

Development of An Information-Analytical System for Assessing and Forecasting Solar Power Plant Energy Generation Based on Meteorological Forecasts and Real-Time Monitoring, With Applications to Reliable and Safe Operation

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Abstract: This paper presents the concept of an information-analytical system for assessing and forecasting the energy generation of solar power plants on the basis of meteorological forecasts and real-time monitoring data. The proposed system integrates weather information, plant-side measurements, SCADA streams, digital performance models, and analytical decision support for short-term and medium-term forecasting. In addition to generation prediction, the study introduces practical monitoring-based methods for extending equipment lifetime and ensuring operational safety. The approach combines solar resource assessment, photovoltaic performance modeling, power forecasting, condition monitoring, availability analysis, and risk-based maintenance support within a unified architecture. A conceptual framework is proposed in which forecast meteorological variables and real-time electrical and thermal measurements are processed by an information-analytical core that evaluates expected generation, identifies deviations, estimates technical condition, and recommends preventive actions. Illustrative simulation-style graphs and engineering diagrams are provided to demonstrate the behavior of the proposed models and the structure of the analytical system.

Keywords: Solar power plant, photovoltaic generation, meteorological forecast, real-time monitoring, short-term forecasting, medium-term forecasting, SCADA, digital model, information-analytical system, condition monitoring, equipment lifetime, operational safety.

1. Introduction:

Solar power generation is inherently variable because

it is strongly influenced by meteorological factors

such as solar irradiance, ambient temperature, cloud cover, humidity, wind speed, and atmospheric aerosols. At the same time, the actual energy delivered by a photovoltaic (PV) power plant depends not only on the available solar resource, but also on the technical condition of the modules, inverters, transformers, protection devices, and auxiliary systems. Therefore, a modern solar power plant should be analyzed not simply as a static energy source, but as a dynamic techno-informational system operating under uncertainty.

Reliable forecasting of PV generation is important for operational planning, dispatch support, energy-market participation, storage scheduling, and maintenance organization. Short-term forecasting, typically from minutes to several hours ahead, is required for near-real-time plant operation. Medium-term forecasting, covering the day-ahead and multi-day horizon, supports dispatch planning, maintenance windows, and expected energy-yield estimation.

At the same time, continuous monitoring makes it possible not only to observe generated power but also to estimate equipment loading, detect abnormal trends, reduce unexpected failures, extend service life, and improve operational safety. This paper develops an integrated information-analytical concept that unifies generation assessment and forecasting with condition monitoring and practical recommendations for safe and reliable exploitation.

2. Research Objective

The goal of this work is to develop an information-analytical system that performs: (i) assessment of the current generation capability of a solar power plant based on meteorological forecasts and real-time monitoring data; (ii) short-term and medium-term forecasting of plant output; and (iii) support for reliable and safe operation through monitoring-based methods for extending equipment lifetime.

The generalized input-output relation of the system can be represented as:

$$Y(t) = F[X_{met}(t), X_{rt}(t), X_{eq}(t), M(t)]$$

where $Y(t)$ denotes the analytical outputs (predicted

power, expected energy, availability, condition indicators, and maintenance recommendations); $X_{met}(t)$ is the vector of forecast meteorological inputs; $X_{rt}(t)$ is the vector of real-time plant measurements; $X_{eq}(t)$ characterizes equipment condition and operating states; and $M(t)$ denotes the applied digital model set.

3. Input Data and Monitoring Variables

The information-analytical system is based on two main information sources. The first source is meteorological forecast data, including global and plane-of-array irradiance, ambient temperature, cloudiness, humidity, and wind speed. The second source is real-time monitoring data collected from the PV power plant, such as string current, array voltage, inverter AC output, bus voltage, transformer loading, internal temperatures, protective relay status, and accumulated energy.

A representative structure of monitoring variables can be written as:

$$X_{rt} = [G_m, T_a, T_{mod}, I_{dc}, V_{dc}, P_{ac}, V_{ac}, E, T_{inverter}, T_{tr}, A_{status}]$$

where G_m is measured irradiance, T_a is ambient temperature, T_{mod} is module temperature, I_{dc} and V_{dc} are DC current and voltage, P_{ac} and V_{ac} are AC power and voltage, E is accumulated energy, $T_{inverter}$ is inverter temperature, T_{tr} is transformer temperature, and A_{status} contains alarms or protection signals.

4. Generation Assessment and Forecasting Models

The generation capability of a solar power plant is estimated by combining forecast meteorological variables and real-time performance indicators. A simplified expected power model may be written as:

$$\hat{P}(t) = P_{nom} \cdot (G_f(t) / 1000) \cdot \eta_{sys}(t) \cdot [1 + \gamma_P(T_{cell}(t) - 25)]$$

where P_{nom} is the plant nominal power, $G_f(t)$ is forecast irradiance, $\eta_{sys}(t)$ is the overall system efficiency including conversion and operational losses, and γ_P is the temperature coefficient of power. In practical applications, $\eta_{sys}(t)$ may also include the effects of soiling, curtailment, mismatch, and availability.

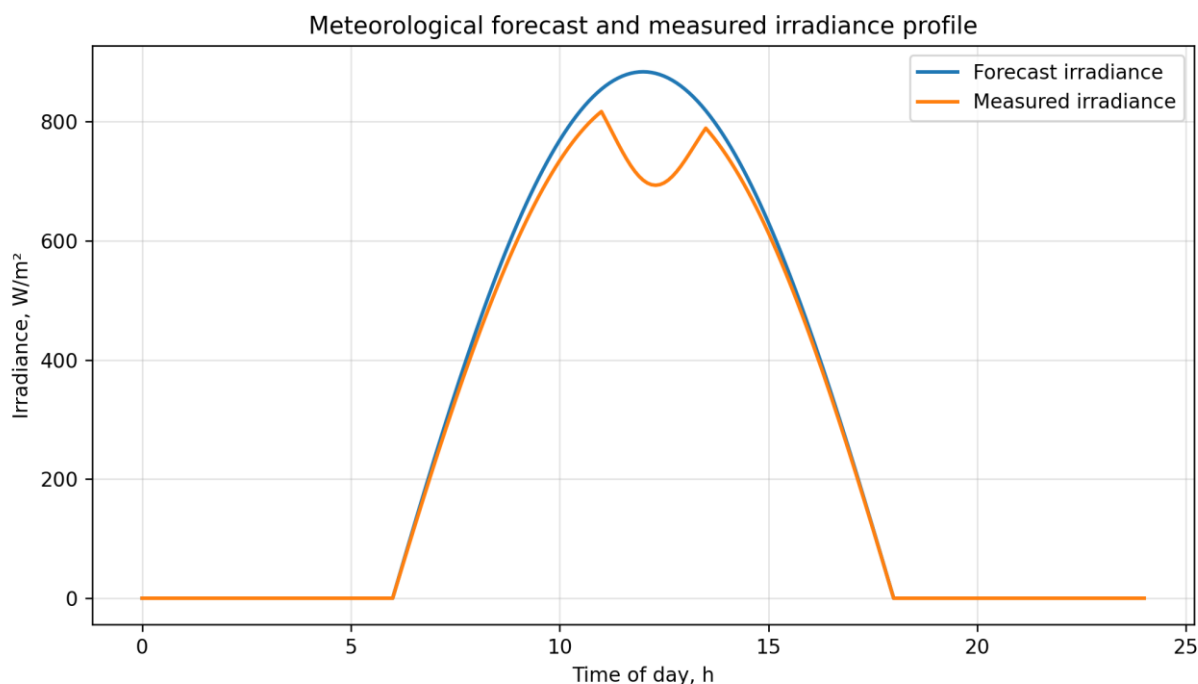


Figure 1. Example of forecast and measured irradiance profiles used for generation assessment and forecasting.

Short-term forecasting can be based on updated forecast irradiance and recent plant measurements, allowing the analytical core to refine the expected

power curve. In this paper, the forecast and actual power trajectories are illustrated using a simulation-style example.

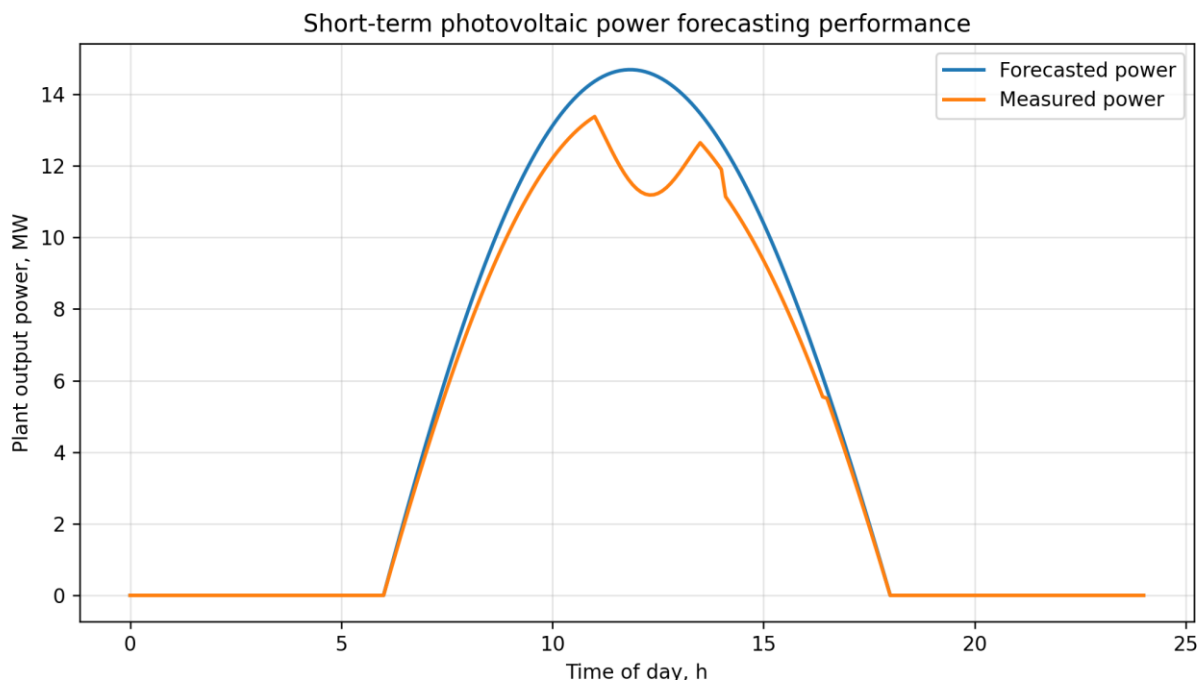


Figure 2. Illustrative short-term forecast of PV plant output power compared with measured power.

The forecast accuracy can be analyzed by studying the temporal profile of the forecast error:

$$e(t) = P_{meas}(t) - \hat{P}(t)$$

Systematic deviations may indicate forecast

imperfections, sudden cloud transients, curtailment, measurement drift, or emerging equipment-related performance losses.

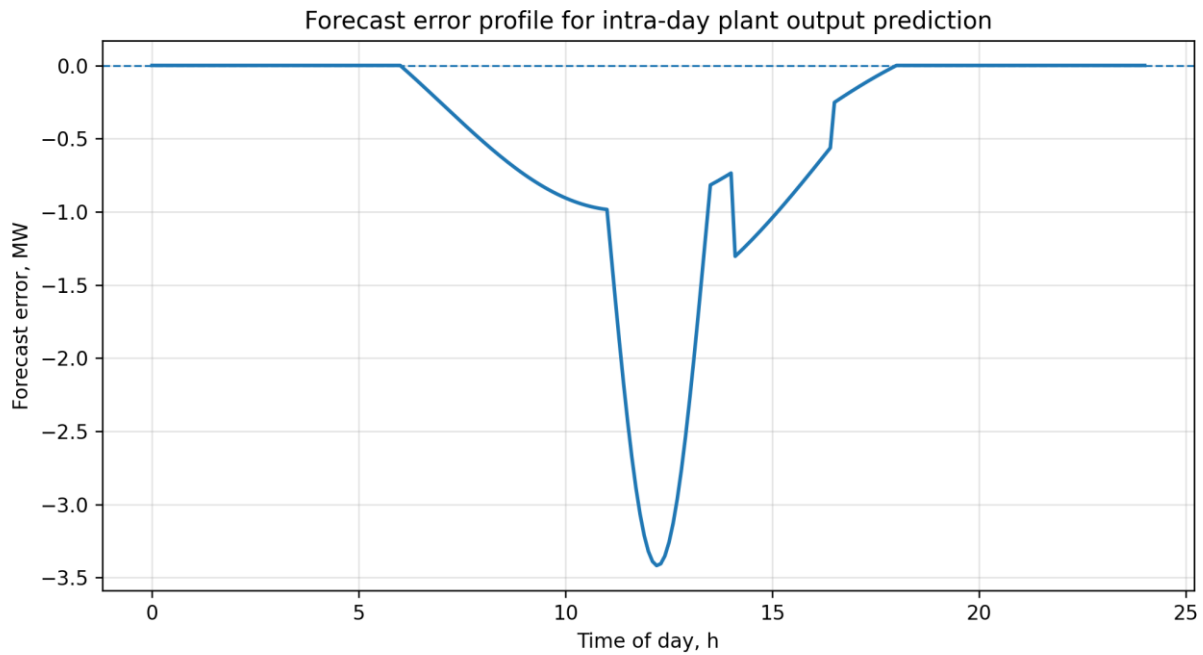


Figure 3. Intra-day forecast error profile for photovoltaic generation prediction.

5. Concept of the Information-Analytical System

The proposed information-analytical system integrates weather forecasting services, real-time plant data acquisition, a central data storage layer,

analytical modules, and decision-support outputs. Its purpose is not only to display power values, but also to transform heterogeneous information into actionable recommendations.

Information-analytical system for PV generation assessment, forecasting, condition monitoring, and safe operation

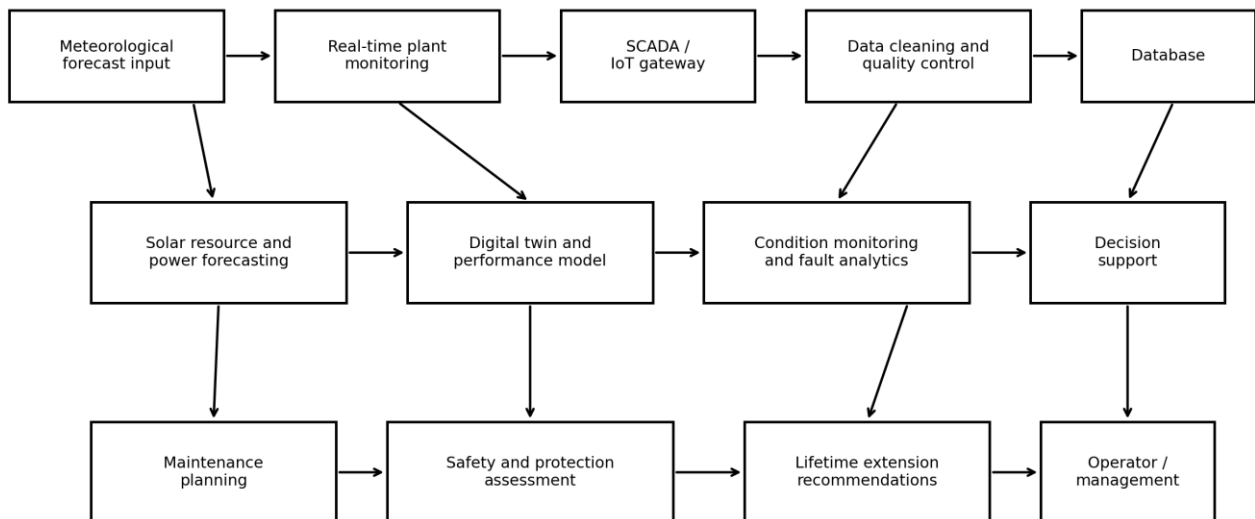


Figure 4. Conceptual architecture of the information-analytical system for generation assessment, forecasting, and safe operation.

The analytical core of the system consists of several functional layers: (1) meteorological-data processing; (2) real-time monitoring and SCADA integration; (3)

digital modeling and generation forecasting; (4) condition monitoring and fault analytics; and (5) maintenance, safety, and operational decision support.

6. Short-Term and Medium-Term Forecasting

Short-term forecasting usually covers the horizon from several minutes to several hours ahead. It is particularly important for inverter loading control, battery charging strategies, internal dispatching, and the operational response to rapidly changing cloud conditions.

Medium-term forecasting generally covers day-ahead and several-day horizons. It allows plant operators to estimate energy production, plan maintenance windows, coordinate with grid requirements, and prepare reserve strategies.

A generic forecasting function may be expressed as:

$$\hat{P}(t+h) = \Phi[X_{\text{met}}(t:t+h), X_{\text{rt}}(t-\Delta:t), \theta]$$

where h is the forecast horizon, Δ is the length of

historical measurement window, and θ is the parameter vector of the forecasting model. Depending on the data volume and practical needs, Φ may be implemented using physical models, statistical regression, autoregressive methods, machine learning, or hybrid forecast fusion.

7. Power-System Integration and Monitoring Scheme

At the plant level, forecasting and operational analysis should be linked to the electrical topology of the station. Therefore, a single-line conceptual scheme is useful for integrating the PV field, DC aggregation, inverters, the low-voltage bus, the step-up transformer, the grid interconnection, and supporting measurement subsystems.

Conceptual DigSILENT-style single-line and monitoring integration scheme

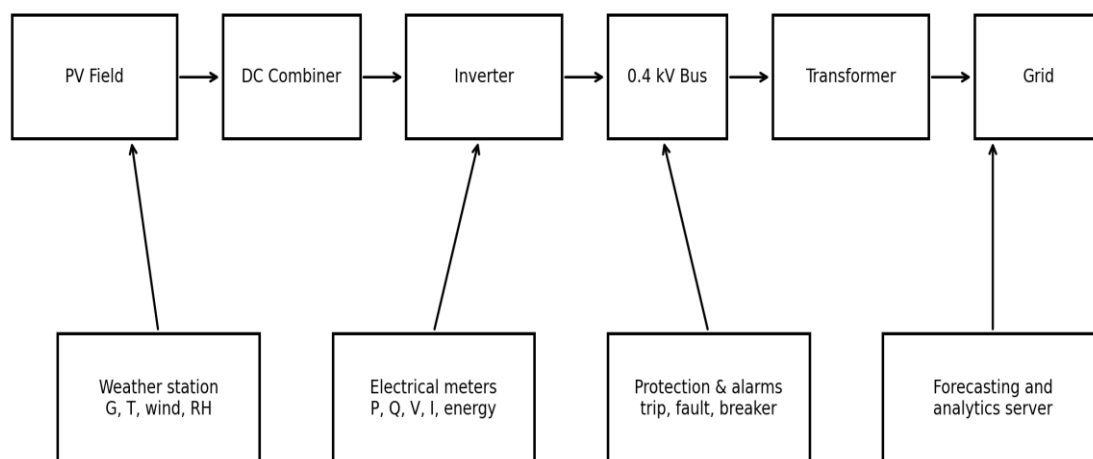


Figure 5. Conceptual DigSILENT-style single-line diagram with integrated monitoring and analytic.

8. Monitoring-Based Methods for Extending Equipment Lifetime

Comprehensive monitoring can significantly increase the useful operating life of inverters, transformers, switchgear, and PV modules. The key principle is to identify harmful operating regimes early and to reduce thermal, electrical, and switching stress before they accumulate into irreversible degradation.

One of the most important stress factors is temperature. For many power-electronic and insulation components, life consumption accelerates nonlinearly as the operating temperature increases. An illustrative relative thermal-stress or aging factor may be represented as:

$$K_{\text{aging}} = \exp[(T_{\text{eq}} - T_{\text{ref}}) / \beta]$$

where T_{eq} is an equivalent component temperature, T_{ref} is a reference temperature, and β is a

technology-dependent coefficient. Although the exact form must be calibrated experimentally, this

simplified indicator is useful for operational interpretation.

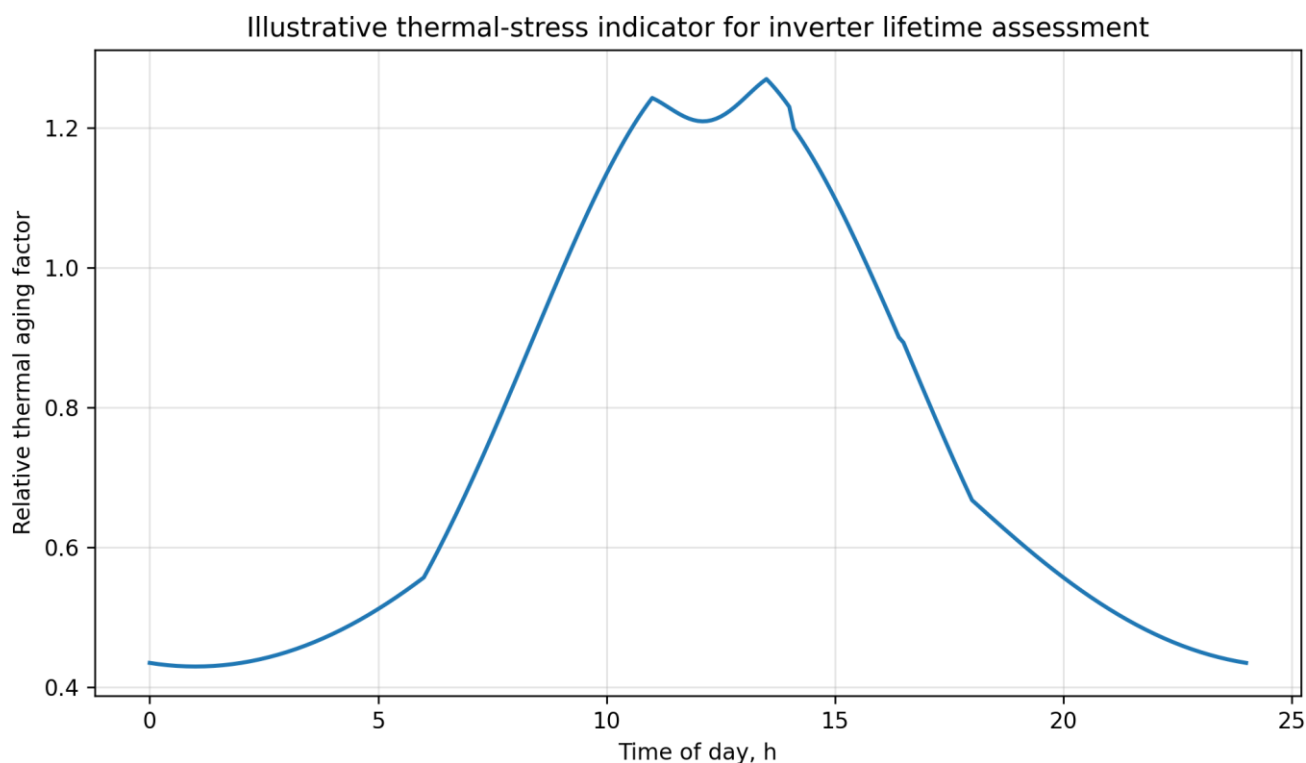


Figure 6. Illustrative thermal aging indicator for inverter or power-electronic lifetime assessment.

Based on comprehensive monitoring, the following practical methods are recommended to extend equipment lifetime:

1. Dynamic temperature-aware derating of inverters during extreme thermal stress conditions.
2. Early cleaning or inspection scheduling when performance loss and thermal load indicate abnormal operating regimes.
3. Monitoring of transformer and inverter temperatures to prevent prolonged overheating.
4. Trend analysis of availability and condition indicators to identify gradual deterioration before failure.
5. Periodic verification of protection settings, breaker status, and DC insulation quality.
6. Comparison of parallel strings and inverters to

reveal hidden mismatch, degradation, or partial outages.

9. Operational Safety and Reliability Indicators

In addition to energy forecasting, the proposed system should calculate operational indicators such as availability, performance ratio, alarm frequency, abnormal shutdown count, and a generalized condition index. These indicators allow the operator to connect generation analysis with reliability and safety assessment.

An availability indicator may be defined as:

$$A = T_{up} / (T_{up} + T_{down}) \cdot 100\%$$

while a generalized condition index may be formed from weighted stress, alarm, and performance-deviation measures. Tracking these quantities over time helps identify deterioration trends and supports risk-informed maintenance.

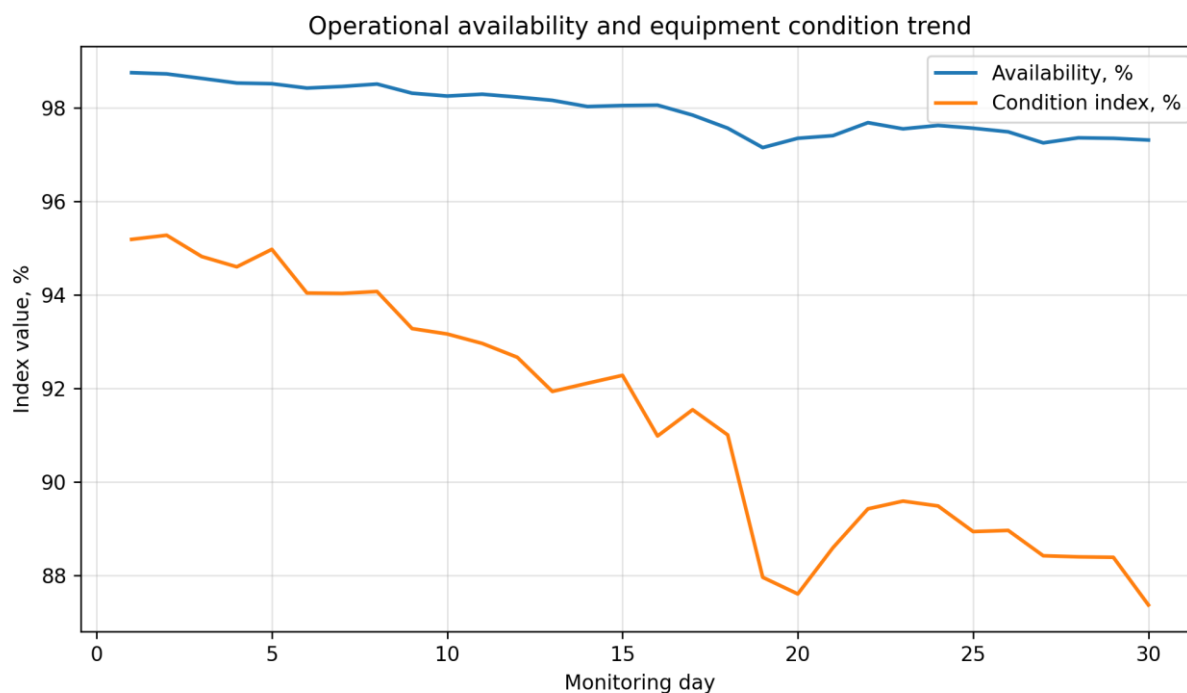


Figure 7. Example trend of operational availability and equipment condition index.

To ensure safe operation, the information-analytical system should automatically check whether temperature, voltage, current, and alarm variables remain within permissible ranges. Whenever limit violations or dangerous combinations are detected, the system should escalate to warnings, protective actions, and recommended operator intervention.

10. Proposed Analytical Workflow

The complete analytical process may be implemented as a sequential workflow starting from forecast and monitoring data collection and ending with recommendations for operation, safety, and maintenance.

Forecasting and safe-operation analytical workflow

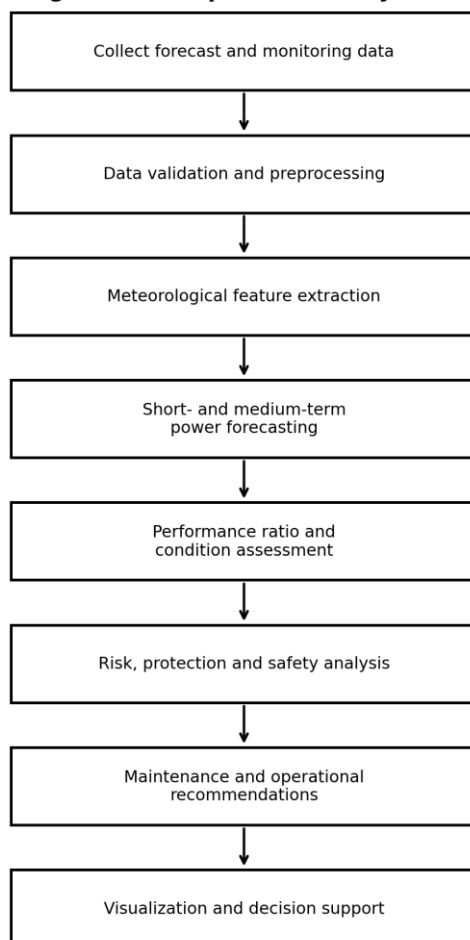


Figure 8. Workflow of the forecasting, condition-monitoring, and decision-support process.

11. Scientific Novelty and Practical Significance

1. A unified information-analytical concept is proposed in which solar generation assessment, short-term and medium-term forecasting, condition monitoring, and safe operation support are integrated into one framework.
2. Meteorological forecast data and real-time plant measurements are jointly used, allowing dynamic correction of the expected generation profile and more reliable operational analysis.
3. The concept extends forecasting beyond energy prediction by incorporating equipment condition, availability, and safety-oriented analytics.
4. Monitoring-based practical methods are proposed for lifetime extension of critical equipment, especially inverters, transformers, and protection devices.
5. The framework supports a transition from passive

observation to proactive operation, preventive maintenance, and risk-informed decision-making.

12. DISCUSSION

The presented figures and schemes are simulation-style scientific illustrations intended to reflect the logic of PV forecasting and plant analytics. They are designed in an engineering visualization style similar to that commonly used in MATLAB-based analytical studies and power-system engineering environments.

In a full-scale implementation, the proposed system can be expanded with sky-imager input, numerical weather prediction ensembles, machine-learning correction modules, storage scheduling, and probabilistic risk assessment. Further improvement can also be achieved by integrating maintenance records and component-level historical failures into the analytical database.

13. CONCLUSION

An information-analytical system concept has been developed for assessing and forecasting solar power plant generation on the basis of meteorological forecasts and real-time monitoring. The proposed framework combines forecasting, condition monitoring, availability evaluation, and safe-operation support within a unified digital architecture.

The study shows that generation forecasting should not be isolated from equipment monitoring. On the contrary, the combination of power prediction, thermal and electrical condition assessment, and operational safety analytics allows plant operators to improve energy management, extend the life of equipment, and reduce the probability of dangerous or economically harmful operating regimes.

The next stage of research should include calibration and validation using real SCADA archives and meteorological forecast data from an operating solar power plant. Forecast accuracy can then be quantified by MAE, RMSE, MAPE, and coefficient of determination, while operational recommendations can be validated against actual maintenance and event records.

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