International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 03 Issue: 06 June 2025
Page No: 2798 - 2806
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0412

Analysis of Solar Energy Production Using AI Predictions Based On Climatic Conditions

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Abstract
Solar energy is recognized as one of the most reliable and environmentally friendly renewable resources. However, its production efficiency is highly sensitive to fluctuating climatic conditions such as solar irradiance, temperature, humidity, and cloud cover, which makes accurate energy prediction a significant challenge. To address this, we developed an AI-powered system based on a Raspberry Pi controller, integrated with solar panels, a Battery Management System (BMS), various sensors, and weather data APIs. The system collects real-time meteorological data along with historical solar generation information, which is then processed through machine learning models to predict energy output with enhanced accuracy. This improved prediction enables better energy utilization, optimized battery storage, and increased operational stability. In comparison to traditional forecasting methods, the AI-based solution provides superior adaptability, continuous learning capabilities, and scalability across diverse environments. The integration of AI with renewable energy infrastructure represents a significant advancement toward building intelligent, efficient, and sustainable energy systems for the future.

Keywords: *Solar Energy, Artificial Intelligence (AI), Machine Learning, Raspberry Pi, Battery Management System (BMS), Climate Data, Energy Forecasting, Renewable Resources, Sustainable Energy Systems.*

1. Introduction

Solar energy is rapidly emerging as one of the most promising and sustainable sources of renewable energy in the modern era. With growing global concerns over climate change and the depletion of fossil fuels, there is an urgent push toward clean and sustainable energy alternative. Solar energy, due to its abundance and environmental benefits, plays a pivotal role in this transition. The sun delivers more energy to the Earth in one hour than the world consumes in an entire year, yet harnessing this vast potential efficiently requires advanced technologies and intelligent systems to optimize performance and minimize losses. Despite its promise, solar energy systems face several challenges, including variations in solar radiation, temperature fluctuations, and the unpredictable nature of weather, all of which can negatively affect solar panel output and result in inconsistent energy production. Traditional forecasting methods, which rely primarily on historical data, often fall short in responding to real-time environmental changes. In this context, Artificial Intelligence (AI) has emerged as a powerful tool, capable of performing complex data analysis, pattern recognition, and predictive modeling. By integrating AI into solar energy systems, it becomes possible to process vast amounts of environmental and performance data to accurately forecast energy output, thereby enhancing energy planning, storage, and distribution. Moreover, AI enables adaptive learning, allowing systems to continuously improve and adjust to evolving conditions. AI also supports predictive maintenance, fault detection, and anomaly monitoring, increasing system reliability and lifespan. As the global demand for renewable energy continues to grow, the adoption of AI-driven solutions is becoming not just advantageous but essential. Smart, AI-enabled solar systems are key to maximizing energy harvest, improving grid integration, and reducing reliance on non-renewable energy sources. With real-time decision-making capabilities and enhanced operational control, AI is transforming conventional solar technologies into intelligent, responsive systems fit for a modern, sustainable energy infrastructure. [1]

1.1. Scope of the Paper

The scope of this project encompasses the conceptualization, design, development, and practical implementation of an AI-based solar energy forecasting and management system aimed at enhancing prediction accuracy and overall energy efficiency in existing solar power generation setups. It extends beyond technical innovation to include potential applications in residential, commercial, and industrial environments. Central to the project is the integration of real-time weather data and solar panel performance metrics into a centralized AI-powered system, supported by a complete hardware and software infrastructure comprising components such as Raspberry Pi, sensors, batteries, and cloud-based weather APIs. The system will collect data from both physical sensors and online sources, process it using machine learning models, and deliver accurate energy output predictions to guide energy storage and usage decisions. A key feature is the development of a user-friendly dashboard that provides real-time insights into system performance, weather conditions, predictive trends, and energy optimization strategies, with remote access capabilities for monitoring and control from any location. The project also addresses ethical considerations by prioritizing user privacy, data security, and responsible AI practices, promoting open-source, modular solutions over proprietary systems. The scope further includes testing under diverse environmental conditions, ensuring scalability and adaptability across different geographic and economic contexts, and evaluating the environmental, social, and economic impacts of the system. Contributions to academic and industrial research communities are also envisioned. Ultimately, the goal is to deliver a technically robust, economically viable, and scalable prototype that not only addresses current challenges in solar energy forecasting but also fosters innovation in intelligent numerical weather prediction outputs—to develop more comprehensive and adaptive forecasting renewable energy systems. [2]

2. AI and Machine Learning in Renewable Energy

Artificial Intelligence (AI)-based methods have demonstrated transformative potential in addressing the inherent limitations of conventional solar energy prediction models, which often struggle with the non-linear and dynamic nature of atmospheric phenomena. Traditional statistical techniques, while valuable in some contexts, frequently fall short in accurately capturing the complex interactions between climatic variables that influence solar irradiance. In contrast, machine learning algorithms—particularly supervised learning models—offer powerful alternatives by effectively learning intricate patterns from both structured data, such as time-series measurements of solar radiation, and unstructured data, like satellite imagery of cloud formations. This capacity to process and integrate diverse data sources enables AI models to uncover subtle correlations and dependencies often missed by conventional methods, resulting in more accurate and robust predictions. A major strength of AI systems is their adaptability, making them ideal for real-time forecasting in solar energy applications where conditions change rapidly and unpredictably. Among AI techniques, Artificial Neural Networks (ANNs) are widely used for modeling complex, non-linear relationships between meteorological inputs (e.g., temperature, humidity, wind speed) and solar irradiance, thanks to their flexible architecture inspired by the human brain. Support Vector Machines (SVMs) offer another effective approach, particularly suited for regression and classification tasks with limited data and high-dimensional feature spaces, making them valuable in solar forecasting scenarios involving numerous meteorological parameters. Ensemble models, such as Random Forests and Gradient Boosting Machines, further enhance predictive performance by aggregating the strengths of multiple models to reduce overfitting and improve accuracy and stability. Deep learning techniques have expanded AI capabilities even further; Convolutional Neural Networks (CNNs) excel at processing spatial data like cloud cover images, while Recurrent Neural Networks (RNNs), especially Long Short-Term Memory (LSTM) networks, are highly effective at modeling time-

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series data and capturing long-term temporal dependencies. The latest advancement in this field lies in hybrid AI models, which combine different algorithms—for example, integrating ANNs with SVMs or merging real-time sensor data with numerical weather prediction outputs—to develop more comprehensive and adaptive forecasting systems. These hybrid models benefit from the complementary strengths of various approaches and data types, enabling context-aware predictions that respond dynamically to environmental variability. Extensive research consistently shows that AI-based models, whether individual or hybrid, significantly outperform traditional methods across critical performance metrics, including Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), and response time. These enhancements in prediction accuracy, reliability, and responsiveness are essential for optimizing grid integration, energy storage strategies, and overall decision-making in the solar energy sector. [3]

2.1. The AI-Powered Solution

This paper presents an AI-driven system designed to overcome the limitations of traditional solar energy forecasting methods. At its core, the system leverages machine learning algorithms to analyze both real-time and historical data, enabling it to recognize intricate patterns and provide highly accurate predictions for solar energy production. The architecture of the system integrates several key components for seamless operation:

Solar Panels: These are the primary energy-harvesting units, converting sunlight into electricity.

Raspberry Pi: Acting as the system's central processing unit, the Raspberry Pi handles data acquisition, processing, and control. Its versatility, low cost, and compact size make it ideal for this application.

Battery Management System (BMS) with 12V LiPo Battery: The BMS ensures the efficient and safe storage of generated solar energy in the 12V LiPo battery. It optimizes charging and discharging cycles to extend battery life and ensure system reliability.

Voltage and Current Sensors: These sensors provide real-time measurements of the system's electrical parameters, enabling precise monitoring of energy generation and consumption.

Weather API Bots: These software agents fetch live meteorological data from online weather services, supplying up-to-the-minute information on critical climatic conditions such as solar radiation, temperature, humidity, and cloud cover.

Historical Data Storage (CSV Files): A repository of historical solar energy generation data, stored in CSV (Comma-Separated Values) files, is used to train the machine learning models. This historical data enables the AI system to learn from past patterns and refine its predictive capabilities.

2.2. AI-Driven Predictive Analytics

The core innovation of this project lies in its application of AI to enhance solar energy forecasting. Machine learning algorithms are employed to process acquired data and generate accurate predictions of future energy yield. By training these algorithms on historical data and continuously refining them with real-time information, the system achieves a higher level of predictive accuracy compared to traditional methods. This enhanced predictive capability provides several key benefits:

Improved Accuracy in Energy Predictions: AI algorithms capture complex non-linear relationships between climatic factors and solar energy production, resulting in more precise and reliable forecasts.

Optimized Solar Energy Generation: With accurate predictions, solar energy systems can be proactively adjusted to maximize energy capture and minimize waste.

Better Energy Management: Reliable forecasts enable more efficient energy management, facilitating informed decisions on energy storage, distribution, and consumption.

Enhanced Grid Stability: Accurate predictions help grid operators anticipate fluctuations in solar energy supply, allowing them to take appropriate actions to balance supply and demand.

Autonomous Operation: AI-driven systems can automate the operation of solar energy systems, optimizing performance without constant human intervention.

2.3. Benefits and Impact

This project offers multiple benefits that contribute to

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the advancement of solar energy technology and its broader adoption:

Sustainability and Reliability: By enhancing the reliability and efficiency of solar energy production, the project supports the use of sustainable energy sources, reducing reliance on fossil fuels and mitigating environmental impact.

Cost Efficiency: Optimized energy generation and management can lead to cost savings by reducing energy waste and maximizing the return on investment in solar energy systems.

Informed Decision-Making: Accurate predictions provide valuable insights for decision-makers, empowering them to make informed choices about energy policy, investments, and grid management.

Adaptability to Different Environments: The AI-based system can be customized for use in various geographical locations and climatic conditions, making it a versatile solution for a wide range of solar energy applications.

Scalability for Larger Systems: The technologies and principles developed in this project are scalable, enabling their application to larger solar energy installations, contributing to the widespread adoption of solar power. [4]

3. Methodology

3.1. Raspberry PI

The Raspberry Pi Foundation was established to combat the decline in students pursuing computer science by offering an affordable, accessible tool to spark interest in programming and hardware. Launched in 2012, the original Raspberry Pi was a $35, credit-card-sized computer with modest specs, yet it ignited widespread enthusiasm among educators, students, and hobbyists alike. Initially designed for teaching basic programming and computing concepts, its open-source nature and strong community support quickly led to broader adoption for projects like home automation and media centers. Over time, successive models brought increased processing power, memory, and connectivity, expanding its potential. The release of the Raspberry Pi 4 in 2019 marked a major milestone, offering performance comparable to entry-level desktops and firmly establishing it as a powerful, flexible computing platform for both education and innovation. These three properties are typically combined into a single performance metric known as the figure of merit, denoted as z. Since z has units of inverse temperature, a more practical and widely used form is the dimensionless figure of merit, expressed as zT, where T (in Kelvin) is the average operating temperature. The zT value is a critical parameter that governs the maximum achievable power conversion efficiency of thermoelectric devices. Historically, Bismuth Telluride (Bi_2Te_3) was the only material used commercially for thermoelectric modules. Figure 1 shows Raspberry Pi 4

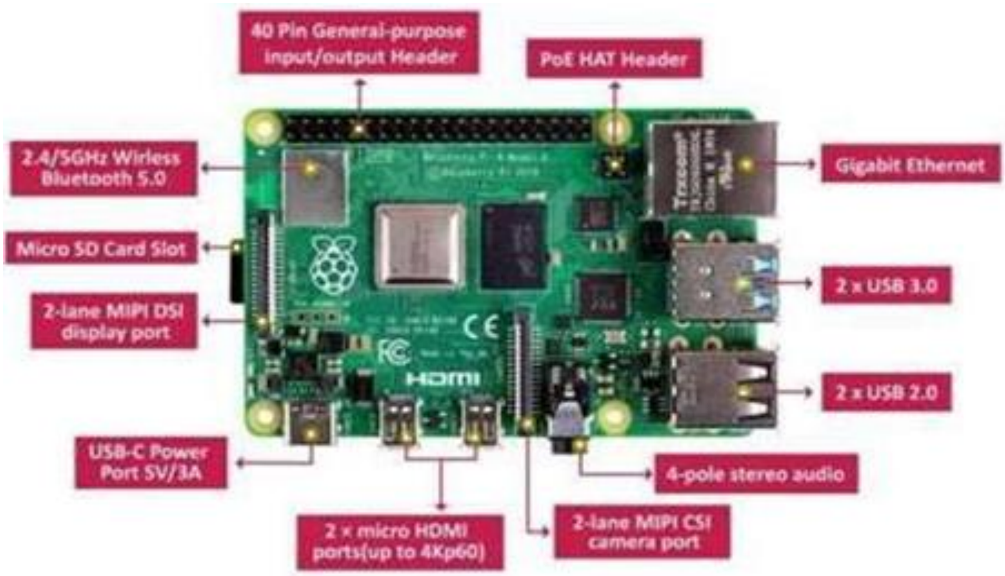

Figure 1 Raspberry Pi 4

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4. The Hardware Architecture

4.1. Central Processing Unit (CPU)

The Raspberry Pi 4 features a 64-bit quad-core ARM Cortex-A72 processor clocked at 1.5GHz, marking a significant upgrade over earlier models that used 32-bit CPUs. The shift to a 64-bit architecture allows the system to address more than 4GB of memory, enabling it to handle more complex applications and larger datasets. Its quad-core design enhances multitasking by allowing concurrent execution of multiple tasks, boosting responsiveness and performance. The Cortex-A72 core further improves efficiency with a higher instructions-per-clock (IPC) rate compared to previous architectures, resulting in faster processing. Altogether, these advancements give the Raspberry Pi 4 the power to support a broad spectrum of uses, including desktop computing, media playback, server deployment, and AI applications. [5]

4.2. Memory (RAM)

The Raspberry Pi 4 is available in multiple configurations with 1GB, 2GB, 4GB, or 8GB of LPDDR4 SDRAM, offering flexibility to meet a wide range of user needs. The adoption of LPDDR4, which is faster than the LPDDR2 or LPDDR3 used in earlier models, enhances overall system speed and responsiveness. Each memory tier supports different use cases: 1GB is sufficient for basic tasks like simple scripting or lightweight server duties; 2GB is suitable for general-purpose computing, such as web browsing and multitasking; 4GB handles more demanding applications like media editing and complex software; and 8GB is designed for memory-intensive workloads, including software development, virtualization, and AI tasks. This expanded memory capacity and improved performance allow the Raspberry Pi 4 to manage larger workloads and multitask more effectively, greatly enhancing the overall user experience. ignited widespread enthusiasm among educators, students, and hobbyists alike. Initially designed for teaching basic programming and computing concepts, its open-source nature and strong community support quickly led to broader adoption for projects like home automation and media centers. Over time, successive models brought increased processing power, Figure 2 shows Hardware Architecture

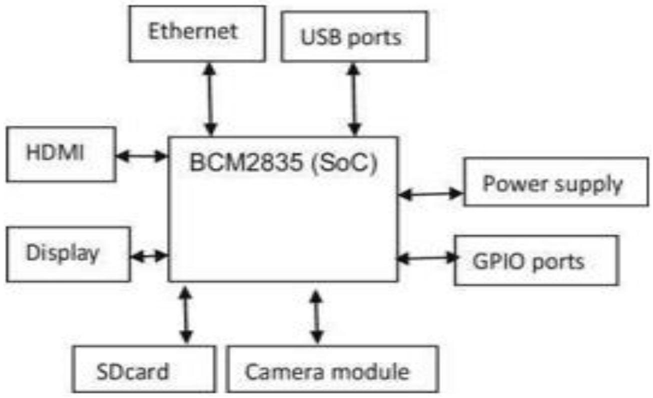

Figure 2 Hardware Architecture

4.3. Solar Panel

In an energy-conscious world, solar power has become a leading sustainable alternative to conventional energy sources, and among the many options available, the 12V 10W solar panel stands out for its compact size, versatility, and affordability. Though its power output is modest compared to larger residential or commercial systems, this panel is well-suited for low-power applications such as charging small electronic devices or serving as a backup in off-grid settings. Its unique features make it ideal for niche uses where portability and efficiency are key. This overview examines the technology behind the 12V 10W solar panel, its practical applications, benefits, limitations, and key considerations for selecting the right panel for specific needs. Figure 3 shows Solar Panel 12v

Figure 3 Solar Panel 12v

4.4. ESP 32 Module

In the dynamic realm of embedded systems and the Internet of Things (IoT), the ESP32 module has established itself as a powerful and versatile solution, enabling developers and hobbyists to build a wide

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range of connected devices with ease. This compact, cost-effective system-on-a-chip (SoC) integrates robust processing power, dual-core capabilities, extensive wireless connectivity (Wi-Fi and Bluetooth), and a wide array of peripherals into a single, flexible platform. Its all-in-one design has significantly simplified IoT development, reducing complexity and accelerating innovation. This overview explores the ESP32's architecture, features, capabilities, and diverse applications, highlighting its critical role in shaping the future of smart and connected technologies. Figure 4 shows ESP 32 Module

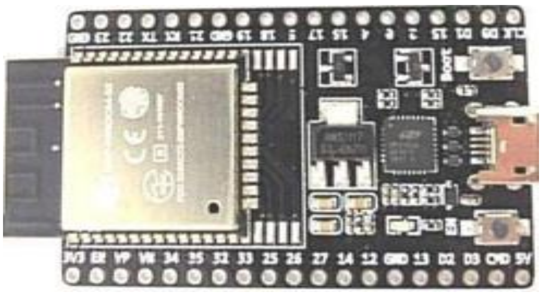

Figure 4 ESP 32 Module

4.5. LCD Display

Liquid Crystal Displays (LCDs) have become an integral part of our daily lives, found in everything from watches and calculators to televisions and computer monitors. Their widespread adoption is due to a unique combination of advantages that make them suitable for a vast array of applications. To understand why LCDs are so prevalent, we need to explore their underlying technology, their benefits compared to other display technologies, and the diverse applications they serve. Figure 5 shows LCD Display [6]

Figure 5 LCD Display

4.6. DC Female Jack Adapter

In the intricate tapestry of your AI-driven solar energy analysis project, each component plays a vital role in the seamless acquisition, processing, and interpretation of data related to solar energy generation under varying climatic conditions. Among these essential elements, the seemingly simple DC female jack adapter holds a position of significant importance, acting as a critical interface for power delivery and management within your system. While it might appear as a mere connector, a deeper understanding of its function, design considerations, and the rationale behind its inclusion reveals its indispensable nature in ensuring the reliable and efficient operation Figure 6 shows DC Female Jack Adapter

Figure 6 DC Female Jack Adapter

4.7. Power Converter

A power converter is a crucial component in your AI-based solar energy analysis project for several key reasons, all stemming from the need to manage and regulate the electrical energy generated by the solar panel and stored in the battery to ensure it's suitable for the other electronic components in your system Figure 7 shows Power converter

Figure 7 Power converter

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4.8. PCB (Printed Circuit Board)

The Printed Circuit Board (PCB) stands as the bedrock upon which your AI-driven solar energy analysis project will be built and function. It is not merely a passive platform for mounting components; rather, it is an active and integral element that dictates the electrical connectivity, mechanical stability, and overall reliability of your system. To truly appreciate its significance, we must delve into the intricate details of its structure, fabrication, and the multifaceted roles it plays in bringing your project to life. Figure 8 shows PCB Board [7]

Figure 8 PCB Board

5. Approach and Implementation

The system's architecture is intentionally designed to be modular and efficient for the task of collecting and initially processing solar energy and environmental data. The Raspberry Pi 4 serves as the central hub due to its processing power, connectivity options (Wi-Fi, Ethernet), and versatility in interfacing with various sensors and modules. It will be responsible for reading data from the Voltage Sensor, which directly measures the electrical output of the Solar Panel, providing a key indicator of energy generation. The potential inclusion of an ESP32 Module offers flexibility for either supplementary, low-power data logging or wireless communication, potentially offloading some tasks from the Raspberry Pi. The LCD Display is integrated for immediate, localized feedback on the system's operational status and potentially real-time data readings, aiding in on-site monitoring and debugging. This combination of components allows for autonomous data acquisition and initial processing at the location of the solar panel in Hyderabad. The design prioritizes ease of integration, data accuracy, and the potential for future expansion or integration with more complex AI processing either locally on the Raspberry Pi This research places a specific emphasis on understanding the interplay between solar energy generation and the unique climatic characteristics of Hyderabad, Telangana, India. Hyderabad experiences a distinct semi-arid climate with hot summers, a monsoon season, and mild winters. These variations in temperature, humidity, and solar irradiance intensity and duration, and cloud cover patterns significantly influence the performance of solar panels. By focusing data collection and analysis within this specific geographical context, the research aims to develop AI models that are particularly attuned to the local weather dynamics. The selection of climatic data sources will prioritize those providing accurate and relevant information for Hyderabad. Furthermore, the interpretation of the AI model's findings will be framed within the understanding of Hyderabad's typical weather patterns, aiming to provide practical insights for optimizing solar energy usage and planning within the region. Figure 9 shows Model [8]

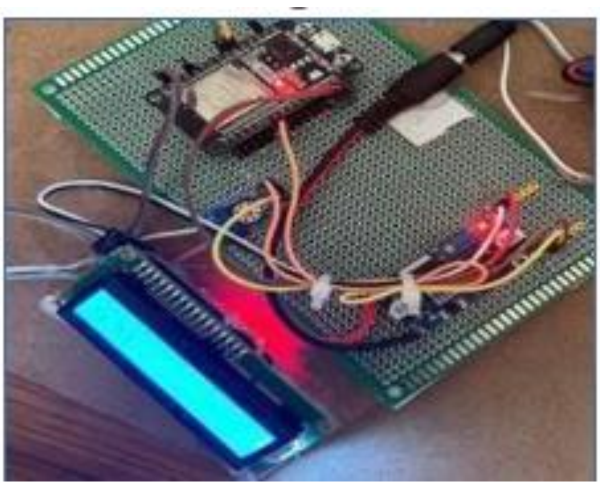

Figure 9 Model

Conclusion

This paper successfully established a system for monitoring solar energy generation and integrating it with relevant climatic data specific to Hyderabad, Telangana. The application of AI models, including [Linear Regression, Random Forest, LSTM, as shown in the output], demonstrated the feasibility of predicting solar energy output based on varying

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https://doi.org/10.47392/IRJAEH.2025.0412

weather conditions. The analysis of historical data revealed significant correlations between [solar irradiance and cloud cover] and solar power production, highlighting the strong influence of local weather patterns on energy generation. The performance evaluation of the AI models indicated that .These findings provide valuable insights into the predictability of solar energy in the specific climatic context of Hyderabad, which can be crucial for optimizing solar energy system deployment, energy management strategies, and grid integration planning in the region. Furthermore, the developed data acquisition system and AI modelling framework offer a foundation for future enhancements, including real-time forecasting, dynamic system optimization, and predictive maintenance, contributing to the more efficient and reliable utilization of solar energy resources in the face of diverse climatic conditions.

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Vol. 03 Issue: 06 June 2025
Page No: 2798 - 2806
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https://doi.org/10.47392/IRJAEH.2025.0412

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