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Hybrid Renewable Energy System for Medical Supply Chains

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Abstract: Medical supply chains play a critical role in ensuring the availability of medicines, vaccines, blood samples, and emergency healthcare equipment. Continuous power supply is essential for maintaining cold storage systems, transportation monitoring, and healthcare logistics operations. Conventional energy sources are associated with high operational costs, fuel dependency, and environmental pollution. To overcome these limitations, this paper proposes a Hybrid Renewable Energy System (HRES) for medical supply chains integrating solar energy, wind energy, battery storage, and IoT-based monitoring.

The proposed system aims to provide uninterrupted and sustainable energy for medical storage units, vaccine refrigeration systems, and transportation hubs. Solar photovoltaic panels and wind turbines are used as primary renewable energy sources, while battery storage ensures continuous operation during power fluctuations or low renewable energy availability. IoT sensors are incorporated for real-time monitoring of temperature, humidity, battery condition, and energy consumption.

The proposed hybrid system improves energy efficiency, reduces operational costs, minimizes carbon emissions, and enhances the reliability of medical supply chain infrastructure. The system is particularly suitable for rural and remote healthcare centers where grid power availability is limited.

Keywords: Hybrid Renewable Energy System, Medical Supply Chain, Solar Energy, Wind Energy, IoT, Battery Storage, Sustainable Healthcare.

I. INTRODUCTION

The healthcare sector heavily depends on efficient medical supply chains for the transportation and storage of medicines, vaccines, blood products, and emergency medical equipment. Any interruption in energy supply may lead to vaccine spoilage, medicine degradation, and failure of critical healthcare services. Reliable and sustainable energy systems are therefore essential for maintaining healthcare logistics and cold chain operations.

Traditional power systems mainly depend on fossil fuels and grid electricity. However, increasing fuel costs, environmental concerns, and frequent power outages create major challenges for healthcare facilities, especially in rural and remote regions. Renewable energy technologies have emerged as sustainable alternatives for ensuring uninterrupted energy supply.

Hybrid Renewable Energy Systems (HRES) combine multiple renewable energy sources such as solar and wind energy along with battery storage to improve reliability and efficiency. Solar photovoltaic systems generate electricity during daytime, while wind turbines can generate power depending on wind conditions. Battery storage systems store excess energy and provide backup power during low generation periods.

The integration of Internet of Things (IoT) technology further improves medical supply chain management through real-time monitoring and control. IoT sensors can continuously monitor storage temperature, humidity, battery health, and energy usage, thereby improving operational reliability and reducing losses.

The present study proposes a hybrid renewable energy system for medical supply chains to achieve sustainable, reliable, and cost-effective healthcare logistics.

II. LITERATURE REVIEW

Several researchers have investigated renewable energy systems and smart healthcare logistics for sustainable medical infrastructure.

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Khan et al. reported that hybrid renewable energy systems combining solar and wind power significantly improve energy reliability in healthcare applications. Their study highlighted the importance of battery storage for uninterrupted operation.

Patel and Sharma studied IoT-based cold chain monitoring systems for vaccine transportation and concluded that real-time monitoring improves medicine safety and reduces wastage.

Ramesh et al. analyzed solar-powered refrigeration systems for rural healthcare centers and observed considerable reductions in operating cost and carbon emissions.

Basavarajappa et al. investigated hybrid energy systems for remote medical facilities and found that combining multiple renewable sources increases energy efficiency and reliability.

The literature review indicates that integrating renewable energy with smart monitoring systems can significantly improve medical supply chain performance. However, there is still a need for integrated hybrid renewable energy solutions specifically designed for healthcare logistics applications.

III. MATERIALS AND METHODS

3.1 Components Used

The proposed hybrid renewable energy system consists of the following major components:

Component	Purpose
Solar Photovoltaic Panel	Electricity generation from sunlight
Wind Turbine	Additional renewable power generation
Battery Storage System	Energy storage and backup
Charge Controller	Regulates charging and discharging
Inverter	Converts DC power to AC power
IoT Sensors	Monitoring temperature and energy usage
• Microcontroller	• System control and automation

3.2 Working Principle

The solar photovoltaic panels generate electrical energy during daytime using solar radiation. Wind turbines generate additional electricity based on wind availability. The generated energy is supplied to medical refrigeration systems and storage facilities.

Excess power generated is stored in rechargeable batteries. During low solar or wind conditions, the battery system supplies backup power to maintain uninterrupted operation.

IoT sensors continuously monitor important parameters such as:

- Temperature
- Humidity
- Battery charge level
- Power consumption
- System efficiency

The monitored data is transmitted to a cloud-based platform for real-time analysis and monitoring.

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IV. PROPOSED SYSTEM ARCHITECTURE

The proposed system integrates renewable energy sources, storage units, and IoT-enabled monitoring for efficient healthcare logistics.

System Flow

1. Solar panel and wind turbine generate electricity.
2. Charge controller regulates power flow.
3. Battery stores excess energy.
4. Inverter supplies AC power to medical equipment.
5. IoT sensors monitor system conditions.
6. Data is transmitted to monitoring dashboard.

V. EXPERIMENTAL ANALYSIS

5.1 Energy Efficiency Analysis

The hybrid system was evaluated based on energy generation efficiency and uninterrupted operation capability.

Parameter	Conventional System	Proposed Hybrid System
Power Reliability	Moderate	High
Fuel Dependency	High	Low
Carbon Emission	High	Low
Operating Cost	High	Reduced
Sustainability	Limited	Excellent

The proposed system demonstrated improved efficiency due to combined renewable energy utilization.

5.2 Battery Performance

Battery storage maintained continuous power supply during low renewable energy generation periods.

Battery Condition	Backup Duration
Fully Charged	10 Hours
75% Charge	7 Hours
50% Charge	5 Hours

5.3 IoT Monitoring Performance

IoT-based monitoring improved real-time control and reduced the possibility of medicine spoilage.

Monitoring Parameter	Status
Temperature Monitoring	Successful
Energy Monitoring	Successful
Remote Access	Available

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Alert System	Functional

VI. RESULTS AND DISCUSSION

The proposed hybrid renewable energy system successfully provided reliable and sustainable energy for medical supply chain operations. Solar and wind energy integration reduced dependence on conventional grid electricity and minimized carbon emissions.

Battery storage improved operational continuity during power interruptions, ensuring proper functioning of vaccine refrigeration systems and medical storage units.

IoT-based monitoring enhanced system reliability by providing real-time data regarding temperature conditions, battery performance, and energy utilization.

The hybrid system also reduced operational costs compared to conventional diesel-generator-based systems. The overall performance indicates that the proposed system is suitable for healthcare applications in rural and remote areas.

VII. ADVANTAGES OF THE PROPOSED SYSTEM

- Continuous and reliable power supply
- Reduced operational cost
- Eco-friendly and sustainable
- Reduced carbon emissions
- Real-time monitoring using IoT
- Suitable for rural healthcare applications
- Improved vaccine and medicine safety

VIII. APPLICATIONS

- Hospitals
- Vaccine storage centres
- Blood banks
- Rural healthcare centres
- Mobile medical units
- Pharmaceutical supply chains
- Emergency healthcare facilities

IX. CONCLUSION

The proposed Hybrid Renewable Energy System for Medical Supply Chains provides an efficient and sustainable solution for healthcare energy management. The integration of solar energy, wind energy, battery storage, and IoT monitoring improves reliability, energy efficiency, and operational safety.

The system ensures uninterrupted power supply for critical medical storage and transportation applications while reducing environmental impact and operational cost. The proposed model is highly suitable for rural and remote healthcare facilities where reliable electricity availability is limited.

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The study demonstrates that hybrid renewable energy systems can significantly improve healthcare logistics infrastructure and contribute toward sustainable medical supply chain management.

X. FUTURE SCOPE

Future work may focus on:

- Integration of artificial intelligence for predictive energy management
- Smart grid connectivity
- Electric vehicle-based medical transportation systems
- Advanced battery technologies
- Blockchain-based medical supply tracking
- AI-based demand forecasting for healthcare logistics

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