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Viabilidad Económica y Técnica de Nanoredes: Una Solución Para Reducir el Impacto de la Escasez de Energía en Ecuador provocada por las Sequías

Economic and Technical Feasibility of Nanogrids: A Solution to Reduce the Impact of Energy Shortage in Ecuador Caused by Droughts

Viabilidade Económica e Técnica das Nanorredes: Uma Solução para Reduzir o Impacto da Escassez de Energia no Equador Causada pelas Secas

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Resumen

Los nanoredes residenciales representan una solución prometedora para abordar la escasez de energía causada por fallas o déficits de generación debido a las sequías en Ecuador. Este documento explora la viabilidad de adoptar un sistema de nanored de uso residencial, enfocándose en el uso de energía renovable para mejorar la fiabilidad del suministro eléctrico y reducir la dependencia de la red eléctrica, mejorando así la resiliencia energética. El estudio analiza los diferentes aspectos necesarios para implementar una nanored, incluyendo la selección de fuentes de energía renovable adecuadas, sistemas de almacenamiento de energía y caracterización de la carga. Una vez seleccionada la arquitectura, un estudio de optimización utilizando software especializado evalúa la arquitectura básica para determinar la solución óptima, considerando aspectos como la capacidad de autonomía y la inversión requerida para cada configuración de la red. Finalmente, el documento concluye con un análisis de los resultados, identificando la configuración de la red que ofrece un buen periodo de retorno de la inversión y una capacidad de autonomía suficiente para evitar cortes de energía durante intervalos cortos de tiempo.

Palabras clave: Nanoredes; Energías Renovables; Cortes de Energía; Sequías.

Abstract

Residential nanogrids represent a promising solution to address energy shortages caused by generation failures or deficits due to droughts in Ecuador. This paper explores the feasibility of adopting a residential nanogrid system, focusing on the use of renewable energy to improve power supply reliability and reduce dependence on the power grid, thereby improving energy resilience. The study analyzes the different aspects necessary to implement a nanogrid, including the selection of suitable renewable energy sources, energy storage systems and load characterization. Once the architecture is selected, an optimization study using specialized software evaluates the basic architecture to determine the optimal solution, considering aspects such as the autonomy capacity and the investment required for each network configuration. Finally, the document concludes with an analysis of the results, identifying the network configuration that offers a good return on investment period and sufficient autonomy capacity to avoid power outages during short intervals of time.

Keywords: Nanonetworks; Renewable energy; Power outages; Droughts.

Resumo

As nanorredes residenciais representam uma solução promissora para resolver a escassez de energia causada por falhas de geração ou défices devido a secas no Equador. Este artigo explora a viabilidade da adoção de um sistema de nano-rede residencial, com foco na utilização de energia renovável para melhorar a fiabilidade do fornecimento de energia e reduzir a dependência da rede elétrica, melhorando assim a resiliência energética. O estudo analisa os diferentes aspetos necessários para implementar uma nanorrede, incluindo a seleção de fontes de energia renováveis adequadas, sistemas de armazenamento de energia e caracterização de carga. Uma vez selecionada a arquitetura, um estudo de otimização com recurso a software especializado avalia a arquitetura básica para determinar a solução ótima, considerando aspetos como a capacidade de autonomia e o investimento necessário para cada configuração de rede. Por fim, o documento conclui com uma análise dos resultados, identificando a configuração de rede que oferece um bom período de retorno do investimento e capacidade de autonomia suficiente para evitar cortes de energia em curtos intervalos de tempo.

Palavras-chave: Nanoredes; Energia renovável; Falhas de energia; Secas.

Introduction

The present electric sector in Ecuador possesses an installed capacity of 8,827 MW to serve the increasing needs of its populace. This capacity is derived from 58.6% hydroelectric energy, 32.8% thermal energy, and 2.6% other sources. In 2022, the total energy supply consisted of 73.6% from hydroelectric generation, demonstrating a clear dependency of the electric sector on natural water resources (Renovables, 2018). In this context, complex climatic anomalies that impact the environment have intensified in frequency and severity due to global climate change (Campozano et al., 2020). One of these anomalies is drought, a natural catastrophe causing severe impacts on water resources due to significantly diminished precipitation, resulting in arid conditions and water scarcity over prolonged periods (Jiang et al., 2022), (Desbureaux & Rodella, 2019), (Vicente-Serrano et al., 2020).

During severe drought conditions, the usable capacity of the power system experiences a significant decrease. The reduction in precipitation levels decreases water flow, leading to a reduction in the water levels of reservoirs in hydroelectric plants, which significantly reduces usable capacity. Even thermal power plants are affected due to their reliance on water cooling systems. Thus, this reduction in the availability of water resources can lead to electricity shortages (Casey et al., 2020). The tropical areas of South America have encountered periods of dryness influenced by the El Niño phenomenon and the atypical positioning of the Humboldt Current. These occurrences affect the Amazon rivers and subsequently impact the Ecuadorian rivers responsible for supplying water to hydroelectric plants (Villegas-Ch & García-Ortiz, 2023). This has resulted in considerable reductions in electricity generation, as seen in past events affecting the Paute-Molino hydroelectric power station in 1995, 1999, 2009, and more recently in 2023 and 2024 (Ronnie J. Araneda-Cabrera, 2021).

Countries abundant in water resources with significant hydropower potential are acutely vulnerable to fluctuations in water availability, which severely affect electricity production (Vaca-Jiménez et al., 2019). Consequently, water scarcity often results in severe power shortages, a condition that occurs when demand exceeds supply due to inadequate generating capacity(Ou et al., 2016). The electricity sector is crucial for economic stability, as shortages adversely affect economic development by reducing productivity within affected countries (Xue & Wang, 2021). This situation forces both major industries and small businesses to invest in costly diesel-based generators, contributing to increased carbon emissions (Grainger & Zhang, 2019). In the case of Ecuador, severe droughts have precipitated an energy crisis, compelling the Ministry of Energy to implement power rationing measures, including scheduled outages lasting up to eight hours. This crisis has markedly affected the local economy, escalating the demand for generators, batteries, and emergency lighting as businesses strive to maintain operational efficiency amid erratic electricity supply (EL Comercio, 2024), (CNN, 2024), (La Hora, 2024).

The development of nanogrids based on renewable resources provides a viable solution to alleviate the effects of power outages. Nanogrids are compact, localized power systems capable of operating either independently or in conjunction with the main electricity grid (Rajendran Pillai et al., 2023). These systems enhance reliability and resilience by their ability to automatically switch between grid-connected and islanded operations (Tsolakis et al., 2020). This functionality allows neighborhoods to maintain power during utility grid failures, intermittent outages due to energy crises, and even natural disasters (Mooyman & Wheeler, 2022). Additionally, nanogrids can prevent cascading failures by segmenting the grid into smaller, autonomous units that can operate independently, thereby localizing the impact of disturbances (Hirsch et al., 2018). Nanogrids also offer economic benefits by minimizing electricity costs through the efficient utilization of locally generated energy (Zakis et al., 2019) and the incorporation of different energy sources and technologies, including solar panels, wind turbines, inverters, and batteries, as well as advanced energy management systems. This adaptability enables them to meet specific energy demands and provides the flexibility to scale from single-phase to three-phase systems or to directly power DC appliances, thus reducing conversion steps and enhancing overall system efficiency (Syed & Morrison, 2021).

Economic feasibility studies demonstrate that nanogrids not only address immediate energy needs due to droughts but also offer sustainable financial benefits. For example, one study examines the effects of basic demand control measures on the payback period, aiming to optimize energy utilization and projecting a payback period of eight years (Zakis et al., 2019). Another study investigates a nanogrid setup that combines photovoltaic arrays, wind turbines, and diesel generators, resulting in a reduced payback period of four years, showcasing the efficacy of hybrid systems in boosting economic returns (Hamatwi et al., 2016). Furthermore, a study in a rural setting in Pakistan examines a nanogrid deployment that incorporates a mix of renewable resources, revealing a longer payback period of twelve years. These results indicate promising payback periods depending on the grid settings, location, and policy regulations (Ali et al., 2022).

The present study explores the feasibility of leveraging renewable resources in Riobamba, a location in Chimborazo, Ecuador, to implement a nanogrid to reduce dependency on the main grid and avoid possible shortages due to failures or lack of capacity. The investment required is considered a critical factor. This article is organized as follows: the methodology section, where the fundamentals of nanogrids are reviewed, includes an analysis of the renewable resources available in the area and the evaluation of the consumption to be served. Once the base architecture is selected, the optimal grid configurations are evaluated using Homer Energy Pro software, as presented in the analysis and results section. Finally, in the conclusions section, the findings derived from the research are showcased.

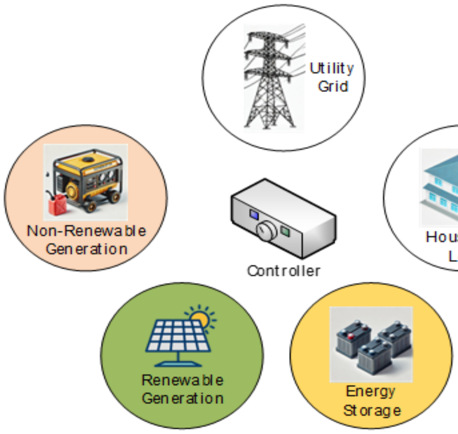
Methodology

Nanogrids Fundamentals

Microgrids are small power networks designed to supply electricity to a limited community, large infrastructures, or a particular region. These systems have the capability to function autonomously from the primary grid, establishing themselves as a dependable energy source for isolated or underserved areas (Akinyele, 2017). Nanogrids are smaller versions of microgrids, typically used to serve a single building or a small set of loads. Two distinct operational modes are available for nanogrids: islanded mode, allowing them to function independently, and grid-connected mode, in which they operate in conjunction with the main grid or additional microgrids and nanogrids (Jie & Naayagi, 2019). Nanogrids can be configured as direct current, alternating current, or hybrid systems. Among these options, direct current nanogrids have gained popularity due to their higher efficiency and stability (Chattopadhyay, 2022).

The general model of a nanogrid, as illustrated in Figure 1, shows its fundamental structure and components. Primarily, the energy input element includes renewable and non-renewable resources, battery storage, or a combination, with photovoltaic (PV) solar panels and wind turbines being the predominant energy sources employed in nanogrid applications. Additional components include converters and controllers based on power electronics devices, which are utilized for managing energy resources. The load, which may consist of single-phase, three-phase AC loads, and DC loads, represents the element served by the grid. Another crucial component is the gateway, which facilitates the connection between the nanogrid and the main grid, allowing for either bidirectional or unidirectional power flow depending on the specific application. The protection unit is essential for safeguarding the system against potential faults. Furthermore, nanogrids can integrate metering and supervision units (MSU) alongside control and load management units (CMU), enabling intelligent monitoring, control, and protection (Chattopadhyay, 2022).

Figure 1: *Basic Nanogrid Structure*



Note: *Elaborate by Authors*

The energy required by the loads constantly changes throughout the day; therefore, a controller is necessary to manage the balance between generation and consumption. Depending on the requirements, nanogrid control structures can be configured in several ways (Yerasimou et al., 2021):

Centralized Control: All components are connected to a single controller, which requires high bandwidth for system communication and is susceptible to cascading failures.

Decentralized Control: Characterized by having controller nodes for each device, this scheme reduces the risk of cascading failures and communication bandwidth requirements. However, it lacks global control or system-wide view.

Distributed Control: Based on the decentralized scheme, this approach includes interconnections between nodes, which requires high bandwidth.

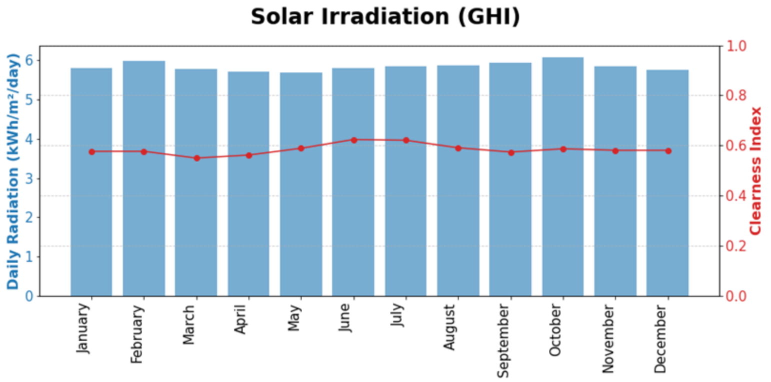
Hybrid Central Control: This configuration combines a distributed scheme with a master controller to manage individual control nodes, improving system reliability, but depending on the communication capability.

Hybrid Distributed Control: Communication between controller nodes is conducted through power lines.

Assessment of Available Renewable Resources in Riobamba

Exploring the resources available in the area where the nanogrid can be installed is essential to estimate the amount of electricity the energy system can generate. Riobamba is an urban center situated in the Chimborazo province of Ecuador, positioned at an elevation of around 2,754 meters above the sea level. This geographical location is characterized by temperate weather conditions and a well-defined rainy season. It experiences a significant amount of sunlight throughout the year and relatively clear skies due to the high elevation (Estupiñán Sosa et al., 2022). Figure 1, describes the average daily solar irradiance and the clearness index in Riobamba, showing slight variations. The clearness index ranges from 0.55 in March to 0.624 in June, suggesting relatively clear skies throughout the year. Daily radiation levels exhibit low variability, demonstrating a maximum of 6.08 kWh/m² in October and a minimum of 5.68 kWh/m² in May. This implies that the area consistently receives solar radiation during the year, making it highly suitable for photovoltaic generation.

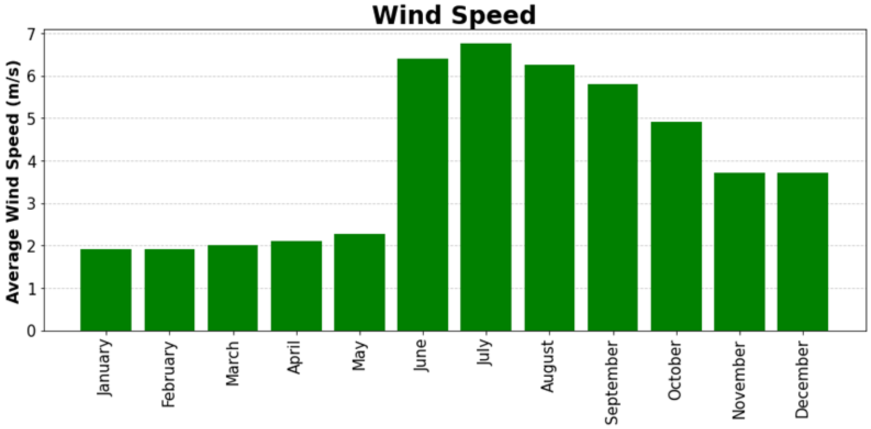
Figure 2: *Average Daily Solar Irradiation and Clearness Index in Riobamba*



Note: *Elaborate by Authors* **-** *Source: Nasa Prediction of Worldwide Energy Resources*

Eolic energy depends on the wind speed threshold, with speeds below 4 m/s considered the lower limit and speeds above 6 m/s deemed good for wind generation. Figure 3 describes the average wind speed throughout the year. Speeds below 3 m/s are noted from January to May, a period during which wind generation may not be optimal. October to December shows moderate wind speeds, suggesting suitability for small-scale wind generation. The period from June to September exhibits very good potential for wind generation with wind speeds above 6 m/s. This data indicates significant seasonal variation in wind speed during the year, presenting high potential only in the middle of the year. This suggests that at the beginning and end of the year, complementary energy sources may be required to ensure a consistent energy supply.

Figure 3: *Average Daily Wind Speed in Riobamba*

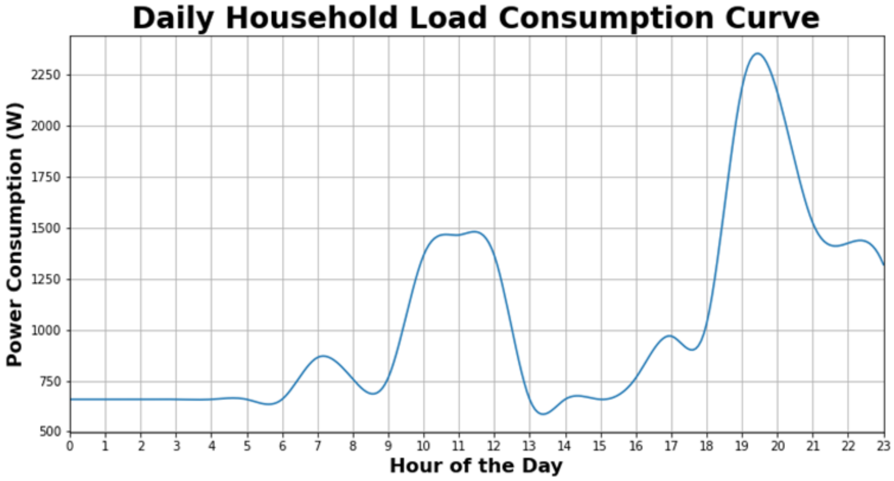


Note: *Elaborate by Authors* **-** *Source: Global Wind Atlas*

Load Consumption

The nanogrid is expected to supply a typical household load, as detailed in Figure 4, which studies the daily consumption pattern. The analysis reveals that, as anticipated, there exist two distinct peak hours: one occurring between 10:00 and 12:00 during the midday period, characterized by a peak power consumption of 1463W. This peak corresponds to typical household activities such as cooking, heating, and the use of electronic devices. Solar energy generation is typically highest during midday, around this peak consumption period, and can directly supply this demand, reducing the reliance on stored energy or grid power. However, the major consumption occurs in the evening, particularly between 19:00 and 21:00, with the highest peak reaching 2183W at 19:00. This significant increase in power demand is due to activities like cooking dinner, lighting, entertainment systems, and other household electronics being used simultaneously. During these hours, solar resources are not available, making it critical to incorporate energy storage solutions such as batteries.

Figure 3: *Daily Load Consumption*



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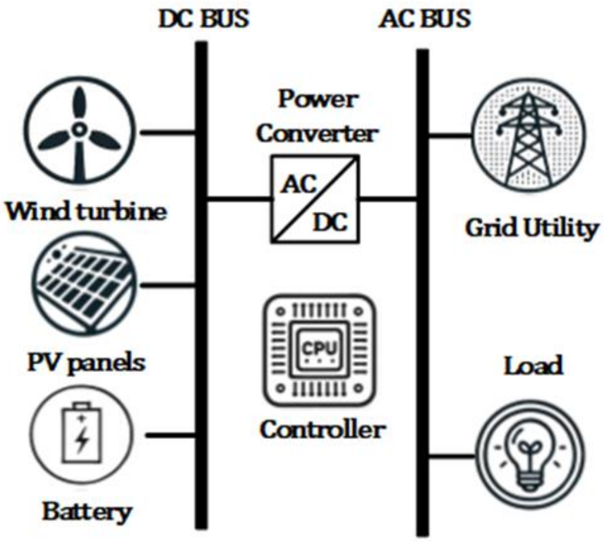
Architecture proposed

Once energy resources and demand are characterized, the architecture of the nanogrid is proposed. The topology, as illustrated in Figure 4, includes PV panels and wind turbines for electricity supply. This combination explores their complementary nature: solar panels generate energy during sunny conditions, while wind turbines produce power during windy conditions, at night, or on overcast days, maximizing the utilization of renewable resources. A bank of batteries is primarily used for energy storage and for maintaining a stable energy supply, storing excess energy during periods of low demand or high production and supplying the load during peak demand periods or when renewable energy is insufficient. Converters are included to integrate the nanogrid into the existing AC grid infrastructure, ensuring operation in conjunction with the main grid. All components are managed through a centralized topology. This configuration requires a controller to manage the optimal dispatch of different energy sources based on demand and supply conditions.

Figure 4: *Base Nanogrid Architecture*



Note: *Elaborate by Authors*

Analysis and results

To assess the most suitable setup of the suggested nanogrid, Homer Energy Pro is employed. This software provides a comprehensive platform for optimizing microgrid and nanogrid designs, taking into account a variety of technical and economic factors. The evaluation process within Homer Energy Pro necessitates an examination of the economic attributes of the nanogrid elements, ensuring that the proposed configuration is both cost-effective and efficient. The input data required includes the cost, lifespan, and maintenance expenses of the nanogrid components as primary variables. Local pricing data, as outlined in Table 1, is critical for this analysis, as it provides a realistic basis for the economic evaluation.

Table 1: *Nanogrid Elements Cost*

	Cost of capacity installed ($/kW)	**Operation and maintenance ($/year)**	**Lifetime(years)**
PV panels	1000	30	25
Wind Turbine	2000	20	50
Battery Bank	400 – 1 hour	10	10
DC/AC Converter	550	0	10
	Cost equipment ($)		**Lifetime(years)**

Controller	250	30
	Cost of Energy($/kWh)	
Main Grid	0.096	

The evaluation conducted by the software explores different network topologies based on the nanogrid architecture to determine the optimal solution. The results summarized in Table 2 indicate that the baseline scenario is the main grid, which, based on demand, estimates an energy purchase of 4109 kW with an annual cost of $450.91. Introducing the nanogrid significantly alters the dynamics of the system. The first configuration introduces PV panels without storage, giving the lowest cost of energy at $0.088 and reducing the energy purchase to 2822 kW. However, this system does not offer autonomy. Incorporating storage to the PV panels increases the initial investment, resulting in a cost of energy of $0.09. This configuration increases generation, reducing the energy purchase to 2615 kW and providing a partial autonomy of 3.5 hours, offering a balance between cost and energy independence. The more complex configuration, which includes all elements of the architecture, requires a higher initial investment of $3131. This topology incurs a higher cost of energy but maximizes energy production to 1884 kW annually, reducing the purchased energy to 2225 kW and providing an autonomy of 5 hours. This configuration, while costlier, significantly enhances energy independence and resilience.

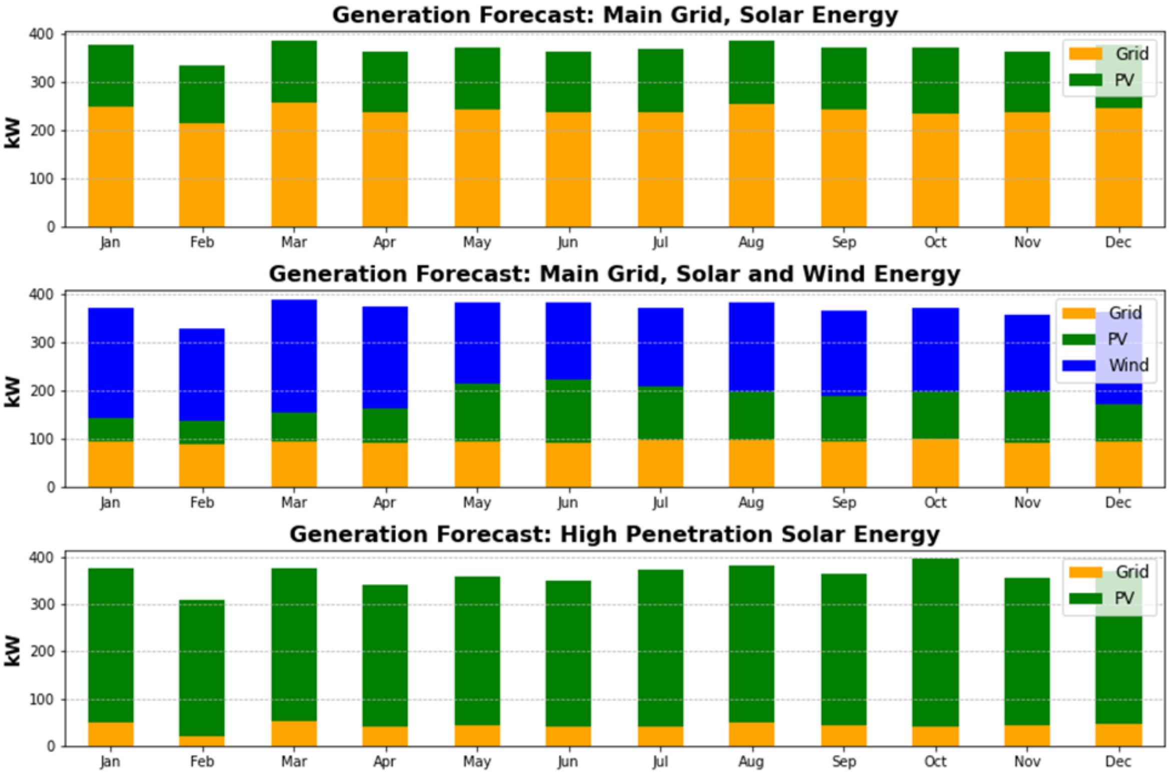
Table 2: *Comparative Analysis of Nanogrid Configurations with Cost and Energy Metrics*

Power Supply				**Cost**					
Main Grid	**PV panels**	**Wind turbines**	**Battery Bank**	**Initial Capital ($)**	**Cost of Energy ($/kWh)**	**Annual Operating Cost ($/year)**	**Energy Produced (kW/year)**	**Energy Purchased (kW/year)**	**Grid Autonomy (hours)**
🟧				0	0.096	450.91	0	4109	0
🟧	🟩			1193	0.088	291.48	1287	2822	0
🟧	🟩		🟥	1633	0.090	350.35	1494	2615	2

🟧	🟩	🟦	🟥	3131	0.150	392.42	1884	2225	5
🟧	🟩		🟥	8523	0.352	470.25	3356	753	22

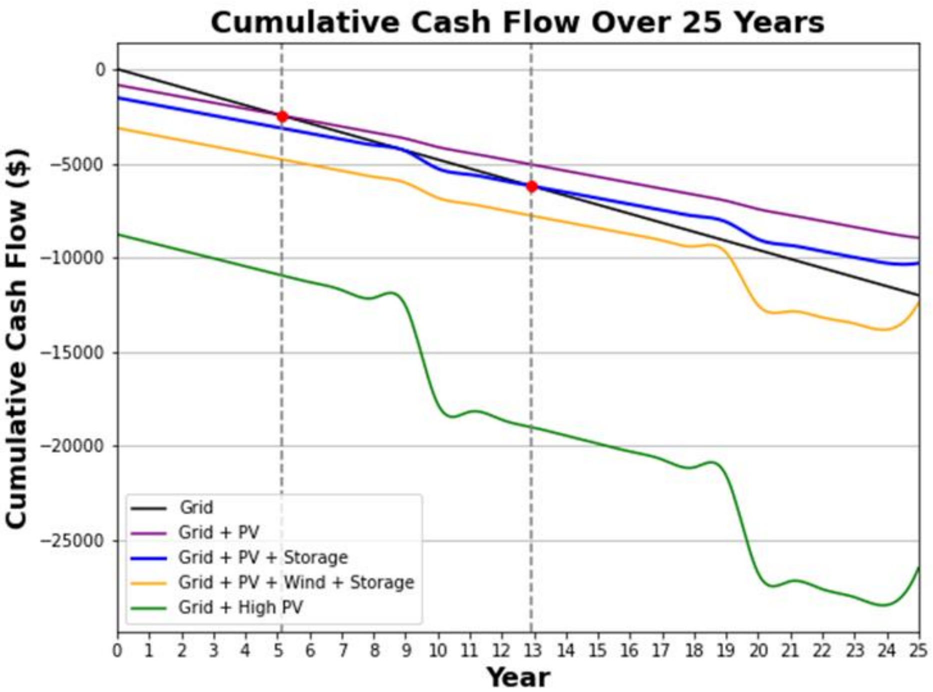
The amount of energy expected to be produced during the year for three nanogrid configurations is presented in Figure 5. The first configuration shows a grid with PV panels and storage systems, reducing the amount of energy purchased each month due to the consistent solar energy harvested throughout the year. This indicates that the homogeneous solar irradiation across the seasons ensures a stable, environmentally friendly energy supply. In the second configuration, wind energy is integrated. The energy contribution from wind power is variable, with peak production during the middle of the year, corresponding to the seasons with the highest average wind speeds. This configuration enhances renewable energy production, increasing the resilience and independence of the nanogrid during these peak months. The third configuration emphasizes a nanogrid with a high penetration of solar energy, showing that increasing the number of solar panels and storage achieves greater independence and significantly reduces the energy purchased. This configuration constitutes the optimal choice for maximizing the amount of renewable energy while maintaining main grid support.

***Figure 5:** Generation Nanogrid Forecast*



Another factor to consider for evaluating the feasibility of the nanogrid is the economic performance. Figure 6 presents the cumulative cash flow expected over the next 25 years. The main grid serves as the reference for comparison, showing a consistent linear decrease with a yearly cost of $480. The configuration that includes a high penetration of solar energy involves the highest initial investment and contributes a considerable amount of grid independence; however, over the 25-year period, no payback is reached. The same occurs for the configuration that includes PV panels and wind turbines. Although the investment is lower, resulting in an increase in energy purchased, it still maintains a good amount of renewable energy generated. Even though the investment is not as high as the high-solar configuration, the investment is not retrieved over the analyzed period.

Figure 6: *Cumulative Cash Flow*



The two configurations that achieve payback over the period are the nanogrid with PV panels without storage and the nanogrid with PV panels and a battery bank. The configuration with PV panels without storage achieves the shortest payback period, crossing with the main grid trend around 5 years, indicating a quick return on investment. However, the lack of energy storage results in complete dependency on the main grid when solar energy is unavailable. Adding a battery bank to the PV system increases the initial investment and consequently extends the payback period to 13 years. Despite the longer payback period, this configuration offers a period of two hours of energy autonomy, reducing reliance on the main grid during times when solar power is insufficient.

Conclusion

Considering potential power shortages due to faults or insufficient capacity caused by droughts, the configuration that ensures the highest autonomy is the optimal solution. However, the high investment cost and the low cost of energy from the utility grid affect the payback period, making these high-autonomy grids unable to achieve a return on investment within the considered period. In this context, when considering the economy as the optimization objective, the configuration that includes only PV panels is the most viable option. Nevertheless, the lack of storage capabilities in this configuration does not prevent shortages when the utility grid and solar energy are unavailable. Therefore, the most effective solution considering both economy and autonomy is the configuration that integrates solar energy with storage. This setup offers a relatively short payback period compared to the cost of energy and provides the necessary autonomy to supply power during short-term outages. By prioritizing critical loads, this configuration can extend the duration of power supply during grid interruptions. In conclusion, while configurations with the highest autonomy offer inviable high costs, a combination of solar energy and energy storage operated in conjunction with the utility grid offers a more balanced approach. This provides a feasible payback period and ensures reliability during outages.

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