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Original Research Article

Exploration of the connection and effective management utilization between smart home systems and renewable energy devices

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Abstract: This paper explores the connection and effective management of smart home systems with renewable energy devices. Analyzing the current status of connections and existing issues, it proposes effective management strategies such as energy monitoring and data analysis, energy storage system management, and device operation control. Through two practical case studies, the paper validates the feasibility and benefits of the collaborative application of smart homes and renewable energy devices. Research indicates that by unifying communication protocols, applying middleware, and leveraging Internet of Things (IoT) technologies, combined with intelligent management strategies, the utilization efficiency of renewable energy in smart homes can be significantly improved, achieving energy-saving and environmental protection goals. Finally, the paper looks ahead to future development trends, pointing out that the deeper integration of artificial intelligence technologies and the improvement of industry standards will further promote the integrated development of smart homes and renewable energy.

Keywords: Smart home systems; Renewable energy; Energy management; Sustainable development

1. Introduction

In the context of the increasingly severe global energy crisis and environmental problems, the development and utilization of renewable energy have drawn extensive attention. Renewable energy sources like solar energy and wind energy, with their clean and sustainable characteristics, are gradually emerging as crucial alternatives to traditional energy.

At the same time, smart home systems are witnessing rapid proliferation. They have evolved from simply offering individual products to sophisticated intelligent systems where various products are interconnected. These systems are designed to create a more convenient, comfortable, and intelligent living environment for people[1]. Notably, smart home technologies play a vital role in energy management. They not only significantly enhance living comfort, energy efficiency, and security but also optimize the utilization efficiency and functionality of living spaces[2]. More importantly, smart home systems are capable of integrating comprehensive energy management functions, enabling precise optimization and meticulous management of energy supply and consumption[3].

When smart home systems are connected with renewable energy equipment, a host of benefits ensue. Firstly, it can effectively boost the utilization efficiency of renewable energy, maximizing the value of these clean energy sources. Secondly, it helps reduce households' reliance on traditional energy, thereby alleviating the pressure on the existing energy supply structure. Moreover, such a connection can further strengthen the energy-saving and environmental protection attributes of smart homes, ultimately realizing intelligent and efficient management of home energy utilization. This integration holds great practical significance in today's pursuit of sustainable development.

2. Current situation of the connection between smart home systems and renewable energy equipment

Currently, some smart home systems have begun to attempt to connect with solar and wind energy equipment. The common connection methods mainly achieve simple data interaction through sensors and controllers. For example, the inverters in solar photovoltaic power generation systems can be equipped with communication interfaces to transmit data such as power generation capacity and electricity quantity to the central control system of the smart home. Then, the central control system conducts simple equipment regulation based on this information. For instance, when solar power generation is sufficient, solar energy will be given priority to supply power to smart home equipment, and the opening and closing of some non-critical equipment will be controlled.

However, there are still numerous challenges in the connection between smart home systems and renewable energy equipment. Firstly, the communication protocols are not unified. Different brands and types of renewable energy equipment, as well as smart home equipment, often adopt their communication protocols, which creates relatively large obstacles to their interconnection. For example, the monitoring data format of a certain brand's solar panels may not match the format supported by the smart home central control system, resulting in the inability to accurately transmit and analyze the data and thus affecting the collaborative work of the two.

Secondly, equipment compatibility is limited. Due to differences in technical standards and design concepts, many renewable energy equipment and smart home systems have poor compatibility at the hardware and software levels. Some old smart home equipment may not be able to recognize the access of new renewable energy equipment, or there may be abnormal functions after connection, which restricts the expansion and optimization of the overall system.

Finally, there is a lack of an intelligent management mechanism. Most of the existing connections only achieve basic data transmission and simple control and lack a perfect intelligent management mechanism to conduct comprehensive consideration and refined regulation based on multiple factors such as the real-time generation situation of renewable energy, household electricity demand and the state of energy storage equipment, resulting in the utilization efficiency of renewable energy still needing to be improved.

3. Effective management strategies for renewable energy

3.1. Energy monitoring and data analysis

By leveraging the interconnectivity between smart home systems and renewable energy devices, sensors are employed to monitor real-time data such as renewable energy output (e.g., solar power generation and wind energy output), household electricity consumption, and energy storage device capacity. The collected data is transmitted to a centralized management platform. Taking solar photovoltaic (PV) systems as an example, each solar panel is equipped with a power sensor to monitor dynamic changes in its power generation performance.

Leveraging big data analytics, this study conducts an in-depth analysis of historical and real-time monitoring data to uncover intrinsic patterns in energy generation and consumption. By integrating external data sources such as weather forecasts, we develop short-term and medium-term prediction models for renewable energy output. For instance, combining local meteorological data with historical solar power generation profiles enables precise forecasting of photovoltaic output variations over the upcoming days. This predictive capability provides critical technical support for developing proactive energy dispatch plans, thereby optimizing grid stability and resource allocation efficiency. The methodology particularly emphasizes temporal resolution enhancement and uncertainty quantification in renewable energy prediction through multi-source data fusion.

3.2. Energy storage system management

In smart home environments, efficient utilization of energy resources not only facilitates cost savings and enhances sustainability, but also significantly reduces carbon emissions[4]. Therefore, it is imperative to rationally select the type, capacity, and quantity of energy storage equipment (e.g., lithium-ion batteries, lead-acid batteries) based on household energy demands and the power generation capacity of renewable energy installations. For instance, households with abundant solar power generation but substantial nighttime electricity consumption requirements could deploy high-capacity lithium battery energy storage systems to store surplus daytime energy for nocturnal utilization.

Concurrently, scientific charge- discharge control strategies for energy storage devices should be established. The system can provide users with operational guidance for optimizing solar photovoltaic system utilization, encouraging rational scheduling of appliance usage to avoid peak consumption periods, thereby achieving maximal energy utilization efficiency and conservation[5]. Priority should be given to charging energy storage devices during periods of renewable energy surplus. Conversely, during renewable energy shortages or household electricity demand peaks, controlled discharge of stored energy should be implemented to ensure a stable power supply and enhance renewable energy utilization efficiency. A practical implementation example would involve setting thresholds where excess solar generation exceeding instantaneous household demand by a specified percentage triggers battery charging, while prioritized discharge sequencing from energy storage batteries is activated during nighttime demand peaks when solar generation ceases.

3.3. Equipment operation control

For various smart home devices, priority classification is implemented based on their operational criticality and power consumption requirements. When renewable energy generation is limited, essential equipment (e.g., refrigerators, lighting systems, and other life-sustaining devices) will be prioritized for power supply, while non-critical devices (e.g., smart curtain motors, decorative lighting) will be temporarily suspended or operated at reduced power levels. For instance, under conditions of insufficient wind power generation, the smart home system automatically deactivates ambient lighting in living areas while maintaining normal operation of refrigeration equipment.

Intelligent scenario coordination is established according to temporal variations, meteorological conditions, and household activity patterns. During daylight hours, with sufficient solar radiation and unoccupied premises, the system automatically adjusts curtain positions to optimize photovoltaic panel exposure while deactivating non-essential electrical appliances. As solar generation diminishes during evening hours, the system activates low-power lighting configurations to establish appropriate indoor ambiance, concurrently regulating other equipment operations based on the energy storage system status. This dynamic control mechanism ensures optimal balance between energy supply-demand equilibrium and user comfort requirements.

4. Case studies on prioritized utilization of renewable energy

4.1. Case study 1: An Eco-conservation-oriented residential community

Located in a region characterized by abundant solar radiation resources and stable wind conditions, this residential community demonstrates exceptional potential for renewable energy utilization. The area maintains an annual average sunshine duration of approximately 2,000 hours and an annual average wind speed range of 3–5 m/s. Developed under the philosophy of ecological conservation, the community aims to establish a highly self-sufficient, green, and low-carbon living environment. A pilot project involving 50 households was implemented to integrate smart home technologies with renewable energy systems. Each residence is equipped with a smart home system and a hybrid solar-wind power generation infrastructure.

In terms of renewable energy equipment configuration, a solar photovoltaic power generation system and small-scale wind power generation equipment have been deployed. Each residential rooftop is equipped with a solar panel array averaging 8 kW in power output, comprising 32 monocrystalline silicon solar panels. Each panel has a rated power of 250 watts, dimensions of 1640×992×40 mm, and achieves a photoelectric conversion efficiency of approximately 20%. These panels incorporate advanced surface coating technology to minimize dust accumulation and enhance light absorption, ensuring stable power generation performance over extended operational periods. The system employs a Huawei SUN2000-8KTL-M1 inverter with a maximum conversion efficiency of 98.6%, featuring an input voltage range of 150–1000 V and an output voltage of 220 V. This inverter integrates intelligent monitoring and communication capabilities, converting direct current (DC) to alternating current (AC) while transmitting real-time operational data, including power output, cumulative energy generation, voltage, and current—to the smart home system at 5-second intervals. This ensures continuous monitoring of solar power generation status. Additionally, a multi-angle adjustable bracket system (0–60° tilt range), integrated with an intelligent solar tracking system, automatically optimizes panel orientation every 15 minutes based on solar positioning. This dynamic adjustment maintains near-vertical alignment with sunlight, enhancing power generation efficiency by approximately 25% compared to traditional fixed-angle installations.

A small-scale wind turbine with a rated power of 3 kW was installed in the open area of a residential courtyard. The turbine features a rotor diameter of 4 meters, with blades manufactured from glass fiber-reinforced plastic (GFRP) using advanced aerodynamic design principles. This material combination ensures superior strength and flexibility, enabling efficient power generation at low wind speeds (cut-in wind speed as low as 2.5 m/s). The turbine achieves full power output at the rated wind speed of 10 m/s and demonstrates structural resilience with a maximum survivable wind speed of 50 m/s, ensuring stable operation under complex wind conditions.

The system incorporates a high-precision anemometer with 0.1 m/s measurement accuracy for real-time wind speed monitoring. An integrated power monitoring module updates electrical output data at a 1 Hz frequency, while a Zigbee wireless communication protocol transmits real-time parameters, including wind speed and power generation, to the smart home system for comprehensive energy management. To ensure structural stability and operational safety, the turbine is mounted on a 10-meter tower constructed from Q235 steel. The foundation employs a cylindrical concrete structure with a 2-meter diameter and 1.5-meter depth, engineered to withstand local wind loads and external mechanical stresses.

5. Conclusions and outlook

This study investigates the integration and effective management of smart home systems with renewable energy devices such as solar and wind power. It analyzes existing challenges, explores key technologies and management strategies, and validates their feasibility and effectiveness through practical case studies. By adopting unified communication protocols, middleware, and IoT technologies, seamless connectivity can be achieved. Furthermore, energy monitoring, storage management, and device regulation strategies significantly enhance the utilization efficiency of renewable energy in smart homes, thereby advancing energy conservation and environmental sustainability goals.

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