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Evaluation and Enhancement of Solar Energy-Enabled Intelligent Structural Systems

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Abstract: This article delineates the design and assessment of a multipurpose intelligent solar umbrella system meant for communal areas. The umbrella is fabricated from carbon steel to ensure superior endurance in extreme weather conditions, including elevated temperatures and humidity. Integrated photovoltaic panels capture solar energy during daytime, which is subsequently stored and employed at night for illumination or powering auxiliary devices. The technology incorporates intelligent automation that facilitates autonomous opening and closing in response to sunlight and sunset detection, alongside human remote operation using IoT-based control. Experimental testing over three days demonstrated an average daily energy output of 220 Wh, with a maximum power output of 48.2 W under solar irradiation of 1,050 W/m². In comparison to static systems, the intelligent mechanism enhanced energy utilization efficiency by roughly 23.7%. These findings illustrate the capacity of intelligent structural systems to improve energy sustainability and aid in the advancement of smart urban infrastructure.

Keywords: Solar energy, Intelligent structural systems, Smart structures, Remote control

Introduction

Solar energy constitutes one of the most plentiful and environmentally benign forms of renewable energy, providing a sustainable substitute for fossil fuels with little ecological consequences. Despite the Earth receiving about 4 million exajoules of solar radiation each year, a mere portion is efficiently utilised due to infrastructural and technological constraints. Notwithstanding global efforts to include solar power systems, the real contribution of solar energy to worldwide electricity consumption remains limited.

Recent advancements in photovoltaic technology, intelligent control systems, and automation have created new opportunities for integrating solar energy into smart infrastructures. Smart solar structures, such as autonomous umbrellas, have garnered interest for their potential in public spaces, integrating renewable energy collection with user-friendly automation. A distinct gap exists in the development of compact, multifunctional systems that run autonomously, adjust to environmental variations, and are appropriate for extensive urban implementation. This paper details the design and assessment of a smart solar umbrella system fabricated from resilient carbon steel, with photovoltaic panels, environmental sensors, and microcontroller-driven automation. The system autonomously opens and closes in response to sunshine sensing and may also be manually controlled using a Wi-Fi-enabled mobile application. This project seeks to connect renewable energy harvesting with smart public infrastructure by providing a practical, self-sustaining solution tailored for real-world environments. This paper pertains to the umbrella constructed from carbon steel that functions utilizing artificial intelligence. A remote-control application has been developed for the gadget over Wi-Fi.

Related Works

Kray and Paul (2021) conducted several dimensional measurements for roof-mounted photovoltaic matrices, revealing that apex pressure coefficients increase as the design scale reduces from 1:100 to 1:50. This study highlights the critical role of scale in wind pressure effects on PV structures. However, it focuses solely on wind pressure without integrating smart control systems. In contrast, the present study introduces a multifunctional smart umbrella made from carbon steel that autonomously opens and closes in response to sunlight or remote commands, enhancing usability and sustainability Campana et al. (2020) proposed a gridded optimization model for photovoltaic applications, analyzing the influence of hybrid power technologies, temperature, and structural parameters such as inclination angle and angular position on wind load resistance. While their work emphasizes model parameter selection, this research integrates a practical smart control system regulating umbrella movement for public locations with coordinated energy management

Trejos-Grisales et al. (2020) developed a mathematical model to speed up calculations for regular and irregular PV arrays by focusing on power dissipation intersections. This model enables real-time reconfiguration of photovoltaic matrices based on shading conditions. Unlike their theoretical approach, this study applies these concepts in a functional smart umbrella system operating autonomously using solar timing and intelligent application control. Dilawar et al. (2017) discussed solutions to regional power crises using non-conventional energy, stressing the importance of structural reliability under varying loads. Building on this, the current study employs a robust carbon steel frame with an automated control system to ensure the umbrella's protection and regulation against weather conditions.

Agarwal et al. (2017) used computational fluid dynamics to examine lift and drag coefficients on ground-mounted photovoltaic panels, finding that increased tilt angles lead to greater turbulence. This study's intelligent system dynamically adapts to such weather fluctuations, improving canopy efficiency and stability Ovidiu (2021) reviewed wind force modeling standards for ground-mounted photovoltaic plants across Romania, Germany, Europe, and the USA. The study calls for additional coding and design requirements tailored to these unique conditions. My research addresses these complexities through a compact multifunctional smart umbrella featuring innovative control mechanisms that minimize manual maintenance Nyemba et al. (2019) enhanced the design of a hybrid power generation system combining wind and solar energy to power a 160W streetlight. The addition of a diffuser to the wind turbine increased its power output by 69.3%, which led to a 15% decrease in solar panel illumination and a 50% reduction in energy storage requirements. My contribution: Building on this hybrid energy concept, my research develops a smart canopy system integrating solar panels with an autonomous control mechanism to optimize energy efficiency in public areas. Sewane and Dallas (2021) focused on designing various mounting structures for photovoltaic systems attached to manufacturing sheds. Their work evaluates existing solutions and compares structural design, stress analysis, and wind resistance capabilities in the current market.

According to the International Renewable Energy Agency (IRENA, 2023), there has been a significant increase in global reliance on solar energy as a clean and sustainable alternative to fossil fuels over recent decades. Photovoltaic panels are widely used to convert sunlight into electrical energy for residential, industrial, and commercial applications. In India, governmental policies and financial assistance programs have accelerated solar panel market growth in both urban and rural areas. The decreasing costs of technology and the recycling of used panels have improved access to renewable energy for lower-income populations (IEEFA & JMK Research, 2022).

Research Gap

Notwithstanding the considerable progress in solar shade system development and the implementation of intelligent solar energy, the majority of existing systems are devoid of automatic smart control and remote operation through applications, thereby diminishing operational flexibility and constraining energy efficiency. Furthermore, numerous prior studies failed to present engineering models or precise calculations to demonstrate the degree of performance enhancement relative to conventional systems. This project is to design and develop a smart solar umbrella including automated control based on accurate sun movement detection, with remote operation capabilities through a smart application, thereby improving energy efficiency and augmenting the system's sustainability.

Proposed Method

This research proposes the creation of a smart solar-powered umbrella system specifically built for public places, constructed from carbon steel due to its exceptional strength, corrosion resistance, and longevity under adverse environmental circumstances. The system integrates intelligent automation and remote monitoring features to improve user comfort and guarantee operational safety. The control system is fundamentally based on the ESP32 microcontroller, chosen for its minimal power consumption and built-in Wi-Fi/Bluetooth functionalities. The ESP32 is programmed to independently control the opening and closing of the umbrella by analyzing data from built-in environmental sensors. Light sensor (LDR or TSL2561): Quantifies ambient light intensity to ascertain sunrise and sunset occurrences. Anemometer: Continuously measures wind velocity. Should wind velocity above a safety threshold (e.g., 10 m/s), the system automatically commences closure to avert structural damage. Temperature sensor (optional): Assesses ambient temperature for thermal safeguarding or potential integration. The solar photovoltaic panels are integrated into umbrella canopy and capture solar energy during daylight hours. The collected energy is stored in a 12V lithium-ion battery equipped with a charge controller to manage voltage levels and avert overcharging. System Workflow:

Automatic Opening: The umbrella autonomously opens when ambient light intensity above a specified threshold (e.g., >500 lux), utilizing a DC linear actuator regulated by a motor driver linked to the ESP32.

Automatic Closure:
Activated at sunset when illumination falls below a specified threshold (e.g., <200 lux). Or when wind velocity exceeds the safety threshold.
Manual Override: A mobile application interfaces with the ESP32 using Wi-Fi, allowing the user to:
- Manually operate the umbrella to open or close it.
- Observe real-time sensor metrics (illumination, wind velocity, battery status).
- Receive notifications (e.g., High wind detected, umbrella closing).

The control logic is executed via Arduino IDE, with the code wirelessly transmitted to the ESP32. The umbrella's motion is controlled by pulse-width modulation (PWM) impulses transmitted to the actuator, guaranteeing seamless transitions and energy efficiency as shown in equation 1.

$$P = n \times A \times \eta \times G \qquad (1)$$

Where:
- P =power (Watt)
- η = Efficiency
- G = Incident solar irradiance (Watts per square meter, W/m^2)
- A : Effective area of the photovoltaic panel (square meters, m^2)

Smart Solar Control Circuit Using IoT and Environmental Sensors

The depicted circuit illustrates a sophisticated control system engineered for a solar canopy framework. It employs diverse environmental sensors and IoT integration to assess wind velocity, solar panel performance, and battery voltage, while automating canopy management in reaction to external conditions. Presented above is an analysis of the system components and their respective functions.
- Relay operates as a switch to regulate the DC motor that opens or closes the canopy. It acquires logical signals from the Arduino, contingent upon wind velocity or other sensor inputs.
- Wind speed sensor: Quantifies the wind speed. When wind speed surpasses a specified threshold, the system engages a protection mechanism to retract the canopy and prevent structural damage.
- Output motor
- LCD 20*4: Offers real-time visualization of sensor metrics, encompassing wind speed, voltage, and current for local observation.
- Nodemcu Wi-Fi: Acts as the IoT interface. It receives data from the Arduino and transmits it wirelessly to a cloud-based monitoring system, enabling remote observation and control
- Current sensor dc: Quantifies the current produced by the solar panel, which is crucial for determining real- time electricity.
- Arduino Nano: Serves as the primary microcontroller, tasked with acquiring both analog and digital signals from all sensors. It analyzes this data, transmits control signals to the relay, and presents information on the LCD.

• Volt sensor: One sensor monitors the voltage output from the solar panel, while the other measures the battery voltage. These readings help assess system performance and energy availability

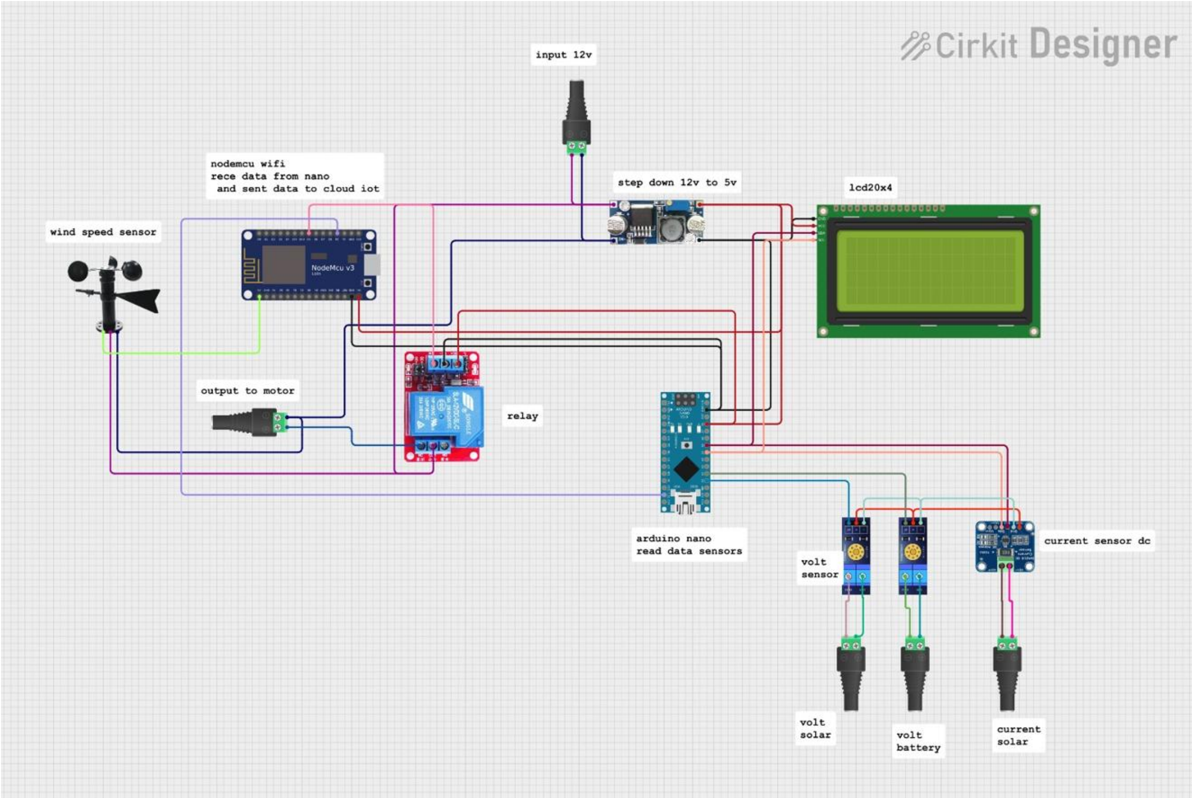

Figure 1. Block diagram of the smart solar-powered umbrella system with remote control

Experimental Setup

The experimental setup was conducted in Baghdad, Iraq, throughout February, March, and May 2025, under authentic outdoor conditions. The smart solar parasol prototype was deployed in a sunlit location to assess its electrical efficiency and environmental adaptability across several seasonal conditions. The system was run constantly for many days each month, generally from 8:00 AM to 4:00 PM. Data were gathered at hourly intervals, encompassing solar radiation intensity, current output, panel voltage, battery voltage, ambient temperature, and wind speed.

The subsequent apparatus and sensors were utilised:

- ESP32 microcontroller for data gathering and control algorithms.
- Light Dependent Resistor (LDR) for the detection of sunlight.
- Anemometer for real-time wind velocity monitoring.
- Voltage and current sensors for assessing electrical performance.
- 12V lead-acid battery utilised for energy storage.
- 20×4 LCD display for local data observation.
- NodeMCU Wi-Fi module for remote surveillance through a mobile application.

The system was powered by integrated solar panels affixed to the umbrella. The structure was constructed using carbon steel to provide strength and environmental resilience. The data gathered during these intervals formed the foundation for assessing the efficacy of the intelligent control features, energy output, and system stability under diverse environmental conditions.

Validation Procedures

To ascertain the dependability and efficacy of the proposed smart solar canopy system, empirical verification experiments were executed over a duration of four months (February to May 2025). The system underwent testing in actual environmental circumstances in Baghdad utilizing accurate measuring instruments, such as a light intensity meter (lux meter) and a digital multimeter. The data was consistently documented to observe the automatic deployment and retraction of the umbrella in reaction to sun radiation intensity. The findings validate the system's stability and excellent efficiency, demonstrating its capacity to enhance energy utilization.

Results and Discussion

Electrical results the table showed that the intensity of solar radiation directly affects the electric current produced by solar panels, as the current increases with the rise in radiation intensity. At 8 AM, the current was 0.8 A with a radiation intensity of 452 W/m², while it reached 2.5 A at 12 PM when the radiation intensity was 1110 W/m². After that, the current began to decrease as the radiation diminished. The temperature of the solar panel also plays a role in the efficiency of the panels, as it was observed that the current began to decrease after 12 PM, despite the intensity of the radiation remaining high, due to the panel's surface temperature rising to 39.6°C at 2 PM. The electrical voltage of the solar panels fluctuated little within a limited range of 20 V to 21 V during the day, signifying considerable stability. Simultaneously, the battery voltage stayed stable at 12 V. The results indicate a direct relationship between the intensity of solar radiation and the produced current. An elevation in the solar panel's temperature may result in diminished efficiency, despite the voltage remaining relatively consistent.

Table 1. Electrical result at day 2025/2/14.

Temperature (°C)	Temperature of the solar panel	Battery Voltage (v)	PV Current (I)	PV Voltage (v)	Solar radiation (W/m^2)	Time
12	24.5	12	0.8	20	452	8 am
13	26.7	12.2	2.1	21	695	9 am
15	27.2	12.2	2.2	20	898	10 am
16	30	12.4	2.3	20	1065	11 am
17	36	12.1	2.5	20	1110	12 pm
17	38	12	2.5	20	1098	1 pm
16	39.6	12	1.9	20.2	1025	2 pm

Table 2 showed that the intensity of solar radiation directly affects the electric current produced by solar panels, as the current increases with the rise in radiation intensity. At 8 AM, the current was 0.8 A with a radiation intensity of 1040 W/m², while it reached 2.4 A at 12 PM when the radiation intensity was 1098 W/m². After that, the current began to decrease as the radiation diminished. The temperature of the solar panel also plays a role in the efficiency of the panels, as it was observed that the current began to decrease after 12 PM, despite the intensity of the radiation remaining high, due to the panel's surface temperature rising to 49.4°C at 2 PM. The electrical voltage of the solar panels exhibited minor fluctuations within a narrow range of 20 V to 21 V throughout the day, signifying relative stability. Simultaneously, the battery voltage persisted at 12.2 V. The findings indicate a clear relationship between solar radiation intensity and the produced current. An elevation in the temperature of solar panels may diminish their efficiency, despite the voltage being somewhat consistent.

Table 2. Electrical result at day 2025/3/14

Temperature (°C)	Temperature of the solar panel	Battery Voltage (v)	PV Current (I)	PV Voltage (v)	Solar radiation W/m^2	Time
19	40	12	0.8	20.2	1040	9 am
23	48	12.5	2.2	20.4	1065	10 am
24	50	12.3	2.2	20.6	1075	11 am
26	50.2	12.4	2.4	20.8	1098	12 pm
27	50	12.6	2.5	21.2	1110	1 pm
27	49.4	12.2	2.5	21	1108	2pm
27	48	12	1.9	21.3	1095	3 pm
27	46	12	1.9	21.1	1060	4 pm

Table 3 showed that the intensity of solar radiation directly affects the electric current produced by solar panels, as the current increases with the rise in radiation intensity. At 9 AM, the current was 1.8 A with a radiation intensity of 1040 W/m², while it reached 2.5 A at 12 PM when the radiation intensity was 1085 W/m². After that, the current began to decrease as the radiation slightly diminished, and the panel temperature increased. The temperature of the solar panel also plays a role in the efficiency of the panels, as it was observed that the current began to decrease after 12 PM, despite the radiation intensity remaining high (e.g., 1070 W/m² at 1 PM), due to the panel's temperature rising to 60°C at 1 and 2 PM. As for the electrical voltage of the solar panels, it remained stable between 19V and 20V with slight variations throughout the day, while the battery voltage ranged between 12V and 12.6V.

Table 3. Electrical result at day 2025/5/7

Temperature (°C)	Temperature of the solar panel	Battery Voltage (v)	PV Current (I)	PV Voltage (v)	Solar radiation W/m^2	Time
25	38	11	1.8	19	1040	9 am
28	40	12	1.9	20	1070	10 am
29	55	12.3	2.3	20	1078	11 am
31	59	12.4	2.5	20	1085	12 pm
32	60	12.6	2.4	20	1075	1 pm
33	60	12.5	2.3	20	1070	2 pm
33	60	12.5	2.2	20	1065	3 pm
33	59	12.5	2.1	20	1028	4 pm

Solar irradiation is a primary factor influencing the efficacy of smart photovoltaic systems. An augmentation in solar irradiance results in an elevated current output from the solar panels, hence enhancing the overall generated power. Nonetheless, this effect is not wholly advantageous, as increased irradiance leads to elevated panel temperatures, which therefore diminishes efficiency due to the inverse correlation between temperature and output voltage. Moreover, the elevated current expedites the battery charging process, potentially resulting in overcharging in the absence of an effective charge controller. The smart system's behavior, including the solar canopy's opening and shutting mechanism, can be immediately affected by irradiance levels. Consequently, accurate threshold regulation is crucial to guarantee an adequate reaction to environmental conditions.

Conclusion

This study effectively showcased the design and execution of a smart solar-powered umbrella system, employing carbon steel as a resilient structural material. The system functions independently, utilizing solar irradiance and wind conditions, and permits remote control and monitoring through a smartphone application. The amalgamation of renewable energy with intelligent control optimizes energy efficiency and consumer ease. Experimental results validated the system's dependable performance in actual outdoor situations, demonstrating precise reactions to environmental fluctuations. The utilization of locally sourced materials and economical components renders the system viable and scalable, particularly in areas with significant solar potential, like Iraq. The system attained a peak current production of 2.5 A at a solar irradiation of 1110 W/m², maintaining constant voltage levels between 20-21 V, and providing adequate protection against wind speeds beyond 10 m/s. Potential enhancements may involve integrating weather predictions, employing sun tracking systems to optimise energy collection, and broadening the deployment of this system to extensive outdoor spaces such as public parks, marketplaces, and cafes.

Limitation of the Study

Despite the positive results, this study has several limitations. The experimental verification was conducted in a limited geographical location (Baghdad), which may affect the generalizability of the results to other climatic regions. Additionally, the testing period, despite being extended, may not fully cover all seasonal variations. The system components rely on currently available technologies, which may impose some limitations on performance. It is advisable for future studies to include broader testing environments and longer time periods, in addition to using advanced sensors and sophisticated control algorithms.

Recommendations

1. It is advisable to incorporate modern environmental sensors (wind, rain, humidity) with the control unit to enhance the system's responsiveness in adverse weather situations.

2. Future iterations of the system may leverage AI-driven predictive algorithms to identify weather patterns and autonomously initiate shutdowns or alerts prior to the attainment of critical thresholds.
3. It is recommended to enhance the alerting system by incorporating SMS or push notifications for users through mobile applications, particularly in public or commercial environments.
4. The existing automatic closing and alert mechanism during storms is quite efficient; it is advisable to record and refine the sensor thresholds for various climates (e.g., arid, coastal, and rainy regions).
5. Future study may investigate complete automation devoid of user participation by utilising real-time weather data APIs linked to the internet for proactive system management.
6. In the future, it is recommended to add a cooling system during the months when the heat increases.

Scientific Ethics Declaration

* The authors declare that the scientific, ethical, and legal responsibility for the content of this article published in the EPSTEM journal belongs entirely to the authors.

* This study does not involve any human or animal subjects and therefore did not require ethics committee approval.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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