

INCREASING SOLAR ENERGY YIELD IN UZBEKISTAN THROUGH UAV INSPECTION AND COMPUTER VISION

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Abstract

Expanding photovoltaic capacity creates a parallel need to maintain the electricity yield of installed systems. This thesis draft reviews research on thermal fault detection, module mapping, cross-site learning, soiling estimation, and maximum power point tracking, and evaluates their relevance to Uzbekistan. It proposes integrating drone-based RGB and infrared observations with electrical and environmental measurements to guide maintenance. The central research question is whether this integration can recover more energy per unit of maintenance expenditure than conventional inspection and scheduled cleaning. Published detection results establish technical feasibility, but do not establish a corresponding percentage increase in energy production. A prospective field study is therefore proposed, with independent site testing and controlled evaluation of cleaning and repair. The expected contribution is a locally validated decision-support framework rather than a claim of demonstrated national energy savings.

Keywords: photovoltaic energy yield; Uzbekistan; unmanned aerial vehicles; computer vision; thermal inspection; condition-based maintenance.

Introduction and importance for Uzbekistan

Solar development involves both constructing new generation capacity and obtaining reliable output from existing installations. Installed capacity, measured in kW or MW, describes rated power; energy yield, measured in kWh over a defined period, describes actual production. A computer vision system can support improved yield by locating avoidable losses and enabling corrective action. It does not itself increase the intrinsic conversion efficiency of a solar cell. This distinction is essential when evaluating claims about “solar energy increase.”

Uzbekistan has a strong solar resource. The International Energy Agency’s solar policy roadmap reports a median global horizontal irradiation of approximately 4.52 kWh/m²/day, with a reported range of 4.0–5.0 kWh/m²/day [1]. These are resource estimates, not guarantees of panel output: electricity production also depends on orientation, temperature, equipment condition, shading, and operating constraints. Meanwhile, a June 2025 World Bank release projected national electricity demand to exceed 120 billion kWh by 2030 [2]. Together, these findings provide a strong motivation for research that improves the utilization of solar infrastructure.

The scale of planned investment also makes operational performance significant. In May 2024, the World Bank announced financing for a 250 MW photovoltaic project with a 63 MW battery energy storage system in Bukhara [3]. The battery figure describes power capability, not energy capacity in MWh. Separately, a May 2025 World Bank operation supported electricity distribution modernization and renewable integration [4]. These announcements demonstrate that generation, storage, and networks must be considered together; they should not be interpreted as proof that every announced facility is currently operational.

Review of related research

Drone-based thermal inspection and fault classification

Bommes et al. [5] developed a computer vision pipeline for extracting and classifying photovoltaic modules from UAV infrared videos. Their dataset contained

4.3 million infrared images of 107,842 modules across seven plants. A ResNet-50 classified ten common anomaly categories with reported test accuracy exceeding 90%. The pipeline extracted modules from 512 of 561 plant rows, while problematic flight trajectories and segmentation errors contributed to failures. This work demonstrates the feasibility of processing large inspection datasets and identifies acquisition quality as an operational dependency. Its classification accuracy should not be interpreted as a measured increase in plant energy yield. For the proposed Uzbekistan study, it provides a useful baseline for module extraction and anomaly classification, followed by electrical verification.

Mapping and cross-site generalization

Inspection becomes actionable when an abnormal module can be located for maintenance. Bommès et al. [6] used structure-from-motion and drone trajectory information to map 99.3% of 35,084 modules across five plants. Reported absolute geolocation error was 5.87 m for one evaluated plant, whereas relative within-row errors ranged from 0.22 to 0.82 m. Consequently, a maintenance system should evaluate identification at row and module level instead of assuming that GPS alone identifies the correct panel. Linking detections to persistent equipment identifiers would also allow repeated observations to be compared.

Cross-site robustness remains a separate challenge. In a supervised contrastive learning study, Bommès et al. [7] evaluated source-to-target transfer across four plant datasets. AUROC ranged from 73.3% to 96.6% across nine transfer combinations. This variation shows why performance from a random image split cannot establish reliability at an unseen installation. A model trained elsewhere should therefore be evaluated on independent Uzbek sites, sensors, and inspection dates. These two works are cited as research preprints; their publication status is distinguished from the journal articles reviewed here.

Soiling estimation and electrical energy optimization

Skomedal and Deceglie [8] proposed the Combined Degradation and Soiling method, which decomposes a photovoltaic performance time series into soiling, degradation, and seasonal components. Their study uses bootstrapping to quantify uncertainty and reports improved estimates on simulated data. Its importance is methodological: a decrease in output should not automatically be attributed to dirt. A complementary vision system could indicate the spatial distribution of visible contamination, while normalized electrical measurements establish whether cleaning is likely to recover energy.

Electrical control addresses a different part of the problem. Esram and Chapman [9] compared maximum power point tracking (MPPT) techniques. MPPT selects an electrical operating point to improve energy extraction under changing conditions. It complements inspection, but does not remove contamination or repair damaged modules. The proposed study should retain a documented MPPT baseline, so that maintenance gains are not confused with simultaneous controller changes.

Synthesis. The reviewed methods address complementary tasks: detecting anomalies, locating equipment, transferring models, separating loss mechanisms, and optimizing operating points. Their reported metrics are not directly interchangeable. The opportunity is to evaluate their integration through verified maintenance outcomes and recovered kWh, rather than to combine unrelated accuracy values into a claim of overall superiority.

Proposed research design

Aim. Develop and evaluate a UAV-assisted decision-support system that identifies recoverable photovoltaic losses and prioritizes maintenance under Uzbek operating conditions.

Research questions. How well do RGB and thermal models generalize across local sites and seasons? Does combining visual findings with electrical measurements improve maintenance decisions? Does condition-based intervention increase normalized energy yield relative to scheduled maintenance, after accounting for inspection cost and resource use?

Acquisition and diagnostic pipeline

The prospective study should include installations with contrasting environments, such as an urban rooftop and utility-scale sites in different regions. The number of sites, modules, and observation periods should be finalized through access agreements and a power analysis; no local dataset is assumed to exist at present. Repeated inspections should record RGB imagery, radiometric thermal data, timestamps, module identifiers, flight geometry, irradiance, module temperature, wind conditions, and inverter or string measurements. Acquisition conditions should remain sufficiently consistent to make repeated thermal comparisons interpretable.

The pipeline would first detect or segment modules, associate observations with equipment identifiers, and classify candidate anomalies. RGB imagery would support visible shading and contamination assessment; thermal data would identify abnormal temperature patterns. A fusion stage would combine these outputs with normalized electrical deviations to recommend verification, cleaning, or repair. Thermal appearance alone should not determine an electrical fault label. Labels should be established through technician review and suitable electrical checks, with ambiguous cases retained explicitly.

Evaluation and validation

All images of the same physical module and inspection sequence should remain within one data partition. At least one complete site should be reserved for external evaluation, supplemented by a later inspection period when feasible. This prevents adjacent video frames and repeated module views from creating misleadingly optimistic test results. Baselines should include an electrical-only monitoring rule, a simple thermal threshold, a conventional CNN, and the pro-posed fused system. Ablations should test the individual contributions of RGB data, thermal data, and electrical measurements.

Detection evaluation should report class-wise precision, recall, F1-score, precision–recall area, false alarms per inspected module, and localization success. Operational evaluation should report inspection time, confirmed faults, maintenance

cost, water consumption where cleaning applies, and recovered energy. Rare faults require explicit uncertainty reporting and threshold selection based on the cost of missed faults and unnecessary site visits.

Measuring energy improvement

Energy improvement requires a credible counterfactual. Comparable strings or array sections should be allocated to condition-based and conventional maintenance, preferably by random assignment where operationally feasible. Baseline output and exposure should be documented before intervention. A suitable estimate is a difference-in-differences comparison of normalized specific yield:

$$\hat{\delta} = (YT_{\text{post}} - YT_{\text{pre}}) - (YC_{\text{post}} - YC_{\text{pre}}), \quad (1)$$

where T and C denote intervention and comparison groups, and Y is specific yield adjusted for irradiance and temperature. The estimator requires comparable baseline trends and exposure; repeated measurements should be analyzed with clustering at the intervention unit. Grid outages, curtailment, and concurrent repairs must be documented. Decisions should prioritize expected recoverable energy and verified repair needs rather than image confidence alone.

Expected contribution, limitations, and conclusion

The expected contribution is a locally validated connection between aerial observations, confirmed loss mechanisms, and maintenance outcomes. A reusable dataset with site-separated evaluation could support further research in Uzbek universities and energy companies. Operators could benefit from geographically organized inspection reports and prioritization of interventions by expected recoverable energy. These benefits remain hypotheses until tested in the proposed field study.

Several limitations must be addressed. Thermal patterns depend on irradiance, wind, viewing angle, and reflections; a hotter region is not automatically a failed cell. Visible dust does not uniquely determine transmission loss. Models may fail when transferred between sensors, module types, or sites. Cleaning and repair opportunities may also be constrained by access, technician availability, and available water. Finally, recovering panel output may not increase delivered electricity during grid curtailment. Monitoring, maintenance, and network constraints should therefore be evaluated together.

Uzbekistan's solar resource and growing electricity demand make improved photovoltaic operation a relevant research direction. Existing work supports the feasibility of UAV inspection, automated classification, and loss estimation, but does not justify a universal energy-gain percentage. The strongest thesis contribution would be to demonstrate whether an integrated monitoring and maintenance workflow produces measurable additional kWh at an acceptable cost under local conditions. Such evidence would convert computer vision performance into an operationally meaningful assessment of solar energy improvement.

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