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Assessing Grid Resilience for Optimal Integration of Renewable Energy Sources in Kenya

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1. Introduction

This study aims to assess renewable energy integration strategies to enhance grid resilience in Kenya, addressing the challenges of maintaining grid stability amidst climate-induced disruptions and the increasing penetration of intermittent renewable sources. The research employs a comprehensive methodology, combining quantitative assessment of grid infrastructure and renewable integration dynamics with qualitative evaluation of resilience strategies, utilizing key metrics such as the Resilience Index (RI), System Average Interruption Frequency Index (SAIFI), and System Average Interruption Duration Index (SAIDI)[1]. The expected output includes a set of optimal renewable integration strategies and targeted grid adaptation measures to achieve a more resilient, sustainable, and reliable electricity system in Kenya, with significant implications for policymakers, grid operators, and energy stakeholders in ensuring a stable and reliable power supply while achieving renewable energy targets and reducing the carbon footprint[2].

2. Literature Review

2.1 Overview of Kenya's Power Grid

Kenya's electricity grid has undergone significant expansion in recent years. From 2016 to 2021, the installed generation capacity increased by 28.53%, rising from 2,327 MW to 2,990 MW[3]. This growth demonstrates Kenya's commitment to diversifying its energy sources and meeting the escalating demand for electricity. The generation mix comprises various sources, with geothermal power being the largest contributor at 1,694 MW, accounting for 60% of the effective generation capacity. Independent Power Producers (IPPs) play a significant role, generating 1,037 MW (38%) of the effective capacity. Renewable energy sources from the government company, Rural Electrification and Renewable Energy Company (REREC), contribute 2% of the effective capacity through off-grid generation[3].

Despite the progress, Kenya's power grid faces challenges. The growth in peak demand, which increased from 1,636 MW in 2016 to 2,036 MW in 2021, necessitates continuous expansion to meet the demand-supply gap effectively. The dominance of geothermal and thermal sources, which serve as base load effective capacity raises concerns about the grid's vulnerability to grid disruptions caused by severe and unpredictable weather[3].

2.2 Resilience Metrics and Quantification Methods

Metrics such as reliability indices, prove an inadequate spectrum of determining grid resilience. However, resilience-focused metrics, such as resilience trapezoid approach, are needed to track performance degradation, disruption duration, and recovery[4]. Adapting these metrics to the Kenyan context is crucial for the successful quantification of grid resilience[5].

2.3 Applications of System Resilience Curves (SRCs)

System Resilience Curves (SRCs) visualize and help analyze the resilience of complex systems like the electric grid. SRCs plot the system's performance over time in response to a disruptive event, revealing critical phases such as disruption, degradation, response, adaptation, and recovery[6]. In the context of Kenya's power grid, SRCs can be applied to:

1) Assess the grid's ability to absorb and adapt to disruptions. This is done by examining the slope and shape of the SRC during the disruption and degradation phases, grid operators can then evaluate the grid's resilience and identify vulnerabilities.
2) Evaluate the effectiveness of response and recovery measures by providing data on the speed and extent of the grid's recovery following a disruption. The data acquired can then guide the development and implementation of effective response and restoration strategies.
3) Compare the resilience of different grid configurations and scenarios by comparing resilience levels across various renewable energy integration scenarios, helping to identify optimal strategies for enhancing grid resilience.

2.4 Renewable Energy Integration Concept

A conceptual framework for isolated grids with high renewable penetration involves real-time analytics to drive dynamic load allocation based on consumer priority profiles. However, challenges arise in maintaining grid stability, coordination, and resilience against uncertainties and unpredictable climatic conditions[7], [8], [9].

3. Methodology

3.1 Grid Resilience Metrics Framework

The study employs a comprehensive Grid Resilience Metrics Framework to assess the resilience of Kenya's power grid. Three key metrics are utilized:

(i) Resilience Index (RI) quantifies the fraction of demand served during disruptions. It is calculated using the formula:

$$RI = 1\frac{ENS}{Demand} \qquad (1)$$

where ENS is the Energy Not Served and Demand is the total energy demand during the disruption period. RI values range from 0 to 1, with higher values indicating greater resilience and indicated in figure 1[10].

(ii) System Average Interruption Frequency Index (SAIFI), which measures the average number of interruptions experienced by a customer annually and is calculated as;

$$SAIFI = \frac{\sum C_i}{\sum C_s} \qquad (2)$$

Where; C_i *is the total number of customer interruptions.*
C_s *represents the total number of customers served.*

A lower SAIFI value indicates a more reliable and resilient grid.

(iii) System Average Interruption Duration Index (SAIDI): SAIDI quantifies the average outage duration experienced by customers over a year, and is calculated as;

$$SAIDI = \frac{\sum_{all} C_i}{\sum C_s} \qquad (3)$$

Where; $\sum_{all} C_i$ *is the sum of all customer interruptions while,* $\sum C_s$ *is the total number of customers served.*

A lower SAIDI value suggests shorter outage durations and improved grid resilience (fig 1).

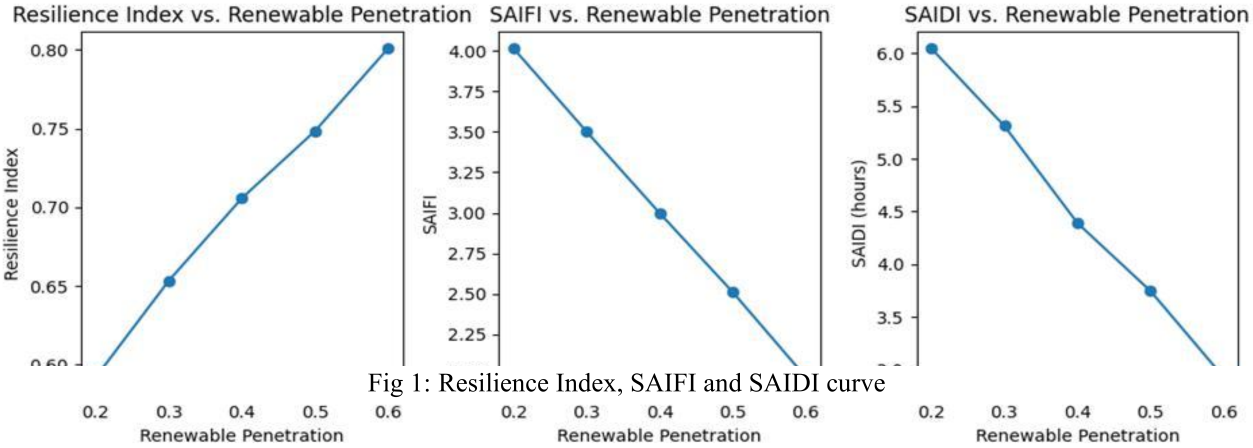

Fig 1: Resilience Index, SAIFI and SAIDI curve

3.2 System Resilience Modeling and Analysis

A performance function *P(t)* is formulated for resilience quantification, parameterized using weighted indicators like load served, frequency stability, ramp rate, and unmet demand. Calculated as;

$$P(t) = \omega_1 \cdot LS(t) + \omega_2 \cdot FS(t) + \omega_3 \cdot FR(t) + \omega_4 \cdot UD(t) \qquad (3)$$

Where; *LS(t)* is the load served, *FS(t)* is the frequency stability, *FR(t)* is the flexible ramp rate and *UD(t)* is the unmet demand.

These metrics provide an understanding of the grid's ability to withstand and recover from disruptions. By analyzing historical data and conducting simulations, the study assesses the impact of renewable energy. However, simulations project a 30% reduction in SAIFI and a 25% reduction in SAIDI by 2025 with strategic renewable integration and grid upgrade.

4. Results

4.1 Model-Based Resilience Assessment

From the case study of Nairobi County, where electricity consumption is the highest, the Resilience Index (RI) averages 0.67 for the current 20% renewable penetration scenario. This indicates that the grid's ability to maintain functionality during disruptions is relatively low[11], [12]. These improvements suggest that the grid will be able to clear faults more quickly and recover from disturbances more efficiently, rather than simply increasing the availability of power supply.

Figure 2 demonstrates the positive impact of increasing renewable penetration on resilience metrics, highlighting the grid's enhanced capability to respond to and recover from disruptions, rather than solely focusing on meeting supply and demand. For instance, as renewable penetration increases from 20% to 60%, the Resilience Index improves from 0.67 to 0.85, indicating a higher proportion of demand being met during disruptive events. Similarly, SAIFI decreases from 4.5 to 3.1 interruptions per customer annually, while SAIDI reduces from 11.5 to 8.5 hours showcase the benefits of strategic renewable integration in enhancing grid reliability and minimizing the impact of outages on consumers. These findings underscore the potential for Kenya to achieve a more resilient, sustainable, and future-proof electricity system by optimizing the integration of renewable energy sources while simultaneously strengthening the grid infrastructure.[13]

4.2 Optimal Renewable Integration Strategies

The study proposes a phased capacity expansion plan targeting 60% geothermal, 30% wind, and 10% solar by 2030 as per Kenya's Least Cost Power Development Plan (2024-2043). Deployment of distributed energy storage systems is recommended for flexibility and grid capabilities. Grid adaptation and improvement measures, such as infrastructure reinforcement and advanced control systems, are emphasized[6], [12]. Supportive regulatory frameworks and market mechanisms are identified as crucial for sustainable renewable energy development. Capacity building and workforce development programs

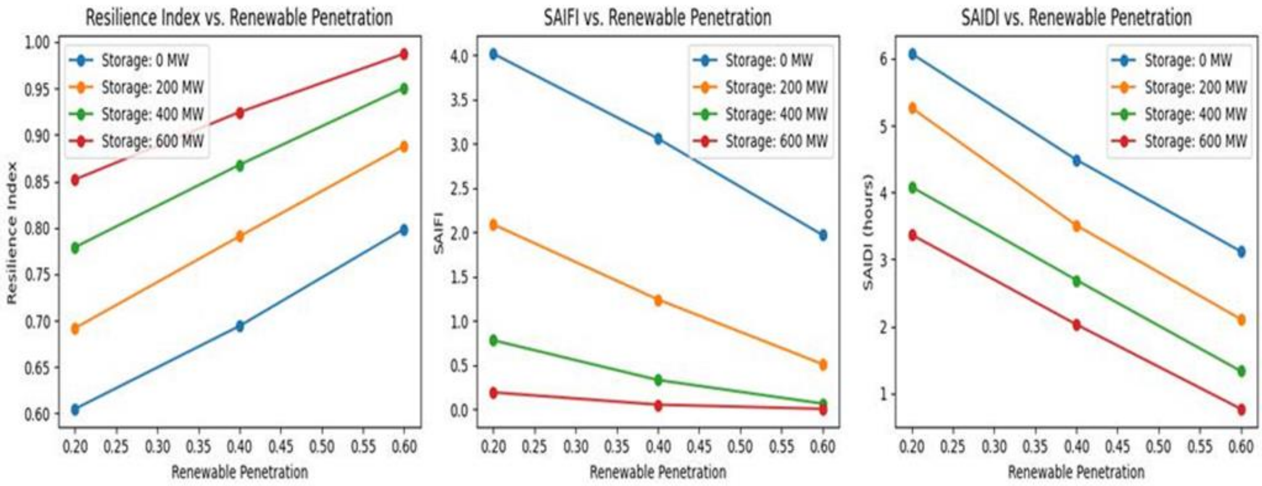

Fig 2*:* Projected optimization of RI, SAIFI and SAIDI

are highlighted as essential for effective integration and management of renewable technologies.

5. Conclusions

This research paper presents a compelling case for enhancing grid resilience through strategic renewable energy integration and targeted grid adaptation measures in Kenya. The model-based resilience assessment, utilizing key metrics such as the Resilience Index (RI), SAIFI, and SAIDI, provides evidence for the benefits of increasing renewable energy penetration. The case study of Nairobi County demonstrates that with the current 20% renewable penetration scenario, the grid's ability to maintain functionality during disruptions is relatively low, with an average RI of 0.67[14]. However, simulations project a 30% reduction in SAIFI and a 25% reduction in SAIDI by 2025 with strategic renewable integration and grid upgrades, suggesting improved grid performance in clearing faults and recovering from disturbances[15]. The proposed phased capacity expansion plan, targeting 60% geothermal, 30% wind, and 10% solar by 2030, aligns with Kenya's Least Cost Power Development Plan (2024-2043).

The deployment of distributed energy storage systems, infrastructure reinforcement, advanced control systems, and supportive regulatory frameworks are identified as crucial elements for achieving optimal renewable integration and enhancing grid resilience. Capacity building and workforce development programs are also highlighted as essential for the effective integration and management of renewable technologies[7]. By harnessing the potential of renewable energy resources while simultaneously strengthening the grid infrastructure, Kenya can ensure reliable and affordable access to electricity for its growing population and economy, while also contributing to its climate change mitigation goals[9], [16]. The study underscores the importance of creating an enabling environment for sustainable renewable energy development through supportive policies, market mechanisms, and capacity-building initiatives, which will drive innovation, attract investment, and facilitate the transition to a cleaner and more resilient energy future.

REFERENCES

[1] R. Rocchetta, “Enhancing the resilience of critical infrastructures: Statistical analysis of power grid spectral clustering and post-contingency vulnerability metrics,” *Renewable and Sustainable Energy Reviews*, vol. 159, p. 112185, May 2022, doi: 10.1016/j.rser.2022.112185.

[2] M. R. Elkadeem, A. Younes, S. W. Sharshir, P. E. Campana, and S. Wang, “Sustainable siting and design optimization of hybrid renewable energy system: A geospatial multi-criteria analysis,” *Appl Energy*, vol. 295, Aug. 2021, doi: 10.1016/j.apenergy.2021.117071.

[3] “Annual Report and Financial Statements for the Year Ended 30 June 2021,” Nairobi, Kenya, Jun. 2021.

[4] T. Kataray *et al.*, “Integration of smart grid with renewable energy sources: Opportunities and challenges – A comprehensive review,” *Sustainable Energy Technologies and Assessments*, vol. 58. Elsevier Ltd, Aug. 01, 2023. doi: 10.1016/j.seta.2023.103363.

[5]M. Ouyang and L. Dueñas-Osorio, “Multi-dimensional hurricane resilience assessment of electric power systems,” *Structural Safety*, vol. 48,pp. 15–24, May 2014, doi: 10.1016/j.strusafe.2014.01.001.

[6] D. S. M. and J. L. D.-G. A. G. Selga, “Analysis and enhancement of Barcelona’s power grid resilience," Energy Reports",” Nov. 2022.

[7] J. Liu, X. Chen, H. Yang, and K. Shan, “Hybrid renewable energy applications in zero-energy buildings and communities integrating battery and hydrogen vehicle storage,” *Appl Energy*, vol. 290, May 2021, doi: 10.1016/j.apenergy.2021.116733.

[8] J. Wang, A. Pratt, K. Prabakar, B. Miller, and M. Symko-Davies, “Development of an integrated platform for hardware-in-the-loop evaluation of microgrids before site commissioning,” *Appl Energy*, vol. 290, May 2021, doi: 10.1016/j.apenergy.2021.116755.

[9] T. Kataray *et al.*, "Integration of smart grid with renewable energy sources: Opportunities and challenges – A comprehensive review," *Sustainable Energy Technologies and Assessments*, vol. 58, p. 103363, Aug. 2023, doi: 10.1016/j.seta.2023.103363.

[10] A. Nikoobakht and J. Aghaei, "Resilience promotion of active distribution grids under high penetration of renewables using flexible controllers," *Energy*, vol. 257, Oct. 2022, doi: 10.1016/j.energy.2022.124754.

[11] P. Cicilio *et al.*, "Electrical grid resilience framework with uncertainty," *Electric Power Systems Research*, vol. 189, Dec. 2020, doi: 10.1016/j.epsr.2020.106801.

[12] A. G. Selga, D. S. Muñoz, and J. L. Dominguez-García, "Analysis and enhancement of Barcelona's power grid resilience," *Energy Reports*, vol. 8, pp. 1160–1167, Nov. 2022, doi: 10.1016/j.egyr.2022.08.119.

[13] M. Panteli and P. Mancarella, "The Grid: Stronger, Bigger, Smarter? Presenting a Conceptual Framework of Power System Resilience," IEEE Power and Energy Magazine," vol. 13, no. No 3, May 2015.

[14] A. M. Martínez Sánchez, C. A. Saldarriaga Cortés, and H. Salazar, "An optimal coordination of seasonal energy storages: A holistic approach to ensure energy adequacy and cost efficiency," *Applied Energy*, vol. 290. Elsevier Ltd, May 15, 2021. doi: 10.1016/j.apenergy.2021.116708.

[15] Y. Wang *et al.*, "Coordinating Multiple Sources for Service Restoration to Enhance Resilience of Distribution Systems," *IEEE Trans Smart Grid*, vol. 10, no. 5, pp. 5781–5793, Sep. 2019, doi: 10.1109/TSG.2019.2891515.

[16] W. Zhuang, S. Zhou, W. Gu, and X. Chen, "Optimized dispatching of city-scale integrated energy system considering the flexibilities of city gas gate station and line packing," *Appl Energy*, vol. 290, May 2021, doi: 10.1016/j.apenergy.2021.116689.