-raising-ambition-455-percent-2030.

Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. Renewable and Sustainable Energy Reviews, 15, 1513–1524. https://doi.org/10.1016/j.rser.2010.11.037.

SOLCAST. (2022). Historical and TMY Data. Retrieved from https://solcast.com/historical-and-tmy-data/.

Publications related to the Ph.D. dissertation.

Mendyl, A., Mabasa, B., Bouzghiba, H., & Weidinger, T. (2022). Calibration and validation of global horizontal irradiance clear sky models against McClear clear sky model in Morocco. *Applied Sciences, 13*(1), 320. https://doi.org/10.3390/app13010320.

Mendyl, A., Bourguiba, H., Tadili, R., & Weidinger, T. (2023). Thermal performance assessment of an indirect solar dryer: A case study of bananas. *Potravinarstvo Slovak Journal of Food Sciences*, 17, 550–564. https://doi.org/10.5219/1883.

Mendyl, A., Demir, V., Omar, N., Orhan, O., & Weidinger, T. (2024). Enhancing solar radiation forecasting in diverse Moroccan climate zones: A comparative study of machine learning models with Sugeno integral aggregation. *Atmosphere*, *15*(1), 103. https://doi.org/10.3390/atmos15010103.

Other publications

Ammari, N., Alami Merrouni, A., **Mendyl, A.,** Chaabelasri, E., Weidinger, T. (2024) Energy, Economic and Environmental (3E) Analysis for an Optimal CSP Technology Integration in Morocco. *Energies*. 17(12), 3020. https://doi.org/10.3390/en17123020

Houria, B., **Mendyl, A.**, Kenza, K., & Gábor,G. Short-term predictions of PM10 and NO_2 concentrations in urban environments based on ARIMA search grid modelling. CLEAN–Soil, Air, Water, (2024), e2300395.https://doi.org/10.1002/clen.202300395.

Khomsi, K., Bouzghiba, H., **Mendyl, A**., Al-Delaimy, A. K., Dahri, A., Saad-Hussein, A., … & Abbas, N. (2024). Bridging research-policy gaps: An integrated approach. *Environmental Epidemiology*, 8(1), e281. doi:10.1097/EE9.0000000000000281

Mendyl, A., & Weidinger, T. (2023) Exploring wind patterns and evaluating wind energy prospects in North-Western Hungary. Egyetemi Meteorológiai Füzetek, University Notes of Meteorology, 35, 132–141. https://doi.org/10.31852/EMF.35.2023.132.141

Weidinger, T., Balogh, E., **Mendyl, A**., Fritz, P., Tordai, Á. V., Gandhi, A., & Schmelz, T. (2023). Surface layer's sound speed profiles: Climatological analysis and application for the CNOSSOS-EU noise model. Technische Mechanik - European Journal of Engineering Mechanics, 43(1), 162–177. https://doi.org/10.24352/UB.OVGU-2023-053.

Weidinger, T., **Mendyl, A**. (2022). Magyarország sugárzási és szélklímája, a szél- és napenergia felhasználás meteorológiai háttere. (The radiation and wind climate of Hungary, the meteorological background of wind and solar energy use.) In: OLÁH, RÓBERT (szerk.) „... születtem, elvegyültem és kiváltam." - Tanulmánykötet Dr. Makra László professzor 70. születésnapjára / „... I was born, received and found individuation." - Volume of Studies in Honor of 70-year-old Prof. Dr. László Makra Nagykőrös, Magyarország : Magánkiadás (2022) 618 p. pp. 577-611. 35 p. (In Hung).

Conferences

Bouzghiba, H., Ajdour, A., **Mendyl, A.,** & Géczi, G. (2024). Evaluating Two-Dimensional Horizontal Grids in a Deterministic Air Pollution Model: Estimating the Impact on Outputs, Inputs, and ANN-CHIMERE. Paper presented at the EGU General Assembly 2024, Vienna, Austria (Abstract No. EGU24-411). https://doi.org/10.5194/egusphere-egu24-411.

Bouzghiba, H., **Mendyl, A**., Géczi, G., Weidinger, T., & Khomsi, K. (2024). Advancing Air Quality Prediction: An Evaluation of WRF Model Configurations and Their Impact on Meteorological Parameters in Hungary. Presented at the 36th Annual Conference of the International Society for Environmental Epidemiology (ISEE), Santiago, Chile. (Accepted).

Mendyl, A., Gandhi, A., Musyimi, P. K., Székely, B., and Weidinger, T. (2022). Comparative analysis of wind and solar energy potential from differnet climate regions, case studies of Morocco , India and Kenya , EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-380, https://doi.org/10.5194/egusphere-egu22-380, 2022.

Mendyl, A., Musyimi, P. K., Gyöngyösi, A. Z. & Weidinger, T. (2023). Analysis of Wind Data and Assessment of Wind Energy Potential in North-West Hungary, EMS Annual Meeting 2023, Bratislava, Slovakia, 4–8 Sep 2023, EMS2023-114, https://doi.org/10.5194/ems2023-114, 2023.

Musyimi, P. K., **Mendyl, A**., Agustiyara, A., Székely, B., and Weidinger, T. (2023). Hourly reference evapotranspiration analysis using synoptic meteorological measurements and ERA5 reanalysis data from Kenyan Counties, EMS Annual Meeting 2023, Bratislava, Slovakia, 4–8 Sep 2023, EMS2023-331, https://doi.org/10.5194/ems2023-331, 2023.

Weidinger, T., & **Mendyl, A**. (2022). Thermal Performance Assessment of an Indirect Solar Dryer: A Case Study of Bananas. Paper presented at the XXII International Scientific Conference, Risk Factors of Food Chain, Wgierska Gorka, Poland.

Weidinger, T., Parászka, V., Balogh E., Fritz, P., Gandhi, A., Mendyl, A., Tordai, Á. V. (2022). Structure of the CNOSSOS-EU new generation noise propagation model and meteorological data background. 48. Meteorological Scientific Days, November 17-18, 2022, The Atmosphere is our life, Observation, modeling, forecasting. Summary of lectures, Hungarian Meteorological Services, 13 p. https://mta.hu/esemenynaptar/2022-11-17-eletterunk-a-legkor-megfigyeles-modellezes-elorejelzes-48-meteorologiai-tudomanyos-napok-4523 (In Hung)

Weidinger, T., Tordai, Á., Gandhi, A., & **Mendyl, A**. (2022, June). Surface Layer's Sound Speed Profiles: Climatological Analysis and Application for the Cnossos-EU Noise Model. Paper presented at the Conference on Modelling Fluid Flow (CMFF'22).