**Resilience Engineering Framework Integration in Off-Grid Renewable Energy Systems**

Candidate Supervisor

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# **Table of Contents**

1[. Introduction](#_INTRODUCTION)

1.1 [Problem Contextualization](#_1.1_Problem_Contextualization)

1.2 [Purpose and Objectives of the Thesis](#_1.2_Scope_and)

1.3 [Relevance of Resilience Engineering in Minigrids](#_1.3_Relevance_of)

1.4 [Thesis Structure](#_1.4_Thesis_Structure)

2. Literature Review

2.1 Energy Access Context

2.2 Minigrids: Definition and Characteristics

2.3 Resilience Engineering: Fundamental Concepts

2.4 EDA Exploratory Data Analysis

2.5 Anomaly Detection: Applications and Methods

3. Methodology

3.1 Description of the study context

3.2 Design and Implementation of the Resilience Engineering Framework

3.3 Methodologies for integrating anomaly detection into the framework

4. Design and Implementation of Anomaly Detection Algorithm

4.1 Algorithm Selection for Anomaly Detection

4.2 Data Collection and Preparation

4.3 Algorithm Implementation

4.4 Exploratory Data Analysis

5.4 Results

5. Evaluation of Minigrid Resilience

5.1 Resilience Indicators

5.2 Resilience Analysis Before and After Implementation

5.3 Results and Interpretation

6. Analysis and Discussion

6.1 Analysis of the results obtained from the application of the integrated framework

6.2 Discussion of theoretical and practical implications

6.3 Limitations and potential improvements

7. Conclusions

7.1 Summary of main results

7.2 Study limitations

7.3 Potential Future Developments

8. Acknowledgments

9. [Bibliography](#_11._BIBLIOGRAPHY)

~~11. Appendices~~

~~11.1 Technical Details of the Anomaly Detection Algorithm~~

~~11.2 Additional Graphs and Tables~~

# **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

An integrated approach utilizing the theoretical and practical principles of Resilience Engineering is crucial in a world of constant change, whether we are talking about phenomena relating to climate change, geopolitical instabilities or simply the reliability of a more or less complex energy system.

Being able to rely on continuous service is crucial in contexts of full electrification (think of the need to service critical infrastructure) as well as in contexts of rural electrification. In a community where the energy supply is tied to a single source and its life and economy depend on it, it is more necessary than ever to define, from the earliest stages, a system capable of overcoming technical, operational and community shortcomings. [[5]](#_[5]_Saeid_Charani)

## 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.

The increasing demand for electricity and the need for sustainable energy sources have led to the development of various decentralized energy systems, including minigrids. However, these minigrids are often subject to disturbances and failures, which can have significant impacts on the communities they serve. Resilience engineering, which focuses on the ability of a system to adapt and recover from disturbances, is therefore highly relevant in the context of minigrids. This thesis will discuss the relevance of resilience engineering in minigrids, highlighting its importance in ensuring the sustainability and reliability of these energy systems.

Resilience engineering is a proactive approach to engineering that focuses on the ability of a system to anticipate, respond to, and recover from disturbances and failures [[6]](#_[6]_Hollnagel_et). It recognizes that disturbances are inevitable and that the goal is not to prevent them but to manage them in a way that minimizes their impact.

Minigrids, on the other hand, are small-scale, decentralized electricity distribution systems that serve a limited geographical area. They are often used in remote or rural areas where there is no access to the centralized grid. Minigrids can be powered by various energy sources, including fossil fuels, renewable energy, or a combination of both.

The relevance of resilience engineering in minigrids can be seen in several ways:

*Improved System Reliability*: Minigrids are often the sole source of electricity for the communities they serve. Any disruption in the supply of electricity can have significant impacts on the community's social and economic well-being. Resilience engineering can help improve the reliability of minigrids by ensuring that they can withstand and recover from disturbances quickly.

*Cost-Effective*: Resilience engineering focuses on managing disturbances rather than preventing them. This approach can be more cost-effective than trying to prevent all disturbances, which can be expensive and often not feasible. By managing disturbances effectively, minigrids can reduce the need for costly repairs and replacements.

*Increased Sustainability*: Resilience engineering can help increase the sustainability of minigrids by ensuring that they can adapt to changing conditions. For example, minigrids that are designed with resilience engineering principles can better adapt to changes in energy demand, climate change, and technological advancements.

*Improved Safety*: Minigrids that are designed with resilience engineering principles can be safer for both the operators and the communities they serve. By anticipating and managing disturbances, minigrids can reduce the risk of accidents and injuries.

Resilience engineering is highly relevant in the context of minigrids. It can help improve the reliability, cost-effectiveness, sustainability, and safety of these energy systems. By focusing on the ability of minigrids to anticipate, respond to, and recover from disturbances, resilience engineering can ensure that minigrids can continue to provide essential electricity services to the communities they serve, even in the face of challenges and uncertainties. As the demand for decentralized energy systems continues to grow, the importance of resilience engineering in minigrids cannot be overstated.

## 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 study on the state of the art of minigrids in rural contexts. The components and characteristics useful for the discussion are defined. This is followed by a study of modern methodologies of Resilience Engineering, Exploratory Data Analysis 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

### Energy Planning

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)

Focusing on the African continent in pursuit of the ambitious goal of achieving universal access to modern energy services across Africa by 2030, it becomes imperative to explore diverse pathways within the electricity sector. Such exploration not only aids policy-makers and investors in making informed decisions but also plays a pivotal role in shaping the design of power systems. [[7]](#_[7]_M._Bazilian,)

Holistic energy systems planning endeavors to ensure that energy-related policy and investment choices encompass all viable options on both the supply and demand sides, aligning with broader national objectives such as sustainable development. However, a fundamental prerequisite is the establishment of robust national energy planning capability.

Energy planning capacity serves as a cornerstone, enhancing a country's capacity to anticipate and adapt to rapid changes while capitalizing on emerging opportunities and addressing new challenges. This asset appreciates over time as experts accumulate practical experience, enrich the local knowledge repository, and foster collaborations with stakeholders across various sectors. Historically, inadequate national planning capacity has resulted in suboptimal policy and investment decisions, contributing to unequal access to modern energy services.

Furthermore, energy planning transcends national boundaries, particularly for smaller nations with limited energy resource potentials, such as hydropower. Collaborative ventures involving infrastructure-sharing with neighboring countries offer the potential for economies of scale, highlighting the interconnected nature of energy planning across geopolitical borders.

Over the past two decades, numerous developing nations have embraced extensive policies advocating for liberalization and privatization, often under the influence of major international funders and development organizations. While these policies have occasionally bolstered the operational efficiency of individual national utilities, their impact on expanding energy access has been modest at best. This is primarily due to the fact that catering to the electricity needs of the most marginalized populations isn't financially lucrative for utilities.

This discourse mirrors the ongoing dialogue within OECD countries over the same period, where the outcomes have been similarly varied. The purported advantages of liberalizing these predominantly fragile markets remain ambiguous. In instances where liberalization has been ideologically imposed on these nations, it often proves detrimental, despite originating from well-meaning intentions.

Similar to many sectors of public policy, energy policy formulation heavily relies on analytical models. However, these models exhibit significant variations in outputs, temporal and spatial scopes, sophistication levels, terminology, underlying assumptions, system boundaries, and theoretical frameworks. Consequently, the findings generated from these analyses necessitate substantial filtration and translation to effectively inform the design and implementation of governmental policies.

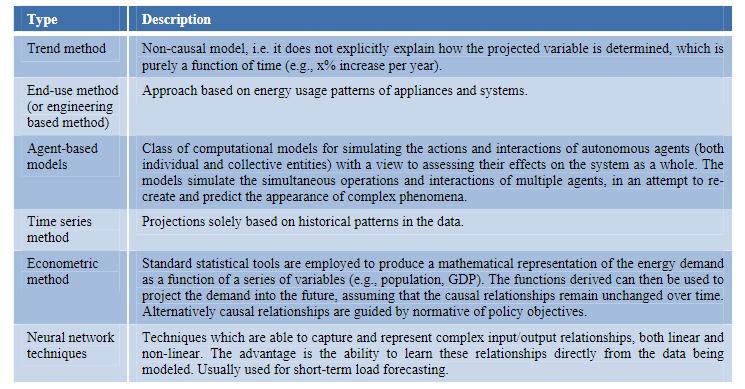
In line with this perspective a noticeable disparity between the inquiries posed by policymakers and the outcomes derives from modeling exercises. Within the realm of energy policy, power system analyses represent a subset of broader energy system modeling endeavors. Integrated resource planning models (IRP) commonly serve as pivotal tools within the power sector for strategic decision-making processes.

Power system analyses, management, and planning encompass various timeframes, spanning from sub-second activities like load balancing to multi-decade projections for capacity expansion. Fundamental to this planning is a set of electricity demand projections, forming the basis for capacity expansion strategies. Such planning often centers on least-cost optimization methodologies, considering a spectrum of constraints such as existing infrastructure conditions, financial accessibility, environmental policies, and energy security imperatives.

Across governmental planning agencies and utilities globally, an array of modern mathematical techniques is commonly employed. These range from fuzzy logic and evolutionary programming to mixed-integer linear programming and multi-objective optimization. Recent research in this domain reveals a discernible trend towards incorporating uncertainties and adapting to liberalized market dynamics.

However, for many power systems in sub-Saharan Africa, excessively sophisticated methodologies may not be imperative initially for initiating generation and infrastructure planning processes.

Energy demand projections constitute a pivotal element in the majority of planning initiatives. Various tools and methodologies of differing degrees of complexity, as outlined in Table 1, are employed to forecast future demand.



**Table 1:** Selected methods for energy demand forecasting (adapted from: McDowall & Eames (2006) and Thomas (2006)) [[7]](#_[7]_M._Bazilian,)

Each approach to energy demand projection possesses distinct strengths and weaknesses. The selection of the appropriate method hinges on several factors, notably the nature and availability of underlying data, as well as the purpose of the analysis and the timeframe involved.

In many long-term planning endeavors conducted in sub-Saharan Africa (SSA), demand projections often rely on econometric relationships tied to income (GDP) and population growth projections, coupled with elasticity relationships. Furthermore, certain methodologies incorporate explicit terms for household connections and large point demands. For instance, consider Equation 1 as depicted in PIDA (2011):

(1)

Where:

* is the unconstrained demand
* is the GDP elasticity of electricity demand
* is the average annual consumption of electricity of one household
* is the number of new connections in a year
* is the additional demand from new large demand points

In contexts where a significant portion of the population lacks access to electricity services, traditional techniques reliant on aggregates like GDP and exogenous inputs such as future annual grid connections of households may not be optimally suited. In such scenarios, alternative approaches, such as solving for a future goal and back-casting, rather than forecasting based solely on historical trends, become necessary. Ensuring that the analytical approach aligns with the specific policy and investment inquiries at hand is paramount. It has been contended that in severely supply-constrained electricity systems, demand projections hold less significance compared to capacity expansion planning and associated financing. Put differently, in typical developing country settings, additional supply tends to stimulate its own demand.

### 2.1.2 Historical Energy Trends

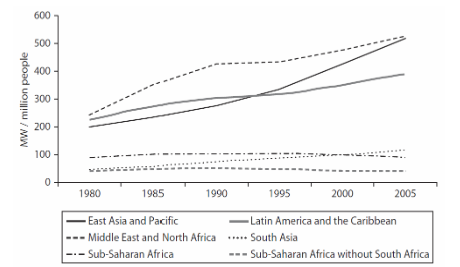
Sub-Saharan Africa grapples profoundly with a dire lack of access to electricity and subpar quality of supply, characterized by issues of cost and reliability where infrastructure exists. An estimated 580 million individuals across the continent lack access to electricity, with the majority residing in rural areas (IEA, UNDP, and UNIDO, 2010). The electrification rate in SSA stands at approximately 30%, with urban areas showing higher rates at 60% compared to rural areas at 14% (IEA, UNDP, and UNIDO, 2010).

Numerous sources offer comprehensive analyses of the energy landscape in Africa, such as Eberhard et al. (2011) [[8].](#_[8]_Anton_Eberhard,) Recent academic literature on Africa's power systems prominently features discussions concerning solar power in North Africa. Additionally, much of the literature pertaining to the power sector in SSA understandably focuses on the Republic of South Africa (RSA). Nonetheless, there exists a dedicated cohort of researchers who focus on SSA as a whole or on specific countries within the region. Despite this, the literature on power sector scenarios in sub-Saharan Africa remains relatively sparse.

The total average per capita consumption in SSA (excluding RSA) is around 155 kWh (based on EIA data). These figures are minute compared to Sth. Africa where this value is approximately 4770 kWh per capita or other OECD countries.

The installed capacity in Africa will need to grow by more then 10% just to meet Africa’s suppressed demand, keep pace with projected economic growth and provide additional capacity to support efforts to expand electrification. Most new capacity would be used to meet non-residential demands from the commercial and industrial sectors. [[7]](#_[7]_M._Bazilian,)

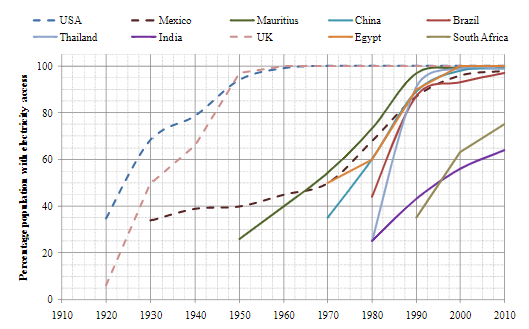
Figure 2 shows the total electricity generation capacity installed per million persons (MW/mln) in several regions. It is argued that is a relatively rough metric as it does not take into account a number of different and crucial parameters, including: T&D Transmission and Distribution losses, load patterns, locational constraints, intermittency, temporal reserve, availability, operating efficiency, and outage rates. Compared to the other world regions, the ratio of electricity generation capacity per million inhabitants is low in Africa, particularly in sub-Saharan Africa. The figure for SSA (excluding RSA) was roughly 129 MW/mln in 2008 only considering people with electricity access; if the entire population is included, the total is about 40 MW/mln.



**Fig.2:** MWs installed per one million by region [[8]](#_[8]_Anton_Eberhard,)

History presents compelling evidence that significant increases in the percentage of households with access to electricity can be achieved over relatively short periods. For instance, electrification rates surged notably in several countries, including the USA and UK during the early 20th century, and more recently in China, Brazil, and Thailand (refer to Figure 3).

As an illustrative case, Thailand witnessed a remarkable transformation, with the percentage of the population with access to electricity escalating from approximately 25% to nearly 100% within a decade. However, for most nations, this transition typically spans at least three decades, if not longer. Across these countries, prioritizing electrification, particularly in rural areas, stemmed from high national priorities driven by economic development or equity objectives.



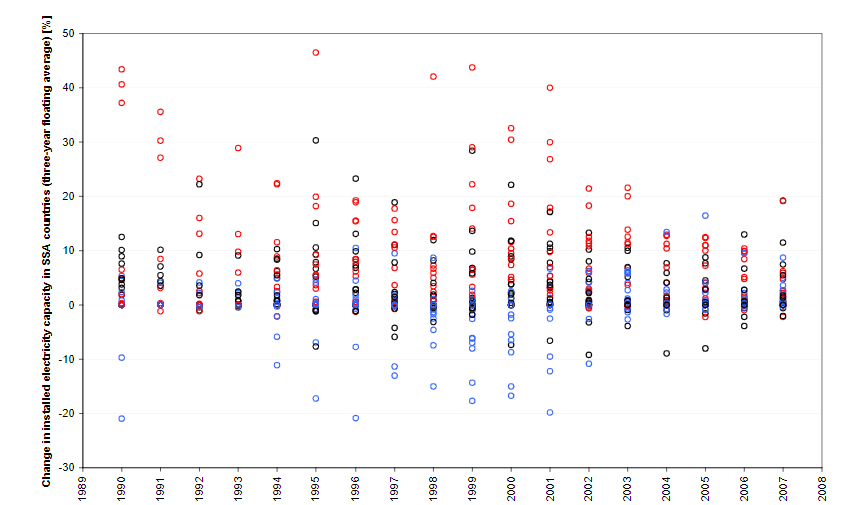
**Fig. 3:** Evolution of household electrification over time in selected countries [[7]](#_[7]_M._Bazilian,)

While several countries in sub-Saharan Africa (SSA) have experienced remarkable growth, roughly quadrupling their installed capacity over the past two decades, these advancements mostly originated from a relatively modest initial installed capacity. However, the majority of countries in the region have witnessed sluggish growth or even a decline in installed capacity.

On average, installed electricity capacity in SSA (excluding RSA) has expanded relatively steadily at a rate of around 1.7% per annum. Examining the historical growth (or contraction) rates in African countries (refer to Figure 4) yields valuable insights for several reasons. First, it elucidates that there is no discernible pattern indicating an overall increase in growth rates over time. Despite the growing recognition of the pivotal importance of energy, particularly electricity, efforts to augment generating capacity have not shown a consistent upward trajectory in recent years.

Nevertheless, there are early indications suggesting a potential acceleration in the expansion of Africa's generation capacity. Data on donor commitments to power projects suggest that, over the last five years, an average annual commitment of 3 GW of generation projects has been made. Additionally, the Annual Report of the Infrastructure Consortium for Africa 2010 highlights a significant increase in member commitments to energy projects in sub-Saharan Africa, rising from USD 1.2 billion in 2006 to USD 8.0 billion in 2010.

Secondly, while the growth rate exhibits a wide range of values, it typically falls between 0% and 10%, with the bulk of countries experiencing growth rates between 0% and 5%. Thirdly, the variability of the change in installed capacity is high, although it has been decreasing over time, especially in recent years. Finally, the graphical representation indicates that countries with larger systems (depicted as red dots in the figure), characterized by greater existing capacity and transmission and distribution grids, tend to expand their capacity more rapidly than countries with medium and small electricity systems. In fact, with a few exceptions, countries with smaller electricity systems (represented by blue dots in the graph) exhibit relatively low growth rates or even negative growth, particularly towards the end of the 1990s.



**Fig. 4:** Rate of increase (or decrease) in installed electricity capacity (with three year floating average) in SSA countries arranged by tertile (red, black and blue dots features countries with relatively large, medium, and small generating capacity, respectively, in 2008). Data: authors’ compilation from EIA

Of course, SSA countries and regions are well aware of the problems of energy access, both in terms of quantity and quality, and have developed national targets and regional plans. UNDP and WHO (2009) calculated that 68 developing countries have electricity targets.

### Prospects for Africa

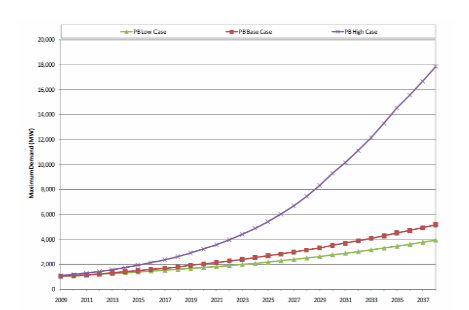
In this section is briefly considered some of the datasets and projections for the power sector in Africa. For an initial sense of scale, using EIA data, Africa has a current installed generating capacity of about 122 GW, SSA (excluding RSA) had 31 GW. This compares roughly to 28 GW in Argentina.

Africa is included in the major energy outlooks from the International energy Agency (IEA), the US dept of Energy’s Energy Information Agency (EIA), British Petroleum (BP) and other international committee. Each dataset has different levels of descriptive information coverage and aggregation. We primarily relied on the EIA dataset as it was the most transparent and complete in terms of accessible country time-series data. It is useful to look at results of these high level global exercises to get a sense of the numbers being fed into the *Global Energy Dialogue*.

Most of the African sub-regions have carried out forecasting exercises for peak energy demand, commonly both in terms of peak demand (or generation capacity) and consumption (or generation). Those projections are normally based on studies conducted at the national level. Despite forecasting methods that vary considerably, the regional plans and related documents entail a wealth of quantitative information that is all too often underutilized in further analysis and planning.

The New Partnership for Africa's Development (NEPAD), the Southern African Development Community (SADC), the Forum of Energy Ministers in Africa (FEMA), the Economic Community of West African States (ECOWAS), the East African Community (EAC) and the Central African Economic and Monetary Community Commission (CEMAC), among others, have produced strategies for electrification and increasing access to modern fuels.

A closer look at some of the regional forecasts in the interests of comparison is useful. A SAPP electricity demand forecast to 2025 shows a projected annual growth of about 2% (SAPP, 2010); the annual growth rates are projected to be higher outside RSA. Nexant shows projected WAPP average growth of 7.6% (ranging from 5-12.6%). The EAC/EAPP Demand Forecasts show very large ranges in forecasted annual growth. They provide very detailed analysis of each country’s national forecasts and the extend them to 2038 where appropriate. Interestingly, the forecasts for many of the countries show the same kind of exponential growth shown in next figure and reflect more typical trend or regression-based forecasts for “low and base” cases. Figure 5 shows the forecast to 2038 (in MW) for peak demand in Kenya, including showing sharp growth in the “High Case” from 1 GW to over 18 GW to 2038.

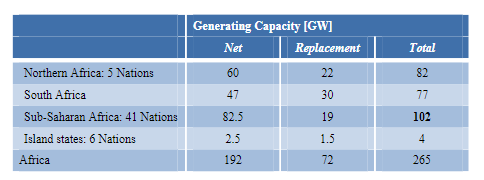


**Fig.5:** Peak demand forecasts for Kenya [[7]](#_[7]_M._Bazilian,)

In [[8]](#_[8]_Anton_Eberhard,) are shown several scenarios for Africa. They considered three type of demand: market, suppressed and social to help create three scenarios (constant access, regional target and national targets). The overall average annual electricity demand growth rate was estimated at 5.8%.

The objective of the context is to establish an infrastructure development programme articulated around priorities and phases and, prepare an implementation strategy and process including, in particular a priority action plan. The peak demand projections from initial Programme for Infrastructure Development in Africa (PIDA) shows an average 6.7% growth (with regional annual growth rates ranging from about 6-9%) over the period 2009-2040. The initial results assume that the access rate will increase from 42% in 2009 to 65% in 2030; these rates are projected to be similar in 2040.

The African Development Bank undertook a universal access scenario assessment through 2030. In Table 2 is shown the results of the capacity additions estimated. Without South Africa the total equals 102 GW, so approximately an average of 6% annual growth.



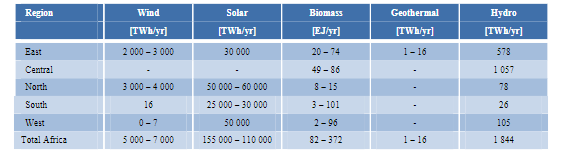
**Table 2:** Universal Energy Access scenario to 2030 (African Development Bank)

### Generation Technology

Now we investigate the various projections in terms of technology and energy resources. A special attention is given to renewable energy potentials, following the sustainable energy goal propose by the United Nations, in order to give a sense of scale to the possibilities.

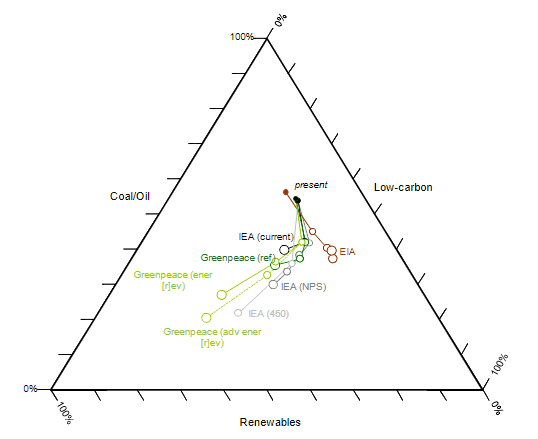
In [[8]](#_[8]_Anton_Eberhard,) is reported that over 900 TWh (approximately 220 GW installed capacity) of economically viable hydropower potential in Africa remains unexploited, located primarly in the Democratic Republic of Congo, Ethiopia, Cameroon, Angola, Madagascar, Gabon, Mozambique and Nigeria. Similarly, the Intergovernmental Panel on Climate Change (IPCC) estimates the technical hydropower potential at 1174 TWh (or 283 GW of installed capacity), only eight percent of which has been developed. Interestingly,this unused potential is about ten times the current installed generating capacity in SSA if RSA is excluded.

The International Renewable Energy Agency (IRENA) is now designing future renewable energy scenarios. The focus of their work will be on providing detailed, regional specific technology information with a clear focus on renewable energy. The following Table shows that the technical potential for renewables is enormous, and largely untapped in Africa. The accounting of biomass remains contentious; still, even using conservative assumptions, the potentials are significant.



**Table 3:** Technical potential for renewable energy in Africa by region (IRENA)

In Figure 6 is used a ternary graph to plot selected (international organization) projections in terms of electricity production in Africa by types of energy sources, namely coal and oil, renewables, and low-carbon (nuclear and gas). Such representation allows visualizing the foreseen transition in the electricity generation and corresponding technological and resources shift. The portfolio of generation types critically impacts power system design and operation (including the amount of total installed capacity required because of issues such as intermittency, ramping rates, and inertial response). All of the projections foresee a decrease, in relative terms, of carbon intensive resources in Africa in the coming two decades, including those scenarios without an explicit focus on climate change mitigation. Also, most projections feature an increase in low-carbon technologies in a first phase, before the share of renewable picks up significantly.



**Fig.6:** Projections of electricity generation in Africa by types of by different organisations, 2010-2030. Note: the size of the dots is proportional to the total electricity generation projected; with present estimates (filled dots), estimates in 2030 (last dot of each scenario), and intermediary estimates. Data: own compilation from IEA WEO 2010, EIA IEO 2010, and Greenpeace 2010

SEZIONE 5

## Minigrids: Definition and Characteristics

## Resilience Engineering: Fundamental Concepts

## 2.4 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

## 5.1 Resilience Indicators

## 5.2 Resilience Analysis Before and After Implementation

## 5.3 Results and Interpretation

# 6. ANALISYS AND DISCUSSION

## 6.1 Analysis of the results obtained from the application of the integrated framework

## 6.2 Discussion of theoretical and practical implications

## 6.3 Limitations and potential improvements

# 7. CONCLUSIONS

## 7.1 Summary of main results

## 7.2 Study limitations

## 7.3 Potential Future Developments

# 8. ACKNOWKEDGMENTES

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