**Resilience Engineering Framework Integration for Complex Adaptive Systems Operation in Off-Grid Renewable Energy Systems**

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# **INTRODUCTION**

## 1.1 Problem Contextualization

More than 1.4 billion people worldwide do not have access to electricity. Roughly 85% of these people live in rural areas and a large proportion live in Africa [[1]](#_[1]_International_Energy). To date many utilities and governments have been unable to meet the energy needs of rural areas, as the focus has often been on meeting the demand of major industries or highly-populated urban areas such as the Nigeria’s area in Western Africa or the area around Lake Victoria on the Ugandan side. [[2]](#_[2]_Increasing_Rural)

In the contemporary landscape of energy systems, minigrids have emerged as pivotal infrastructures, particularly in remote or off-grid areas, offering a decentralized and sustainable solution to electricity provision. However, ensuring the reliable operation of minigrids amidst diverse challenges poses a significant concern. Anomalies, ranging from equipment malfunctions to extreme weather events, can disrupt normal operations, leading to service interruptions and potential safety hazards. Addressing these challenges necessitates not only robust anomaly detection mechanisms but also a holistic approach that integrates principles of resilience engineering.



Fig.1: Share of the population with access to electricity (2020).

Data compiled from multiple sources by World Bank

## 1.2 Purpose and Objectives of the Thesis

The primary objective of this work is to develop a comprehensive understanding of how resilience engineering concepts can inform and improve anomaly detection strategies by leveraging insights from resilience engineering literature and methodologies, this study aims to enhance the robustness and adaptability of anomaly detection algorithms, thereby bolstering the overall resilience of minigrid operations.

Through the analysis of an Open-Source dataset concerning a photovoltaic production plant, an EDA Exploratory Data Analysis and the implementation of an Anomaly Detection algorithm will be carried out in order to highlight critical points in the system.

The aim of this thesis work is to structure a multidisciplinary and multiobjective approach in which the resilience engineering framework is applied to a photovoltaic energy production system. By fostering a deeper understanding of the interplay between resilience engineering and minigrid operations, this research endeavors to inform future strategies for enhancing the reliability and sustainability of decentralized energy systems.

## 1.3 Relevance of Resilience Engineering in Minigrids

Resilience engineering, a paradigm rooted in the fields of safety and systems engineering, emphasizes the ability of systems to adapt and recover from disruptions while maintaining essential functions. By shifting the focus from preventing failures to managing and mitigating their consequences, resilience engineering offers a promising framework for enhancing the performance and reliability of complex systems like minigrids. This thesis seeks to explore the application of resilience engineering principles to the domain of anomaly detection within minigrids.

## 1.4 Thesis Structure

The thesis work is organized with an initial review of the existing literature in Chapter 2 to build a solid and up-to-date background. It starts with an analysis of the Energy Access context, aligned with the Sustainable Development Goal (SDG) 7 Energy Access objective. This is followed by a definition of Complex Adaptive Systems (CAS) and their correlation with Renewable Energy Systems (RES). The application of RES in off-grid contexts through minigrids is introduced, including a definition and its characteristics. Subsequently, Resilience Engineering is discussed, leading to its practical application through Exploratory Data Analysis (EDA) algorithms and Anomaly Detection.

Chapter 3 describes the methodology by delving into the study context, the Resilience Engineering framework, and the integration of Anomaly Detection within it.

Chapter 4 addresses the Design and Implementation of the Anomaly Detection Algorithm, detailing the model and the code developed in the Python language.

Chapter 5 examines the Evaluation of Minigrid Resilience through the development of indicators and an impact analysis of the same.

Chapter 6 presents a final analysis and critical discussion of the results obtained, highlighting limitations and potential developments.

The work concludes with acknowledgments in Chapter 8 and the Bibliography in Chapter 9.

# **LITERATURE REVIEW**

## Energy Access Context

There is no universal definition of the term “Energy Access.” IEA (2011) gives the following definition: “a household having reliable and affordable access to clean cooking facilities, a first connection to electricity and then an increasing level of electricity consumption over time to reach the regional average.” However, the definition implicitly assumes the regional average level of consumption as the acceptable minimum need which can be problematic due to its potential for encouraging wasteful consumption and perpetuation of unsustainable lifestyles. [[3]](#_[3]_Subhes_C.)

Globally, approximately 759 million individuals, constituting 1 out of every 10 people, lack access to essential electricity for illuminating their homes, preserving perishable food items, or mitigating the effects of escalating temperatures. Roughly 2.6 billion individuals are compelled to resort to polluting biomass sources like charcoal, coal, and animal waste for cooking purposes. These statistics present an intolerable reality.

In Sub-Saharan Africa and Asia, the largest disparities in electricity and clean cooking accessibility are observed across 20 countries. These regions also contribute to the 80 percent of nations worldwide that grapple with inadequate electricity provision. The absence of access to clean, modern energy undermines efforts to achieve Sustainable Development Goals (SDGs) aimed at poverty alleviation, educational enhancement, and public health amelioration. For instance, replacing antiquated stoves and open fires could prevent the deaths of 800,000 children annually, who succumb to indoor air pollution exposure. Hence, the imperative of SDG7 is to address these energy disparities by 2030. [[4]](#_[4]_SEforALL_and)

## Characteristics of CAS Complex Adaptive Systems

## Minigrids: Definition and Characteristics

## Resilience Engineering: Fundamental Concepts

## 2.5 EDA Exploratory Data Analysis

## 2.5 Anomaly Detection: Applications and Methods

# METHODOLOGY

## Description of the study context

## Design and Implementation of the Resilience Engineering Framework

## Methodologies for integrating anomaly detection into the framework

# DESIGN AND IMPLEMENTANTION OF ANOMALY DETECTION ALGORITHM

## Algorithm Selection for Anomaly Detection

## Data Collection and Preparation (Dataset?)

## Algorithm Implementation

## 4.4 Exploratory Data Analysis

## Results

# 5. EVALUATION OF MINIGRID RESILIENCE

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## 5.3 Results and Interpretation

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# 7. CONCLUSIONS

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## 7.2 Study limitations

## 7.3 Potential Future Developments

# 8. ACKNOWKEDGMENTES

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