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

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1. Introduction

Introduction

Background and motive for the study

- Growing importance of grid resilience in the face of climate change
- Need for strategic integration of renewable energy sources in Kenya
- Kenya's vulnerability to climate-induced power disruptions

Research objectives and hypotheses

- Assess the impact of renewable energy integration on grid resilience
- Develop strategies to enhance grid resilience against disruptions
- **Hypothesis**: Strategic renewable energy integration will significantly contribute to grid resilience

Significance of the study

- ✓ Contribute to the effective enhancement of grid resilience in Kenya
- ✓ Inform policymakers and stakeholders about optimal approaches
- ✓ Support Kenya's sustainable energy transition and development goals

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Kenya's Power Grid Overview

Current power grid infrastructure and generation mix

- Installed generation capacity growth from 2,327Mw(2016) to 2,990 (2022)
- Power generation dominance of geothermal, hydro and thermal sources (60%)
- Role of independent power producers (IPPs), contributing 1,037Mw (38%)

Challenges and gaps in Kenya's power grid

- Grid vulnerability to climate-induced disruptions
- Relatively untapped potential of renewable energy sources
- Need for continuous expansion to meet growing energy demand

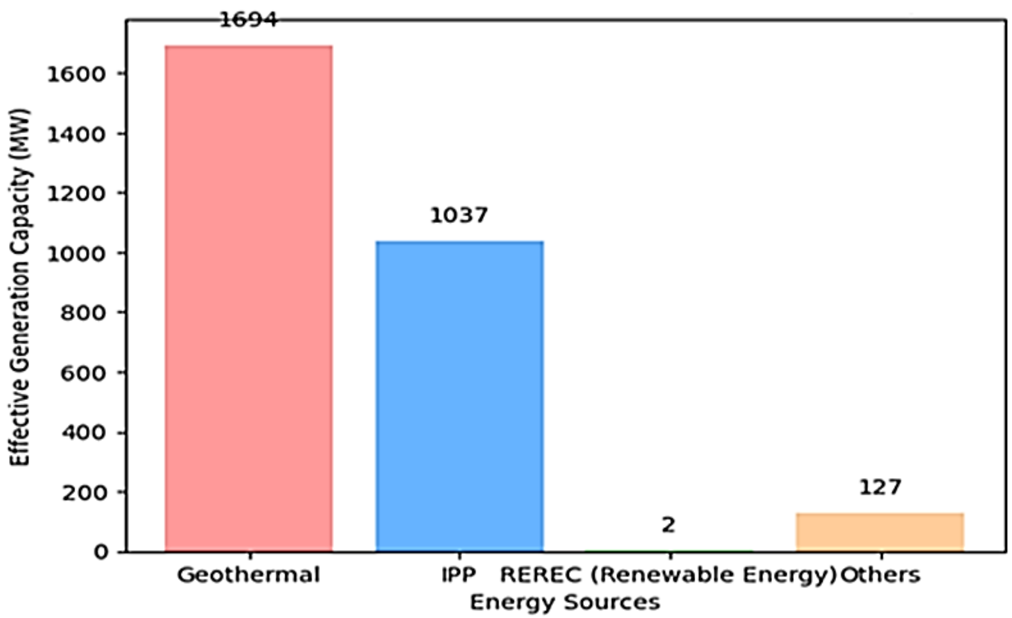

Figure 1: Kenya's Effective Generated Power Capacity Distribution

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Literature Review

Grid resilience metrics and quantification methods

1) Resilience Index (RI)
2) System Average Interruption Frequency Index (SAIFI)
3) System Average Interruption Duration Index (SAIDI)

Applications of System Resilience Curves (SRCs)

- Graphical representation of system performance during disruptions.
- Phases of resilience: nominal performance, degradation, recovery, and restoration

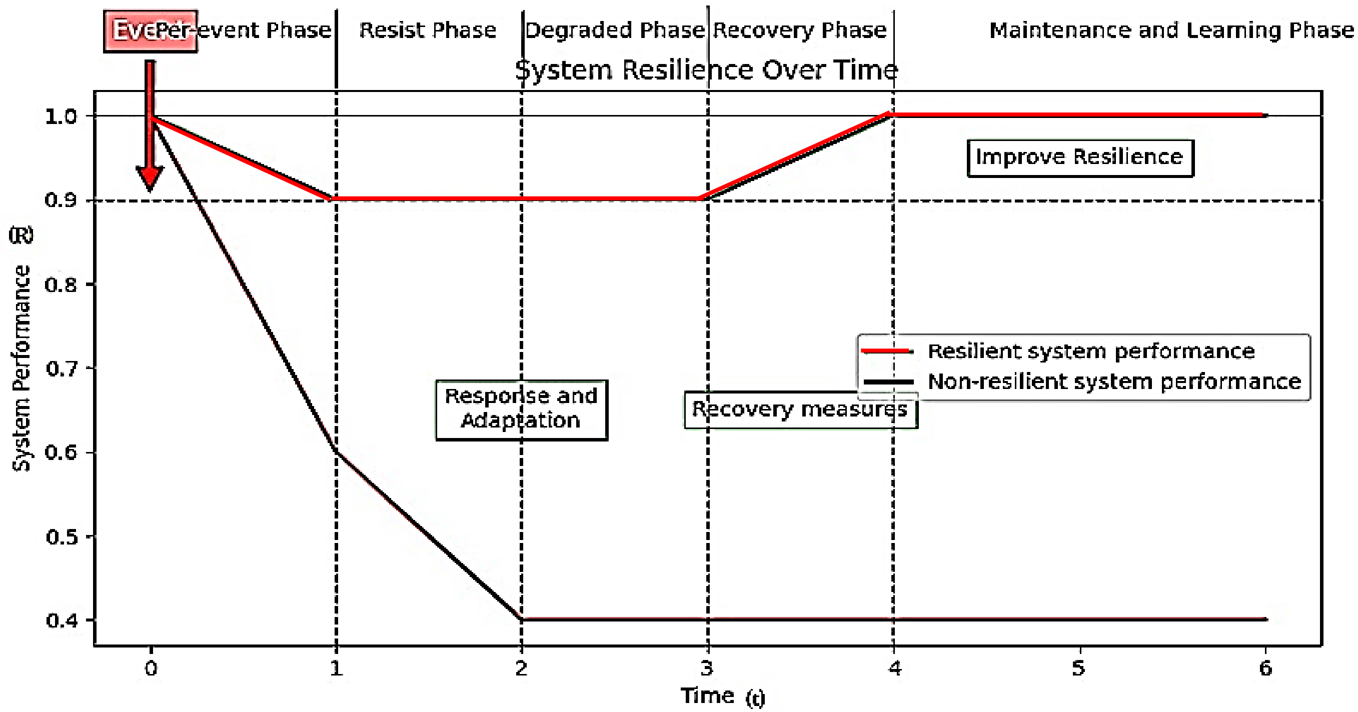

Figure 2: System Resilience Trapezoid

Renewable Energy Integration Concept

- ***Connectivity status verification***: checking the connection status of the isolated grid with the utility grid.
- If the **connection is lost**, the system transitions into an **islanded mode**, relying on RES for power generation.
- Demand response programs – **load shifting during peak** demand to enhance **grid flexibility** and **stability**.
- Integration of demand response with RE integration.
- Ensure essential services and facilities receive uninterrupted power supply even during supply constraints.

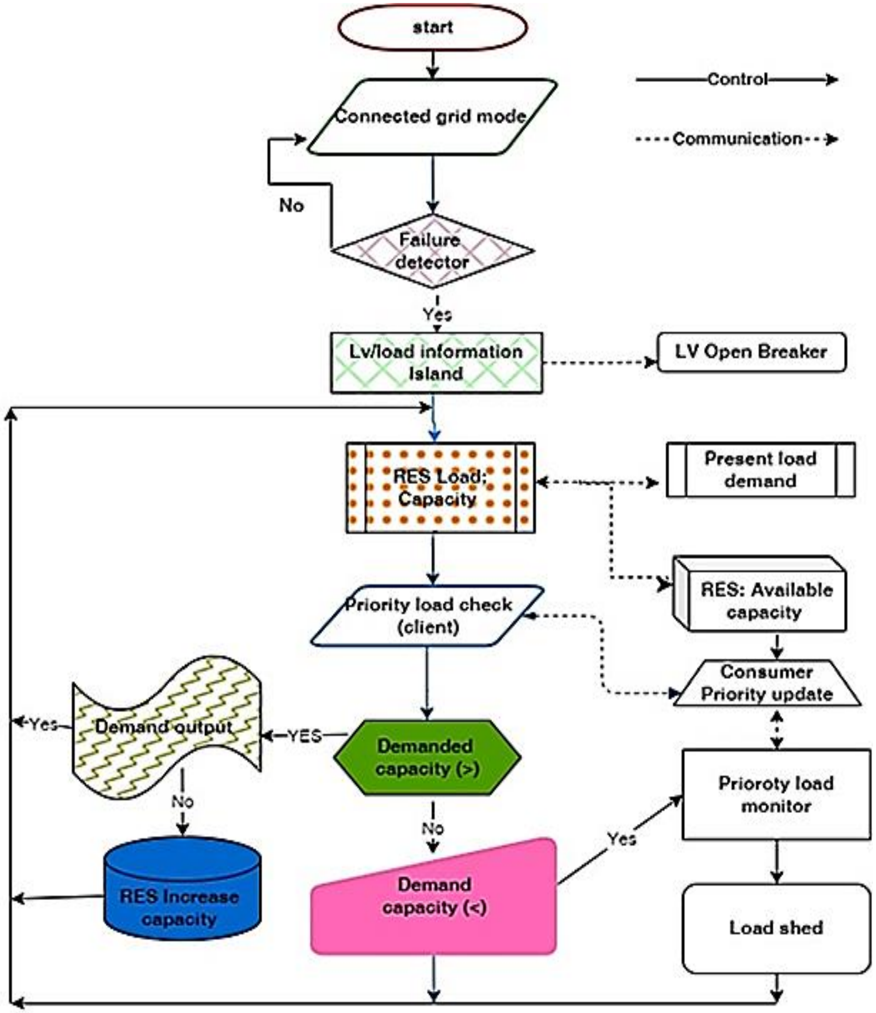

Figure 3: Conceptual Flowchart for Isolated Grids with High Renewable Penetration

2. Methodology

Grid Resilience Metrics Framework

-A systematic approach to quantify and assess the resilience of power grids.
- Important in enabling the evaluation of grid performance during disruptive events and guides resilience enhancement strategies

(i) Resilience Index (RI)

- ✓ Quantifies the fraction of total demand served during disruptions
- ✓ Ranges from 0 to 1
- ✓ A high value of **1 signifies high** resilience, while a low value (0) value signifies low resilience of complete failure to meet demand.

Resilience Index (RI) calculation

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

Energy Not Served (ENS): 600 MW
Peak Demand (Demand): 2,036 MW
Therefore, RI value:

$$RI = 1 - \frac{600}{2,036}$$

RI≈0.705

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Grid Resilience Metrics Framework Cont.

(ii) System Average Interruption Duration Index (SAIDI) based evaluation

- ✓ Measures the average duration of interruptions experienced by customers in a year.
- ✓ Reflects the grid's ability to quickly restore service after disruptions.
- ✓ *SAIDI is influenced by*; grid system design and configuration, maintenance practices, restoration processes and resources and environmental factors.
- ✓ SAIDI provides a quantitative measure of the grid's ability to minimize the impact of interruptions on customers.
- ✓ It helps identify areas of the grid that are more vulnerable to prolonged outages and require targeted investments for improvement.

SAIDI calculation;

$$\boldsymbol{SAIDI = \frac{\sum_{all} C_i}{\sum C_s}} \tag{2}$$

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

- The result is expressed in **hours or minutes per customer/year**
- **A lower** SAIDI value indicates **better grid performance** in terms of faster restoration times and reduced impact of interruptions

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Grid Resilience Metrics Framework Cont.

(iii) System Average Interruption Frequency Index (SAIFI) *evaluation*

- ✓ Measures the average number of interruptions experienced by customers in a year
- ✓ Indicates the grid's ability to withstand and recover from disturbances
- ✓ Provides a proxy for the grid's stability amid disturbances, a key component of resilience planning.

SAIFI calculation;

$$SAIFI = \frac{\sum C_i}{\sum C_s} \quad (3)$$

C_i is total number of customer interruptions.

C_s is total number of customers served

Case:

•Nairobi County case study: **Historical SAIFI: 4.5** interruptions per customer per year

•Projected SAIFI reduction: 30% (3.1 interruptions) by 2025 through RE integration.

Nairobi County	Sum of Numerator SAIFI	Sum of Numerator SAIDI	No. of Customers	SAIDI	SAIFI
Nairobi North	4,464,806.22	11,50,220.19	879,437	13.1	5.1
Nairobi South	3,569,047.22	10,548,724.07	985,463	10.7	3.6
Nairobi West	3,919,018.35	8,760,965.72	817,949	10.7	4.8
Grand Total	**11,952,871.78**	**30,810,909.98**	**2,682,849**	**11.5**	**4.5**

Grid Resilience Modeling and Analysis

- A performance function ***P(t)*** is formulated for resilience quantification and parameterized using weighted indicators;
- ✓ Load served,
- ✓ Frequency stability,
- ✓ Ramp rate, and (recovery rate)
- ✓ Unmet demand
- The ***P(t)*** metrics provide an understanding of the grid's *RI* quantification.

Formula

$$\boldsymbol{P}(\boldsymbol{t}) = \omega_1 \cdot LS(t) + \omega_2 \cdot FS(t) + \omega_3 \cdot FR(t) + \omega_4 \cdot UD(t) \quad (4)$$

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.

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Quantifying and Visualizing Grid Resilience

- Enables data-driven decision-making and communication of resilience trends
- Quantitative evaluation of grid resilience using time-series simulations
- ✓ Resilience metric (R) defines system's ability to respond and restore during disruptions
- ✓ Parameter tuning aligned with grid operator priorities
- Visualization of supply continuity performance under increasing renewable generation
- ✓ Average Resilience metric computed across Monte Carlo experiment iterations

$$\text{Average Resilience} = \frac{1}{N}\sum_{i=1}^{N} R_i \quad (5)$$

```
# Define the simulation parameters
num_iterations = 1000
renewable_penetration_scenarios = [0.2, 0.3, 0.4, 0.5, 0.6]
```

Where; *Ri is the resilience metric per simulation run*

N is the total simulation runs

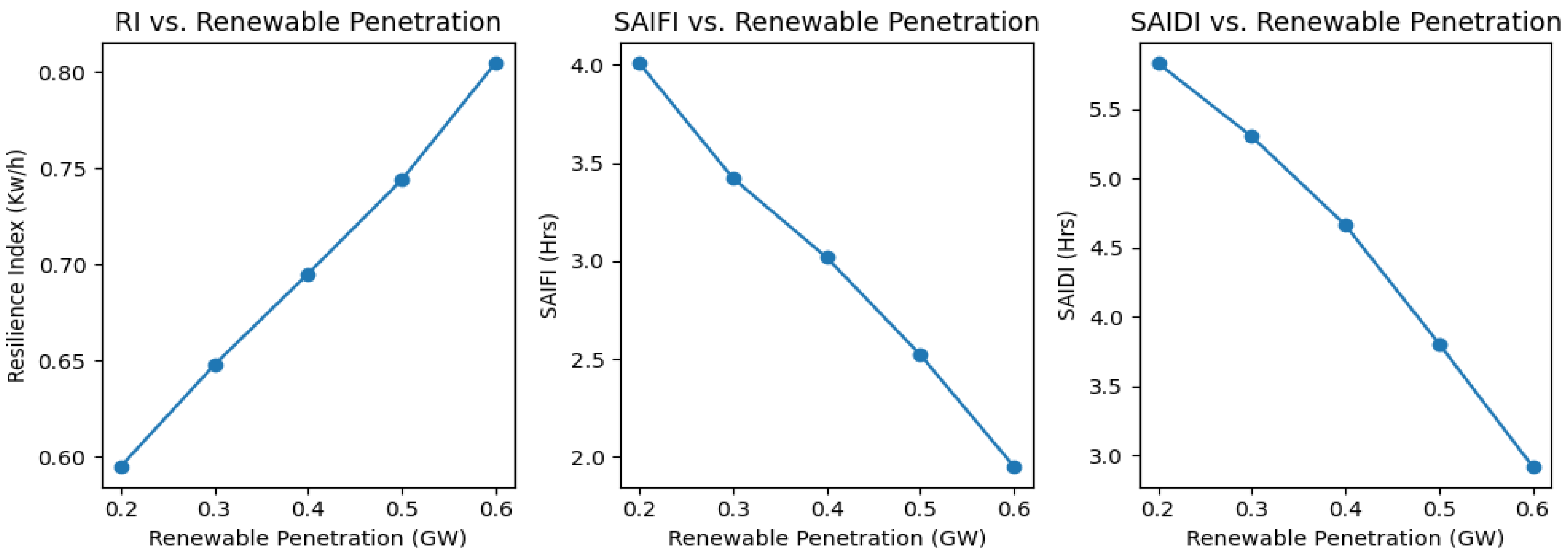
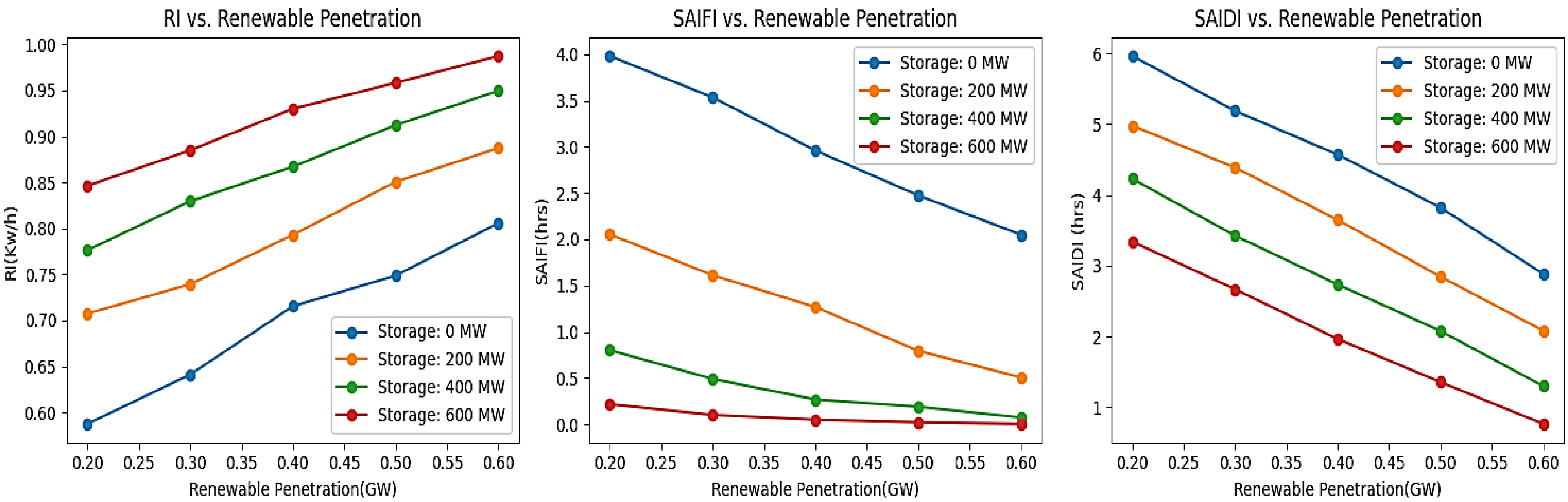


Figure 4; RI, SAIFI and SAIDI

3. Results

Results



Figures 5; Projected Optimization of RI,SAIFI and SAIDI

- The **Resilience Index graph** shows a clear upward trend as renewable penetration increases,
- Indicating an improvement in the grid's ability to meet demand during disruptive events.
- The **SAIFI graph** demonstrates a decrease in the frequency of interruptions as renewable penetration increases.
- The **SAIDI graph** shows a decreasing trend in the duration of interruptions as renewable penetration increases.
- A phase capacity expansion plan targets 60% geothermal, 30% wind, and 10% solar by 2030.

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Results Cont...

Model-based Resilience Assessment

- ✓ Resilience Index (RI) result quantifies the fraction of total demand served during disruptions
- ✓ Current scenario, (RI constrained at between 0 and 1) an average of 0.67 (67%) of peak demand is met during disruptions) with 20% RES penetration.
- ✓ Projected 30% (11.5hrs.) reduction in SAIFI and 25% (8.5hrs) reduction in SAIDI by 2025 through strategic renewable integration.
- ✓ This translates to fewer and shorter power interruptions for customers.
- ✓ Grid adaptation and improvement measures
- ✓ Distributed energy storage systems for RES, infrastructure reinforcement, and advanced control systems.

4. Conclusion

Conclusion

Key Findings and Contributions

- ✓ Strategic renewable energy integration enhances grid resilience in Kenya
- ✓ Providing key insights and recommendations based on the study's findings
- ✓ Proposed capacity expansion plan and grid adaptation measures
- ✓ Identifying the critical renewable energy penetration threshold beyond which grid resilience declines.
- ✓ Need for advanced control mechanisms to accommodate higher renewable penetration while maintaining grid stability.

Optimal renewable integration strategies for grid resilience enhancement

- ✓ Recommendations for policymakers and stakeholders
- ✓ Develop a comprehensive framework for renewable energy integration
- ✓ Energy planning by prioritizing investments and interventions based on the study's insights.

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THANK YOU