

Assessment of The Reliability and Energy Generation Potential of Solar Power Plant Equipment Under Variable External Conditions

Xurramov Bobir Sobir o'g'li

Scientific Technical Center for Design Bureau and Experimental Production of the Academy of Sciences of the Republic of Uzbekistan, PhD, Senior Researcher, Uzbekistan

Baratov Laziz Suyun o'g'li

Assistant at the Department of Energy and Electrical Technology, Jizzakh Polytechnic Institute. Independent researcher at the Institute of Energy Problems, Uzbekistan

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Abstract: The article proposes a method for assessing the combined effect of variable solar irradiance, high temperatures, wind speed, partial cloud cover, dust accumulation, and power grid conditions on the reliability and energy generation potential of photovoltaic power plant equipment. A thermoelectric model for the PV system was developed, and the module temperature was determined as a function of irradiance, ambient temperature, and wind speed, in accordance with the Sandia approach. It was shown that during the calculation day, the temperature effect reduces energy production by up to 11.8% compared to the irradiation-based ideal model. In four external condition scenarios, the daily energy potential varied from 6.45 MWh to 4.80 MWh. In the simplified reliability model for equipment failures, inverters and the power transformer accounted for the main share of expected energy losses; total technical outages amounted to approximately 0.34% of the base annual energy. For the 0.4/10 kV network model corresponding to the PowerFactory configuration, it was shown that Volt-VAR control reduces voltage deviation during cloud cover. The results can be used for monitoring, forecasting, and condition-based maintenance planning.

Keywords: Solar power plant, photovoltaic module, reliability, energy potential, temperature coefficient, degradation, inverter, DigSILENT PowerFactory, MATLAB, Volt-VAR.

Introduction: The active power generated in solar photovoltaic plants is not a fixed value: it simultaneously depends on solar irradiance, spectrum, cell temperature, wind, soiling, shading, humidity, grid voltage, and the technical condition of the equipment. Therefore, it is not sufficient to characterize a plant's efficiency solely by its rated capacity or annual energy output. The actual operating condition is more fully represented when the energy potential is viewed as a chain of "available meteorological resource $\times$ equipment efficiency $\times$ technical availability $\times$ grid constraints."

The IEC 61724-1:2021 standard defines the terms,

measurement instruments, and data collection approaches for monitoring the performance of photovoltaic systems [1]. The Sandia PV Array Performance Model, on the other hand, offers a widely used physico-empirical approach for calculating the electrical performance of modules and arrays as a function of irradiance and temperature [2]. Long-term degradation is also significant: in many field data analyzed by Jordan and Kurtz, the median degradation was around 0.5% per year [3]. Subsequent studies have noted that hot, humid, and mechanically harsh conditions accelerate microcracks, corrosion, delamination, PID, hot spots, and connection defects [4,5].

In practical operation, the inverter and power electronics components require special attention. In a field analysis of 100,000 PV systems, inverter failures were recorded as one of the most common component failures [7]. Therefore, it is appropriate to integrate meteorological variations, the module's thermal regime, and the operational readiness indicators of electrical equipment into a single algorithm for assessing QES.

1. Research Aims and Objectives

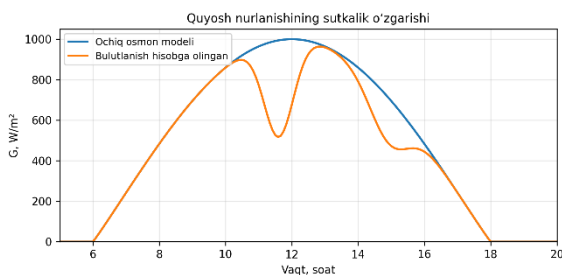


Figure 1. Daily irradiance profile.

As shown in Figures 1 and 2, cloud cover causes short-term sharp decreases in irradiance, whereas the photodiode temperature changes more smoothly due to thermal inertia. As a result, estimating the power using only $G(t)$ can lead to significant errors over certain time intervals.

RESEARCH METHOD AND MATHEMATICAL MODEL

For the calculations, a hypothetical PV system was assumed with a nominal DC power of 1 MWp, connected to a 0.4 kV bus via four 250 kW inverters and feeding energy to the grid through a 0.4/10 kV transformer. The model is not tied to a real system; the parameters were chosen to demonstrate the methodology's sensitivity. In estimating module temperature, Sandia parameters for an open-frame glass/polymer module were used [2].

$$T_m(t) = G(t) \cdot \exp[a + b \cdot v(t)] + T_a(t)$$

$$T_c(t) = T_m(t) + [G(t)/1000] \cdot \Delta T$$

The aim of the study is to develop a simplified yet practical monitoring method for jointly assessing the reliability of QES equipment and its energy generation potential under variable external conditions. To this end: 1) the module temperature is determined based on the irradiance–temperature–wind correlation; 2) active power and daily energy are calculated; 3) the energy loss caused by equipment failures is estimated; 4) For the 0.4/10 kV network model, the dynamic voltage response and the effect of Volt–VAR control are analyzed.

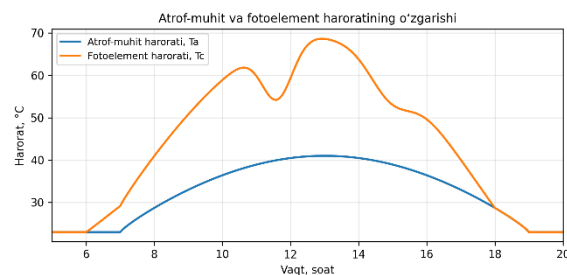


Figure 2. Ambient and photodiode temperature.

where G is the irradiance on the module plane, W/m^2 ; T_a is the ambient temperature, $^{\circ}\text{C}$; v is the wind speed, m/s ; a and b are empirical coefficients dependent on the installation type; and ΔT is the parameter of the temperature difference between the module and the solar cell.

$$P_{pv}(t) = P_{STC} \cdot [G(t)/G_{STC}] \cdot \{1 + \gamma_P [T_c(t) - 25]\} \cdot \eta_{inv} \cdot K_{loss}$$

$$E = \int P_{pv}(t) dt$$

Because $\gamma_P < 0$ in the power model, power decreases as the cell temperature rises above 25°C . Inverter efficiency and cable, mismatch, contact, and other minor losses are accounted for by the K_{loss} coefficient. This simplification is convenient for generating a quick "expected power" curve in operational monitoring.

Table 1. Key parameters of the computational model

Parameter	Value	Note
QES nominal DC power P_{STC}	1000 kWp	Accepted
Power temperature coefficient γ_P	$-0.0038 \text{ 1/}^{\circ}\text{C}$	Typical monocrystalline module value
Inverter efficiency η_{inv}	0.985	Calculated

Total K_loss	0.965	Cable/mismatch/auxiliary losses
Sandia a; b	-3.56; -0.075	Open rack, glass/cell/polymer [2]
ΔT	3 °C	Sandia cell-temperature approach [2]
Transformer	0.4/10 kV	Calculated network model
10 kV cable length	1.2 km	Calculated network model

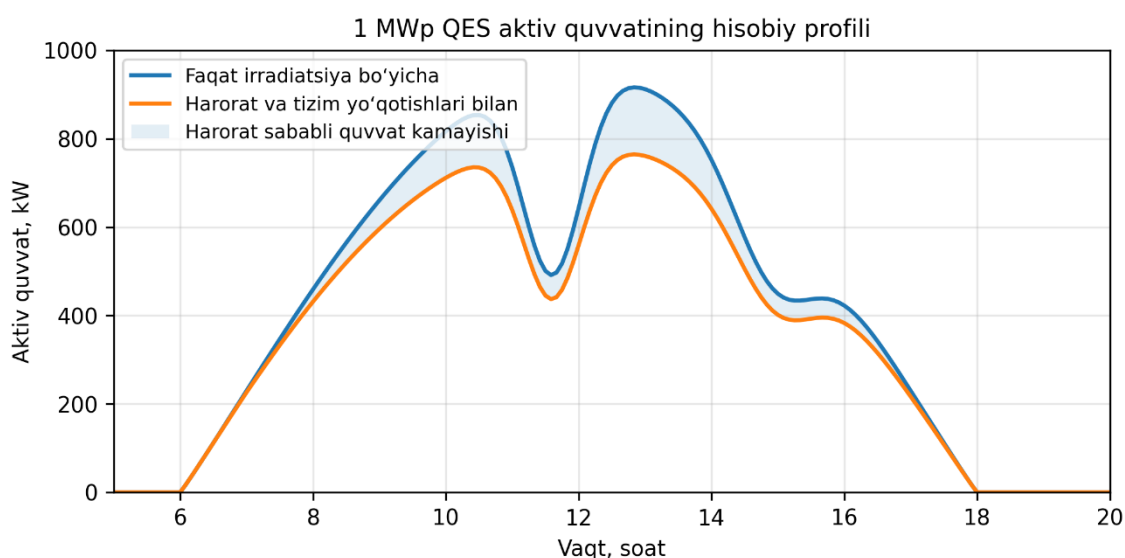


Figure 3. Computational profile of the 1 MWp PV system active power in MATLAB style.

In the calculation day, the ideal energy based on irradiance was 6.33 MWh, while it was 5.58 MWh when thermal and system losses were taken into account. The difference was 11.8%; the maximum photovoltaic cell temperature reached 68.6 °C.

MATLAB-STYLE CALCULATION RESULTS FOR EXTERNAL CONDITIONS

When the temperature sensitivity was examined

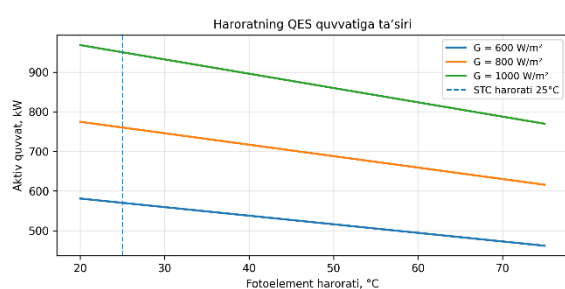


Figure 4. Power sensitivity to the photovoltaic cell temperature.

separately, the maximum power decreased almost linearly with increasing temperature at irradiances of 600, 800, and 1000 W/m². This phenomenon is particularly significant in regions with high insolation but low wind and high summer air temperatures. Calculating $T_c(t)$ over time, instead of just providing thermal losses with an annual global coefficient, allows for a more accurate assessment of peak power, clipping, and grid mode.

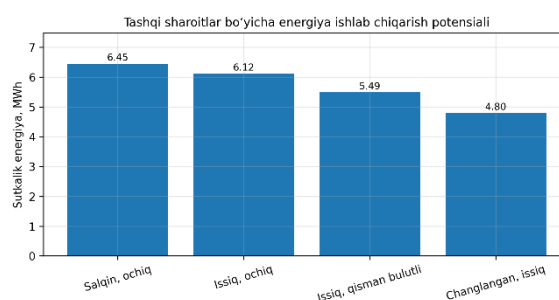


Figure 5. Daily energy potential by scenario.

Table 2. Results of the external condition scenarios

Scenario	E, MWh/day	Pmax, kW	Tc,max, °C	Reduction from baseline, %
Cool, open	6.45	832	55.8	0.0
Hot, clear	6.12	778	71.2	5.1
Hot, partly cloudy	5.49	749	70.7	14.9
Dusty, hot	4.80	656	69.9	25.6

In the cool and clear scenario, the daily energy was 6.45 MWh/day, but the increase in temperature alone reduced it by 5.1%. Combined with partial cloud cover, the reduction reached 14.9%, and when dust and hot conditions were combined, it reached 25.6%. Therefore, when forecasting generation potential, it is more appropriate to calculate the combined effect of factors over the time series rather than using a "one factor, one coefficient" approach.

This result is also important for operational decisions: For example, when optical losses from soiling reach around 10%, the decision to clean the panels can be evaluated not just by irradiance, but by weighing the expected energy yield against electricity prices, water, and service costs. Similarly, the thermal derating of inverters and reactive power mode on hot days must also be included in the forecasting model.

ASSESSING THE RELIABILITY OF QES EQUIPMENT

Reliability is the second important component of the energy potential. While the equipment is operating, the

meteorological model provides the expected power; during a fault or forced maintenance period, part of this potential is lost. For a non-recoverable element, the classical reliability function is given by $R(t) = \exp(-\lambda t)$. For repairable equipment, operational availability can be expressed as $A \approx MTBF / (MTBF + MTTR)$. From an energy perspective, however, it is not only the duration of a failure that matters, but also its share of the total QES power.

$$R(t) = \exp(-\lambda t)$$

$$A = MTBF / (MTBF + MTTR)$$

$$E_{loss,i} \approx E_{year} \cdot \lambda_i \cdot (MTTR_i / 8760) \cdot k_i$$

where λ_i is the expected number of failures per year, $MTTR_i$ is the mean time to repair, and k_i is the share of station capacity lost when that element fails. The following parameters are not intended as real statistical data but rather as a computational scenario illustrating the method's operation. Field studies have noted that inverters are a common source of failures [6,7].

Table 3. Scenario parameters adopted in the reliability calculation

Element	λ , 1/year	MTTR, hours	k	E_loss, MWh/year
Inverters, 4×250 kW	3.2	24	0.25	3.90
Power transformer	0.12	72	1.00	1.76
DC string/BOS	3.0	8	0.03	0.15
AC switching equipment	0.15	6	1.00	0.18
Protection and control	0.40	4	0.10	0.03

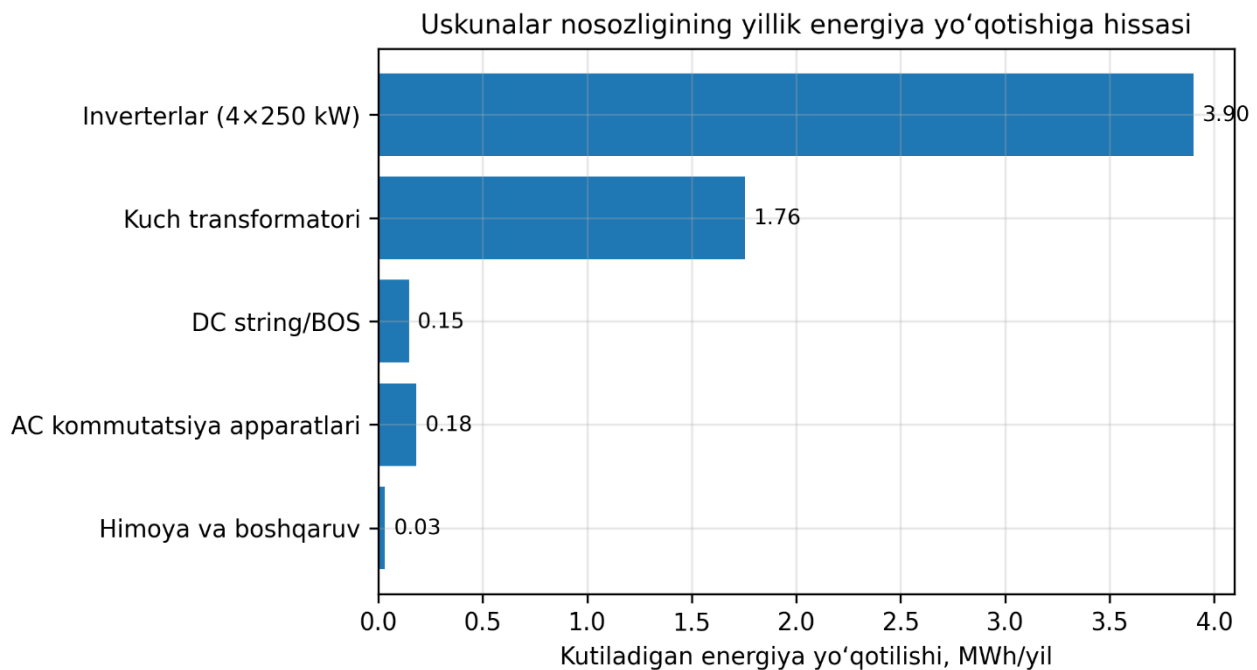


Figure 6. Calculated contribution of equipment failures to annual energy loss.

Assuming a base annual energy of 1780 MWh, the expected total loss due to forced outages was 6.02 MWh/year, or 0.34%. The largest share is attributable to inverters and transformers. This result shows the necessity of jointly considering the components' failure frequency, repair duration, and power impact share.

NETWORK MODEL FOR THE DIGSILENT POWERFACTORY STRUCTURE

The energy potential of the QES is also limited by the

power that can be accepted by the grid. The official DlgSILENT PowerFactory documentation indicates that PV systems are modeled using Quasi-Dynamic Simulation for long-term operation, RMS for short-term events, and EMT for very fast processes [8]. In this article, a simplified 0.4/10 kV model corresponding to the PowerFactory topology was adopted: PV array — MPPT/DC stage — static generator/inverter — 0.4/10 kV transformer — 10 kV cable — external grid.

DlgSILENT PowerFactory uslubidagi hisobiy tarmoq modeli

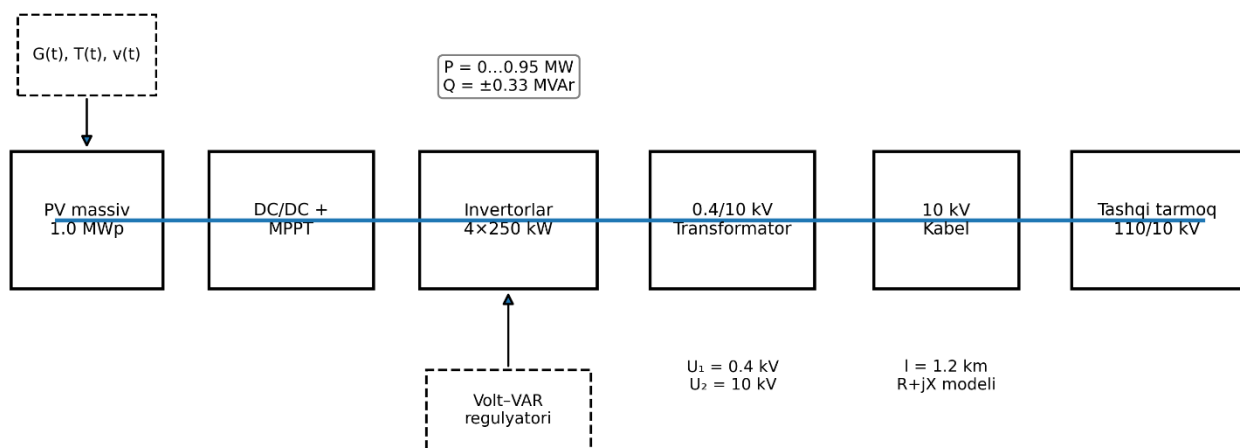


Figure 7. Calculated network diagram of a 0.4/10 kV distribution transformer in DlgSILENT PowerFactory.

When the PV active power rapidly decreases due to cloud shadow, the voltage at the connection point also changes depending on the network's R/X ratio and short-circuit power. If the inverter operates in $Q=0$

mode, the entire voltage compensation is borne by the external network and the transformer. If the smart inverter has a Volt- VAR function, reactive power is automatically adjusted based on local voltage measurement, reducing voltage deviation.

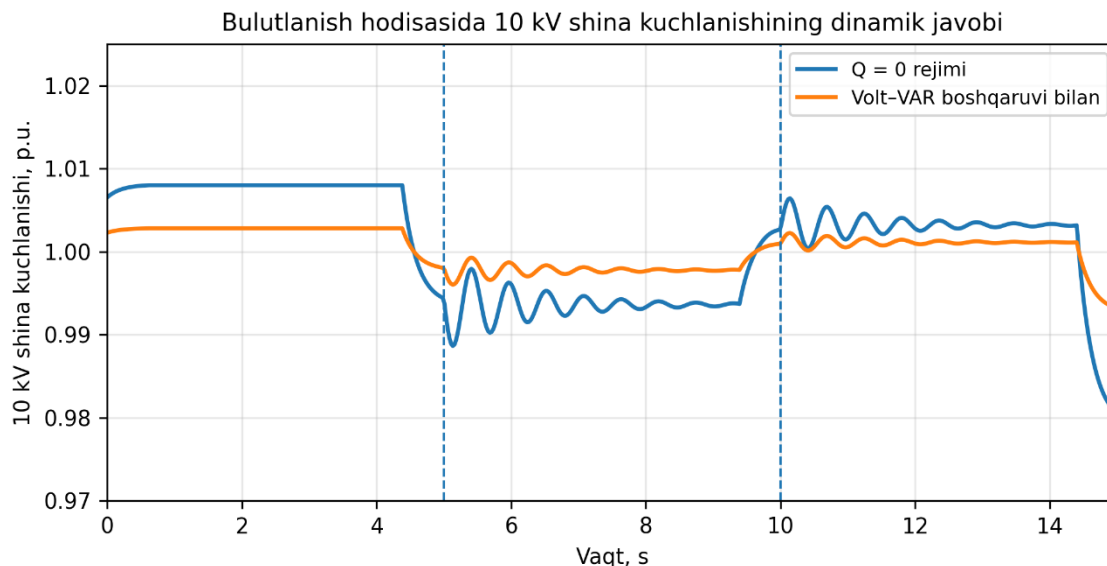


Figure 8. Dynamic response of the 10 kV bus voltage during the clouding event.

During the calculated event, in $Q=0$ mode, the bus voltage fluctuated between approximately 0.988 and 1.008 p.u.; Volt-VAR control significantly reduced the deviation and kept the voltage around 1.0 p.u. The graph is not a copy of the actual PowerFactory calculation but a methodological simulation chart prepared in the style of RMS analysis results.

INTEGRATED ASSESSMENT ALGORITHM AND DISCUSSION

It is not sufficient to assess the technical condition of a

QES using only the PR (Performance Ratio) or a one-time I-V measurement. At a station where external conditions change drastically, the "expected power" must be recalculated for each time point and then compared with the actual measurement. This prevents a decrease in irradiance from being misinterpreted as a fault, and allows actual degradation or inverter derating to be distinguished from meteorological effects.

QES uskunalari holati va energiya potensialini integrallashgan baholash algoritmi

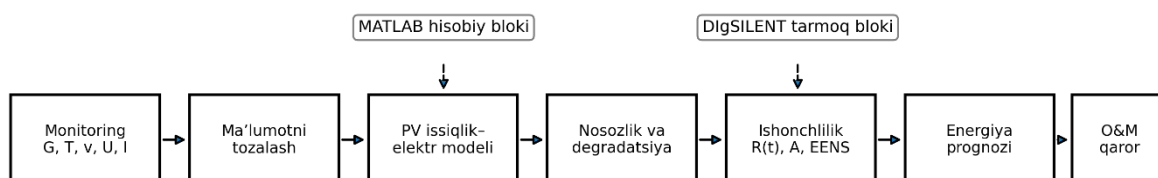


Figure 9. Integrated assessment algorithm for the status of PV equipment and its energy potential.

In the first stage of the proposed algorithm, monitoring data compliant with IEC 61724-1 requirements are collected: G_{POA} , T_{amb} , module or cell temperature, wind, DC/AC voltage and current, inverter status, grid voltage, and event log [1]. In the second stage, values that are incorrect, missing, or outside physical limits are filtered out. In the third stage, $P_{expected}(t)$ and $E_{expected}$ are determined in the MATLAB environment or an equivalent computational package. In the fourth stage, anomalies are detected using the real-expected power difference $\Delta P = P_{meas} -$

$P_{expected}$.

If the residual remains negative over a long period, the causes are checked sequentially: soiling and shading, string imbalance, MPPT limitation, inverter thermal derating, transformer and cable losses, and active power limitation by grid voltage. Seasonal effects are normalized when assessing the degradation trend. Jordan and Kurtz's analysis shows the necessity of incorporating degradation into long-term energy forecasting [3], while Aghaei et al. emphasize that multiple stressors may act simultaneously [5].

1. Recommendations for Practical Application

1) The monitoring interval should be selected to capture rapid changes in inverter power and grid voltage. 2) If a temperature sensor is not available, a Sandia or NOCT-type thermal model can be used, but calibration to local conditions is recommended. 3) MTTRs for the inverter and transformer should be managed separately, and the expected energy losses should be used to determine O&M priorities. 4) If the QES is located in an area sensitive to grid voltage, the Volt-VAR/Volt-Watt settings should be selected in conjunction with the QES energy potential and equipment thermal loading.

The main limitation of the computational study is that real meteorological and fault-report data were not used. Therefore, the numerical values are not universal normative indicators. When applying the methodology to a real PV system, it is advisable to collect data on PV array irradiance, module temperature, inverter P/Q, string current, transformer temperature, and fault/maintenance times for at least one year. After that, the parameters can be identified through regression or optimization.

CONCLUSION

1. When assessing the energy generation potential of a QES under variable external conditions, it is necessary to jointly calculate the factors of irradiance, PV cell temperature, wind, cloud cover, and soiling over time.
2. In the 1 MW computational model, on a selected hot and partly cloudy day, thermal and system losses reduced energy by 11.8% compared to the radiation-based ideal model.
3. In external condition scenarios, daily energy varied from 6.45 MWh to 4.80 MWh; the heat alone caused an approximately 5.1% reduction compared to the baseline cool-open scenario.
4. In the reliability model, the inverter and the power transformer were the main sources of energy loss. Therefore, it is advisable to give these devices high priority in preventive diagnostics and spare parts logistics.
5. In the network model aligned with the PowerFactory structure, Volt-VAR control reduced voltage deviation on the 10 kV bus during cloud cover. This indicates the need to view the QES's interaction with the grid in conjunction with energy forecasting.
6. The proposed integrated algorithm, when calibrated with real SCADA data, can be used for equipment condition assessment, early degradation detection, energy forecasting, and condition-based maintenance planning.

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