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IoT-Based Energy Sharing Network for Off-Grid Villages

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Abstract
Access to reliable electricity remains a significant challenge in many off-grid rural areas, often leading to underutilization of locally generated renewable energy. This paper proposes a decentralized, Internet of Things (IoT)-enabled energy sharing system designed to facilitate electricity redistribution between homes in remote villages. Utilizing Arduino microcontrollers, current and voltage sensors, and wireless communication modules, the system identifies surplus energy in one home and transfers it to another experiencing a deficit. The design is rooted in basic electrical engineering principles, making it affordable and accessible. Real-time data monitoring and relay-based switching ensure smart distribution with minimal losses. The proposed system directly supports Sustainable Development Goal 7 (Affordable and Clean Energy) and Sustainable Development Goal 10 (Reduced Inequalities).
Keywords: *Off-grid Rural Electrification, Decentralized Energy Sharing, Internet of Things (IoT), Arduino Microcontroller, Voltage and Current Sensors, Wireless Communication Modules, Energy Redistribution.*

1. Introduction
A Smart Village is a modern rural community that uses Artificial Intelligence (AI) and the Internet of Things (IoT) to improve key sectors like agriculture, healthcare, education, energy, and governance. Unlike traditional villages, Smart Villages use technology to manage resources efficiently, create economic opportunities, and improve living standards. These villages integrate digital tools such as smart farming techniques, AI-based healthcare (like telemedicine), renewable energy, and digital governance to overcome rural challenges [1-3].

Figure 1 AI and IoT-Driven Smart Grid Technologies for Smart Energy Management

The aim is to bridge the gap between rural and urban areas, offering equal access to services and technology while preserving local culture and the environment. However, challenges such as poor internet, weak infrastructure, digital illiteracy, and high costs still exist. Despite this, global and government initiatives—like India's Smart Village Campaign and the UN's Sustainable Development Goals—are pushing for tech-driven rural development. As AI and IoT become more affordable and accessible, Smart Villages are increasingly seen as a sustainable path forward for empowering rural communities, shown in Figure 1.

2. Literature Review
The growing need for sustainable and decentralized energy solutions has led to increasing research into IoT-based energy sharing systems, especially for off-grid rural communities. These systems aim to utilize locally generated renewable energy (such as solar or wind) and efficiently distribute it among village households using smart technologies. Several studies highlight the role of the Internet of Things (IoT) in enabling real-time monitoring, control, and optimization of energy flows. For example, [Author

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et al., Year] developed an IoT-enabled microgrid model that allows peer-to-peer (P2P) energy trading, enabling households with excess energy to share it with those in need. This improves energy reliability and promotes sustainability. Decentralized energy networks, supported by blockchain and AI, have also been explored for their ability to create transparent and automated energy sharing systems. These technologies help in balancing supply and demand while reducing losses and dependency on central grids. The researchers demonstrated a successful pilot project in an off-grid village where IoT sensors and smart meters were used to monitor consumption and generation, and to automate energy distribution. The results showed improved energy efficiency and reduced blackouts. However, literature also points to several challenges, including: Limited infrastructure and unreliable internet connectivity in rural areas. High initial costs of IoT devices and renewable energy systems. Lack of technical skills among local populations. Despite these barriers, policy support and falling technology costs are driving the adoption of IoT-based energy networks. Initiatives like India's "Saubhagya" scheme and various UN-backed rural electrification projects are promoting the deployment of smart, scalable, and community-managed microgrids. In conclusion, the literature reflects a growing consensus on the potential of IoT-based energy sharing networks to empower off-grid villages. These systems can enhance energy access, reliability, and sustainability, but require strong policy backing, infrastructure support, and community engagement for successful implementation [4-8].

3. Methodology

The implementation of an IoT-based energy sharing network in off-grid villages follows a structured approach involving system design, data acquisition, energy management, and performance evaluation.

3.1. System Design

A decentralized microgrid is established using renewable energy sources such as solar panels. Each household is equipped with IoT-enabled smart meters, sensors, and energy storage units to monitor and control energy usage and generation, shown in Figure 2.

Figure 2 Smart Grid

3.2. Data Acquisition and Monitoring

IoT devices collect real-time data on energy production, consumption, and battery levels. This data is transmitted to a central controller via wireless communication protocols such as LoRa or Wi-Fi, , shown in Figure 3.

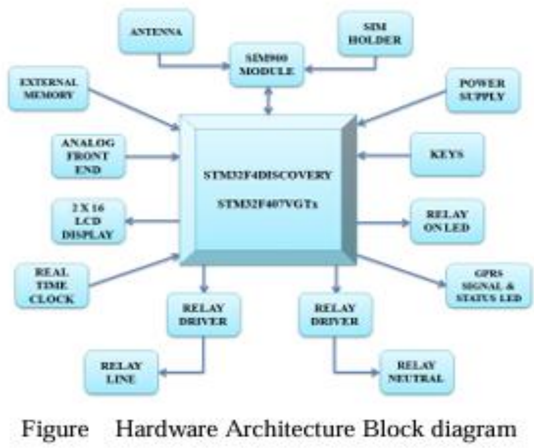

Figure 3 Hardware Architecture Block Diagram

3.3. Energy Sharing Mechanism:

A central control unit or cloud-based platform analyzes the data using predefined algorithms. If a household generates excess energy, the system automatically redirects it to other households with higher demand, enabling peer-to-peer energy sharing.

3.4. Energy Management and Control:

AI or rule-based logic is applied to optimize energy distribution, prevent overload, and ensure fair and efficient sharing. Alerts and usage reports are sent to users via mobile apps or dashboards.

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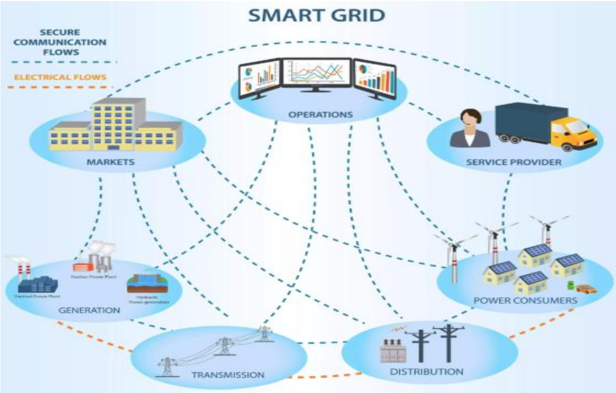

Figure 4 Smart Grid

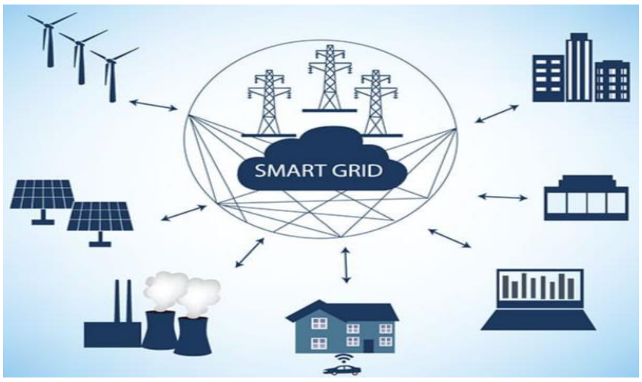

Figure 5 Smart Grid

3.5. Evaluation and Optimization

The system's performance is evaluated based on metrics like energy efficiency, user satisfaction, and reduction in power outages. Feedback is used to refine control strategies and improve network performance.

Figure 6 Microgrid

4. Applications of AI and IOT on Rural Development

4.1. Smart Energy Solutions for Rural Development

Access to reliable and sustainable energy remains a major challenge in rural development. In many remote villages, traditional grid-based electricity is either unreliable or entirely unavailable, making renewable energy solutions critical for rural electrification. The integration of Artificial Intelligence (AI) and IoT-enabled smart energy systems is revolutionizing how energy is generated, distributed, and consumed in these areas. These technologies allow rural communities to optimize energy use, minimize wastage, and efficiently incorporate renewable sources. AI-powered energy management systems use machine learning algorithms to analyze consumption patterns, forecast demand, and dynamically allocate power within the village. This ensures that energy from solar, wind, and bio-based sources is utilized effectively, maintaining a real-time balance between supply and demand. By deploying smart microgrids combined with AI-driven predictive analytics, rural areas can achieve energy self-sufficiency, reduce reliance on fossil fuels, and operate independently of centralized power grids, , shown in Figure 4 to 6.

4.2. AI and IoT in Rural Education and Digital Literacy

Education in rural areas has traditionally been limited by a lack of qualified teachers, educational resources, and reliable internet access. However, Artificial Intelligence (AI) and the Internet of Things (IoT) are reshaping rural education by enabling personalized, technology-driven learning that bridges the gap between urban and rural schooling. AI-powered adaptive learning platforms analyze individual learning patterns, strengths, and weaknesses to deliver customized lesson plans and real-time feedback. These systems use machine learning to adjust content and difficulty levels based on each student's progress, promoting better understanding and retention. Additionally, AI-driven chatbots and virtual tutors provide interactive support, helping students clarify doubts and stay engaged—even in areas with limited teacher availability.

4.3. AI-Driven Rural Healthcare and

Telemedicine

Access to quality healthcare remains a significant challenge in rural areas due to limited medical infrastructure, a shortage of skilled professionals, and restricted access to specialized treatments. Artificial Intelligence (AI) and the Internet of Things (IoT) are revolutionizing rural healthcare by enabling remote diagnostics, predictive analytics, and AI-powered telemedicine services. AI-based diagnostic tools can analyze patient data, medical images, and genetic information to detect diseases at early stages, allowing for timely and accurate treatment. Remote patient monitoring systems track chronic conditions such as diabetes, hypertension, and cardiovascular diseases using AI, providing real-time alerts to doctors and caregivers before conditions become critical. This reduces the need for frequent hospital visits, lowers healthcare costs, and ensures consistent care for patients in remote areas. IoT-connected wearable devices—such as smartwatches, biosensors, and AI-enabled glucose monitors—empower patients to monitor vital signs, detect health anomalies, and share real-time data with healthcare providers. These tools are especially beneficial for elderly individuals, pregnant women, and those with chronic illnesses, supporting early detection and proactive health management.

4.4. AI and IoT in Smart Agriculture and Precision Farming

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) is revolutionizing traditional farming practices by enabling Smart Agriculture—an approach focused on improving efficiency, reducing resource wastage, and increasing crop yields. AI-powered predictive analytics, using machine learning algorithms, analyzes vast agricultural data to support informed decisions on crop forecasting, soil health, and pest management. By processing satellite imagery, weather data, and soil sensor inputs, AI models can predict droughts, disease outbreaks, and ideal planting times, helping farmers boost productivity and adapt to climate challenges. Precision farming, powered by these technologies, allows for the targeted application of water, fertilizers, and pesticides—only where and when needed—minimizing costs and environmental impact. Additionally, IoT-enabled smart irrigation systems use automated soil moisture sensors and AI-driven controls to adjust water distribution in real-time, optimizing usage and promoting sustainable farming practices.

4.5. Smart Governance and AI-Powered Rural Development Policies

Rural governance has long struggled with inefficient service delivery, limited citizen participation, and restricted access to financial and administrative resources. However, the integration of Artificial Intelligence (AI) and the Internet of Things (IoT) is transforming governance in rural areas by enabling data-driven decision-making, real-time infrastructure monitoring, and seamless access to public services. AI-powered data analytics helps policymakers analyse demographic trends, economic indicators, and resource allocation to support evidence-based rural development planning. Machine learning models can predict agricultural yields, monitor climate change impacts, and assess healthcare demands, allowing for more targeted and effective policymaking. IoT-enabled e-Governance platforms enhance service delivery by providing mobile-based access to government schemes, welfare programs, and digital identity services—reducing delays and improving transparency. These platforms also increase citizen engagement, even in remote areas with limited infrastructure. AI is playing a key role in financial inclusion through digital banking, mobile payments, and microloan distribution. By analysing financial data, AI algorithms assess creditworthiness, enabling rural entrepreneurs and farmers to access low-interest loans and subsidies. Additionally, blockchain-integrated smart contracts are being used in aid distribution programs to ensure transparency, reduce fraud, and enhance accountability. By leveraging AI and IoT, Smart Villages can foster efficient, transparent, and inclusive governance—empowering rural communities with digital access to financial, social, and administrative services, and promoting self-sustaining development.

4.6. Future Prospects of AI and IoT in Rural Areas

AI and IoT are playing a transformative role in converting rural communities into Smart Villages. However, their widespread adoption continues to face significant challenges. Limited internet

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connectivity, unreliable power supply, and inadequate infrastructure remain major obstacles that hinder the effective deployment of IoT devices and AI-driven services. Additionally, affordability is a concern, as many rural households lack the financial capacity to invest in smart agricultural tools, digital healthcare systems, and technology-based financial services. Addressing these challenges requires coordinated efforts from both the government and the private sector. Investments in rural broadband connectivity, low-cost smart technologies, and renewable energy infrastructure are critical to creating an enabling environment for AI and IoT adoption. With adequate infrastructure, financial support, and policy backing, AI and IoT technologies hold vast potential to foster inclusive, sustainable development in rural areas and significantly reduce the rural-urban digital divide.

Conclusion

The implementation of IoT-based energy sharing networks offers a sustainable and efficient solution to the energy challenges faced by off-grid villages. By integrating IoT technology with decentralized renewable energy sources, these systems enable real-time monitoring, intelligent energy distribution, and peer-to-peer energy sharing among households. This approach not only optimizes energy utilization but also promotes energy independence, reduces reliance on fossil fuels, and improves the overall quality of life in rural communities. With continued advancements in IoT and supportive government policies, such smart energy networks have the potential to play a crucial role in achieving inclusive and sustainable rural electrification.

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