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RISK- BASED DESIGN OF SOLAR AND WIND ENERGY SYSTEMS

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Abstract

This study addresses the challenges and risks associated with implementing autonomous solar and wind energy systems in remote communities, focusing on a risk-based design approach. These systems, while crucial for decarbonization and energy independence, face complexities due to meteorological variability, technical limitations, and socio-economic constraints. This research employs an interdisciplinary methodology, integrating system analysis, risk assessment, and geoinformation analysis, to identify and classify key risks, including climatic, technological, and social factors. By developing failure scenarios and implementing mitigation strategies such as hybrid energy systems, intelligent control, and robust maintenance plans, the study aims to enhance the reliability and sustainability of these systems. The findings emphasize the importance of comprehensive risk management, advanced forecasting, and local capacity building to ensure the long-term effectiveness and economic viability of renewable energy solutions in remote settings. This approach not only reduces operational and capital risks but also ensures resilience against extreme conditions, fostering a sustainable energy future for underserved communities.

Keywords: renewable energy systems, remote community, climate variability, hybrid energy systems, solutions

I. Introduction

In recent decades, renewable energy sources (RES) have become central to sustainable development, serving as an integral tool for decarbonisation and increasing energy independence, particularly in the context of energy supply to remote rural communities [1,2]. Projections from the International Energy Agency indicate a substantial increase in the global use of renewable energy sources (RES), rising from 35.3% of energy consumption in 2025 to more than 40% in 2028. This upward trend is anticipated to continue (Fig. 1). Unlike the traditional centralised energy system, which is characterised by a high dependence on fossil fuels and significant losses during energy transmission, decentralised solar and wind installations provide autonomous energy supply, help reduce greenhouse gas emissions, and contribute to a more adaptive and sustainable energy infrastructure [3,4].

Despite the clear environmental and economic benefits, the operation of renewable energy systems in remote communities faces numerous risks and uncertainties [5]. Among the key factors limiting the effectiveness of these systems are [6]:

– the instability of generated power due to varying meteorological conditions,
– maintenance challenges,
– equipment degradation,
– socio-economic barriers affecting operational sustainability.

These factors necessitate an integrated approach to the design of autonomous power systems, aimed at considering potential threats and developing strategies to mitigate them [7,8].

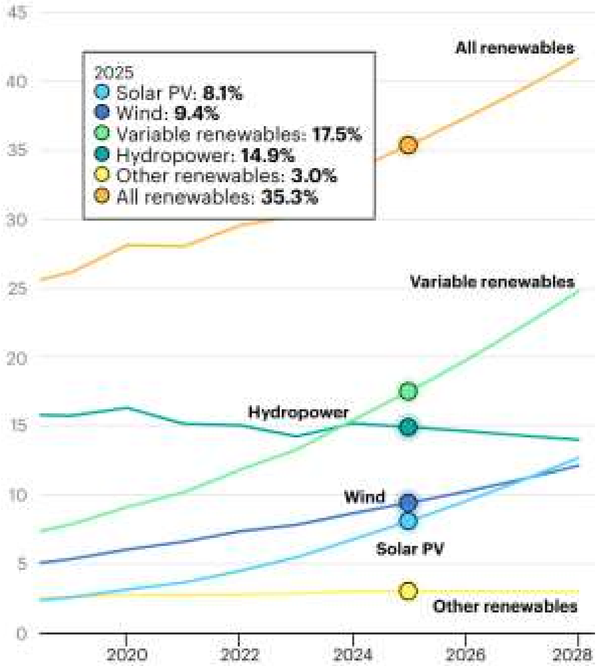

Fig. 1: *Renewable Energy Systems generation by 2020-2028, https://www.iea.org/data-and-statistics/charts/share-of-renewable-electricity-generation-by-technology-2000-2028*

In this context, risk-oriented design is of particular importance, involving a comprehensive analysis of uncertainties, systemic management of operational risks, and optimization of the architecture of energy systems from the standpoint of long-term sustainability [9,10]. This methodological approach allows for accounting for the impact of climatic and seasonal variations, developing fault-tolerant operating scenarios, and integrating intelligent energy supply management systems that provide predictive control and adaptation to changing conditions [11].

Risk-based design is a methodological approach to the development of engineering systems that places a key emphasis on the analysis and management of risks at all stages of the life cycle—from conceptual design to operation and disposal. In the context of solar and wind energy systems intended for remote villages, this approach involves the early identification and assessment of potential threats, such as climate variability, technological failures, economic constraints, and social factors [12].

Scenarios of failures and instability of energy supply are developed to account for the uncertainty and variability of external conditions. Design solutions focus on ensuring the sustainability of systems, including safety margins to withstand extreme weather conditions such as hurricanes, snowfalls, and droughts, as well as addressing seasonal and daily fluctuations in energy generation [13,14]. To minimize risks, hybrid energy systems combining solar and wind generation with energy storage are widely used, along with intelligent control systems that optimize the distribution of energy resources and predict consumption. An essential element of the sustainability of such systems is the development of backup mechanisms, including the ability to connect to the grid or use additional generators [15].

Power system operation is based on adaptive strategies, including algorithms for forecasting energy production based on meteorological data, remote monitoring and diagnostic systems for equipment, and optimized maintenance and component replacement plans to minimize the likelihood of failures. This is especially important for remote villages, where the lack of backup energy sources makes power supply critically vulnerable [16].

This article focuses on risk-based design, which not only reduces operational and capital risks but also improves the economic efficiency of investments in renewable energy sources [17]. In the context of climate change, this approach ensures the creation of autonomous power systems that are resistant to extreme conditions, making them a reliable and long-term solution for providing energy supply in remote communities [18].

This study examines key risks affecting the performance of solar and wind power plants in remote communities and identifies innovative mitigation strategies aimed at improving the reliability and efficiency of autonomous power systems.

II. Methods

This study is based on an interdisciplinary approach, incorporating methods of system analysis, quantitative and qualitative risk assessment, and expert forecasting. The comprehensive nature of the methodology allows for the consideration of a wide range of factors affecting the efficiency and reliability of autonomous solar-wind energy systems in remote communities. In combination with theoretical and empirical methods, a thorough analysis of risk-forming parameters and the development of strategies to mitigate them are provided.

The first stage of the study involves a system analysis aimed at identifying and classifying key risks affecting the design and operation of renewable energy systems. Within this stage, four main risk groups are identified:

- climatic and meteorological (variability of solar radiation, wind speed, and extreme weather events).
- technical and technological (failure of equipment, instability of energy storage devices, and energy conversion losses).
- social and infrastructural (limited availability of technical services and insufficient training of local specialists).

This classification allows for the systematization of potential threats and the determination of priority areas for risk management.

Geoinformation analysis is used for spatial risk assessment and the optimal placement of energy facilities, including the processing of data on solar radiation, wind speed, and direction, as well as their seasonal and daily fluctuations. Within this stage, geoinformation technologies (GIS) are employed to integrate satellite and ground meteorological data. This enables the identification of the most favorable areas for the installation of solar panels and wind generators, considering both climatic and infrastructural conditions.

Thus, the applied research methods facilitate a comprehensive identification of risk-forming factors, their quantitative and qualitative assessment, and the development of optimal risk management strategies. This contributes to enhancing the reliability, sustainability, and economic efficiency of autonomous solar-wind energy systems designed for operation in remote settlements.

III. Results and discussion

Designing solar and wind energy systems for remote communities is a complex engineering task that requires the consideration of numerous technological, operational, and infrastructure factors. The effective implementation of such systems demands a detailed analysis of potential risks that could affect their reliability, sustainability, and efficiency in the long term (Fig. 2).

A key factor determining the efficiency of renewable energy sources is their resource base. Due to the high dependence of solar and wind installations on variable meteorological conditions, the instability of incoming energy can significantly limit their productivity. To reduce this uncertainty, a thorough assessment of climate parameters in a particular region is required, taking into account seasonal and daily variations [19,20]. Additionally, advanced forecasting methods should be applied, utilizing machine learning algorithms and statistical modeling to minimize errors in assessing the availability of solar and wind energy.

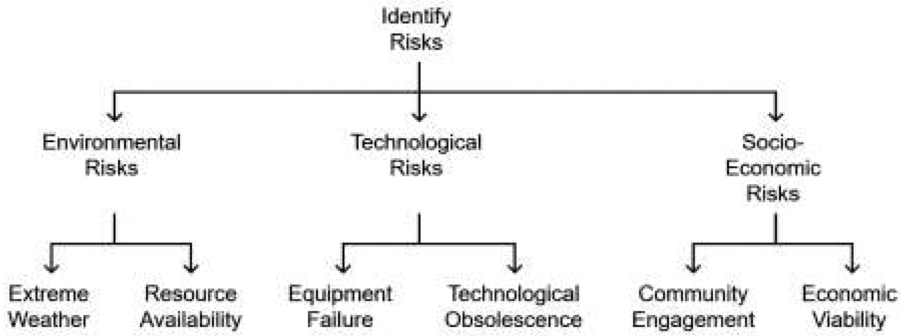

Fig. 2: *Identifying risks in renewable energy systems*

The technical equipment used has a significant impact on system stability. The operation of power plants in remote areas places increased demands on their reliability and resistance to extreme climatic conditions [21,22]. Therefore, it is critical to use equipment that has undergone rigorous testing and certification, as well as to implement regulated maintenance procedures. In particular, the complexity of integrating individual system components (generators, battery units, converters, and controllers) requires special attention. For example, batteries, despite their key role in energy storage, remain the most vulnerable element, subject to degradation due to temperature fluctuations. Accordingly, it is necessary to carefully calculate their capacity, develop thermal protection strategies, and optimize operating modes.

Equipment degradation, the complexity of maintenance, and the high cost of component replacement are significant limitations that should be considered when designing autonomous power systems. The introduction of modern remote monitoring systems, fault diagnostics, and preventive maintenance strategies helps extend equipment service life and optimize operating costs.

Another critical aspect affecting system efficiency is the installation process and subsequent operation. Limited availability of qualified specialists and underdeveloped infrastructure can make it challenging to install equipment in remote areas. This requires detailed planning of logistics and construction work, the involvement of professionals, and the use of modular solutions that simplify the assembly and adjustment process. Further maintenance may also be difficult due to the remoteness of service centers, making it necessary to train local personnel in basic operational skills and troubleshooting.

Additionally, it is important to consider environmental factors. For example, noise pollution from wind turbines and sunlight reflection from solar panels can impact both the environment and local communities, requiring appropriate mitigation measures.

One of the most significant challenges is the integration of renewable energy sources into existing energy infrastructure. Compatibility with local power grids requires the implementation of additional converters, load control devices, and voltage stabilizers. Without these measures, voltage fluctuations may occur, potentially leading to unstable operation for connected consumers. Therefore, system design should include the development of mechanisms for managing energy flows and regulating network parameters to ensure uninterrupted power supply.

To effectively mitigate these risks, a comprehensive approach is required, including (Fig. 3):

– a detailed assessment of resource potential,
– selection of reliable equipment,
– utilization of advanced forecasting and design techniques,
– development of maintenance strategies.

Socio- economic and infrastructural barriers also significantly impact the sustainability of autonomous power systems. The limited availability of qualified technical personnel, insufficient awareness among the local population about equipment operation, and logistical difficulties necessitate an integrated approach to training and service support. Developing specialized training programs for professionals and localizing the production of key components can enhance the autonomy of power systems and reduce operational costs. An essential element of sustainable system operation is training local residents in basic maintenance and troubleshooting, which will increase system autonomy and lower service costs.

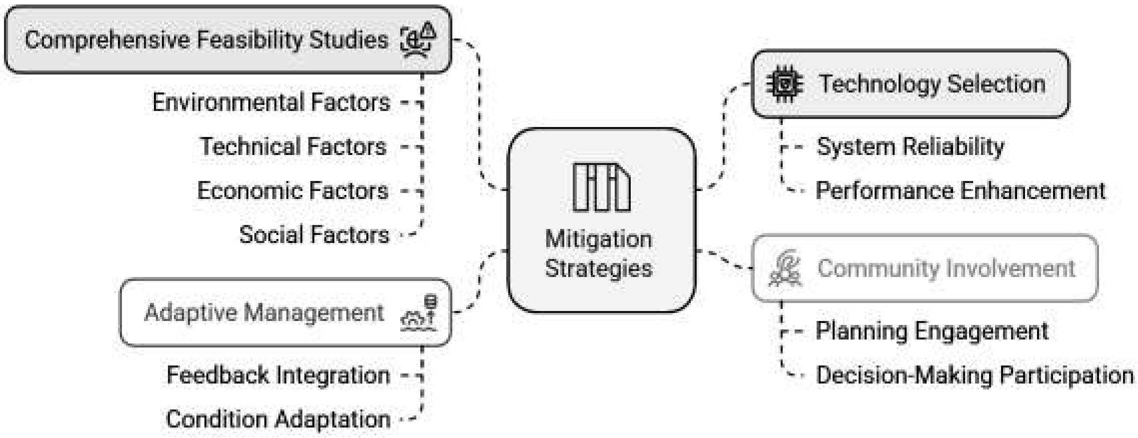

Fig. 3: *Risk mitigation strategies*

Finally, providing backup energy sources, such as hybrid systems or battery storage, will help minimize the impact of unforeseen factors and improve energy supply reliability.

Thus, with proper design and risk management, solar and wind energy systems can be successfully implemented in remote villages. This will ensure a stable and environmentally friendly electricity supply, contributing to improved living standards and infrastructure development in regions with limited access to traditional energy resources.

V. Conclusion

This study demonstrates the critical importance of a risk-based approach to the design and operation of off-grid solar-wind energy systems for remote communities. Despite the significant environmental and economic benefits of renewable energy sources, their implementation is associated with several technical, operational, and infrastructural challenges that require comprehensive analysis and the development of risk management strategies.

One of the key factors affecting the reliability of autonomous power systems is the high variability of climatic conditions, which creates the need for advanced forecasting methods and adaptive solutions in power supply architecture. The integration of hybrid systems combining solar panels, wind generators, and energy storage devices, along with intelligent control algorithms, enhances power supply stability and reduces dependence on weather fluctuations.

Overall, the study shows that the successful integration of renewable energy sources into remote communities is possible through comprehensive risk analysis and the implementation of adaptive management strategies. An integrated approach—including a detailed assessment of resource potential, the use of reliable equipment, the implementation of intelligent forecasting and monitoring systems, and the development of effective service strategies—creates the foundation for ensuring the long-term sustainability and economic efficiency of autonomous solar-wind energy systems.

Thus, competent design and effective risk management enable the successful implementation of renewable energy sources, which, in turn, helps improve the quality of life in remote communities, reduce dependence on centralized energy systems, and create a more sustainable and environmentally friendly energy infrastructure.

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