Enhanced surface solar irradiance prediction integrating ARIMA, LSTM, and attention mechanisms: A case study in Bhutan

Sangay Gyeltshen[1], Kiichiro Hayashi[2], Linwei Tao[1] and Phub Dem[1]
[1]Department of Civil and Environmental Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan.
[2] Institute of Materials and Systems for Sustainability, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan.
Email ID: sangye89@gmail.com

Introduction

Surface solar irradiance (SSI) forecasting is essential for optimizing solar power operations and grid management in the expanding renewable energy sector [1]. Current approaches face limitations: ARIMA models assume stationarity and struggle with nonlinear patterns [2], while LSTM models lack interpretability despite capturing temporal dependencies [3]. Building on our previous hybrid ARIMA-LSTM with attention mechanism (AM) model with Bayesian optimization [4], this study conducts a comparative evaluation with grid search optimization to validate the effectiveness of different hyperparameter tuning strategies for enhanced SSI forecasting in renewable energy applications.

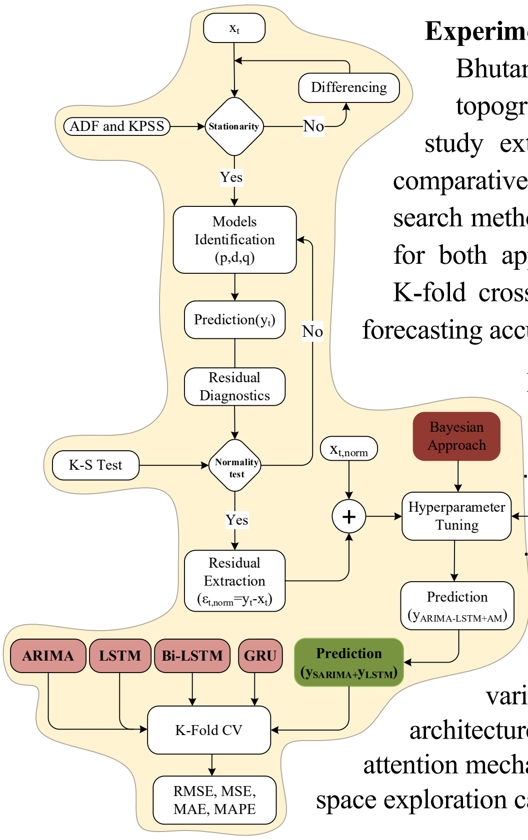

Fig. 1. General framework [4]

Experimental Procedures

Bhutan, a Himalayan kingdom (26°42'N-28°15'N, 88°45'E-92°25'E) with diverse topography ranging from 90 m to 7,255 m elevation, serves as the case study [5]. The study extends our hybrid ARIMA-LSTM-AM architecture [4] by implementing a comparative optimization framework encompassing both Bayesian optimization and grid search methodologies. Hyperparameter tuning was conducted using identical search spaces for both approaches, followed by model training and performance evaluation through K-fold cross-validation to establish the optimal optimization strategy for enhanced SSI forecasting accuracy.

Results and Discussion

K-fold cross-validation (K=5) revealed that Bayesian optimization substantially outperformed grid search in hybrid ARIMA-LSTM-AM model optimization, achieving RMSE of 5.58 W/m² versus 30.63 W/m² for grid search (Table 1). The 5-fold performance highlights the critical role of optimization strategy selection, with Bayesian optimization's sequential exploration proving more effective than grid search's exhaustive approach for this complex hyperparameter space. These findings align with the "No Free Lunch" theorem [6], confirming that optimization effectiveness varies across problem domains. The superior performance combines both the hybrid architecture's strengths—ARIMA's trend modeling, LSTM's temporal dependencies, and attention mechanism's dynamic weighting [7]—with Bayesian optimization's efficient parameter space exploration capabilities.

Table 1: Hyperparameters tuned using grid and Bayesian approaches

Parameters	Bayesian Approach	Grid-Search
Activation Function	tanh	tanh
Batch Size	64	32
Dropout Rate	0.2200	0.02
Learning Rate	0.0005	0.001
LSTM layers	1	1
LSTM Units	47	64
Optimizer	rmsprop	adam
L1	0.00043	0.001
L2	0.00034	0.0002

Acknowledgement

Author acknowledged Royal Government of Bhutan for providing the data and Nagoya University for their academic support.

References

[1] D. Y. Goswami, *Principles of Solar Engineering*. CRC Press, 2022.
[2] C. Voyant, M. Muselli, C. Paoli, and M.-L. Nivet, "Optimization of an artificial neural network dedicated to the multivariate forecasting of daily global radiation," *Energy*, vol. 36, no. 1, pp. 348–359, Jan. 2011, doi: 10.1016/j.energy.2010.10.032.
[3] X. Qing and Y. Niu, "Hourly day-ahead solar irradiance prediction using weather forecasts by LSTM," *Energy*, vol. 148, pp. 461–468, Apr. 2018, doi: 10.1016/j.energy.2018.01.177.
[4] S. Gyeltshen, K. Hayashi, L. Tao, and P. Dem, "Statistical evaluation of a diversified surface solar irradiation data repository and forecasting using a recurrent neural network-hybrid model: A case study in Bhutan," *Renewable Energy*, vol. 245, p. 122706, Jun. 2025, doi: 10.1016/j.renene.2025.122706.
[5] S. N. Uddin, R. Taplin, and X. Yu, "Energy, environment and development in Bhutan," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 9, Art. no. 9, Dec. 2007, doi: 10.1016/j.rser.2006.03.008.
[6] D. H. Wolpert and W. G. Macready, "No free lunch theorems for optimization," *IEEE Transactions on Evolutionary Computation*, vol. 1, no. 1, pp. 67–82, Apr. 1997, doi: 10.1109/4235.585893.
[7] A. Vaswani *et al.*, "Attention is All you Need," in *Advances in Neural Information Processing Systems*, Curran Associates, Inc., 2017. Accessed: Apr. 06, 2024. [Online].