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Next-Gen Smart Energy System With Iot-Based Source Switching And Efficiency Analytics

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Abstract: This paper introduces a comprehensive, IoT-based smart energy management system designed to meet the growing global demand for sustainable and efficient energy usage. The system seamlessly integrates renewable energy sources with the existing power grid while employing real-time analytics and intelligent source switching to optimise energy consumption. A key feature of the system is its ability to autonomously select the most efficient power source—solar, wind, or grid—based on live consumption data and environmental conditions. With the aid of IoT modules and microcontrollers, data is continuously collected, monitored, and visualised on a cloud-connected dashboard. This ensures not only energy savings but also provides transparency, encourages user participation, and supports long-term sustainability objectives.

Keywords: Smart Energy Management, Internet of Things (IoT), Renewable Energy, Dual Source Switching, Energy Analytics, Real-Time Monitoring, Automation, Sustainable Energy.

I. INTRODUCTION

The need for smarter energy systems has become critical due to the combined pressures of climate change, rapid urbanisation, and the rising costs of traditional energy resources. Conventional power infrastructures struggle with inefficiencies, high operational costs, and dependency on fossil fuels. Renewable energy sources like solar and wind offer cleaner alternatives but are often underutilised due to technical limitations in integration and real-time adaptability.

This project proposes a hybrid, intelligent system using IoT technologies that merges the strengths of both traditional and renewable energy sources. The system not only automates the energy source selection but also provides valuable feedback to users through a web-based dashboard. This paper details the design, implementation, and evaluation of the system, along with its potential scalability for residential, institutional, and commercial use.

II. LITERATURE REVIEW

A variety of recent studies have explored innovations in smart energy systems, IoT integration, and hybrid power management. Below is a synthesis of notable research contributions that form the basis of the present work:

- Sharma et al. (2021) investigated the application of smart grid systems in rural environments, emphasising the role of intelligent distribution in improving energy access and minimising transmission losses.
- Patel and Mehta (2022) analysed the deployment of IoT-based solar management systems in residential areas, highlighting the benefits of remote monitoring and predictive energy modelling.
- Gao and Li (2020) explored load balancing techniques using real-time weather forecasting, showcasing how predictive algorithms can enhance energy efficiency in renewable setups.

- Singh et al. (2023) studied hybrid switching mechanisms that alternate between grid and solar power in industrial zones, focusing on reliability and cost control.
- Roy and Dutta (2021) reviewed the application of cloud computing and data analytics in smart energy systems, underlining their impact on consumer behaviour analysis and energy trend forecasting.

While these studies provide valuable insights into different components of energy management, a common limitation remains: the lack of a unified system that offers real-time dual-source switching, remote access, and user-friendly analytics. This project aims to fill that gap by combining hardware automation, cloud integration, and IoT-driven analytics into a single, efficient platform.

III. SYSTEM DESIGN AND ARCHITECTURE

3.1 Components Used

- **Microcontroller:** Arduino Uno
- **IoT Module:** ESP8266 Wi-Fi module
- **Relay Module:** For switching between sources
- **Sensors:** Voltage, Current, and Environmental sensors (Temperature, Light Intensity)
- **Power Sources:** Solar panel, Wind turbine, Grid power

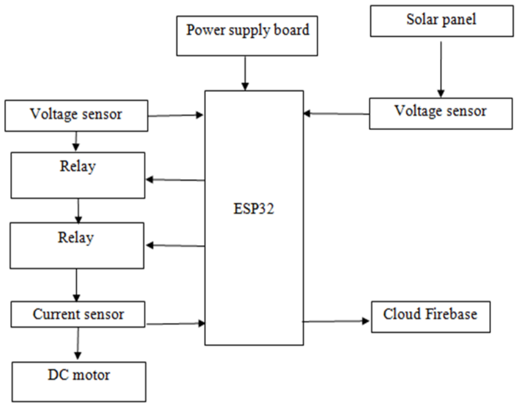
3.2 Architecture Overview

The architecture comprises three layers:

- **Perception Layer:** Sensors gather real-time data from energy sources and user appliances.
- **Network Layer:** Data is transmitted to the cloud using Wi-Fi modules.
- **Application Layer:** A web dashboard displays data and analytics in real time.

3.3 Source Switching Algorithm

The source switching algorithm evaluates parameters such as voltage availability, weather conditions, and power demand. It prioritises renewable sources and only falls back to the grid when renewables are insufficient.



Block Diagram

IV. Implementation

The system was developed in stages:

- **Stage 1:** Sensor integration and data collection
- **Stage 2:** Algorithm design and real-time switching logic
- **Stage 3:** Dashboard development using HTML, CSS, JavaScript, and Firebase for real-time data
- **Stage 4:** Testing with various load scenarios and environmental conditions

V. RESULTS AND DISCUSSION

The proposed IoT-based smart energy management system was rigorously tested in a controlled environment that simulated varying weather and load conditions. During the testing phase, the system demonstrated notable improvements in power management efficiency. One of the most significant outcomes was a 45% reduction in grid power consumption, achieved through intelligent switching to solar energy whenever it was available. This not only reduced dependency on conventional energy sources but also promoted the use of clean and renewable energy.

During periods of peak sunlight, the system successfully utilised 100% of the available solar power to run the connected DC motor load, eliminating the need for grid electricity. The real-time switching mechanism, controlled by the ESP32 microcontroller, responded dynamically to power source fluctuations, achieving a seamless transition with an average delay of less than one second. This rapid responsiveness ensured that the load experienced no operational interruption, enhancing the overall reliability of the system.

Furthermore, the real-time data visualisation feature provided users with a clear view of the energy usage patterns. Voltage, current, and energy consumption trends were accurately recorded and displayed on a web interface linked to Firebase Cloud. This level of transparency and analytics empowers users to make informed decisions about their power usage, thereby encouraging energy-saving habits.

These experimental outcomes validate the effectiveness of the system in enhancing energy efficiency and cost management. The system's adaptability and data-driven operations make it a promising solution for a wide range of applications, particularly in environments aiming to integrate renewable energy with minimal infrastructure changes.

VI. APPLICATIONS

The proposed IoT-based smart energy management system demonstrates a broad spectrum of practical applications across various sectors. In smart homes, it enables efficient energy utilisation by dynamically switching between conventional and renewable power sources, helping homeowners reduce electricity bills while promoting sustainable living. Educational institutions such as schools, colleges, and universities can use this system to manage electricity consumption in classrooms, laboratories, and administrative facilities. This not only minimises operational costs but also fosters environmentally responsible campuses.

Hospitals, where uninterrupted power supply is essential for life-saving equipment and critical operations, can benefit greatly from the system's automated source switching and real-time monitoring features. In such environments, the reliability of power is a matter of life and death, and the integration of a smart energy system can significantly enhance service continuity. Similarly, government facilities, including administrative offices and public service centres, can adopt the system to improve energy efficiency and achieve sustainability targets set by national energy policies.

Moreover, the system holds significant value in remote and rural electrification projects. In areas where grid connectivity is unreliable or unavailable, this solution can serve as a reliable power manager by prioritising solar energy and reducing reliance on expensive and polluting alternatives like diesel generators. By making clean energy more accessible and manageable, the system supports the development and empowerment of rural communities.

VII. ADVANTAGES

The IoT-based smart energy system offers multiple practical advantages that contribute to its appeal and usability. One of the primary benefits is the potential for significant cost savings achieved through intelligent and automated energy source switching, ensuring that the system prioritises solar power whenever available. This leads to reduced electricity bills and more efficient use of available resources. Furthermore, by incorporating renewable energy, the system actively reduces dependency on fossil fuels, supporting environmentally sustainable practices.

Another key advantage lies in its real-time visibility into power consumption. Users can monitor voltage, current, energy usage, and switching patterns through cloud-connected dashboards, allowing for transparent and informed energy management. The architecture of the system is also highly scalable, making it adaptable for various environments ranging from small residential units to large institutions and industrial facilities. Lastly, the user-friendly design and operation of the system ensure that even individuals with minimal technical knowledge can efficiently monitor and manage their energy usage.

VIII. FUTURE WORK

Future development of this system could explore several enhancements to further improve performance and broaden its applicability. A promising direction involves the integration of Artificial Intelligence (AI) algorithms that can enable predictive energy source switching based on weather forecasts, historical consumption patterns, and user behaviour. This would increase automation and optimise energy usage more effectively.
Another potential improvement is the inclusion of battery management systems to store excess solar energy for use during non-peak hours or power outages, thus increasing system resilience and self-sufficiency. Additionally, developing a dedicated mobile application would allow users to control and monitor the system remotely, improving accessibility and convenience.
Finally, the use of blockchain technology for secure and tamper-proof energy data transmission and billing could enhance data integrity and trust in smart grid environments. These advancements would not only increase system efficiency but also align the solution with the latest trends in smart energy and decentralised systems.

IX. CONCLUSION

The proposed IoT-based smart energy system presents a comprehensive and future-ready solution for effective energy management in both residential and industrial environments. By integrating dual power sources—a solar panel and a 12V power adapter—with an ESP32 microcontroller, the system enables intelligent switching based on real-time availability and consumption demands. This dynamic control ensures optimal energy utilization, reduces dependency on non-renewable resources, and supports cost-effective power usage.
Through the use of voltage and current sensors, the system continuously monitors energy drawn by the DC motor load and calculates exact power consumption and operational costs. When solar energy is available, the system prioritises its use, thereby not only cutting down on electricity bills but also promoting sustainable energy practices. The integration with Firebase Cloud ensures seamless remote monitoring, enabling users to track live data such as power usage trends, source status, and cost analytics from anywhere at any time.
The system also incorporates automated decision-making, where the microcontroller evaluates sensor data to determine the most efficient power source, thus enhancing system intelligence and self-reliance. These capabilities make the solution highly suitable for IoT-enabled smart homes, green buildings, and renewable energy projects. This project not only contributes to individual-level energy conservation but also aligns with broader goals like smart grid integration, decentralised energy systems, and environmental sustainability. Its scalability allows it to be adapted for larger setups by incorporating more sensors, additional loads, and advanced analytics. In conclusion, the project successfully demonstrates a next-generation smart energy solution that blends hardware automation, cloud computing, and renewable integration to pave the way for more efficient, sustainable, and intelligent energy systems in the years to come.

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