International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

IOT and AI-Based Smart Energy Management System for Solar Power Generation

T. Devi Sri Prasad[1], Dr. M. Rambabu[2], Y. Gnaneswara Kumar[3], Y. Harini[4], Sk. Pareesha[5], P. Sudheer Kumar[6], M. Chandra Sekhar[7]

[1,3,4,5,6]B. Tech Student, GMR Institute of Technology, Rajam,532127, India
[2]Professor, GMR Institute of Technology, Rajam,532127, India

A B S T R A C T

The increasing demand for renewable energy necessitates optimized solar power generation. This project proposes an IoT and AI-based smart energy management system to enhance performance prediction, ensure reliable power output, and promote economic utilization of solar resources. By integrating IoT sensors, cloud computing, and AI algorithms, the system enables real-time monitoring, predictive maintenance, and intelligent energy management, maximizing energy efficiency and reducing grid dependency. MATLAB simulations were employed to model system components like solar panels, batteries, and loads, allowing for performance analysis under varying conditions such as fluctuating solar irradiance and diverse load profiles. A comprehensive hardware kit, featuring an Arduino microcontroller, sensors for irradiance, temperature, voltage, and current, and actuators like relays and LEDs, was assembled to validate the system's functionality. The microcontroller was programmed to read sensor data, control actuators, and communicate with other devices, effectively transforming the hardware into a functional IoT-based smart energy management system. This integrated approach, combining simulations and hardware implementation, provides a robust framework for developing smart energy management systems, contributing to a more sustainable energy future by optimizing solar power generation and minimizing energy waste.

Keywords: Renewable energy optimization, Cloud computing, Predictive maintenance, Intelligent energy management.

1.INTRODUCTION

The The world is witnessing a significant shift towards renewable energy sources, driven by the need to reduce greenhouse gas emissions and mitigate climate change. Solar energy has emerged as a promising alternative to traditional fossil fuels. However, solar power generation is intermittent and weather-dependent, making it challenging to ensure a stable and reliable energy supply. To address this challenge, this project proposes the development of an IoT and AI-based smart energy management system for solar power generation. The proposed system aims to enhance performance prediction, reliable power output, and economical utilization of renewable resources. By leveraging the capabilities of IoT, cloud computing, and AI, the proposed system enables real-time monitoring, predictive maintenance, and intelligent energy management. The increasing demand for renewable energy sources has necessitated the optimization of solar energy generation. The proposed system utilizes IoT, cloud computing, and AI to enable real-time monitoring, predictive maintenance, and intelligent energy management. This ensures maximum energy efficiency, reduced energy waste, and improved overall performance of solar power generation systems.

A dual approach is employed to validate the proposed system. Firstly, a simulation-based approach utilizing MATLAB models the system's components, analysing performance under various conditions. Secondly, a hardware-based approach involves designing and implementing a comprehensive hardware kit comprising an Arduino microcontroller, sensors, actuators, and communication modules. The kit is programmed to read sensor data, control actuators, and communicate with devices, creating a functional IoT-based smart energy management system. The proposed system has the potential to optimize energy efficiency, reduce energy waste, and improve the overall performance of solar power generation systems. This project contributes to the development of smart energy management systems, providing a comprehensive analysis of IoT and AI applications in solar power generation

2. LITERATURE REVIEW

[1]. Integrating Internet of Things (IoT) technology into solar power monitoring systems has significantly enhanced real-time data collection and analysis, leading to improved energy optimization and fault detection. For instance, a system utilizing Node MCU with voltage sensors effectively collects, processes, and visualizes real-time data from solar panels, offering a comprehensive monitoring solution that enables efficient management of solar power generation. Similarly, another implementation employs an ESP-01 Wi-Fi module based on the ESP8266 microcontroller interfacing with Arduino to gather real-time data from sensors measuring current, voltage, and light intensity, ensuring

seamless and reliable data transfer. These advancements facilitate remote monitoring and proactive maintenance, thereby enhancing the overall efficiency and sustainability of solar energy systems.

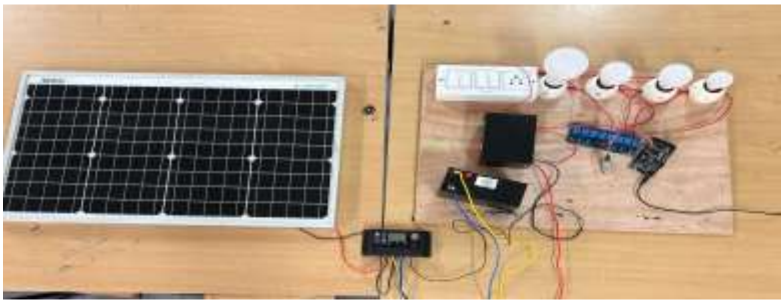
[2]. Comprehensive reviews of IoT-based intelligent energy management systems for photovoltaic (PV) power generation highlight the integration of IoT, cloud computing, and predictive analytics as key components. These reviews underscore the importance of real-time data collection, advanced analytics, and seamless communication in optimizing energy production and consumption. The insights gained from such studies validate the effectiveness of integrating IoT and related technologies in enhancing the performance and sustainability of PV systems.

[3]. A practical application of IoT in solar energy is demonstrated through a monitoring system that utilizes Arduino, sensors, and an IoT dashboard. This system provides real-time visualization of solar power generation and consumption, enabling users to monitor performance metrics and detect faults promptly. Such implementations exemplify the practical benefits of IoT in enhancing the reliability and efficiency of solar energy systems.

[4]. The evolution of the internet has been instrumental in enabling connected devices that form the backbone of intelligent energy systems. The proliferation of IoT devices has facilitated seamless communication and data exchange between various components of energy systems, paving the way for sophisticated monitoring and control mechanisms that enhance energy efficiency and sustainability.

3. HARDWARE IMPLEMENTATION

This diagram illustrates foundational solar power setup, illustrating the core components required for energy generation and basic management, which can be expanded upon to create an IoT-based smart energy management system. The visible 40W monocrystalline solar panel converts sunlight into electricity, subsequently regulated by a charge controller to ensure safe battery charging. This battery stores the energy for later use, powering a series of lights controlled by a relay module and manual switches.



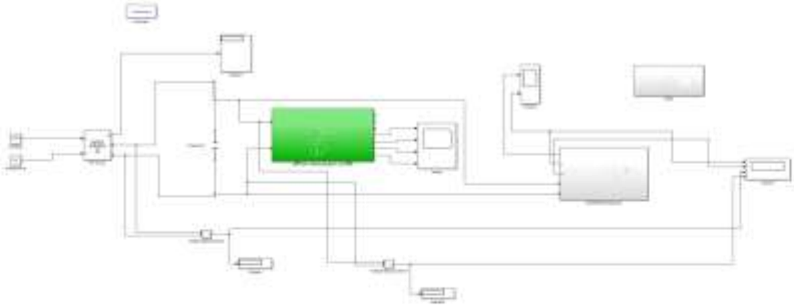
System Architecture and Design for IOT

To transform this basic setup into an IoT-enabled system, sensors would be integrated to monitor parameters like solar irradiance, temperature, voltage, and current, transmitting this data via a microcontroller with internet connectivity to a cloud platform. This allows for real-time monitoring and remote control, enabling users to track performance and manage energy consumption efficiently. The addition of IoT capabilities would facilitate data-driven decision-making, optimizing energy usage and enhancing system reliability by providing insights into performance trends and potential issues. This upgrade would move beyond simple manual control to a system that intelligently manages solar power generation, storage, and consumption, ultimately maximizing efficiency and reducing waste.

The solar charge controller of an IoT and AI-based smart energy management system for solar power generation, the charge controller, as depicted in the image, represents a critical component within a more complex, interconnected network. While the image shows its basic function of regulating solar panel output to charge a battery and power loads, an IoT and AI system would significantly enhance this process. IoT sensors would monitor parameters like solar irradiance, battery voltage, temperature, and load consumption, transmitting this data to a cloud platform. AI algorithms would then analyse this information to optimize the charge controller's operation, predicting energy generation based on weather patterns, adjusting charging cycles to maximize battery lifespan, and intelligently managing load distribution. For example, AI could prioritize charging during peak sunlight hours and schedule high-energy consumption tasks for periods of surplus generation. Moreover, the system could provide real-time monitoring and remote control, allowing users to track energy production, consumption, and battery health via a mobile app or web interface. Predictive maintenance would be enabled by AI's ability to detect anomalies in sensor data, preventing system failures and optimizing maintenance schedules. Essentially, the charge controller's fundamental role is amplified within an IoT and AI framework, transforming it from a standalone device into an intelligent node within a smart energy ecosystem.

4. SYSTEM DESIGN IN SIMULATION

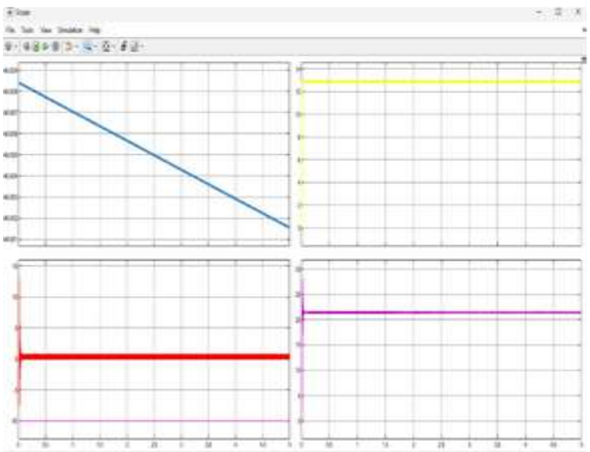
This Simulink model represents a solar power system with battery storage, designed to convert solar energy into usable electricity and provide a reliable power supply to a load. At its core, the model likely includes a block representing a PV module model, which takes irradiance and temperature as inputs and produces voltage and current. This PV block is likely fed by constant blocks or signal builders providing the irradiance and temperature data. A complex subsystem block encapsulates the Battery Management System (BMS) logic, which includes State of Charge (SOC) estimation, charge/discharge control, and protection mechanisms such as overvoltage, overcurrent, and overtemperature protection.

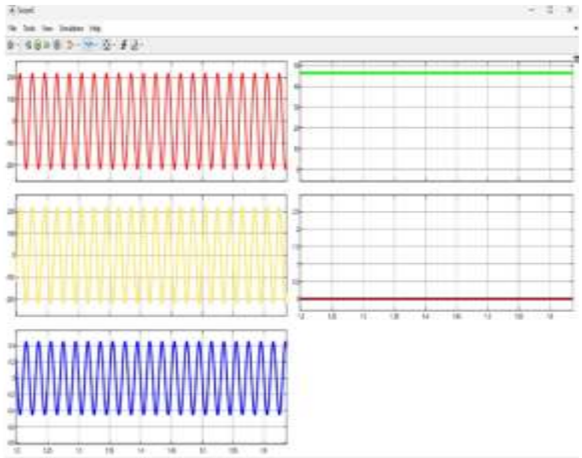


Simulation for IOT based smart energy management system for solar power generation

The model also includes a battery model, often an equivalent circuit model, representing the battery's electrical characteristics. A DC-DC Converter, likely a boost converter, steps up the PV voltage for charging the battery or a buck converter steps down the battery voltage for the load. The load itself is represented by a block, which could be a resistive load, a motor, or a more complex model. To capture data at different points in the system, voltage measurement, current measurement, and power measurement blocks are included. Display blocks show the values of voltage, current, power, SOC, and other relevant parameters.

The Simulink model can be used to simulate various scenarios, such as off-grid power systems, grid-tied systems with battery backup, peak shaving/load leveling, and performance analysis. By examining the block parameters, signal scopes, and simulation results, one can gain a deeper understanding of the system's behavior, performance, and efficiency. The specific application and objectives of the system can be further understood by analyzing the model's parameters and simulation results, providing valuable insights for design optimization and performance improvement.





5. AI IMPLEMENTATION

Two enhanced energy forecasting in solar energy management system. Artificial intelligence techniques were implemented using various machine learning models. These models help predicting the system solar power generation based on multiple weather-related Parameters. The data set using in this project is solar.csv where we are taking different type of data from last one year. Such as

Date-Hour(NMT) – Timestamp of the reading, Wind Speed (m/s),Sunshine (min),Air Pressure, Radiation (W/m²) ,Air Temperature (°C),Relative Air Humidity (%),System Production (kWh) – The output of the solar energy system.

The data was split into 80% for training and 20% for testing using **(train _ test _split).** The following machine learning models were trained and evaluated:

I. Linear Regression

II. Ridge Regression

III. Lasso Regression

IV. Decision Tree Regression

V. Random Forest Regression

Each model was tested using:

R^2 Score – Indicates how well the model explains variation (closer to 1 is better).

Mean Squared Error (MSE) – Measures average squared prediction error.

Mean Absolute Error (MAE) – Measures average absolute prediction error.

Random Forest Regressor achieved the highest R^2 score (0.7283)

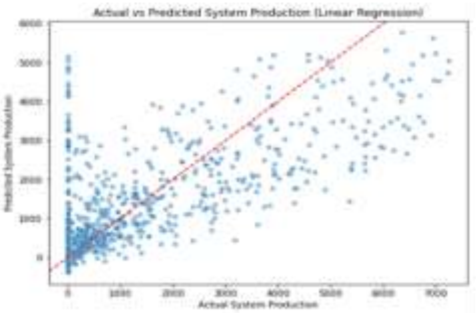
Indicating better accuracy in predicting solar energy production compared to other models.

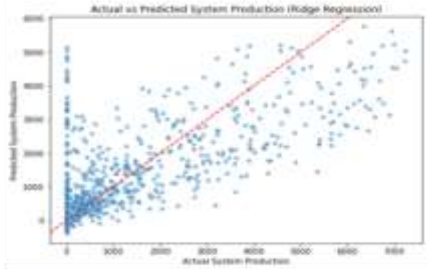
6. VISUALIZATION AND SEASONAL ANALYSIS

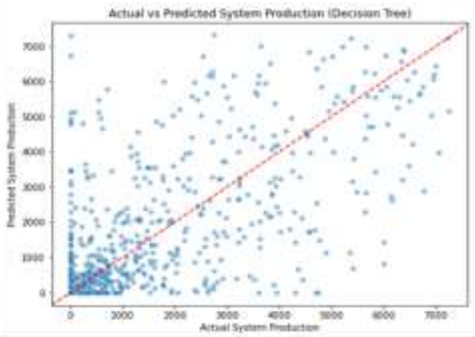
Scatter plots were created to visualize the correlation between actual and predicted system production values for all models.

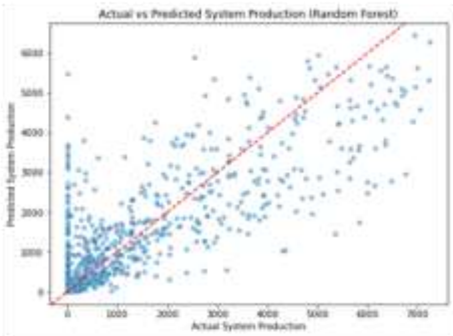
An identity line was added in each plot to assess the deviation from perfect predictions.

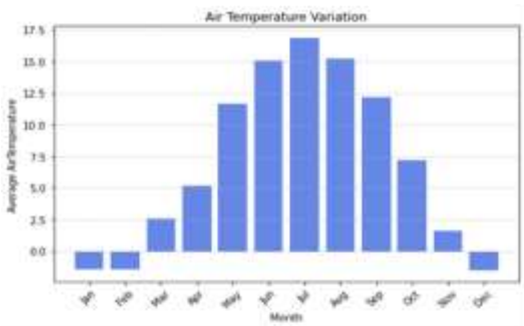
Monthly average values of the environmental parameters were computed and plotted using bar charts, revealing seasonal patterns such as higher radiation and sunshine in summer months

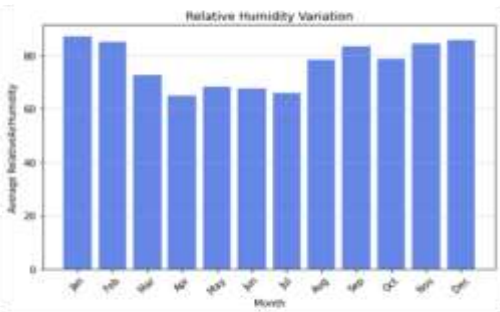


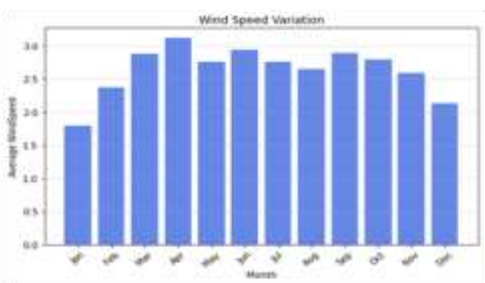


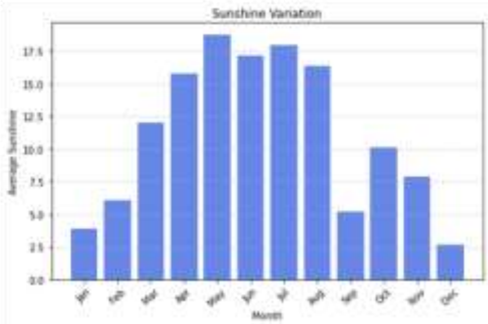












MODEL	**R^2**	**MSE**	**MAE**
LINEAR REGRESSION	0.6123	767116.73	461.70
RIDGE REGRESSION	0.6123	767116.69	461.70
LASSO REGRESSION	0.6123	767116.56	461.69
DECISION TREE	0.5133	963010.12	412.92
RANDOM FOREST	0.7283	537461.34	328.13

CONCLUSIONS:

The integration of IoT and AI is revolutionizing the solar energy sector by developing intelligent energy management systems. These systems leverage real-time data acquisition from a network of sensors to gain a comprehensive understanding of solar installation performance, enabling precise monitoring and control. AI algorithms analyse the collected data to predict potential equipment failures, dynamically adjust energy consumption, and optimize energy production, enhancing system reliability, reducing downtime, and minimizing operational costs. Additionally, AI-powered solar irradiance forecasting facilitates seamless grid integration, allowing grid operators to effectively manage fluctuating solar power generation.

The benefits of this integration are numerous, including real-time monitoring and demand response capabilities, rapid fault detection and diagnosis, and intelligent battery management that maximizes lifespan and efficiency. While challenges such as data security, interoperability, and implementation costs remain, the integration of IoT and AI represents a significant leap forward in the pursuit of a sustainable and reliable solar-powered future.

Future Scope:

The future of IoT and AI-driven smart energy management for solar power is on the cusp of significant breakthroughs, fuelled by escalating automation and intelligence. Sophisticated AI algorithms will enable precise predictive maintenance, self-healing systems, and optimized energy storage, minimizing downtime and maximizing efficiency. Advanced grid integration, personalized energy management, and integration with emerging technologies like blockchain, edge computing, and 5G will revolutionize the field, leading to expanded applications in solar-powered EV charging, smart agriculture, and sustainable energy solutions. These advancements will pave the way for a more resilient, efficient, and sustainable energy future, driven by the seamless convergence of IoT and AI.

References

[1]. Challa Krishna Rao, Sarat Kumar Sahoo, Ranco Fernando Yanine," A literature review on an IoT-based intelligent smart energy management systems for PV power generation", Hybrid Advances 5(2024)100136

[2]. Hainan Zhang, Haribo Feng, Kasun Hewage and Mehrdad Arash pour "Artificial Neural Network for Predicting Building Energy Performance: A Surrogate Energy Retrofits Decision Support Framework" 2022, 12(6), 829

[3]. Maisagalla Gopal1, T Chandra Prakash2, N Venkata Ramakrishna3, Bonthala Prabhanjan Yadav "IoT Based Solar Power Monitoring System "Materials Science and Engineering

[4]. Shahwaiz Ahmed Hashmi1, Chaudhry Fahad Ali2, Saima Zafar2 "Internet of things and cloud computing-based energy management system for demand side management in smart grid"Int J Energy Res. 2020;1–16

[5]. P. Pawar, M. Tarun Kumar, P. Vittal K, An IoT based Intelligent Smart Energy Management System with Accurate Forecasting and Load Strategy for Renewable Generation, Measurement (2019)

[6]. Leonard Barolli, Flora Amato, Francesco Moscato, Tomoya Enoki do, Makoto Takizawa Editors "Advanced Information Networking and Applications" Proceedings of 34th International Conference on Advanced Information Networking and Applications (AINA-2020)

[7]. Gulsan Demirezen1, Alan S. Fung1, Mathieu Deprez2 "Development and optimization of artificial neural network algorithms for the prediction of building specific local temperature for HVAC control" Int J Energy Res. 2020;1–19.

[8]. ZIMING LIU1, (Student Member, IEEE), DAZHI WANG1, JIAXING WANG1, XINGHUA WANG2, AND HAO LI3 "A Blockchain-Enabled Secure Power Trading Mechanism for Smart Grid Employing Wireless Networks" IEEE Access, VOLUME 8, 2020

[9]. Arezoo Hasan Khani, Seyed Mehdi Hakimi, Mojtaba Bisheh-Niasar a, Miadreza Shafie-khah, Hasan Asadolahi "Blockchain technology in the future smart grids: A comprehensive review and frameworks"International Journal of Electrical Power and Energy Systems 129 (2021) 106811

[10]. Roja Eini, Lauren Linkous, Nasibeh Zohrabi, Sherif Abdelwahed "Smart building management system: Performance specifications and design requirements" Journal of Building Engineering Volume 39, July 2021, 10222

[11]. M.Rambabu, M.Dhananjaya and Dr.G.V.Nageshkumar "Power Balancing Control for AC/DC Microgrid" International Journal of Application or Innovation in Engineering & Management (IJAIEM) Vol- 2, Issue-9, September 2013

[12]. M.Rambabu, M.Venkatesh etc "Three Zone Protection By using Distance Relays in Simulink/ MATLAB" International Research Journal of Engineering and Technology (IRJET)Vol-2,Issue 05,August 2015 PP 810-819 ISSN: 2395-0072 Fast Track Publications.

[13]. M.RamBabu, Raviteja Pachipala, "Quadrature phase locked loop Based Control strategy with dual stage Conversion for Solar PV", International Journal of Pure and Applied Mathematics Vol. No.114 Issue No 8,PP- 1-11 Aug 2017. (Impact Factor:0.338) (Indexed in: Scopus/ Google scholar etc) ISSN no1311-8080 Academic publications https://acadpubl.eu/jsi/2017-114-7-ICPCIT-2017/articles/8/1.pdf

[14]. M.Rambabu, G.V.Nagesh Kumar, S.Sivanagaraju, "Optimal Operation of Real Power Generators in an Integrated Power Systems with Grey-Wolf tuned-SVC for Voltage Profile Improvement Systems", Journal of Advanced Research in Dynamical and Control Systems, jan 2019, vol. 11, no. 2, pp. 14–31(Scopus journal) https://www.jardcs.org/archivesview.php?volume=1&issue=7

[15]. B. Bajibabu Naik, M.Rambabu, "Energy Management by Using Renewable Energy Sources", International Journal of Innovative Technology and Exploring Engineering (IJITEE), Volume.8, issue no. 8, PP 315-321, June 2019 (B Impact Factor-5.54) (Indexed in: Scopus, Google scholar etc) (ISSN:2278-3075(online)) https://www.ijitee.org/portfolio-item/h6342068819/

[16]. M. Rambabu, G.V.Nagesh Kumar, S.Sivanagaraju, Control of Generation Reallocation of Integrated Energy System Using Unified Power Flow Controller", Springer Sept. 2019, vol 5. pp -337-349 DOI: https://doi.org/10.1007/978-3-030-30271-9_31

[17]. M. Rambabu, G.V. Nagesh Kumar, Polamraju V.S. Sobhan," Optimal power flow with renewable energy resources using static VAR compensator and grey wolf optimisation" International Journal of Intelligent Enterprise,Inderscience publications, Vol. 9, No. 3 pp.1-13, 18 Apr 22 ISSN: 1745-3232 [Indexed by SCOPUS, Q4), Paper link: http://dx.doi.org/10.1504/IJIE.2021.10039763