Inefficiencies and Vulnerabilities of the Puerto Rico Electrical Power Systems

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Abstract

Puerto Rico's electricity system faces inefficiencies and vulnerabilities due to obsolete infrastructure, high dependence on fossil fuels, and limited integration of renewable energy. This study analyzes systemic and operational challenges that affect the island's energy resilience through technical diagnostics, public policy analysis, and economic tools such as Levelized Cost of Energy (LCOE) and Integrated Resource Plan (IRP) simulations. Geospatial and cybersecurity assessments identify critical vulnerabilities to natural disasters and digital threats. Results revealed that the aging of the grid reduces reliability, the transition to renewable energies advances slowly despite Law 17-2019, and barriers persist in the adoption of smart technologies. Strategies such as microgrids, distributed generation, and advanced storage are proposed. The study supports a phased modernization plan that prioritizes infrastructure renewal, regulatory reforms, and community inclusion, with the goal of achieving a more sustainable and resilient electricity system for Puerto Rico.

Introduction

Over the years, Puerto Rico's electric power generation and distribution system has been facing numerous challenges, resulting in inefficiencies and vulnerabilities that are hindering the island's energy security, economic stability, and environmental sustainability. As responsible for the generation and distribution of electricity, the Puerto Rico Electric Power Authority (PREPA) has been managing a deteriorating infrastructure that struggles to meet the island's growing energy demand. This system relies primarily on fossil fuels, especially imported oil and natural gas, which increases operating costs. In addition, the island's power grid has been prone to frequent blackouts, exacerbated by natural disasters such as Hurricane Maria in 2017, revealing serious vulnerabilities in the system's resilience.

The main problems of Puerto Rico's electric power system are high energy losses during transmission and distribution, an aging infrastructure that has not been modernized, and difficulties in efficiently integrating renewable energy sources. Frequent blackouts, high electricity costs and poor grid stability contribute to undermine Puerto Rico's economic development. The transitions to renewable energy sources such as solar and wind, while crucial for sustainability, adds additional pressure on the grid to maintain stability and frequency regulation.

The scope of this project is to address the inherent risks, shortcomings, potential for improvement, and existing problems in Puerto Rico's electric energy transmission and distribution system. The causes of energy losses will be analyzed, obsolete infrastructures will be examined, and the challenges posed by the integration of renewable energy sources will be evaluated.

The objectives of this project are to identify critical infrastructure and operational weaknesses within Puerto Rico's electric power system to better understand the factors undermining its efficiency and reliability. It will also evaluate the policy and economic impacts that have shaped modernization efforts, assessing how these influences have either supported or hindered progress. Finally, in its implementation, this plan will propose data-supported strategies to enhance energy resilience, offering practical and sustainable solutions to strengthen the system against future threats and challenges.

Literature Review

Institutional and Technical Challenges
Puerto Rico's electric power system has faced serious institutional and technical challenges over recent decades, resulting from a combination of mismanagement, financial fragility, and a high dependence on fossil fuels. PREPA operated for years under a centralized model, with aging infrastructure and limited investment in modernization, which contributed to a vulnerable and unreliable grid. Technical losses during energy transmission and distribution are high in Puerto Rico due to the poor condition of the electrical infrastructure and the lack of digitalization, which affects operational efficiency and compromises both service stability and economic sustainability. Moreover, reliability indicators such as System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) consistently exceed national averages, reflecting persistent failures in system maintenance and operation [1].

Dependence on diesel and natural gas worsens these problems by introducing price volatility in electricity and threatening service affordability for consumers and businesses. This dependency generates negative economic impacts on island power systems, making Puerto Rico more vulnerable to fluctuations in global fossil fuel markets. Although Act 17-2019 sets a transition toward a 100% renewable energy matrix by 2050, implementation has been slow, and the targets defined in the Integrated Resource Plan (IRP) remain far from being met [2].

The lack of technological modernization, especially in smart grid implementation, has contributed to the system's operational inefficiency. This situation is worsened by the aging infrastructure: most substations, transmission lines, and control systems are over 40 years old. The 2021 transition to private management through LUMA Energy sought to improve this scenario, but has generated controversy due to operational deficiencies, especially during events such as hurricanes or widespread blackouts. Criticisms related to contractual noncompliance, lack of transparency, and limited tangible results have increased public and political dissatisfaction [3].

Regulatory Framework and Renewable Resilience
Act 17-2019, known as Puerto Rico's Energy Public Policy Act, is the legal foundation that establishes a complete transition to 100% renewable energy by 2050. This policy promotes decentralization, the use of clean technologies, and distributed generation. The IRP complements this policy by defining investment priorities, energy demand forecasts, and schedules for renewable integration. The Puerto Rico Energy Bureau (PREB) is responsible for overseeing these processes, evaluating IRP compliance, and ensuring accountability throughout the energy transition [2].

The integration of renewable energies and storage solutions is essential to improve the grid's resilience against extreme events. In this context, decentralized systems such as microgrids and solar cooperatives enable local energy production and reduce dependence on vulnerable centralized infrastructure. An example is the Casa Pueblo solar microgrid in Adjuntas, which, thanks to battery backup, has been able to maintain electricity supply during prolonged outages [4].

Microgrids and distributed energy resources are key to strengthening energy security, promoting energy equity, and empowering communities. In central Puerto Rico, community solar cooperatives are emerging to foster shared ownership models and active citizen participation, promoting a more just and resilient energy system [5].

Methodology

This study was conducted using a systemic and multidisciplinary approach designed to assess and address the structural inefficiencies and operational vulnerabilities of Puerto Rico's electricity system. The methodology integrated technical, economic, and regulatory perspectives to build a comprehensive analysis framework. The approach involved the use of technical and economic evaluation tools, including Levelized Cost of Energy (LCOE) calculations, Integrated Resource Planning (IRP) models, and advanced demand forecasting methods. These tools were selected to evaluate renewable energy integration under different generation and consumption scenarios.

The study also considered the role of energy storage systems, smart grid technologies, and advanced transmission solutions such as Flexible AC Transmission Systems (FACTS) and High Voltage Direct Current (HVDC), with the aim of assessing their potential to enhance operational performance and grid stability. To evaluate climate and cyber resilience, the methodology included vulnerability mapping based on geospatial data and infrastructure exposure, as well as a review of cybersecurity protocols and operational technology (OT) security systems. Furthermore, regulatory analysis and examination of hybrid financing models were conducted to explore strategies for promoting distributed generation, energy self-sufficiency, and microgrid deployment in remote or high-risk areas.

Development of energy storage systems
The study incorporated a comparative technical and economic assessment of different energy storage technologies. The analysis framework included criteria such as efficiency, response time, scalability, lifecycle cost, and compatibility with Puerto Rico's projected demand profiles. Integration modeling was used to simulate potential deployment scenarios based on hourly renewable energy availability and grid demand forecasts. This modeling aimed to support the identification of suitable configurations for improving grid reliability and flexibility.

Digitization and Monitoring of the Electrical System
A diagnostic assessment was carried out to identify potential vulnerabilities in the transmission and distribution network. This involved the review of historical outage records, technical audits, and infrastructure maintenance data. The methodology also evaluated the feasibility of implementing smart grid technologies, including real-time demand-side management systems, automated fault detection, and advanced monitoring tools powered by artificial intelligence.
Consideration was given to the potential integration of FACTS and HVDC technologies to improve long-distance transmission capacity. Additionally, the study reviewed options for system instrumentation such as optical sensors, smart relays, and remote supervision systems.

Promotion of Self consumption and Energy Financing
A regulatory and financial analysis was conducted to examine existing policies and incentives supporting distributed energy resources. This included a review of net metering programs, subsidies, and financing mechanisms available for solar PV, small wind turbines, and residential-scale storage systems. The analysis also explored the technical and financial feasibility of microgrid deployment in remote or underserved areas. Public-private partnership (PPP) models were reviewed to identify investment strategies and institutional frameworks that could enable sustainable energy infrastructure development.

Assessment of system resilience to climate and external risks
To evaluate exposure to natural and external threats, the study applied geospatial vulnerability mapping techniques using data on the location of substations, transmission lines, and control centers. Risk categories included hurricanes, seismic activity, and cyberattacks. The methodology included an engineering assessment of mitigation measures, such as undergrounding of lines and structural reinforcement of critical assets. In parallel, the study examined cybersecurity strategies, including the potential integration of Supervisory Control and Data Acquisition (SCADA) systems, firewalls, and intrusion detection technologies, to assess readiness for cyber threats and ensure continuity of operations.

Results and Discussion

The analysis revealed several key findings regarding Puerto Rico's electrical infrastructure. Energy losses in transmission and distribution exceed 11%, mainly due to aging infrastructure, lack of maintenance, and absence of digitalization. [1]. The grid shows low resilience, evidenced by reliability indicators such as SAIDI and SAIFI consistently surpassing national averages, reflecting frequent and prolonged outages, as shown in Table 1 and Figure 1. [2],[3].

Table 1
SAIDI and SAIFI Comparison (Puerto Rico vs National)

Year	SAIDI PR (red line)	SAIDI National SAIDI (green line)	SAIFI PR (dotted orange line)	SAIFI National SAIFI (dotted blue line)
2020	180 min	90 min	3.0	1.5
2021	175 min	88 min	2.9	1.4
2022	190 min	85 min	3.1	1.3
2023	185 min	83 min	3.0	1.2

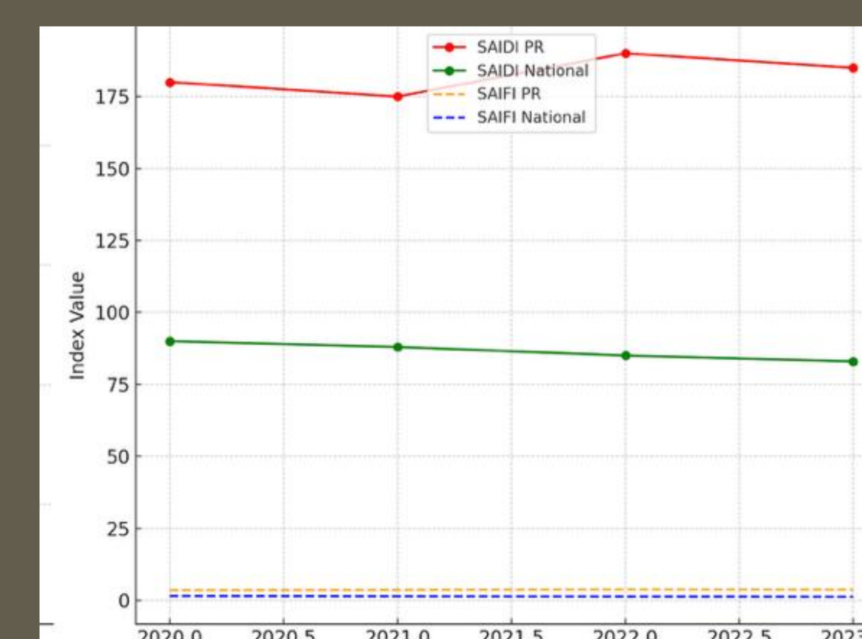

Figure 1
SAIDI and SAIFI Comparison (Puerto Rico vs National)

Additionally, over 70% of electricity depends on imported fossil fuels, exposing the island to price volatility and supply risks. Despite legislative goals, the integration of renewable energy sources remains limited, and compliance with the Integrated Resource Plan is delayed. There is also insufficient adoption of advanced monitoring and automation technologies, affecting fault detection and real-time management. Conversely, community systems like Casa Pueblo's microgrids demonstrate the potential of decentralized generation to enhance resilience and energy equity. Finally, geospatial analysis identifies significant climatic and digital vulnerabilities, with substations and lines exposed to hurricanes and flooding, along with notable cybersecurity deficiencies.

According to the data illustrated in Figure 2, Puerto Rico's energy generation in 2024 is still highly dependent on fossil fuels, which account for approximately 70% of the total mix. Renewable sources remain limited, with solar at 15%, wind, hydro, and other renewables, each contributing only 5%. However, the projected energy scenario shows a significant shift toward renewable energy. Fossil fuel dependency is expected to drop to 30%, while solar energy increases substantially to 40%. Wind rises to 15% and hydro doubles to 10%, reflecting the territory's strategic push for diversification and sustainability. This projected transformation aligns with Puerto Rico's energy policy goals and highlights the importance of investment in infrastructure modernization, decentralized energy systems (microgrids), and increased use of local renewable resources to enhance energy resilience and reduce reliance on imported fossil fuels. [1],[3]

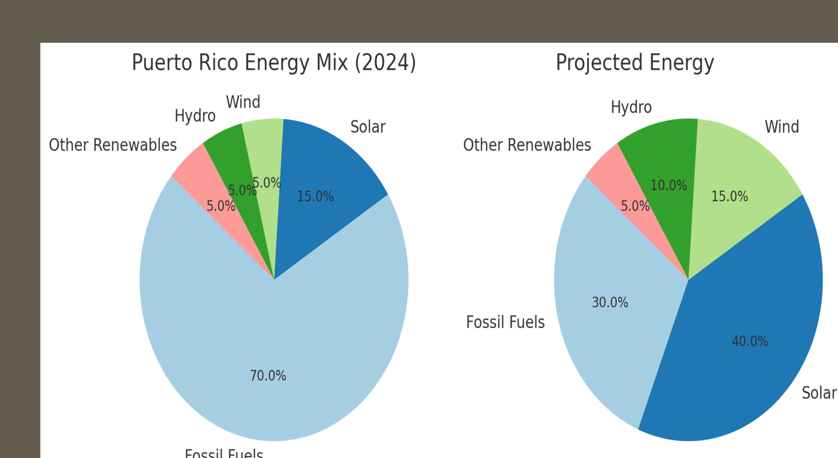

Figure 2
Energy Mix Analysis: Current vs. Projected Scenario

Conclusions

The electric power system of Puerto Rico requires urgent modernization to overcome chronic inefficiencies, infrastructure fragility, and vulnerabilities to natural disasters and digital threats. This study demonstrates the need to adopt a comprehensive strategy that combines technological innovation, regulatory compliance, community participation, and sustainable financing mechanisms. Immediate actions should focus on grid upgrades, expansion of distributed generation, adoption of smart technologies, and strengthening cybersecurity. Furthermore, consistency in public policies and transparent regulatory oversight will be key to achieving energy transition goals. If these reforms are effectively implemented, Puerto Rico can transform its electric system into a resilient, accessible, and sustainable model for other island regions or disaster-prone areas.

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