Intraday Solar and Power Forecasts for Market Participation Optimization

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Research Project Background

Context

Solar PV plants must maintain supply within a tolerance to **avoid penalties**. Solar irradiance forecasts **improve the reliability** of expected power generation and its integration into the grid.

Main objective

To build an **intraday solar irradiance forecast model** and a **resource-to-power generation model** for Enel Colombia's El Paso solar PV plant (86.2 MWp), incorporating operational and meteorological information, GOES satellite data, and sky camera images.

Research question

Up to what forecast horizon does the issued data maintain an acceptable confidence interval?

Specific tasks

- Implement an intraday **solar irradiance forecast** estimation model.
- Implement a **resource-to-power model** that estimates active and reactive power.
- Develop an **expert system** to evaluate KPIs and support market decision-making.

Solar Irradiance Forecast

We developed a solar irradiance forecast model **(LSTM, Bi-LSTM, Transformer)** using two years of meteorological data (from Feb/2022 to Mar/2024) at a 10-minute resolution, forecasting 36 time steps ahead.

Bayesian optimization fine-tuned hyperparameters to efficiently minimize the loss function, preventing overfitting and enhancing irradiance prediction accuracy.

The inputs included GHI, ambient temperature, wind speed/direction, atmospheric pressure, the sine/cosine of the day of the year, and the clear sky index.

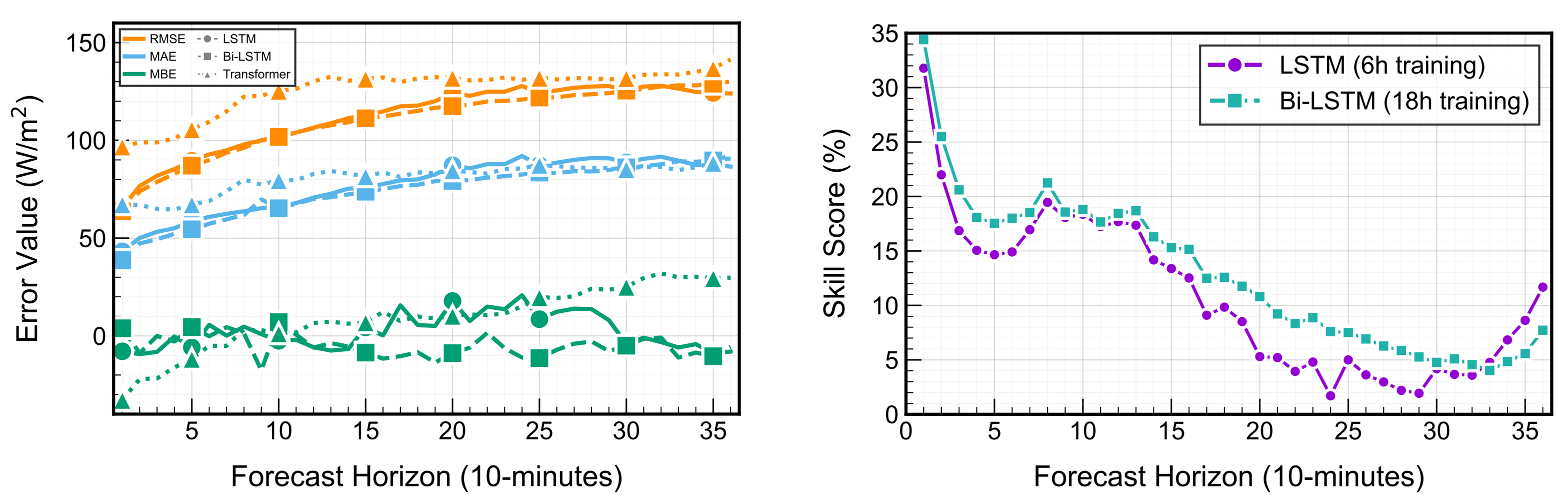

Figure 1. Performance metrics by algorithm (left); Algorithm performance comparison against transformer (right).

The proposed model is **compared with the Global Forecast System (GFS)** to verify if our approach provides greater accuracy and lower computational complexity as an alternative for forecasting.

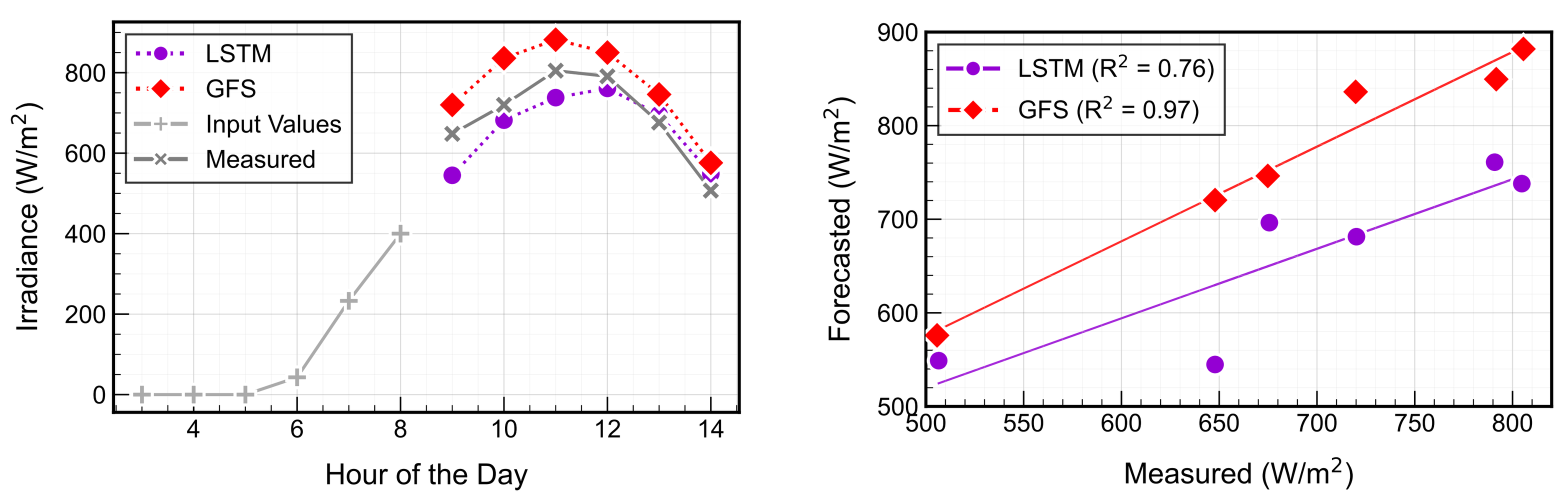

Figure 2. Forecasted solar irradiance (left); Correlation between measured and forecasted irradiance (right).

Images Feature Extraction

Features extracted from **panoramic sky images via an infrared camera** assisted in intra-hour solar irradiance estimation and **cloud movement tracking**. Images were classified as cloudy using statistical thresholds (average <40%, standard deviation 50%, bright pixels <1%).

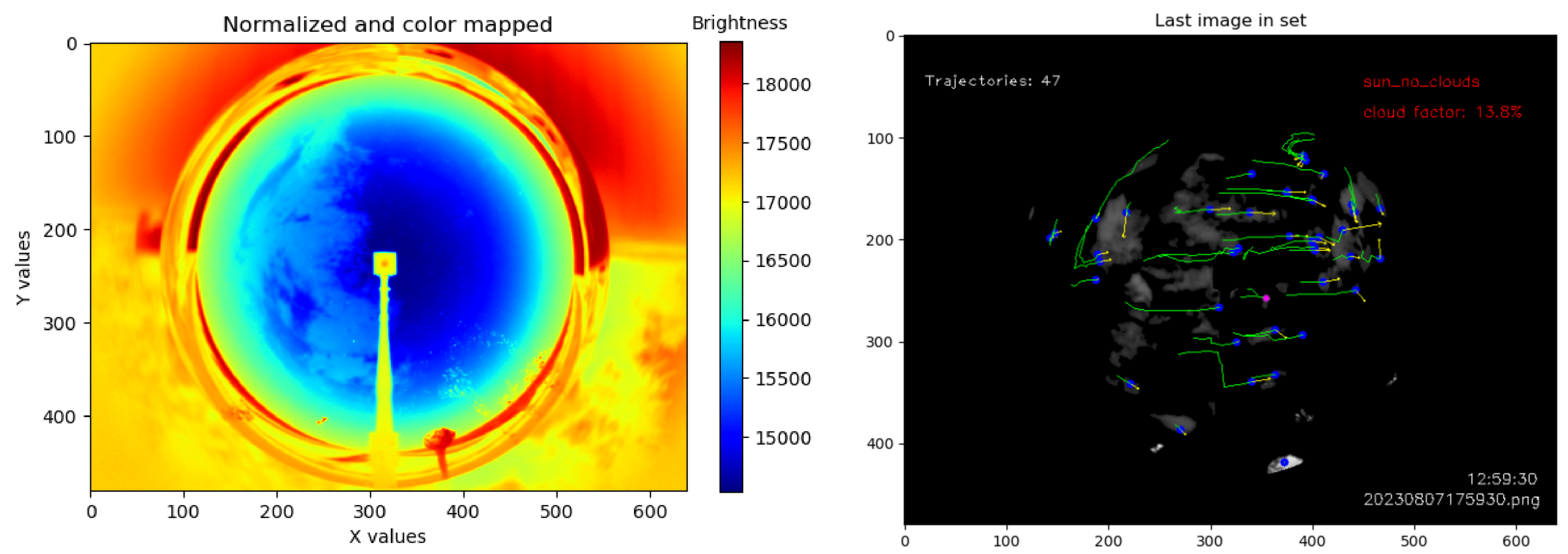

Figure 3. Sky image with color mapping and normalized (left); Image segmentation and tracked trajectories (right).

GOES **Cloud and Moisture Imagery (CMI)** was used with GHI correlations analyzed to enhance forecasting accuracy.

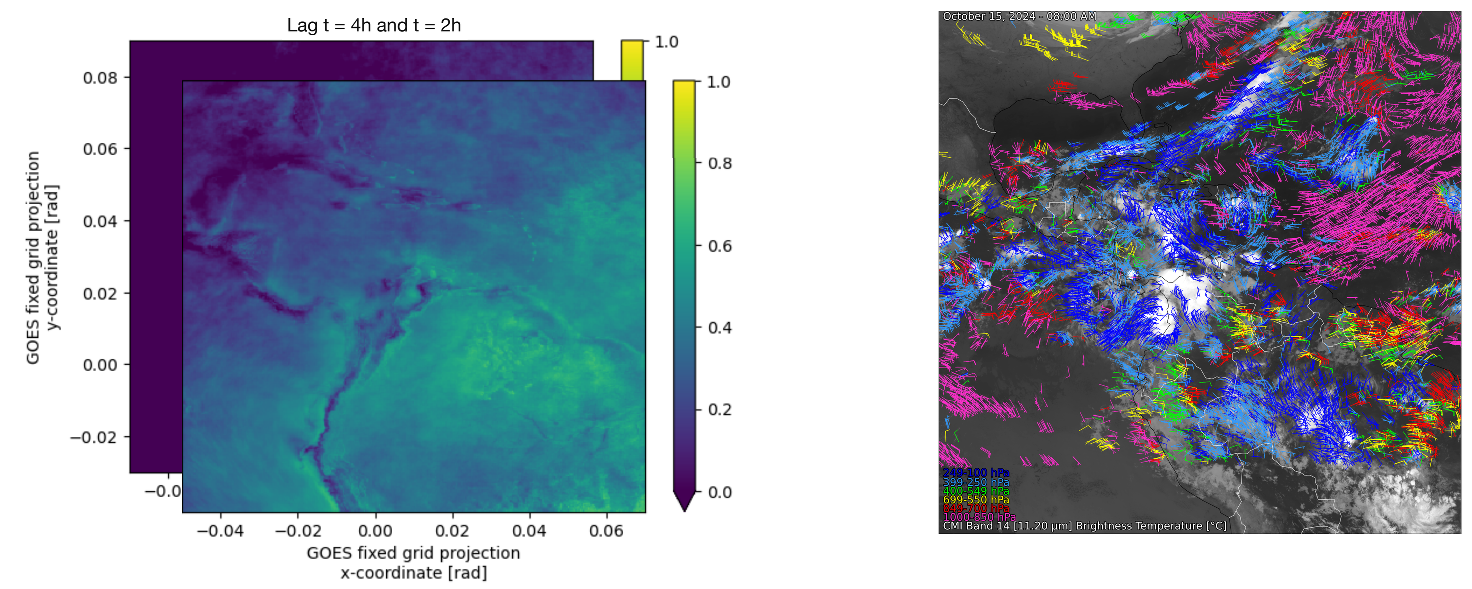

Figure 4. Correlation with solar irradiance for two delays (left); Derived motion wind product (right).

Resource-to-Power Model

An object-oriented tool built on top of `pvlib` followed standard PVPMC modeling steps for a **comprehensive system analysis**: design, effective irradiance, cell temperature, DC production, and AC energy generation.

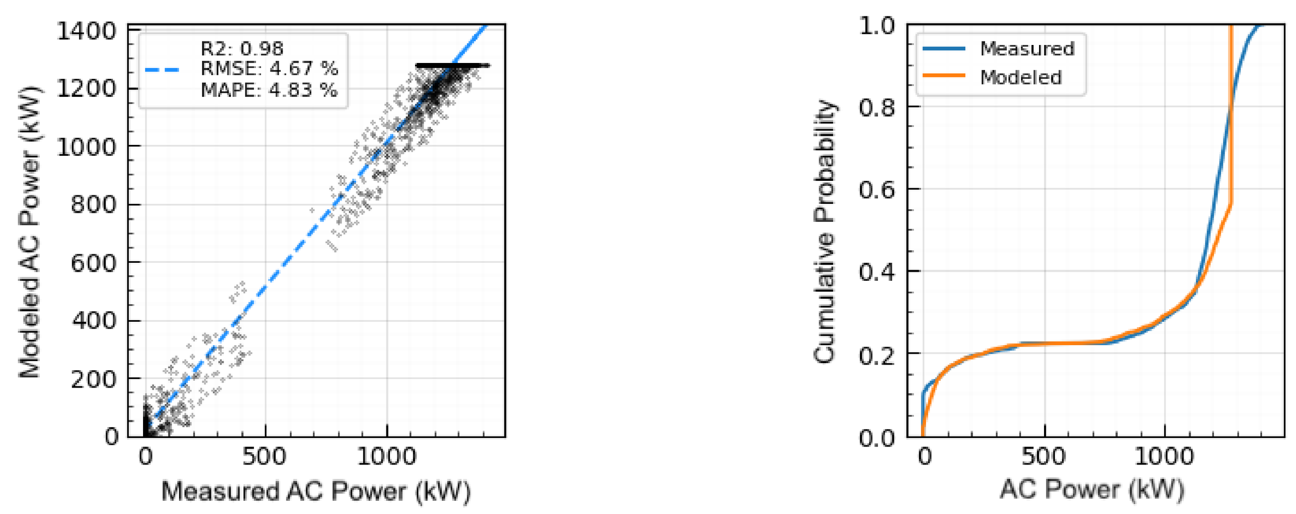

Figure 5. AC power correlation (left); Cumulative distribution function comparison (right).

R^2	RMSE	MAPE	KLD	KS	OC	SDI	SI	PP	CUME
0.98	4.6	4.8	0.1	0.5	1.0	8.8	0	6.4	4.0

Table 1. Distance, statistical, variability, and production metrics in units of %.

Expert System

The software's **microservice design** integrated forecasting, power production, penalties, and derived motion wind for modularity.

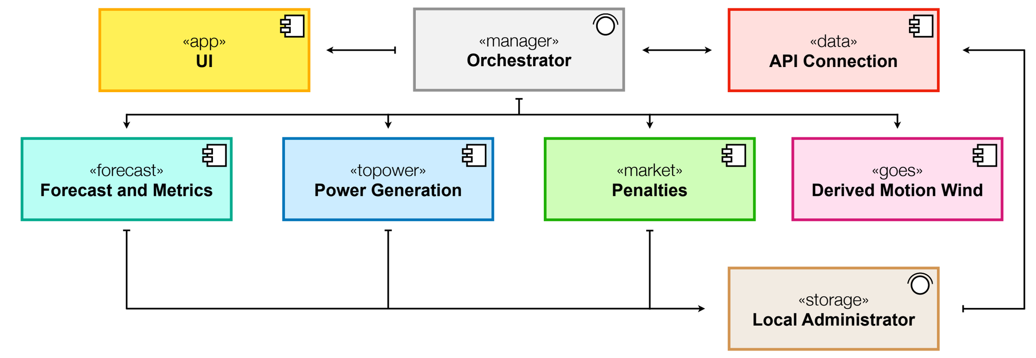

Figure 6. Computational software architecture and workflow.

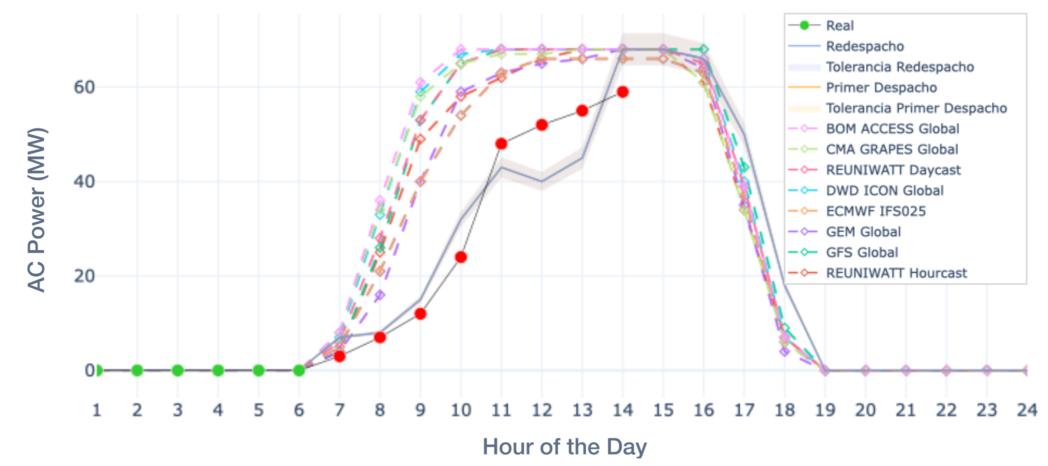

Figure 7. Operational analytics to support market decision making; the red marker indicate the periods in which energy deviation leads to an financial penalty, and the green marker otherwise.

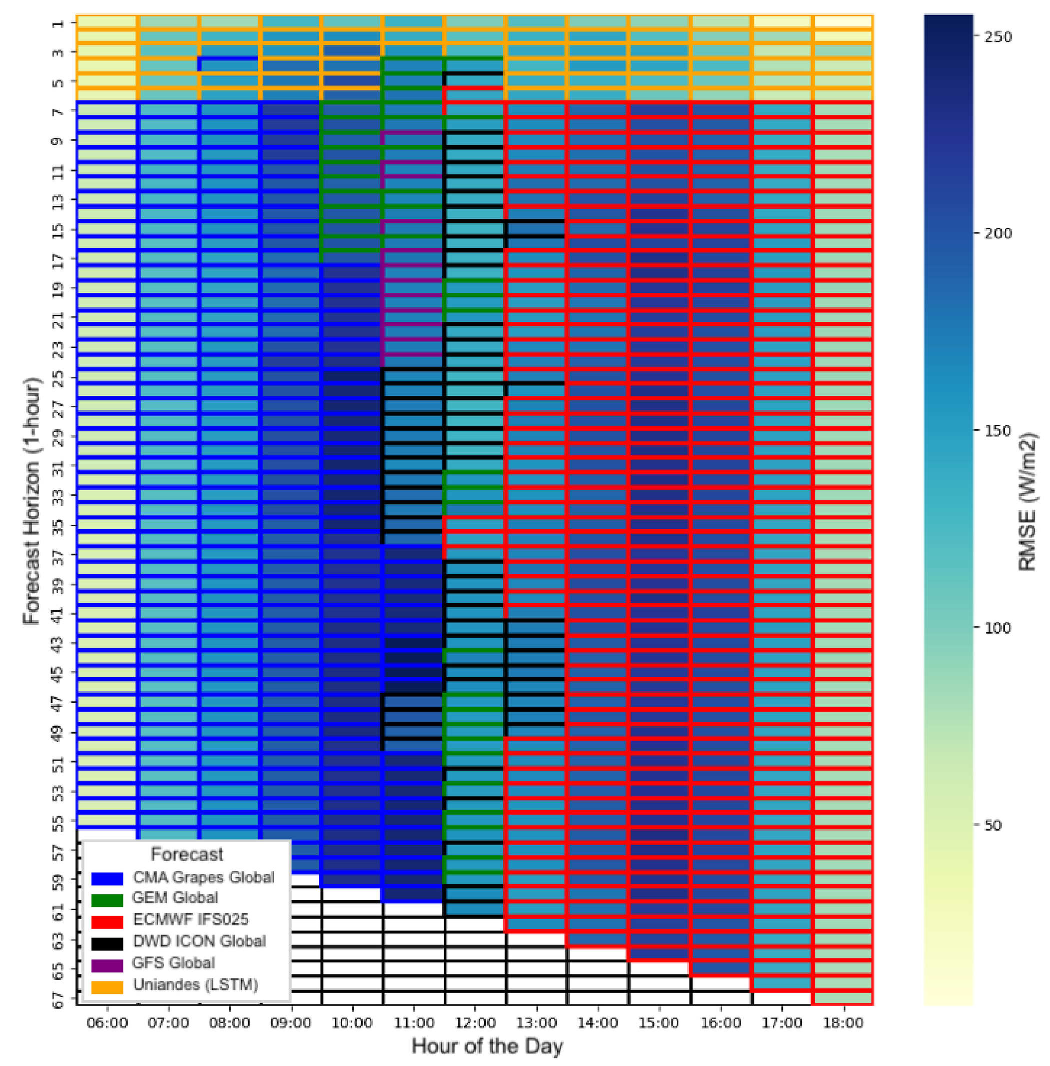

Figure 8. RMSE for the most accurate forecast models at different forecast horizons and hours of the day.

Conclusion and Contributions

- The proposed forecast model matched the accuracy of GFS but offered **higher frequency, adaptability, and continuous learning**, outperforming in real-time applications.
- The combination of satellite and sky camera data **improved short-term cloud prediction**.
- The **extensible physical model** achieved a 6% error rate for AC power and a 4% error rate for accumulated energy estimates.
- Accurate forecasts enabled **reliable intraday market energy offers**, minimizing penalty costs.
- The expert system **facilitated penalty avoidance** by estimating forecasts, production, and cloud conditions under operational scenarios.

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