Green Energy for Remote Villages: Technological Trends, Problems, Solutions

Gulchohra Mammadova
Dept. of Architectural Constitutions and Restoration of Monuments
Faculty of Architecture
Azerbaijan University of Architecture and Construction
Baku, Azerbaijan
rector@azmiu.edu.az

Samira Akbarova
Dept. of Construction of Engineering systems
Water management Faculty
Azerbaijan University of Architecture and Construction
Baku, Azerbaijan
samira.akbarova@azmiu.edu.az

Abstract—**The use of green energy is important for remote villages, where traditional energy supply methods are problematic due to geographical limitations, poor infrastructure, and low population density. The purpose of this study is to analyze scientific publications on the introduction of modern, advanced renewable energy source (RES) technologies in remote rural areas, study current technological trends, systematize them, and analyze existing problems in their implementation based on Azerbaijan's experience in the field of green energy supply to remote smart villages, and develop recommendations for their solution. The results show that micro-solar and micro-wind systems are increasingly being introduced due to their low cost and autonomy. In addition, advanced storage technologies, such as lithium-ion batteries, are critical to addressing the intermittent nature of renewable energy generation. Innovations such as agrivoltaics—which combine agricultural productivity-enhancing technologies with energy production—and compact, silent, low-power wind turbines (up to 50 kW) are in demand, especially in medium- and low-wind regions. Recommendations include focusing on decentralized energy systems, introducing smart grid technologies, and empowering local communities as prosumers. Future research should focus on overcoming infrastructure, technological, and regulatory challenges to fully realize the potential of RES in remote rural areas for sustainable energy supply.**

Keywords—renewable energy sources, rural areas, technologies, innovations, solar energy, wind energy, hybrid systems, Azerbaijan

I. INTRODUCTION (*HEADING 1*)

Meeting the growing demand for energy, complying with pressing environmental restrictions, and mitigating the effects of climate change force states to pursue a policy of widespread use of green energy (GE), which is based on renewable energy sources (RES) [1]. According to forecasts by the International Energy Agency, the global share of various types of RES in energy consumption was 28.1% in 2020 and increased to 33.5% in 2024 (Fig. 1) [2]. The share of renewable energy (RE) capacity is expected to grow steadily and exceed 40% by 2030. Today, GE is becoming increasingly relevant for remote villages, where traditional methods of energy supply are often ineffective due to low population density, climatic and geographical constraints, and the significant energy demands of agricultural activities [3]. In recent years, there has been a growing interest in implementing RE technologies such as solar, wind, geothermal, bio-, and hydropower, which can significantly improve living standards in villages by ensuring energy autonomy [4].

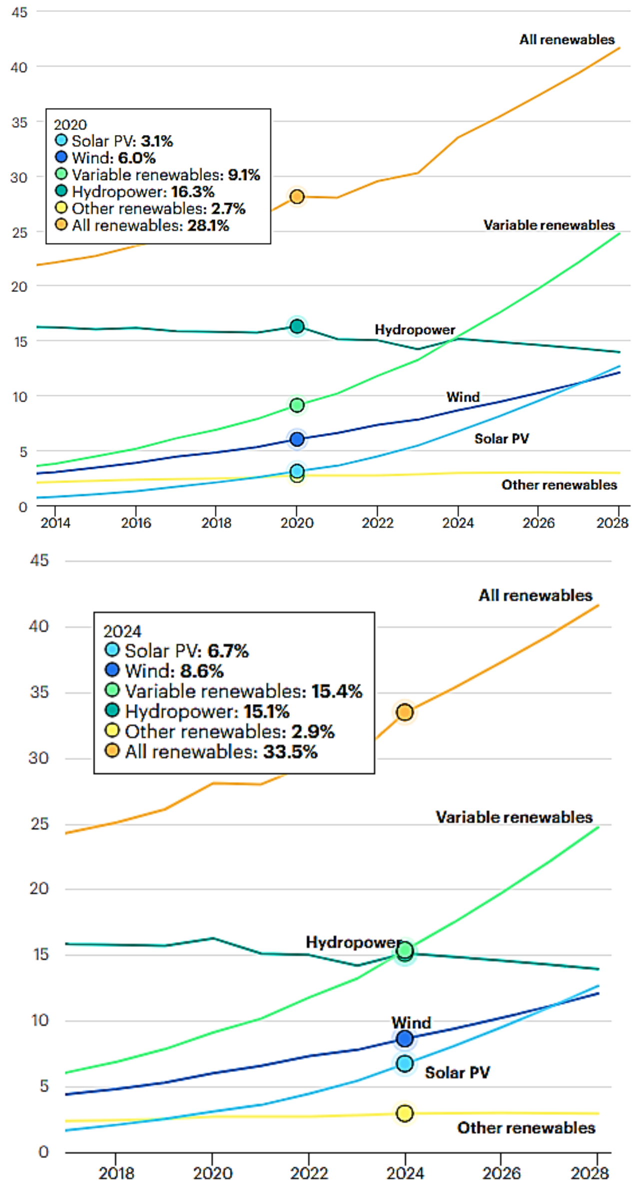

Fig. 1. RE generation by segment 2018-2028

https://www.iea.org/data-and-statistics/charts/share-of-renewable-electricity-generation-by-technology-2000-2028

Rural areas are also undergoing a transformation from centralized energy infrastructure to more decentralized and interactive energy systems. Smart grid technology and other innovations in micro-generation of RE have changed the role of local residents from primary energy consumers to prosumers—individuals who both produce and consume energy [5]. Collective energy consumption, in the form of rural energy cooperatives, has become a widespread model for rural RE initiatives.

Azerbaijan is actively implementing RES projects, highlighting its commitment to diversifying the country's energy balance and reducing dependence on hydrocarbon resources. In the long term, the transition to RES can provide Azerbaijan with both a sustainable energy supply and a reduced carbon footprint, aligning with global sustainable development goals.

Currently, the share of RES in Azerbaijan's energy balance stands at 18%. By 2030, this number will increase to 30%, and by 2050—to more than 40%. RES is one of the country's key development priorities, both in the context of global efforts to reduce carbon emissions and transition to sustainable energy sources and in the construction of smart villages. For Azerbaijan, the development of smart villages is not merely an architectural and construction trend but a strategic initiative aimed at creating a sustainable future, particularly in the restoration of the liberated territories of Karabakh. The region has significant potential for the development of solar (7,200 MW), wind (2,000 MW), and geothermal energy from warm groundwater sources [6,7].

As part of Azerbaijan's smart village initiative, various innovative RE technologies have been developed and implemented. In the village of Agalı (Zangilan district), 200 houses are already inhabited, with 150 more under construction. Solar panels and wind turbines are actively used for electricity generation, while flat-plate and tubular solar collectors provide hot water. RE equipment installed on residential and public building roofs significantly reduces reliance on traditional energy sources. Additionally, a small hydroelectric power plant supplies energy to local facilities. A battery energy storage system (BESS), integrated into the general grid, along with intelligent energy management systems, plays a crucial role in stabilizing the energy network, optimizing electricity consumption, and enhancing energy storage. Agalı also includes bioenergy facilities, where biomass from a buffalo farm and other organic waste is used to generate additional energy [8].

In the second smart village, Dovletyarly (Fizuli district), where 450 houses are planned, significant attention is being given to solar energy development. Solar panels and collectors installed on building roofs provide both electricity and thermal energy, increasing energy autonomy and reducing electricity costs. Additionally, wind turbines will be utilized to further enhance the village's self-sufficiency. Waste recycling technologies are being developed and implemented to improve the environmental sustainability of the energy system.

In the third smart village, Bash Garvard (Aghdam district), 500 houses are planned, with a primary focus on autonomous power supply systems. The village's energy concept relies on solar panels for electricity generation, along with biogas plants capable of converting organic waste (manure, agricultural, and food waste) into biogas for heating and cooking. To improve energy efficiency, a combination of solar and geothermal energy will be used for heating and cooling buildings, significantly reducing operational costs and the carbon footprint.

Despite Azerbaijan's significant RE potential, the widespread transition to RES faces various challenges, including technological, technical, and infrastructural limitations, regulatory barriers, and entrenched interests in the fossil fuel sector [9].

The purpose of this study is to review scientific publications on the implementation of modern advanced GE technologies in remote rural areas, analyze current technological trends, systematize them, examine technical and technological challenges, and develop recommendations for overcoming them, considering Azerbaijan's experience in GE supply to remote villages.

II. Methods

This study aims to comprehensively analyze current technological trends in GE for remote rural areas. A detailed review of scientific publications from 2020 to 2024 was conducted to identify advanced solutions in this field. The authoritative Web of Science platform was used as the primary information source, providing access to peer-reviewed scientific articles and international conference proceedings.

The search for relevant publications was carried out using the key request "Green energy for remote rural areas", which identified 304 scientific papers. The data presented in the Web of Science Core Collection (Fig. 2) indicate the interdisciplinary nature of this research. The largest number of publications are concentrated in the Environmental Sciences category (101), reflecting the active study of the environmental impacts of GE implementation, its effects on ecosystems, and sustainable resource management.

The Energy & Fuels category (85) includes research on the development and optimization of RE technologies. Meanwhile, innovative solutions in autonomous energy supply for remote settlements are covered in the Green & Sustainable Science & Technology category (75).

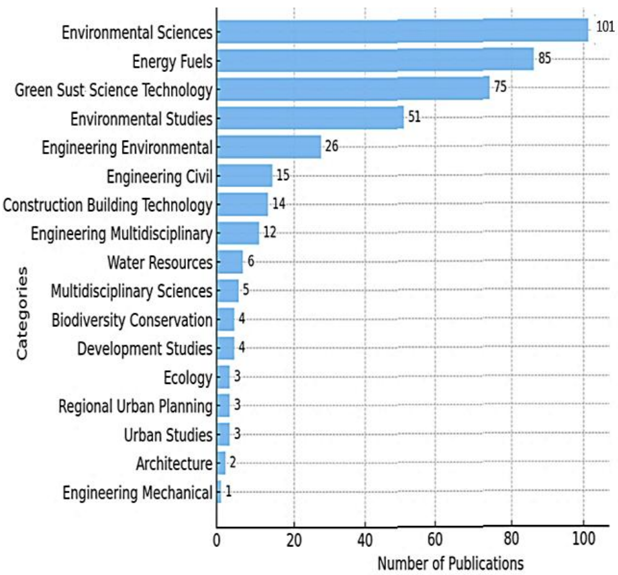

Fig. 2. Distribution of publications by WoS Category

The methodological basis of the study includes the following stages:

- a comprehensive review of current scientific research on GE technologies and their adaptation for hard-to-reach and remote rural areas;

- a comparative analysis of various technologies (solar panels, solar collectors, wind generators) based on key criteria: technical characteristics, adaptation to specific climatic and geographical conditions, environmental safety, and carbon footprint;

- study of empirical data from pilot projects in Azerbaijan (smart villages of Agalı, Dovletyarly, and Bash Garvand) and analysis of implemented technologies to identify key trends.

- identification and systematization of the main challenges hindering the implementation of GE in remote rural areas.

- development of scientifically based recommendations for the further advancement of RE, considering the needs of remote villages and prioritizing technologies with minimal environmental impact and maximum social and economic benefits for the local population.

III. Results

The conducted studies confirm the key role of solar and wind energy in the overall balance of RES, driven by both the intensive development of technologies and their gradual reduction in cost. According to indicators for 2020-2024 (Fig. 1), solar energy consumption has almost doubled, indicating significant progress in its large-scale implementation. However, despite the high growth rate, the development of wind energy remains more dynamic.

The most promising technological trends in solar and wind energy for remote rural areas demonstrate adaptability and a high degree of innovation. Microsolar and microwind power plants have become widespread due to their autonomy, low operating costs, and ability to function without connection to central power grids. The use of such systems minimizes the energy vulnerability of remote settlements, reducing dependence on unstable power lines and expensive infrastructure. Another important development is the introduction of hybrid energy systems integrating multiple energy sources, including solar and wind installations, as well as diesel generators with energy storage. Such systems compensate for the intermittent nature of RE generation, ensuring a reliable energy supply under changing meteorological conditions. Wind energy is often available at night and during periods of low solar activity, complementing the daytime generation of photovoltaic systems. The optimal combination of solar panels and wind turbines ensures a stable energy supply and reduces the need for large-capacity battery systems [10].

Another key area is the development of modular and autonomous energy systems aimed at providing local energy supply for households, farms, and small businesses. The use of such systems reduces dependence on centralized networks, minimizes energy losses during transmission, and ensures electricity availability in hard-to-reach regions. Modern modular solutions include integrated control systems that adapt energy consumption based on real-time generation conditions [11].

Improving energy storage systems remains a critical factor in increasing the efficiency of RE. The introduction of highly efficient battery technologies, such as lithium-ion, sodium-ion, and new hybrid batteries, helps mitigate the impact of weather conditions on energy supply. Modern storage devices offer high energy density, extended service life, and enhanced safety, making them a key component of autonomous energy systems [12].

An important application of solar energy in agricultural production is agrivoltaics, where photovoltaic panels are placed above crops. This approach not only generates electricity but also protects plants from extreme weather conditions such as drought and overheating [13]. Optimizing panel placement helps reduce moisture evaporation, increase crop yields, and use land resources more efficiently.

Innovations in solar panels are unlocking new opportunities for efficient use in remote communities. The development of thin-film solar panels based on amorphous silicon, cadmium telluride, or copper-indium-selenium (CIS) compounds has resulted in lightweight, flexible designs that can be installed on a variety of surfaces, including uneven and mobile structures [14]. Their key advantages include low production costs and the ability to integrate into existing infrastructure solutions.

The emergence of perovskite solar panels has revolutionized photovoltaic generation due to their high solar radiation conversion efficiency, especially in low-light conditions. These panels are characterized by low production costs, easy scalability, and the potential for further efficiency improvements. Bifacial solar panels, capable of capturing light from both the front and back sides, demonstrate a significant increase in productivity—up to 30% compared to conventional models [15]. This makes them particularly effective in high-reflectivity regions, such as snowy or sandy areas.

Innovative 2-in-1 hybrid panels combine traditional solar battery and thermal collector functions, enabling the simultaneous generation of electricity and thermal energy. Their use helps reduce heating costs and enhances overall energy efficiency. The integration of solar panels with built-in energy storage systems using lithium-ion batteries ensures a stable power supply even at night or in cloudy weather, simplifying operation and reducing strain on external networks [16].

Flexible organic solar panels, based on polymer materials, offer high adaptability, low cost, and easy installation, making them particularly promising for mobile solutions and temporary power plants. The use of translucent solar panels allows the integration of photovoltaic elements into building facades, windows, and greenhouses, combining energy generation with natural light preservation to support aesthetic and energy-efficient architecture [17].

The development of ultra-efficient monocrystalline panels, incorporating Passivated Emitter and Rear Contact (PERC) technology, has achieved efficiency rates of up to 25%, making them market leaders in performance and durability.

An additional boost to solar installation efficiency comes from sun-tracking systems, which automatically adjust panel tilt angles. These trackers can increase energy generation by 20–40%, particularly in regions with fluctuating solar exposure [18]. Modern nanotechnology has enabled the development of self-cleaning coatings for solar panels, preventing the accumulation of dust, dirt, and snow, reducing maintenance costs, and ensuring stable electricity generation.

Similar advancements are occurring in solar collectors. The use of advanced materials, such as perovskites, has improved efficiency while lowering production costs. Hybrid solar collectors, which combine photovoltaic and thermal technologies, significantly enhance overall system efficiency. Innovative designs, such as nanoantennas, capture infrared radiation to generate energy even at night, opening new possibilities for 24/7 solar energy utilization. Thermodynamic solar collectors, which use working fluids or gases to store and convert heat, have demonstrated high efficiency in regions with intense solar radiation. Additionally, IoT-controlled solar collectors provide real-time monitoring and automatic regulation of operating parameters, minimizing energy losses, reducing failure risks, and enhancing system reliability [19].

Modern RE advancements are not limited to solar technology—wind energy has also seen significant innovations. The introduction of software-controlled algorithms has improved wind turbine efficiency by 40%, making wind energy more economically viable without requiring major turbine design changes. Optimizing wind turbine placement in a staggered pattern enhances vertical energy transfer, increasing overall efficiency [20].

The development of bladeless wind turbines (Vortex Bladeless) has eliminated risks to birds while reducing production and operating costs by up to 80%. Innovative aerodynamic blade shapes and materials have improved turbine performance, reduced noise, and enhanced resistance to fluctuating wind loads. Typhoon-resistant turbines, designed for extreme weather conditions, can withstand powerful gusts and continue generating energy during hurricanes [21].

Compact and silent wind turbines, such as LIAM F1 UWT, offer high efficiency and are suitable for residential areas, providing clean energy without compromising comfort. In medium- and low-wind regions, low-power wind generators (up to 50 kW) are emerging as a viable solution for individual households and small industries. Modern compact models are characterized by low noise levels, seamless integration into existing power systems, and high reliability, making them particularly relevant in areas where large wind turbines are economically unfeasible [22].

Despite the rapid development and promising potential of RE technologies, large-scale implementation faces several technological and technical challenges. These include infrastructure limitations, integration difficulties with existing energy systems, high initial investment costs, reliance on imported technologies, climatic and geographical constraints, and regulatory barriers. Addressing these challenges requires a comprehensive approach. Nonetheless, modern advancements in solar and wind energy are enabling technology adaptation to various conditions, making them an effective tool for providing sustainable energy to remote settlements [6].

IV. Discussion

The introduction of RES in remote rural areas is a strategically significant step toward sustainable development, but this process comes with a number of systemic and technological challenges. Despite the obvious benefits—such as reducing the carbon footprint, increasing energy independence, and stimulating the local economy—the rapid adoption of RES faces various barriers.

One of the key limitations is the insufficient infrastructure readiness of energy systems, especially in remote rural areas. The limited transmission capacity of electrical networks and the lack of developed distribution systems significantly complicate the integration of RES into regional energy grids. In light of these challenges, modernizing and decentralizing energy networks is necessary, requiring substantial financial investment and organizational efforts.

Technical factors also have a significant impact, including the instability of energy generation due to variable meteorological conditions, as well as the limited capabilities of energy storage systems. The lack of reliable battery solutions prevents the full utilization of generated energy during periods of insufficient solar radiation or weak wind, which is particularly relevant for regions with pronounced seasonal variations.

Financial barriers also play a major role in slowing down the adoption of RE. High initial capital costs, reliance on imported equipment, and a lack of government subsidies create obstacles to the widespread adoption of green technologies. Developing local production of solar panels, wind turbines, and energy storage solutions could help reduce project costs and make them more accessible.

In addition, there is a clear dependence on technological imports, which makes RE projects vulnerable to external economic factors and complicates the timely maintenance of installations. The shortage of qualified specialists in the field of RE is another constraint, highlighting the need for investment in training programs and educational initiatives.

Climate conditions also introduce uncertainties in the operation of RES. For example, solar energy production significantly decreases in winter, necessitating the development of more efficient energy storage and management solutions. Wind turbines, in turn, can experience excessive loads during extreme weather events such as hurricanes and typhoons, requiring improved design solutions to enhance their resilience.

Social factors also play a crucial role in the successful integration of RES. Limited public awareness of the benefits of RE and possible resistance from local communities due to changes in the familiar landscape create additional challenges for project implementation. In this context, actively involving the population in decision-making processes and promoting educational programs on sustainable energy consumption are essential.

Regulatory and legal complexities cannot be ignored. The underdeveloped legislative framework, the absence of clear standards for connecting RES to centralized networks, and bureaucratic barriers significantly slow down the implementation of innovative solutions. Developing government support programs, simplifying licensing procedures, and creating transparent regulatory mechanisms are necessary steps to accelerate the transition to RE.

Despite these challenges, there are several promising ways to overcome them. First, the development of decentralized technologies, such as autonomous solar and wind installations, can enhance the energy independence of rural areas and reduce the burden on centralized energy systems. The introduction of financial mechanisms, including government subsidies, preferential lending, and partnerships with private investors, can significantly lower the costs of implementing green technologies.

Social participation is also of particular importance. Training local populations in the installation, operation, and maintenance of equipment helps increase the adoption of new technologies while creating additional jobs. Research support is crucial for improving the resilience of renewable energy sources to extreme climatic conditions, and integrating artificial intelligence into energy management systems can optimize energy generation and distribution processes.

Thus, the successful implementation of GE projects in remote rural areas requires a comprehensive approach that incorporates technological innovation, financial incentives, regulatory development, and active community involvement. Only by combining these factors can we achieve the sustainable and large-scale adoption of RES, contributing to increased energy security and environmental sustainability in the region.

V. CONCLUSION

The introduction of GE in remote rural areas is a strategically important initiative that contributes to sustainable development, increased energy security, and improved quality of life for local populations. The study confirms that GE technologies, such as solar and wind energy, have significant potential to address energy supply challenges in remote villages. However, their widespread implementation requires consideration of multiple factors, including technological, environmental, economic, and social aspects.

One of the key findings of the study is the growing role of hybrid energy systems that combine multiple energy sources with energy storage and management systems. Such solutions improve the reliability of energy supply, minimize dependence on weather conditions, and reduce operating costs. In particular, projects integrating solar and wind energy, battery storage, and intelligent energy management systems have already been implemented in Azerbaijan's smart villages, such as Agali, Dovletyarly, and Bash Garvarde. This experience can serve as a model for other regions planning a transition to decentralized energy supply models.

Technological innovations, including the development of perovskite, thin-film, and bifacial solar panels, as well as bladeless wind turbines and IoT-controlled energy systems, open up new opportunities for increasing the efficiency and accessibility of renewable energy sources. Additionally, considerable attention is being given to energy storage systems, which play a crucial role in ensuring stability and uninterrupted power supply. In this context, lithium-ion, sodium-ion, and solid-state batteries are particularly important, demonstrating improved characteristics compared to traditional solutions.

Despite technological advancements, several challenges continue to limit the large-scale implementation of renewable energy sources in rural areas. Key barriers include high initial installation costs, the need to adapt technologies to specific climatic conditions, the complexity of integrating with existing infrastructure, and administrative and regulatory obstacles. Overcoming these challenges requires a comprehensive approach, including the development of local production of renewable energy components, government support, investment attraction, and public awareness initiatives highlighting the benefits of renewable energy.

Analyzing Azerbaijan's experience, several important recommendations can be made for the further development of GE in remote villages. First, it is essential to intensify research and development in new materials and technologies to increase efficiency and reduce the cost of RE solutions. Second, mechanisms for state support and incentives, such as subsidies, tax breaks, and financing programs, should be introduced. Third, expanding educational and informational programs to enhance the qualifications of specialists and inform the public about the opportunities and benefits of RE is crucial.

In the long term, decentralized energy systems based on renewable sources can serve as the foundation for sustainable rural development. These systems not only promote energy independence but also create new jobs, foster local business development, and improve environmental conditions. The successful implementation of smart villages in Azerbaijan highlights the effectiveness of an integrated approach to RE adoption, making it a valuable benchmark for the further expansion of GE both nationally and internationally.

Promising areas of research in this field include:

- comprehensive analysis of renewable energy potential: assessing various types of renewable energy sources (res) in specific regions, considering climatic conditions, geographical features, and resource availability, is essential for effective planning and implementation of energy-efficient solutions. modeling and forecasting energy flows can help optimize technology selection and create flexible energy systems capable of adapting to changing conditions.

- development of mathematical models and algorithms: managing power systems with a high share of renewable energy penetration is a pressing issue. analyzing dynamic processes in hybrid power systems that integrate both renewable and traditional energy sources ensures a reliable and sustainable energy supply.

- environmental impact assessment: evaluating the environmental effects of renewable energy sources throughout their life cycle is an integral part of comprehensive analysis. identifying potential environmental risks and developing mitigation strategies help minimize negative ecological impacts.

Thus, the development of green energy in remote rural areas requires a systematic approach, encompassing scientific research, government support, investment, and active local community participation. Only through comprehensive measures can the potential of renewable energy sources be fully realized, ensuring the sustainable development of rural areas.

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