Multi-Objective Evolutionary Optimization with an Artificial Intelligence-Based Approach for Urban Energy Planning

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Background and Motivation

- Rapid urbanization increases demand for sustainable energy.
- Solar PV integration remains highly sensitive to weather variability and air pollution levels.
- Dhaka, Bangladesh experiences elevated particulate concentrations that affects PV performance.
- Aging PV modules is impacted by the weather conditions and air pollution.

Aim of This Investigation

- Power loss happens due to nonuniform aging of the photovoltaic (PV) modules.
- Accurate prediction is crucial for efficient and resilient urban solar planning.

Data Resources: The meteorological variables and urban air quality indicators data were collected for Dhaka, Bangladesh. The 250W aged PV modules data used in the research [1]. A dataset of Particulate Matter ($PM_{2.5}$, PM_{10}) and CO concentrations with Air Quality Index (AQI) values was used [2]. The weather data were collected from the SPAS-Dataset-BD[3].

METHOD

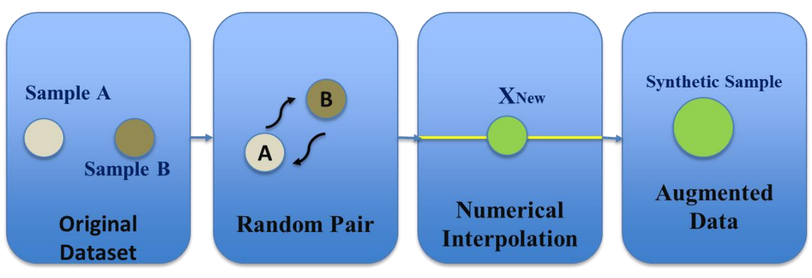
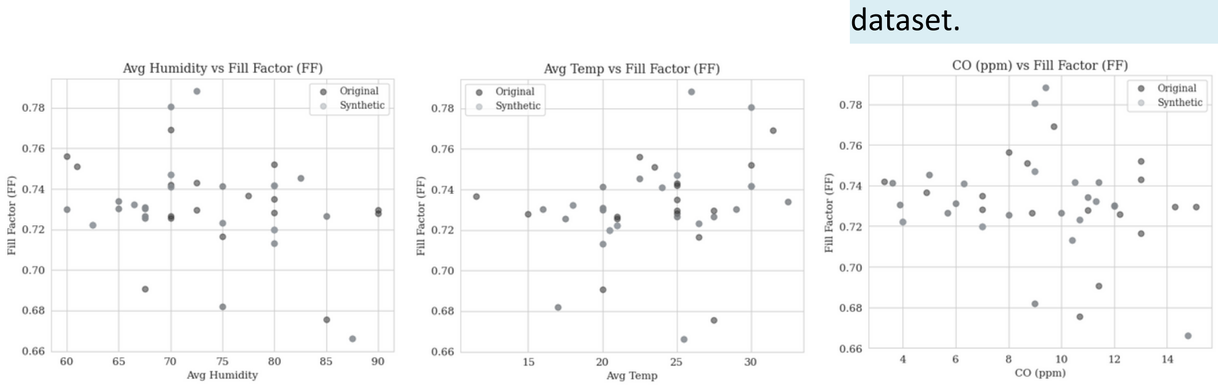


Figure: Workflow of Random-Pair Interpolation-Based SMOTE (RPI-SMOTE). Synthetic samples are generated by selecting a random pair of original data points and linearly interpolating between them, producing new data that enhances the original dataset.



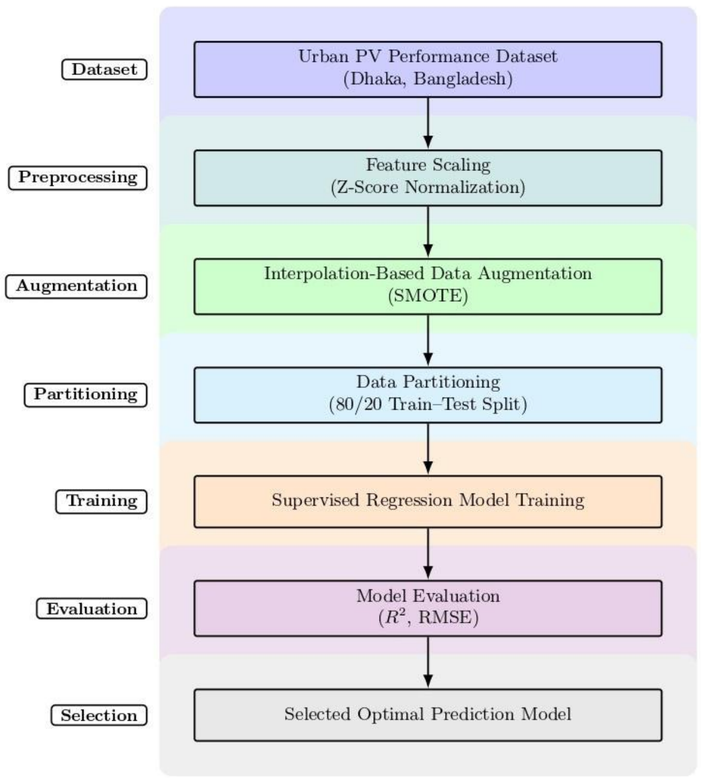
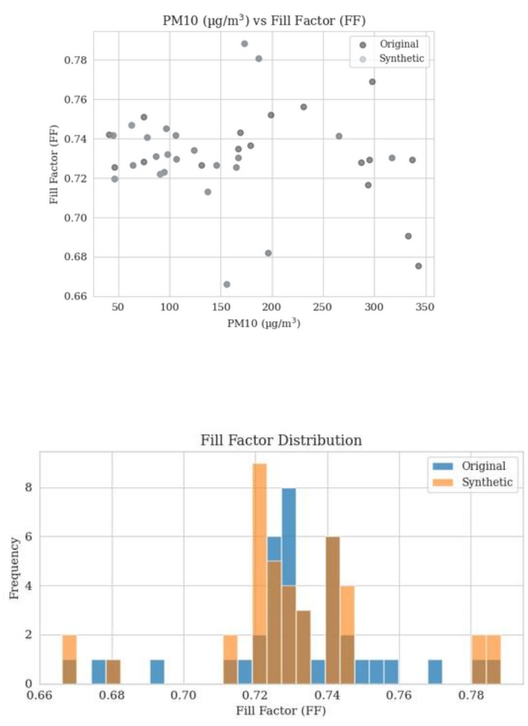


Figure: Overview of the proposed urban PV performance modeling pipeline, starting from the Dhaka Urban PV Performance Dataset and progressing through preprocessing, SMOTE augmentation, data splitting, and regression-based training. Performance comparison using R^2 and RMSE guides the selection of the final optimal prediction model.



RESULT & DISCUSSION

Feature	Original Value Range	Synthetic Value Range
Average Temperature (°C)	11.5 – 32.5	16.0 – 32.5
Average Humidity (%)	60.0 – 90.0	60.0 – 87.5
$PM_{2.5}$ ($\mu g/m^3$, 24 hr)	9.1 – 140.7	10.0 – 115.5
PM_{10} ($\mu g/m^3$, 24 hr)	41 – 343	45 – 317
CO (ppm, 8 hr)	3.3 – 15.1	3.6 – 14.8
Fill Factor (FF)	0.6661 – 0.7884	0.6661 – 0.7884

Table: Comparison of Feature Ranges Between Original and Synthetic Datasets

Training and Testing Performance of Models

Model	Train R^2	Test R^2	Train RMSE	Test RMSE
AdaBoost	0.9288	0.8786	0.00636	0.00939
Gradient Boosting	0.9996	0.8361	0.00045	0.01092
Decision Tree	0.9821	0.7954	0.00318	0.01219
Random Forest	0.9581	0.7903	0.00488	0.01235

Table: Test Set R^2 and RMSE Comparison Highlighting Relative Predictive Accuracy Across Evaluated Models.

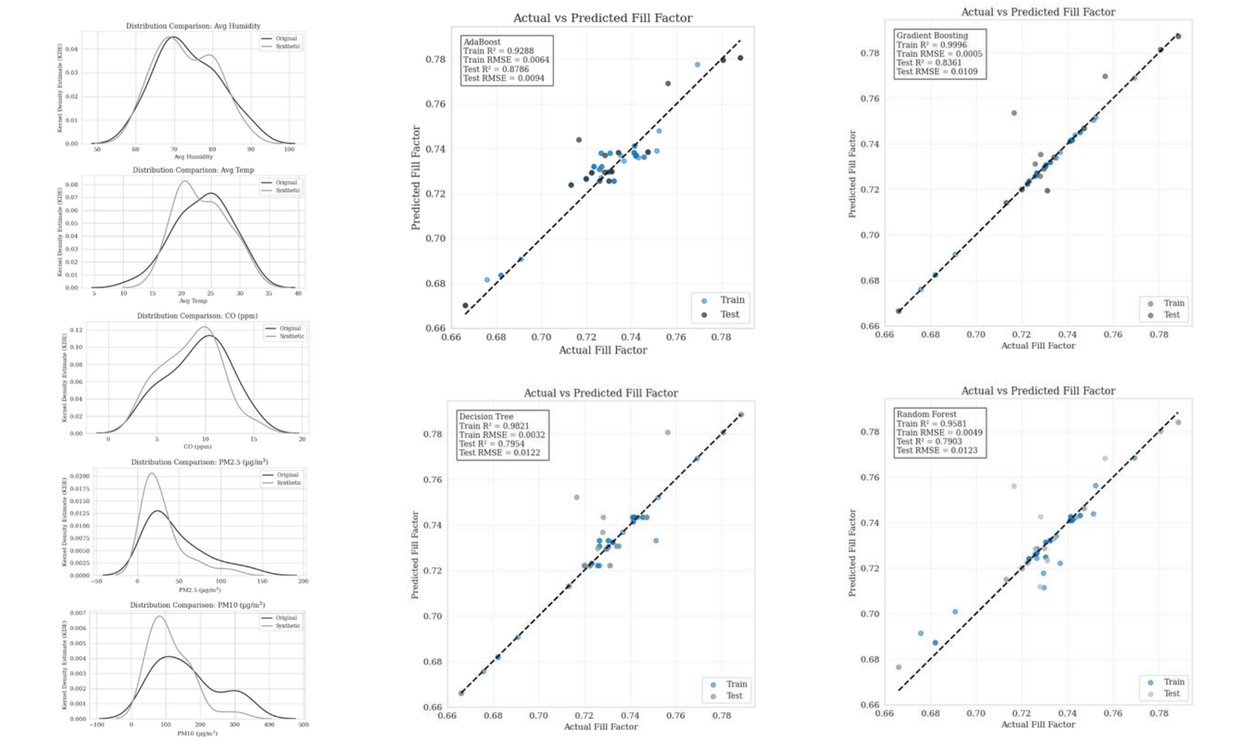


Figure: Distribution of original and synthetic environmental input features, and predicted and observed fill factor values for the regression models, illustrating prediction accuracy using R^2 and RMSE.

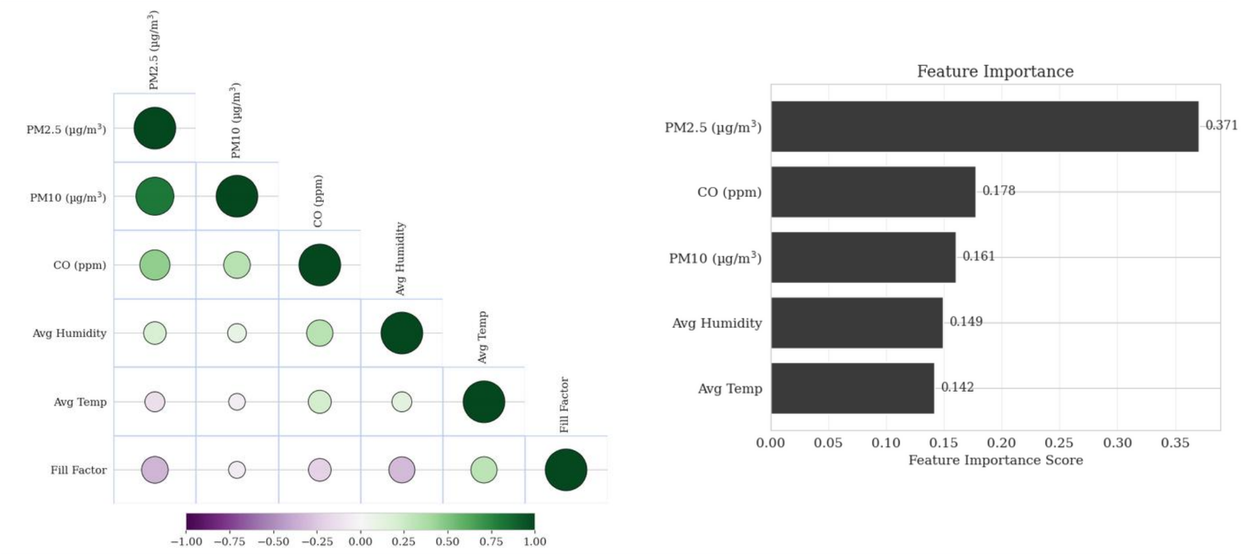


Figure: Feature importance ranking identifies PM2.5 and CO concentration as dominant predictors, highlighting the strong interaction between urban air quality and PV degradation dynamics.

CONCLUSION

- Aged PV module degradation behavior is captured based on weather variability and air pollution levels.
- The developed AI models showed high predictive accuracy measured by regression analysis.
- The Particulate Matter, PM2.5, has mostly impacted the PV degradation that causes power loss in solar systems.

REFERENCES

[1] Al Mansur, Ahmed, et al. Energy Reports 8, 1896-1906, 2022.
[2] Rahman, Mustafizur, et al. Data in Brief 55, 110594, 2024.
[3] Chowdhury, Rup, et al. Data in Brief, 111727, 2025.

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