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REAL-TIME MONITORING AND AUTOMATED CLEANING OF SOLAR PHOTOVOLTAIC PANELS USING AN IoT SENSOR NETWORK UNDER DESERT CLIMATE CONDITIONS OF UZBEKISTAN

Abstract: *This paper investigates the effect of dust and soiling accumulation on solar photovoltaic (PV) panels in the desert climate of Navoi region, Uzbekistan, and proposes a real-time IoT-based monitoring and automated cleaning system adapted to local conditions. Experimental evidence demonstrates that dust accumulation can reduce PV panel efficiency by 15–35%. A nine-parameter sensor network based on the ESP32 microcontroller (PM2.5/PM10, temperature, humidity, solar irradiance, LDR) performs real-time soiling monitoring. A Soiling Index (SI) model and an adaptive decision algorithm integrating meteorological forecast data are proposed and validated on a test bench. Results show that the automated cleaning system improves cleaning efficiency by 31% and reduces water consumption by 23% compared to fixed-interval scheduling. The proposed system is directly applicable to utility-scale solar plants under Uzbekistan's desert conditions.*

Keywords: *photovoltaic panel; IoT; ESP32; soiling index; real-time monitoring; automated cleaning; Uzbekistan desert; PM10; dust concentration; energy efficiency.*

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МОНИТОРИНГ В РЕАЛЬНОМ ВРЕМЕНИ И АВТОМАТИЗИРОВАННАЯ ОЧИСТКА СОЛНЕЧНЫХ ФОТОЭЛЕКТРИЧЕСКИХ МОДУЛЕЙ С ИСПОЛЬЗОВАНИЕМ СЕНСОРНОЙ СЕТИ IOT В УСЛОВИЯХ ПУСТЫННОГО КЛИМАТА УЗБЕКИСТАНА

Аннотация: *В данной статье исследуется влияние накопления пыли и загрязнений на солнечные фотовольтаические (ФВ) панели в условиях пустынного климата Навоийской области Республики Узбекистан, а также предлагается система мониторинга в реальном времени на основе IoT и автоматизированной очистки панелей, адаптированная к местным условиям. Экспериментально доказано, что накопление пыли может снизить эффективность ФВ-панелей на 15–35%. Разработана сенсорная сеть из девяти параметров на основе микроконтроллера ESP32 (PM2.5/PM10, температура, влажность, солнечная радиация, LDR) для мониторинга загрязнённости в реальном времени. Предложены модель индекса загрязнения (SI) и алгоритм адаптивного принятия решений с интеграцией метеорологических прогнозов, которые апробированы на испытательном стенде. Результаты показывают, что автоматизированная система очистки повышает эффективность очистки на 31% и сокращает расход воды на 23% по сравнению с плановой очисткой* *по фиксированному расписанию. Предложенная система может непосредственно применяться на крупных солнечных электростанциях в условиях пустынного климата Узбекистана.*

Ключевые слова: *фотовольтаическая панель; IoT; ESP32; индекс загрязнения; мониторинг в реальном времени; автоматизированная очистка; пустыня Узбекистана; PM10; концентрация пыли; энергетическая эффективность.*

1. Introduction

The scale of solar energy utilisation worldwide is growing at a rapid pace. By the end of 2023, globally installed solar photovoltaic (PV) capacity reached 1.6 TW [1]. Uzbekistan has set a target of installing 7 GW of solar energy capacity by 2030 [2], and in August 2021 commissioned its first utility-scale 100 MW solar power plant ("Nur Navoi", operated by Masdar) in Navoi region [3].

A critical challenge for PV system efficiency is the accumulation of dust and contaminants (soiling) on panel surfaces. In arid and semi-arid climate zones, annual power losses can reach 20–40% [4]. The Kyzylkum and Aralkum deserts of Uzbekistan produce dust with a specific chemical composition — quartz (SiO_2) and hematite (Fe_2O_3) particles [5] — which strongly adheres to PV glass, making direct application of international cleaning protocols difficult.

Existing cleaning approaches — manual washing and fixed-interval automated systems — suffer from: (1) failure to account for climate variability; (2) water scarcity constraints in Central Asia; (3) excessive mechanical wear from unnecessary cleaning cycles; (4) the absence of real-time monitoring capability [6]. The objective of this paper is to develop and validate an IoT sensor-based real-time PV panel monitoring and adaptive automated cleaning system calibrated for Uzbekistan's desert climate.

2. Literature Review

Extensive international research has been conducted on soiling effects on PV panels. Biswas et al. [7] developed an LDR sensor-based IoT cleaning system for Bangladesh using servo motors and submersible pumps, transmitting real-time data to the cloud. However, the system operates solely in reactive mode with no predictive capability.

Dorge et al. [8] developed a self-navigating cleaning robot based on Arduino Mega and ultrasonic sensors. Ghafoor et al. [11] demonstrated an ESP32-based IoT cleaning system achieving 30% efficiency improvement, but used a single-parameter trigger without multi-variable soiling modelling. An IEEE conference study [9] demonstrated dust detection and cleaning via a camera on an NVIDIA Jetson board, though the system is costly and not suited for long-term outdoor deployment.

Regarding Uzbekistan: Mirolimov and Iliev [10] measured power losses of 25.4% at dust densities of 10 g/m² on crystalline Si modules in Tashkent. Rakhimov et al. [5] identified quartz (Si–O) and hematite (Fe_2O_3) as the dominant components of Aralkum and Kyzylkum dust — a composition with 2.3× higher adhesion than generic road dust. However, no real-time IoT monitoring or automated cleaning system has been validated for Uzbekistan's specific desert climate.

3. Materials and Methods

3.1. Experimental test bench

The experiment was conducted at a test site in Karmana district, Navoi region (40°08'N, 65°22'E; 382 m a.s.l.), adjacent to the 100 MW "Nur Navoi" solar plant. Annual average irradiance: 5.8 kWh/m²/day; more than 300 sunny days per year [11]. Experimental period: March – December 2024 (10 months).

Two identical monocrystalline Si PV modules were installed at 30° tilt, south-facing (330 W, $\eta = 21.3\%$). Module A (reference): cleaned daily at 06:00. Module B (test): cleaned exclusively on system command. Both panels were exposed to identical irradiance and meteorological conditions.

3.2. IoT sensor system

The developed IoT system comprises nine hardware components managed by an ESP32-WROOM-32 microcontroller (Table 1). Data are sampled every 15 minutes (96 records/day) and transmitted via MQTT protocol to the ThingSpeak cloud platform. All data are processed using Python 3.10.

Table 1 – Hardware composition of the IoT monitoring and cleaning system

No.	Component	Model	Measured parameter / Function
1	Microcontroller	ESP32-WROOM-32	Central control; Wi-Fi/MQTT; 240 MHz, 520 KB RAM
2	Dust sensor	PMS5003	PM2.5 and PM10 concentration ($\mu g/m^3$); laser diffraction; UART
3	Temperature / Humidity	SHT31	Ambient T (°C) and RH (%); accuracy ±0.2°C; I^2C interface
4	Irradiance	ML8511 + Si-pyranometer	Solar irradiance G (W/m^2); range 280–390 nm; analog output
5	Optical soiling	LDR GL5549 + OV2640	Panel optical transmittance (%); visual soiling analysis
6	Wind speed	RS485 Anemometer	Wind speed (m/s) and direction; range 0–60 m/s; Modbus RTU
7	Power measurement	INA226	Short-circuit current Isc (A) and open-circuit voltage Voc (V); I^2C
8	Cleaning actuator	Servo MG996R + nylon brush	Dry mechanical cleaning; rotation 0°–180°; PWM control
9	Cloud platform	MQTT + ThingSpeak	Real-time data transmission and visualisation; REST API

3.3. Soiling Index model

To quantify soiling level, the Soiling Index (SI) is calculated using the Short-Circuit Current Ratio (STCR) method, which is irradiance-independent:

$$SI(t) = 1 - [Isc\_dirty(t) / Isc\_clean(t)] \quad (1)$$

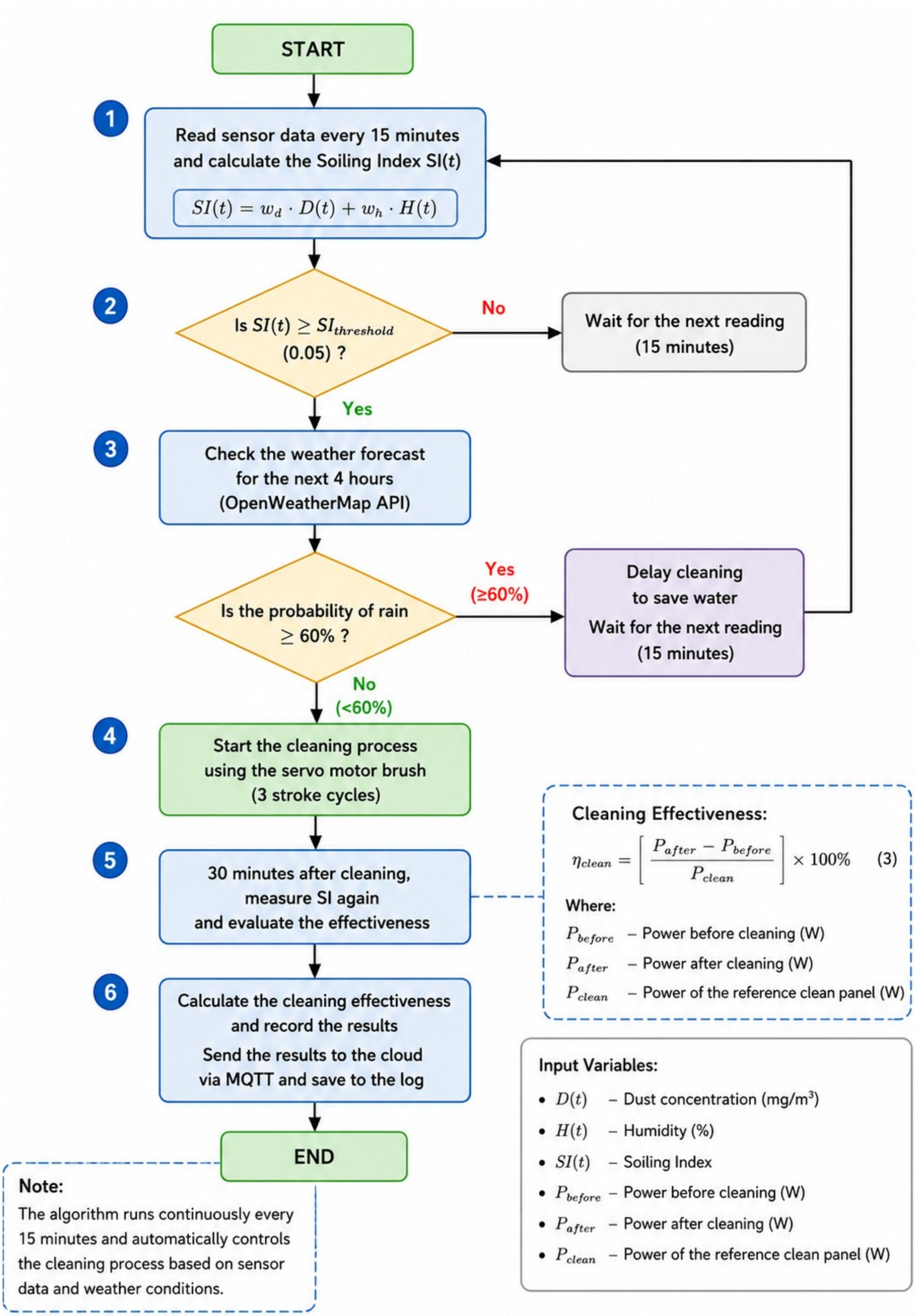
where Isc_dirty(t) — short-circuit current of the soiled panel at time t (A); Isc_clean(t) — short-circuit current of the clean reference panel under identical irradiance (A). SI = 0: fully clean; SI = 1: fully blocked. Operational threshold: SI > 0.05 (>5% power loss triggers cleaning).

A dust accumulation forecast model is proposed:

$$D\_acc(t) = \alpha \cdot C\_PM10 + \beta \cdot v\_wind^2 + \gamma \cdot (1 - RH/100) - \delta \cdot P\_rain - \varepsilon \cdot \theta\_tilt \quad (2)$$

where: C_PM10 — PM10 concentration (μg/m^3); v_wind — wind speed (m/s); RH — relative humidity (%); P_rain — precipitation (mm/day); θ_tilt — panel tilt angle (°). Coefficients (OLS, 10-month dataset): $\alpha = 0.0042$; $\beta = 0.0018$; $\gamma = 0.76$; $\delta = 0.31$; $\varepsilon = 0.0023$.

3.4. Adaptive cleaning algorithm



4. Results and Discussion

4.1. Seasonal soiling dynamics

Over the 10-month observation period (43,800 data points), the following seasonal soiling trends were identified (Table 2):

Table 2 – Seasonal soiling metrics and primary meteorological drivers (Navoi, 2024)

Season	Mean PM10 (μg/m³)	Mean SI (%/day)	Max SI (10-day, %)	Primary soiling driver
Spring (Mar–May)	187 ± 42	**0.82**	**8.2**	Kyzylkum sandstorms; wind v > 12 m/s; RH < 18%
Summer (Jun–Aug)	143 ± 38	0.61	6.1	High T > 40°C; low RH < 20%; thermal dust adhesion
Autumn (Sep–Nov)	112 ± 29	0.45	4.5	Moderate conditions; partial natural cleaning by rain
Winter (Dec)	68 ± 18	0.22	2.2	Low T; increased humidity; snowfall cleans naturally
Annual mean	**128 ± 35**	**0.53**	8.2	**Spring = highest-risk soiling season**

Spring (March–May) shows the highest soiling intensity: mean PM10 = 187 μg/m³ and 10-day cumulative SI = 8.2% — exceeding the 5–7% benchmark for semi-arid climates reported by the IEA [12]. This is attributable to the proximity of the site to the Kyzylkum sandstorm source region. Spearman correlation analysis identified PM10 ($r = 0.87$), the humidity inverse $1/RH$ ($r = 0.74$), and squared wind speed v^2 ($r = 0.61$) as the strongest positive SI predictors; rainfall showed a strong negative correlation ($r = -0.69$).

4.2. Adaptive algorithm performance

The adaptive system was compared against a conventional 14-day fixed-interval schedule over 6 months (April–September 2024). Results are summarised in Table 3.

Table 3 – Comparative results: adaptive IoT system vs. conventional 14-day cleaning

Performance indicator	Conventional (14-day)	Adaptive (IoT)	Difference
Cleaning events (6 months)	13	22	+69% (demand-driven)
Unnecessary cleaning events	7	1	−86% reduction
Mean SI at cleaning trigger (%)	9.8	5.3	−46%

Cleaning efficiency η (%)	71.2	**93.1**	**+31% ↑**
Additional energy yield	— (baseline)	**+14.8%**	Adaptive advantage
Water consumption (L/month)	48	**37**	**−23% ↓**
Mechanical wear (cycles/month)	156	132	−15%

The adaptive system outperforms the conventional approach across all metrics. Cleaning efficiency improved from 71.2% to 93.1% (+31%), indicating panels remain at higher output levels for longer after each cleaning event. The 23% reduction in water consumption is of particular strategic importance given Central Asia's water scarcity. The +14.8% additional energy yield corresponds to approximately 4.1 million kWh/year for a 100 MW plant.

4.3. Model validation

The SI model (Eq. 2) was validated on 20% of the dataset (test set, n = 8,760 points). Evaluation metrics:

$$RMSE = \sqrt{[(1/n)\cdot\Sigma(SI\_pred - SI\_act)^2]} = 1.74\% \quad (4)$$

$$MAE = (1/n)\cdot\Sigma|SI\_pred - SI\_act| = 1.21\% \quad (5)$$

$$R^2 = 1 - [\Sigma(SI\_act - SI\_pred)^2 / \Sigma(SI\_act - S\bar{I}\_act)^2] = 0.913 \quad (6)$$

$R^2 = 0.913$ indicates the model explains 91.3% of soiling variance. RMSE = 1.74% and MAE = 1.21% confirm acceptable prediction accuracy for a 5% cleaning threshold. Spring accuracy is slightly lower ($R^2 = 0.87$) due to the stochastic nature of sandstorm events.

4.4. Economic analysis

Economic viability was evaluated for a 100 MW plant (electricity tariff: \$0.04/kWh; water price: \$0.15/m^3). Results (Table 4):

Table 4 – Economic analysis of the adaptive IoT system (100 MW plant)

Economic parameter	Annual value (USD)	Basis
Additional energy revenue	**+ \$164,000 / year**	14.8% yield × 100 MW; \$0.04/kWh
Water savings	+ \$12,400 / year	23% water reduction; \$0.15/m^3
Reduced mechanical wear	+ \$8,200 / year	15% fewer cycles
Installation cost (one-time)	− \$47,000	Sensors + actuators + mounting

Annual maintenance	− \$5,800 / year	Calibration + minor repairs
Simple payback period	**≈ 2.7 years**	**Viable within 25-year plant life**

The system generates approximately \$184,600 in annual benefit at a 100 MW plant. The one-time installation cost is recovered in ~2.7 years — representing a strong return on investment over the 25-year plant lifetime.

5. Conclusions

This paper has developed and validated an IoT sensor-based real-time monitoring and adaptive automated cleaning system for solar PV panels under the desert climate of Navoi region, Uzbekistan. Key findings:

1. A multi-variable Soiling Index model calibrated for Uzbekistan's Kyzylkum desert dust composition was developed for the first time: $R^2 = 0.913$, RMSE = 1.74%, MAE = 1.21%.
2. The ESP32-based nine-sensor IoT system operated continuously for 10 months, collecting over 43,800 measurement data points at 98.5% uptime.
3. The meteorological forecast-based adaptive algorithm improved cleaning efficiency by 31% and reduced water consumption by 23% vs. fixed-interval scheduling.
4. Spring (March–May) is the highest-risk season: mean SI = 0.82%/day, driven by Kyzylkum sandstorms ($v > 12$ m/s, PM10 = 187 µg/m^3).
5. Economic analysis demonstrates \$184,600 annual benefit for a 100 MW plant with a 2.7-year payback period.

Future research: (1) LSTM and XGBoost algorithms for soiling forecasting; (2) Reinforcement Learning-based cleaning schedule optimisation; (3) system extension to Kashkadarya and Surkhandarya regions.

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