Improved Decision-making Power for Feasibility Assessment of Microgrids in Africa

Optimization of Minigrid Planning

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Preface

This master thesis is the final part of the Renewable Energy System Master's degree program at the Department of Technology Systems (ITS), University of Oslo (UiO).

This work is done in collaboration with SESA, Kube Energy, WeTu, Trønder Energi and the Elico Foundation. The goal of this project is to develop a model and analyse the approach for feasibility studies of microgrids in Africa, with a main focus on improving the decision-making ability of investors.

I would like to express my sincere gratitude to my internal supervisor Josef Noll who supported and helped me when I was stuck in this project. I would also like to thank my external supervisor Charles Ogalu, Endre Skolt, Bjørn Thorud, and Mads Uhlin for providing information and answering my questions while I was doing this project. I am also grateful to ITS PhD Jonathan Muringani for his help in designing the project and making it interesting and useful to the community.

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Abstract

This thesis focuses on the integration of GIS (Geographic Information System) in the analysis and decision-making processes for renewable energy uptake, particularly in the context of minigrids in African countries. The study explores the theoretical background, methodologies, and results obtained through interviews, data analysis, and GIS integration.

The introduction provides an overview of the background, motivation, and scope of the research. It sets the stage for understanding the importance of renewable energy and the specific challenges faced in the African context.

The theoretical section delves into the concept of minigrids, their utilization, and the comparison between on-grid and standalone systems. The section also highlights the expenditures associated with minigrids and the various aspects of energy generation. Additionally, it examines the role of battery storage for minigrids in Africa.

The study further investigates the supply and demand dynamics of renewable energy, aiming to enhance models for renewable energy uptake. It critically evaluates the current state of modeling renewable energy in Africa, identifies shortcomings, and explores avenues for extending knowledge to support decision-making processes.

The methodology section outlines the description and study sites, namely Kenya, Morocco, and South Africa. It presents a GIS-based integration approach, focusing on the creation of reliable data, validity analysis using experts in the field, and data integration using GISARC.

The results and discussion section presents the findings from interviews, including the validity status, commonalities, and discrepancies in arguments. It also assesses the potential for renewable energy using GIS integration and highlights the enhanced decision-making capabilities facilitated by this approach.

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List of Terms and Abbreviations

Terms

GHI	Global Horizontal Irradiation
SESA	Smart Energy Solutions for Africa
UN	United Nations
SHS	Solar Home System

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Chapter I

Introduction and Theoretical Background

1 Introduction

This is a 30 ECTS Master thesis that focuses on empowering the uptake of renewable energy in Africa through comparison and betterment of minigrid system models. The work is a collaboration between Smart Energy Solutions for Africa (SESA) and UiO. A mathematical optimization model of an optimized standalone minigrid system is used to evaluate and analyse the proximity and offset to a similar system in reality.

Access to reliable and affordable electricity remains a global challenge, with millions of people lacking electricity, particularly in developing regions like Sub-Saharan Africa (SSA) and Asia. Since the introduction of United Nation's Sustainable Development Goals in 2015 many African countries have shifted their focus towards clean and affordable energy for all. Traditional centralized grid infrastructure in developing regions often falls short in reaching remote and rural areas due to logistical and economical constraints. One way to address this is decentralized energy systems like minigrids. An expanding market of minigrids have emerged in SSA. Minigrids offer localized electricity networks that can be deployed quickly and independently of the main grid. They provide communities with access to clean and renewable energy sources. While fostering energy independence, they can also stimulate local economic development. In Africa, where energy access gaps are significant, minigrids hold great promise for bringing reliable and affordable electricity to underserved areas, contributing to value creation and increased welfare for millions of people. The market in SSA can be considered in its nascent stage due to some less known factors that are important for investors to acknowledge. Most minigrids in rural African areas have sustainability challenges. One way to avoid this issue is by better decision making in the planning phase.

1.1 Background

Africa is the second largest continent in the world both in terms of size and population. Despite their rich capacity of natural resources, they are tangled with poverty, inadequate infrastructure, limited access to food, healthcare, and education. Despite these difficulties African countries have seen rapid economic growth through the last two decades [3]. By measuring national mean nightlight per capita using satellite images IMF has captured regional and cross border differences and inequalities amongst people. A major increase in nightlight per capita occurred due to improvements in basic infrastructure for lagging areas. The access to clean water, electricity and cell phone service pushes a lagging society towards national level. Yet, this progress has not reached all lagging areas due to security reasons and political instabilities. More importantly due to lacking funds a huge regional inequality can be seen. To counter inequalities and facilitate co-development the project Smart Energy Solutions for Africa (SESA) has been introduced.

SESA is a joint initiative between European Union and nine African countries namely: Ghana, Kenya, Malawi, Morocco, Namibia, Nigeria, Rwanda, South Africa and Tanzania (figure IV.9). The primary objective of SESA is to increase welfare through energy access and prepare scaleable business models in Africa that can be easily replicated and create opportunities for locals to induce in economic growth. Living labs is a way to test, validate and replicate solutions in different regions on small scale. The project will encompass a range of solutions, including decentralized renewable energy systems such as solar photovoltaics, utilizing for example second-life electric vehicle batteries and smart minigrids. Factors like climate-resilient measures and adaptation strategies will also be considered to ensure their smooth and optimal operation. Additionally rural internet service also plays an important role in the progress of rural areas [9].

Since the launch of United Nations Sustainable Development Goals sev-

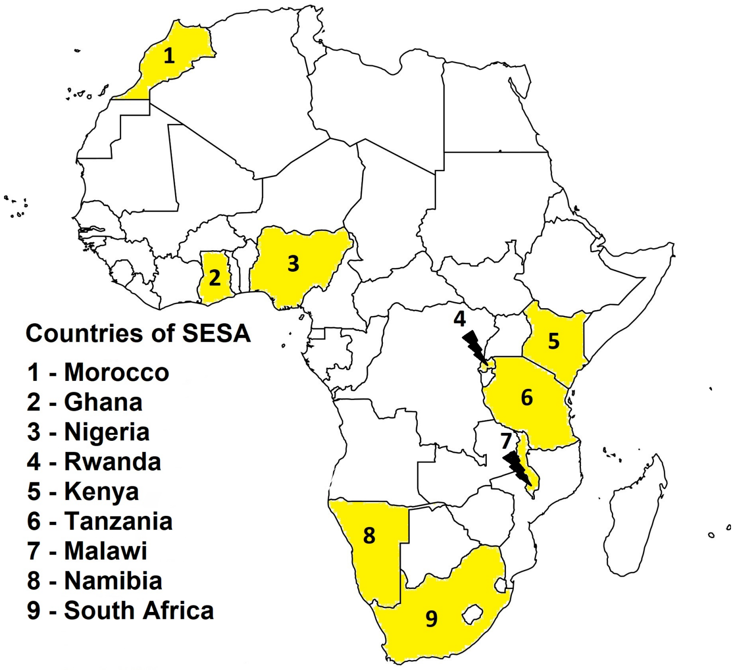

Figure I.1: African countries SESA is operating in

eral African governments have started focusing on fulfilling human rights. All or most of the SDGs apply on all African countries. A fitting solution that directly and/or indirectly empowers sustainable development in African countries is standalone minigrids. They supply affordable and clean energy (SDG 7) with the right policies as a ground foundation. Availability of electricity allows local businesses to enhance productivity and enlarge their economic circle. As an outcome the economy flow in the local area will improve and benefit the society, hence also effecting towards no poverty (SDG 1), better infrastructure (SDG 9) and sustainable cities and communities (SDG 11). For further reach of SDGs a better management and discipline can help reach zero hunger (SDG 2), good health (SDG 3), quality education (SDG 4), gender equality (SDG 5) and clean water (SDG 6) [10].

In the past decade Africa has seen a huge increase in number of minigrids and connections. As of 2020, there are over 3100 minigrids in Africa with 9000 minigrids are planned in the upcoming years. The existing minigrids supply over 78,000 connections with a total installed capacity of around 7,000 kW[1] [2]. Solar is the most abundant and accessible renewable energy source in Africa, followed by wind, geothermal, biomass and hydropower. Today the apparent most utilized minigrid combination is solar with battery storage optionally connected to a deisel generator. According to IEA's *Africa Energy Outlook 2022* by 2030, places with larger than 200 population and further than 10 kilometres from maingrid and standalone micrograds will more often than not gain a minigrid as the optimal solution. The outlook also suggests "minigrids meet 65 % of new connections in sub-Saharan African communities located more than 20 km from a grid and stand-alone systems for most of the rest" [6].

The levelized cost of electricity (LCOE) for renewable minigrids has reduced swiftly over the past years and is estimated to reduce further [5]. Still due to highly subsidized main grid in many African countries, minigrid is out competed [4]. African countries are characterized by their unique challenges compared to other parts of the world. These challenges pose an economic, technical, and social risk when implementing minigrid that many investors and key actors are still unfamiliar with.

1.2 Motivation

The expanding minigrid market in Africa leads to an increased reliance on accurate decision making. To be able to create sustainable minigrid solutions for rural areas less known factors considering technical, economical and social aspects must be acknowledged. A large number of companies are working on solar home systems (SHS) may also be known as nanogrid and minigrid. In order to ensure multi-aspect sustainability it is important to account for community engagement level, local expenditure capability and site comparison. One solution is to supplicate an existing planning model. A planning model can give an overview of the most important factors when planning for minigrid. With improved input it can give better understanding of feasibility, increase revenue and mitigate main grid collision risk.

There is currently little publicly available knowledge on such graphical models that companies use. None the less due to increase focus on microgrid implementation all over Africa, there is a renewed liking for geographic information systems (GIS) specific application of who is doing this, project description, change demand is making, what is the project meant to achieve

This thesis in a collaboration between SESA and UIO and will analyse the impact of less known aspects on minigrids using latest available data. The aim of the project is to achieve a model that gives a broader and more detailed overview of minigrid feasibility planing. This is to make a more accurate cost analyses and optimization while also providing scale ability for use in similar projects across Africa. Model will then be a handy tool for investors and developers to access their project.

1.3 Scope of Work

On going! The objective of this thesis is to develop a confined model for a minigrid feasibility survey. the model is to be used to analyse the sensitivity of the energy system with remarks to the additions of the most relevent parameters: community engagement level, local expenditure capability, infrastructure advancement, electricity prices, fuel prices and dynamic demand. This thesis will compare the new model with existing knowledge base commonly available. This thesis constitutes a 30 ECTS project accomplished within a span of 18 weeks, emphasizing a concentrated approach towards specific facets of study.

The thesis process entails the systematic completion of preplanned tasks, commencing with establishing a theoretical background that forms the basis for defining and specifying model requirements. A comprehensive literature review on minigrid deployment analyses and modeling is to support model selection, definition and refinement parameters.

Subsequently, the results are compared with ongoing projects in Africa to adjust input and output mismatch and ensure validity. Essentially, the model is used to conduct an analysis of minigrid deployment in Sabuli, Wajir, Kenya to provide insight into which factors the system is sensitive to and to explore possibilities of further optimizing the design of minigrid deployment simulation tool with focus on the cost analyses.

This thesis will work to answer the following research questions:

1. What are the key characteristics of successful minigrid systems for renewable energy uptake in Africa, and how can these be compared and improved through optimization models?
2. What are the less known economic, social, and environmental factors that influence the adoption of minigrid systems for renewable energy uptake in Africa, and how can these be modeled and evaluated using optimization?
3. What are the economic, social, and environmental factors that influence the adoption of microgrid systems for renewable energy uptake in Africa, and how can these be modeled and evaluated using mathematical optimization?

Chapter II

Theory

1 Minigrid

1.1 Utilisation

Ongoing!

A minigrid is a decentralized interconnection of an electrical grid with defined limits. It acts as a singular and controllable entity and can be defined as combination of macrogrid, also known as the main grid and nanogrid which is a self sustaining entity like a house. Contrary to microgrid which can operate at either grid-connected mode and island mode, a minigrid operates only in as a standalone and isolated grid. Therefore it is often placed in rural areas with little to no earlier electricity infrastructure. By using renewable energy sources such as solar, wind, hydro, geothermal and biomass a minigrid can supply clean and green electricity to its customers. To counter intermittent energy output generated by these resources, an energy storage system such as batteries can be connected. Energy storage will ensure an optimized and reliable supply of electricity in case of interruption in production.

Hydropower, geothermal, and biomass have more predictable energy outcome then solar and wind. In case of no wind and dark cloud condition a separate diesel generator can be connected to the minigrid. This will increase deliverance reliability of the grid and resilience to power outages due to weather dependent production. The overall adequacy will increase as well

Minigrids can be used to supply electricity for a singular building up to a whole community. The size and coverage scale vary as every minigrid can be tailored uniquely to fit its purpose. Today's largest minigrid placed in Polynesian island of Palau will be capable of generating 108 MW at its peak. Engie EPS will integrate solar PV (35MW) and battery storage (45 MWh) into an already existing diesel-fueled generation of 28 MW-peak [1]. By utilizing already existing infrastructure a smooth and stable transitioning to 100% coverage of demand can be achieved. Meanwhile the renewable energy share in total supply will also increase as Palau shifts towards zero emission and clean energy goals set by United Nations Sustainable Development Goals (UN SDG).

Africa is continent with immense renewable energy potential. In thestruggling to achieve the SDG's, has an immense need of electricity among other basic human right factor. African countries, out of major cities, are typically covered by dispersed populations. In such remote locations where main grid transmission lines are not present either due to the economic health of the state or the difficult geographical positioning of the location, a minigrid is most cost-effective way to deliver energy. Hence many rural communities have already found success using minigrids that can operate autonomously or when connected to a localized distribution network.

1.2 On grid vs. Standalone systems

On grid

Minigrid provides an interactive and functional relationship between the central grid and its users. This interactive relationship allows a minigrid to be connected to and use the services of the central grid, and can support services to the grid when it's beneficial to do so. A minigrid can also island from the grid and operate as a minigrid would, maximizing the benefits to both the central grid and end users.

Off grid

A minigrid is a local electrical grid that can operate in grid-connected and island mode1. A standalone or isolated minigrid only operates off-the-grid and cannot be connected to a wider electric power system1. In contrast, a grid-connected minigrid can be connected to the main grid and can export or import electricity as needed. Standalone minigrids are advantageous in that they do not have to worry about how their system interacts with the larger grid, while grid-connected minigrids can provide additional benefits such as increased reliability and the ability to sell excess energy back to the grid. In power outages when the main electricity grid fails, minigrids can keep going. They can also be used to provide power in remote areas.

1.3 Expenditures

The result from 25 villages 10 000 people plus businesses show that the cost variation is significant depending on the location and size of the project. In Entasopia's PV hub, renting space in the yard of the village chief, cost $75,000 to install. It has 24 panels with a maximum generating capacity of 5.6 kilowatts. A control box below houses the smart meter that measures and controls power to each of the 64 customers in town and also communicates remotely with payments software, cutting off power when credit is exhausted. In remote areas such as Entasopia, where wi-fi is largely absent, all data is sent by SMS. "One bar of mobile signal is all we need," says Moder. "We can be everywhere."

Commercial minigrid PV systems still charge prices for power that are quite high. SteamaCo — and the minigrid partners that it increasingly licenses — charge between two and four dollars per kilowatt-hour. That delivers lighting more cheaply than kerosene, and power more cheaply than a diesel generator. But it is double the price of state-subsidized grid power in a city like Nairobi.

CAPEX

The capital expenditure (CAPEX) of mini-grid projects in Africa can vary depending on several factors. For instance, the size, location, and technology used in the mini-grid system significantly influence the overall CAPEX. According to real-world examples, the initial investment required to establish a mini-grid in isolated areas ranges from $300,000 to 1$ million, considering the procurement of solar panels, batteries, inverters, distribution lines, transformers, and associated infrastructure. These figures are based on projects that have been implemented in various African countries, such as Kenya, Tanzania, and Nigeria. Additionally, economies of scale, efficient procurement strategies, and advancements in renewable energy technologies play a crucial role in optimizing the CAPEX and enhancing the financial feasibility of mini-grid projects.

OPEX

Operating expenditure (OPEX) constitutes a significant portion of the overall cost of running a mini-grid system in Africa. OPEX includes routine maintenance, repairs, system monitoring, fuel or energy source costs, staff salaries, training programs, administrative overheads, and other necessary expenses. Real-world examples indicate that the annual OPEX for mini-grid projects in Africa typically ranges from $20,000 to$100,000, depending on the size and complexity of the system. These figures have been observed in mini-grid projects implemented across various African countries, including Uganda, Ghana, and Rwanda. Implementing efficient maintenance practices, optimizing fuel procurement by leveraging renewable energy sources, and adopting appropriate pricing structures are essential strategies for managing OPEX and ensuring the long-term sustainability of mini-grid systems.

By considering real-world data and experiences from mini-grid projects in Africa, it becomes evident that carefully managing both CAPEX and OPEX is crucial for the successful implementation and operation of mini-grid systems. Strategic cost optimization, leveraging economies of scale, technological advancements, and sustainable revenue generation mechanisms such as tariffs and subsidies are essential to achieve the financial viability and sustainability of mini-grid projects. Continued research and analysis of project costs and operational performance will further contribute to refining the cost models and optimizing the design and deployment of mini-grids, ultimately accelerating the electrification of underserved communities in Africa.

1.4 Energy generation

The cost of a minigrid is affected by types of technological combinations, as mentioned in previous section. Various renewable energy technologies, including solar, hydro, biomass, and wind, can be utilized to power minigrids, often in combination with energy storage systems such as batteries. Minigrids can be powered by renewable technologies such as hydro, geothermal and biomass but these technologies are spatially scarce and not easily accessible all over Africa. Therefore, this study will focus on assessing the solar and wind potential, considering their abundant availability throughout Africa, while disregarding other technologies. Given their availability and potential economic advantages, diesel generators will also be taken into consideration.

Photovoltaic

Ongoing! PV cells, also known as solar photovoltaic cells, work by utilizing the properties of a Pn junction made of semiconductor material, such as silicon. A Pn junction is formed by combining two different types of silicon, one positively charged (P-type) and the other negatively charged (N-type), which creates a barrier that allows for the flow of electrons in one direction.

The illustration shows a light wave reaching into a pn junction (left) and knocking free an electron from its original space (right). How do solar cells work? - YouTube To enhance the efficiency of PV cells, they are usually doped with impurities that create more free electrons in the Pn junction. When light waves hit the cell, they generate energy that excites these free electrons and causes them to move toward the N-type layer, creating a flow of electricity.

PV cells can absorb both direct and diffuse sunlight, which refers to light that has been scattered by the atmosphere. The amount of light that hits the cell depends on factors such as the time of day, location, and the angle of the sun, which is influenced by the azimuth horizontal angle.

To monitor the amount of energy generated by PV cells, energy monitoring systems are used, which typically consist of cables and connectors that connect the cells to an inverter. The inverter converts the DC current generated by the cells into AC current that can be used to power homes and businesses.

Generation monitors are also used to track the output of PV cells and ensure that they are performing optimally. These monitors can detect any faults or issues that may affect the efficiency of the cells.

Types of PV cells

The supply and demand of electricity in Africa pose significant challenges to achieving reliable and sustainable energy access. On the supply side, there are various photovoltaic (PV) technologies utilized in Africa, with crystalline silicon modules being the most prevalent and widely adopted, comprising approximately 80% of the global market share [1][3]. These conventional PV technologies, including thin-film modules and hybrid modules, serve as the foundation for solar energy deployment in the continent. However, there is also a growing emphasis on innovative solutions tailored to local conditions. For instance, floating solar PV systems have gained popularity in some African countries due to their ability to save land and mitigate water evaporation [5].

The choice of PV technology in Africa is influenced by factors such as cost, reliability, and suitability for local environments. While conventional technologies like crystalline silicon modules continue to dominate, the exploration and implementation of innovative solutions demonstrate a commitment to accelerating the transition to cleaner and more sustainable energy systems in Africa [1].

Within the context of mini-grids, which play a crucial role in expanding electricity access in remote areas, PV technologies are also employed. Similar to other applications, crystalline silicon modules, thin-film modules, and hybrid modules are commonly utilized in mini-grid installations in Africa [1][3][8]. Crystalline silicon modules, in particular, hold a significant share in mini-grid deployments [1][10]. Additionally, tailored solutions that account for the unique local conditions are increasingly adopted. This includes the utilization of floating solar PV systems and the implementation of innovative financing models to facilitate mini-grid deployment [1][5].

The choice of PV technology for mini-grid applications in Africa takes into consideration factors such as cost, reliability, and suitability for the specific local context. By leveraging diverse PV technologies and innovative approaches, mini-grids can contribute to addressing the challenges of electricity supply and demand in Africa, ultimately enhancing energy access and promoting sustainable development.

References: [1] "Africa Energy Outlook 2022." International Energy Agency (IEA), 2022. [3] "Photovoltaics Report." Fraunhofer Institute for Solar Energy Systems ISE, 2021. [5] "Floating solar panels in African hydropower reservoirs." Renewables Now, 2021. [8] "MINI-GRIDS." IRENA, 2022. [10] "Off-grid, Mini-grid and On-grid Solar PV Solutions in Africa." Solar Power Africa Conference Exhibition, 2018.

Wind energy

Wind turbines work by harnessing the kinetic energy of wind to generate electricity. The main components of a wind turbine include a propeller-like rotor, low-speed rotation rod, gearbox, high-speed rotation rod, generator, cables, transformer, controls and sensors, and a tower.

When the wind blows, it causes the rotor to rotate, which is connected to the low-speed rotation rod. The gearbox is used to increase the rotational speed from the low-speed rotation rod to the high-speed rotation rod, which drives the generator to produce electricity.

The electricity generated by the generator is transmitted through cables to a transformer, which raises the voltage to make it suitable for transmission over long distances. The controls and sensors on the wind turbine monitor various parameters such as wind velocity, direction, blade pitching, blade dynamics, bearings, and tower sway/leveling, and use this information to adjust the blade alignment with the relative wind flow.

Aero dynamic analysis is used to design the airfoil shapes of the blades to generate lift force and reduce drag. Wind breaks may be used to reduce turbulence and ensure the wind velocity is aligned with the blades. The yawing mechanism is used to turn the nacelle and correct the air alignment with wind direction.

The energy output of a wind turbine is positively correlated with higher wind velocities. However, the tower that supports the wind turbine must be designed to withstand higher wind loads in order to avoid structural failures. The intermittent availability of wind power is a significant limitation of wind energy, which implies that wind turbines are capable of generating electricity solely when the wind is blowing, and the electricity generated may not always be available. Additionally, a theoretical maximum efficiency of wind energy conversion exists, known as The Betz limit. The Betz limit stipulates that wind turbines cannot convert more than 59.3% of the available kinetic energy in the wind. This theoretical maximum efficiency represents the maximum amount of energy that can be harnessed from the wind and places an upper limit on the amount of power that can be generated from a wind turbine.

The electricity generated by the wind turbine is usually in the form of alternating current (AC), which is sent to a substation to be connected to the power grid. Wind turbines are designed to operate for about 20 years before requiring major maintenance or replacement.

Deisel generators

The utilization of diesel generators in mini-grids across Africa is witnessing a shift towards renewable energy alternatives, particularly solar power. While diesel and hydropower systems have traditionally been employed in mini-grids on the continent, there is a growing recognition of the need for enhanced power supply and greater reliance on renewable energy sources. Ongoing initiatives seek to develop and implement mini-grids in Africa that can effectively replace a significant number of diesel generators. The cost of mini-grid projects in Africa is influenced by various factors, including project size, proximity to the main grid, resource availability, consumer density, regulatory environment, import taxes, currency fluctuations, quality standards, generation technology costs, technical expertise requirements, and financing considerations. When evaluating the cost of a mini-grid project, it is crucial to account for the specific context and location. The International Energy Outlook 2020 confirms the prevalence of diesel generators within the off-grid applications, including mini-grids, in Africa.

Fuel prices play a critical role in determining the viability of diesel generators in Africa. Modern diesel gensets typically consume between 0.28

and 0.4 liters of fuel per kilowatt-hour (kWh), resulting in fuel costs ranging from 11 to 16 cents per kWh. The Africa diesel generator market, valued at USD 5.82 billion in 2022, is projected to witness a compound annual growth rate (CAGR) of 6.0% from 2023 to 2030. Similarly, the South Africa diesel generator market is anticipated to experience a CAGR of over 2%, driven by factors such as fuel cost reductions and a reduced dependency on a single fuel source. Fluctuations in fuel prices directly impact the overall cost and availability of diesel fuel, thereby influencing the utilization of diesel generators. Reports indicate that rising fuel prices can significantly impact the economic feasibility of diesel generators in Africa, potentially making them less cost-effective compared to alternative energy sources like solar and bioenergy. However, specific information regarding the specific impact of fuel prices on diesel generators in the context of mini-grids in Africa remains limited.

1.5 Battery storage for minigrids in Africa

Battery storage plays a crucial role in the implementation of minigrids in Africa, particularly in addressing the lack of electricity access in sub-Saharan Africa. The Africa Minigrids Program (AMP) aims to utilize solar-battery minigrids to power households, social services, and businesses, with the potential to drive economic growth in the program's 21 countries. It is estimated that around 567 million people in sub-Saharan Africa lack electricity access, highlighting the urgent need for reliable electricity solutions.

The use of battery-backed mini-grid systems is expected to increase in Africa, with projections indicating the potential for up to 200,000 installations by 2040. These batteries are essential for balancing intermittent solar power during rainy seasons and ensuring continuous access to electricity, particularly for remote populations. While lead-acid batteries have historically been prevalent in African mini-grids, there is a growing adoption of newer technologies like lithium-ion batteries. The choice of battery technology depends on factors such as the specific application, load profile, and cost considerations.

Although detailed information on battery types commonly used in African mini-grids is limited, it is evident that batteries, alongside solar panels and backup diesel generators, play a significant role in ensuring reliable and efficient electricity access. The cost of batteries in mini-grids varies depending on factors such as the type of battery. Historically, lead-acid batteries have been popular due to their lower upfront costs. However, lithium-ion batteries offer longer lifespans and require less maintenance, making them a cost-effective option in the long run. As technology advances, the cost of lithium-ion batteries is expected to decline, making them more competitive in terms of cost-effectiveness.

The cost of lead-acid batteries for mini-grids in Africa typically ranges from $50to$120, while lithium-ion batteries can range from $90to$200 or higher, depending on various factors. As battery technology continues to evolve, overall battery costs are anticipated to decrease, enhancing the feasibility and affordability of newer technologies. This cost trend, combined with the increasing demand for reliable electricity access in Africa, emphasizes the importance of battery storage in enabling sustainable energy solutions.

2 Supply and demand

The supply and demand of electricity in Africa present significant challenges that need to be addressed for sustainable development. The continent experiences a significant gap between energy supply and demand, with energy demand growing rapidly at an annual rate of around 3%, the highest among all continents. However, energy supply continues to lag significantly, resulting in frequent power shortages and inadequate access to electricity, particularly in rural areas.

Several factors contribute to the challenges in meeting the growing demand for electricity in Africa. One major challenge is the lack of access to electricity, with nearly 600 million people lacking access out of the 1.2 billion population. This hampers economic growth, limits social development, and affects the quality of life for millions of people. Furthermore, inadequate infrastructure, limited access to financing, and insufficient policy frameworks hinder the expansion of the electricity sector, making Africa rank among the lowest in the world in terms of investment in generation and grids.

To overcome these challenges, African countries are investing in diverse energy sources, including renewable energy, to expand access to electricity and enhance the reliability of power supply. This includes both grid-connected solutions and off-grid solutions such as mini-grids and distributed renewable energy systems. However, addressing the challenges requires concerted efforts to improve infrastructure, access to financing, and policy frameworks.

Specific challenges in Africa include unreliable power supply, which leads to frequent blackouts and brownouts, hindering business operations and economic growth. High costs of electricity, often due to limited infrastructure and high generation costs, make it difficult to expand access to electricity, particularly in rural areas. Limited access to financing poses a significant barrier to infrastructure development, especially for off-grid solutions. Inadequate policy frameworks further impede private sector investment and may not align with best practices for renewable energy expansion.

Addressing the supply and demand challenges of electricity in Africa is crucial for economic development and improving the quality of life for the population. It requires investment in infrastructure, access to financing, and the implementation of effective policy frameworks that promote renewable energy deployment and address the specific challenges faced in the region. By ensuring a reliable and affordable electricity supply, Africa can pave the way for sustainable development and inclusive growth.

3 Enhancing models for renewable energy uptake

3.1 State of Praxis in Modelling Renewable Energy in Africa

Microgrids are small power systems that can operate independently or in conjunction with the main grid, providing reliable electricity supply to local communities. Feasibility studies play a critical role in determining the viability of microgrid implementation, particularly in Africa where access to electricity remains a challenge. Geographic Information Systems (GIS) based approaches provide a powerful set of tools for conducting comprehensive feasibility studies by incorporating spatial data and analytical techniques. This literature review aims to explore the use of GIS -based approaches in assessing the feasibility of microgrid implementation in Africa, focusing on key methodologies and parameters used in previous studies.

Weighted Linear Combination (WLC) Method: The weighted linear combination (WLC) method is a commonly used GIS-based multi-criteria analysis technique for evaluating the suitability of alternative sites or decision options. This method weights various criteria based on their relative importance and calculates an overall score for each option. Criteria used in the WLC method for microgrid feasibility studies in Africa typically include location parameters, electrification rate, rural population, population density, distance to the main grid, solar irradiance, poverty level, and load profiles. By combining these criteria and assigning appropriate weights, decision makers can evaluate the feasibility of implementing microgrids in specific areas.

$$V(a_i) = \sum_{j=1}^{n} w_j \cdot v_j(a_i) \tag{II.1}$$

In the equation above (Eq.II.1), $V(a_i)$ represents the value function for alternative a_i [7]. The sum across the range of attributes (from 1 to n)

is calculated for the given senario a_i. w_j denotes the normalized weight assigned to the j-th attribute and $v_j(a_i)$ represents the value function for the j-th attribute of alternative a_i.

Implementation of the Analytical Hierarchy Process (AHP) Methodology: The Analytical Hierarchy Process (AHP) is another widely used approach in decision-making processes and has been applied in the context of microgrid feasibility studies. AHP involves pairwise comparisons of criteria to determine their relative importance. Decision makers assign numerical values on a scale of 1 to 9 to quantify the importance of each criterion. This method provides a structured framework for decision making and can be integrated with GIS -based analysis to evaluate microgrid feasibility. The AHP method was used in combination with standardization of fuzzy functions to determine the relative weights of the criteria. This approach allows decision makers to consider the opinions and preferences of various stakeholders in the decision-making process.

Simple Additive Weighting (SAW) Method: The method of simple additive weighting (SAW) is another GIS -based approach used in a decision support system for microgrid feasibility studies. This method involves defining a set of evaluation criteria and standardizing the scores to a common dimensionless unit. Scoring criteria often include factors such as solar generation capacity, wind speed data, population density, load profiles, and geographic characteristics. By applying the SAW method, decision makers can assess the feasibility of a microgrid implementation based on the weighted sum of the standardized criteria scores.

Key parameters for microgrid feasibility studies: The feasibility of implementing microgrids in Africa is influenced by several key parameters that must be considered in the analysis. These parameters provide insights into the technical, economic, social, and environmental aspects of microgrid systems. Some of the key parameters commonly used in feasibility studies are discussed below:

1. Siting parameters: Site parameters include factors such as distance from the main grid, proximity to potential energy resources (e.g., solar, wind), and terrain characteristics. Evaluating these parameters helps determine the feasibility of establishing a microgrid in a particular location. For example, areas that are far from the main grid may benefit more from microgrid solutions, while locations with abundant renewable energy resources may be better suited for sustainable microgrid implementation.

2. Electrification rate: the electrification rate provides information on the current status of electricity access in the target area. It helps identify regions with low electrification rates that can benefit from microgrid implementation. In areas with high electrification rates, the need for microgrids may be lower unless there are specific challenges or requirements that can be met by localized power systems.

3. Population Density: Population density is an important parameter because it affects the energy demand and size of the microgrid system. Areas with higher population density tend to have higher electricity demand, making microgrid implementation more feasible and economically viable.

4. Solar Irradiance and Wind Speed: Solar irradiance and wind speed data are critical in evaluating the microgrid system's potential renewable energy generation capacity. These parameters help determine the availability and reliability of solar and wind resources in the target area, which are essential for sustainable microgrid power generation.

5. Load profiles: Load profiles represent the energy consumption patterns and demand characteristics of the target area. Analysis of load profiles helps in appropriate sizing of the microgrid system to meet the energy needs of the local community. It also

helps in optimizing the energy generation capacity and storage requirements of the microgrid.

6. Poverty levels: consideration of poverty levels is essential to assessing the social impact and affordability of implementing a microgrid. Areas with higher poverty levels may have limited access to electricity and could benefit significantly from microgrids that provide affordable and reliable energy.
7. Cost factors: cost factors include the cost of grid expansion, microgrid installation, operation, and maintenance. Evaluating these costs helps determine the economic viability of implementing microgrids versus grid expansion. Cost factors are critical in decision-making processes because they affect the financial feasibility and long-term sustainability of microgrid projects.
8. Environmental Impacts: Assessing the environmental impacts of microgrid implementation is critical to promoting sustainable energy solutions. Parameters such as carbon emissions, air quality, and land use should be considered to minimize the environmental footprint of the microgrid system.

GIS-based approaches have proven to be valuable tools for conducting comprehensive feasibility studies for microgrid implementation in Africa. The Weighted Linear Combination (WLC), Analytical Hierarchy Process (AHP), and Simple Additive Weighting (SAW) methods were used to evaluate the suitability of alternative sites or decision options based on various criteria. In addition, these studies considered parameters such as site characteristics, electrification rate, population density, solar irradiance, load profiles, and cost factors. By integrating GIS -based analyzes with decision support systems and incorporating a wide range of parameters, stakeholders can make informed decisions about microgrid implementation, ultimately contributing to the goal of improving access to reliable electricity in Africa.

challenges of minigrid deployment:

Minigrid failure can be attributed to various factors categorized into social, technical, economic, environmental, and policy aspects. In the social domain, the lack of community engagement during the planning stage is a significant factor. Without involving stakeholders, sustainable energy planning and development become challenging. Additionally, the lack of education on energy conservation and maintenance, as well as the question of ownership of the infrastructure, contribute to minigrid failure. Installation by unqualified or inexperienced practitioners and the absence of practical preliminary surveys also pose challenges.

In the technical realm, poor and inappropriate design is a major factor limiting the lifespan of minigrids. Lack of standard maintenance procedures, dearth of local skilled practitioners, non-compliance with international standards, use of sub-standard materials, inadequate knowledge of renewable energy, lack of monitoring systems, and poor project supervision further contribute to minigrid failure.

From an economic perspective, the lack of financial support from the government and the absence of a sustainable financial framework hinder successful minigrid deployments. The question of financial responsibility, lack of revenue generation from energy services, and the high cost of component replacements also impact minigrid sustainability.

While not directly causing system failure, the environmental dimension plays a crucial role in sustainability. Factors such as the dearth of comprehensive energy resources assessment, lack of planned environmental assessment, weak environmental awareness, and improper disposal of materials contribute to environmental challenges.

Lastly, ineffective policy initiatives and the lack of political will for widespread application hinder minigrid success. Effective policies, such as feed-in tariffs and tax incentives, are crucial for promoting renewable energy-based minigrids, but their absence in Nigeria contributes to the failure of minigrid projects.

State of praxis solutions:

The success and sustainability of minigrid systems in remote communities depend on various factors. From a social perspective, effective community participation and education are crucial. Engaging the community in planning, development, and management processes fosters a sense of ownership and acceptance. Educating the public on energy efficiency practices and the importance of routine maintenance is also essential. Defining infrastructure ownership and awarding projects to qualified contractors are factors that contribute to long-term viability.

On the technical front, appropriate and realistic design is vital. Training programs can help build local capacity in solar PV systems. Standard maintenance procedures, use of international standards, quality materials, remote monitoring systems, and effective project supervision are all important for sustainable minigrid operation.

Economically, financial support from the government and financial commitment from communities play key roles. The government can provide grants, loans, or tax credits to support minigrid projects. Revenue generation and sound financial frameworks that integrate renewable energy entrepreneurs are necessary for long-term viability.

From an environmental perspective, conducting site-specific resources reports and effective environmental impact assessments (EIAs) are essential. Understanding available energy resources and assessing the environmental impact prior to implementation are crucial. Environmental awareness and research on renewable energy solutions help promote environmentally friendly practices and inform decision-making. **?**

3.3 Extending the knowledge for decision making

a) existing models b) understanding of shortcoming & pitfalls c) new parameters (GIS)

Geographic Information System (GIS) plays a crucial role in minigrid planning in Africa for various reasons. GIS enables the generation of spatial data, which serves as essential input for scenario development in energy systems. The ability to create and analyze spatial data enhances the understanding of geographical factors that influence minigrid planning.

3.4 ... other parameters (least cost)

Chapter III

Methodology

1 Description and study sites

In this study three countries SESA operate in; Kenya, Morocco and South Africa were chosen to analyse challenge varaity and data. These country were chosen on the base of their geological position; Morroco is the most north and west of the African countries SESA operate, while South Africa is the furthest south and lastly Kenya is the furthest east. The selected countries are analysed and summarized on the basis of available data on current energy status.

The indivudual effects of COVID-19 and Russia-Ukraine conflict are not discussed in this study, instead an overall summary is presented. The COVID-19 pandemic and the Russia-Ukraine conflict have had adverse effects on Africa. The pandemic particularly impacted the energy sector as businesses scaled down operations, leading to a decline in power demand. Governments in the region expressed their intention to renegotiate power tariffs with Independent Power Producers (IPPs) to alleviate the burden of rising costs for the population. The renewable energy sector also faced disruptions, including a decrease in solar equipment installations and the cancellation of trade shows. Additionally, the Russia-Ukraine conflict has had a profound impact on inflation, reflected in the comparison of real GDP growth and nominal GDP growth in several African countries (Annual GDP | CBK (centralbank.go.ke)). With over 40% of the sub-Saharan African population living in extreme poverty in

2021, the combined effects of the pandemic and the conflict could potentially push an additional 25 million individuals into extreme poverty by the end of 2022 (World Bank, 2022b).

1.1 Kenya

Kenya with its capital Nairobi has a population of 55.1 million (World Population Dashboard -Kenya | United Nations Population Fund (unfpa.org)). the country has a renewable resource advantage due to its geological position as seen in the figure III.1.

Figure III.1: Map of Kenya and its capital Nairobi. Its major cities can be observed as well as its neighbouring countries and coastline.

It has made significant progress in transitioning to renewable energy sources, which now generate over 80 percent of the country's electricity (Kenya's Clean Energy Transition Gets a Boost from Solar Power - Kleinman Center for Energy Policy (upenn.edu)). In addition, Kenya has been actively working to increase access to the power grid, with electricity access in households rising from 32% in 2013 to 75% in 2022 (Kenya - Energy-Electrical Power Systems (trade.gov)). While urban areas have achieved near-universal access at 100%, rural areas still stand at 65% (Kenya - Energy-Electrical Power Systems (trade.gov)). As of December 2022, Kenya has a total installed capacity of 3601.76 MW, consisting of various energy sources, including hydro (25.5%), geothermal (28.04%), thermal (20.67%), wind (12.84%), solar (7.83%), bioenergy (2.69%), waste heat (2.45%), and 200 MW of imported power (BIANNUAL ENERGY AND PETROLEUM STATISTICS REPORT epra).

The rural population in Kenya constitutes 72% or 37.9 million people as of 2021, and it has been declining over the past two decades (Rural population growth (annual %) - Kenya | Data (worldbank.org)). Kenya's nominal GDP stands at 110.35 billion USD, showing consistent growth for over a decade, except for the year 2020. The GDP per capita was recorded at 2081.8 USD in 2021 (GDP per capita (current US$) - Kenya | Data (worldbank.org)).

Despite the progress made, challenges persist in achieving universal access to electricity in Kenya. These challenges include high connection costs, particularly in rural and peri-urban areas, lack of appropriate incentives to attract private investors, inappropriate technical standards for different types of settlements, difficulties in obtaining wayleaves consents and rights of way, and demands for high compensation. Weak implementation capacity and land access issues also pose obstacles to achieving universal access (Kenya-National-Electrification-Strategy-KNES-Key-Highlights-2018.pdf (worldbank.org)).

Furthermore, the Finance Act 2020 and the Tax Amendment Act 2020 abolished tax exemptions previously enjoyed by businesses in the renewable energy sector in Kenya, leading to the introduction of a 14% value-added tax (VAT) on supplies imported for power plant construction and off-grid solar power equipment. These changes increase capital expenditure costs for independent power producers (IPPs) and impose 14% VAT on solar home system equipment (Kenya - Energy-Electrical Power Systems (trade.gov)).

The energy sector in Kenya faces various challenges, including the need to improve the quantity, quality, and reliability of energy supply. The sector also encounters high initial capital requirements and long lead times for energy infrastructure development. Mobilizing sufficient financial resources for large-scale investments, dealing with high energy costs, low per capita incomes, and low levels of industrialization are additional hurdles to overcome (Environmental and Natural Resource Governance in Kenya (nema.go.ke)).

1.2 Morocco

Morocco with a population of 37.8 million has Rabat as its capital. The population is comprised of a rural population making 35.94% or 13.3 million people. The country has an impressive geological position allowing them to have easier trades Europe as seen in figure **??**. Currently Morocco relies heavily on imported hydrocarbons, with approximately 90% of its energy needs being imported. However, Morocco aims to reduce its dependence on energy imports and increase the security of its energy supply. By the end of 2021, the share of renewable energy in the country's capacity mix stood at 37.1%, slightly below the government's target of 42% set under the Paris Agreement. The goal is to achieve 52% of the total installed capacity from renewable sources by 2030. Currently, Morocco has a total installed capacity of 10,968 MW, with the energy mix consisting of coal (37.08%), hydroelectricity (16.14%), fuel oil (7.67%), natural gas (17.72%), wind (13.37%), and solar (7.58%).

In terms of electricity access, urban areas in Morocco have achieved universal access at 100%, while rural areas stand at 99.83% in 2021. The country has made significant efforts in rural electrification through initiatives like the Generalised Rural Electrification Programme (PERG). The Moroccan Agency for Sustainable Energy (MASEN) plays a crucial role in supporting renewable energy projects, providing a comprehensive institutional framework for private project developers. This framework includes permitting, land acquisition, financing aspects, and securing

Figure III.2: Map of Morocco and its capital Rabat. Its major cities can be observed as well as its neighbouring countries and coastline.

state guarantees for investments. Independent Power Producers (IPP) are also able to develop and sell electricity from renewable energy projects (Morocco - Energy (trade.gov)).

Morocco's nominal GDP is 142.87 billion USD, and it has shown steady growth over time (GDP (current US$) - Morocco | Data (worldbank.org)). The GDP per capita was recorded at 3,795.4 USD in 2021 (https://datacatalog.worldbank.org/dataset/world-development-indicators/).

The energy sector in Morocco faces several challenges, including heavy dependence on energy imports, a relatively low share of renewables in its own energy production, delays in investment due to unclear rules for tariff establishment and revision, limitations in grid infrastructure, energy pricing adjustments, and implementation issues. The high cost of energy subsidies and the impact on the budget deficit have been pressing concerns for the Moroccan government (Morocco's Power Sector Transition: Achievements and Potential (iai.it)). The Office Nationale de l'Electricite et de l'Eau potable (ONEE), the state utility, plays a significant role in Morocco’s electrification progress by subsidizing power prices and not passing on the full cost of generation to consumers (Morocco’s Power Sector Transition: Achievements and Potential (iai.it)).

1.3 South Africa

South Africa has a unique feature of having three capitals which are Cape Town, Pretoria and Bloemfontein as seen in figure **??**. The current population of the country is 60.4 million (World Population Dashboard - South Africa | United Nations Population Fund (unfpa.org)), which includes a rural population of 32% or 19.1 million people in 2021 (Rural population - South Africa | Data (worldbank.org)). The country’s total installed capacity reached 54,669 MW by the end of 2022. The energy mix consists of coal (72.8%), nuclear (3.4%), diesel and gas (6.2%), hydro (1.1%), wind (6.3%), solar (4.2%), and other sources (6%) (Microsoft PowerPoint - Statistics of utility-scale power generation in South Africa in 2022 (FINAL) (csir.co.za)). However, the share of renewables is only 12.5%. South Africa experiences frequent load shedding, with 3,773 hours of power outages recorded, leading to either brownouts or blackouts (Microsoft PowerPoint - Statistics of utility-scale power generation in South Africa in 2022 (FINAL) (csir.co.za)).

Eskom, the state-owned power company, is responsible for generating approximately 95% of South Africa’s electricity. It not only supplies electricity domestically but also exports to Botswana, Lesotho, Mozambique, Namibia, eSwatini, and Zimbabwe. Rural electrification in South Africa stands at around 66%, while urban areas have an electrification rate of approximately 93% (South Africa - Energy (trade.gov)). The Renewable Independent Power Producer Program (REIPPP) aims to increase the nation’s electricity grid capacity through private sector investment in renewable energy sources such as wind, biomass, and small hydro. To address the recent load shedding crisis, the President announced an increase in the procurement of renewable power from independent power producers (IPPs) in 2022 (South Africa - Energy (trade.gov)).

Figure III.3: Map of South Africa and its capitals Cape Town, Pretoria and Bloemfontein. Its major cities can be observed as well as its neighbouring countries and coastline.

South Africa is a large importer of crude oil. However, due to its significant export of coal, the country has become a net exporter (2019-Commodity-Flow-and-Energy-Balance.xlsx (live.com)). In terms of economic indicators, South Africa's GDP in 2021 was 419.0 billion USD, with a per capita GDP of 7,055.0 USD (GDP (current US$) - South Africa | Data (worldbank.org)).

The energy sector in South Africa faces several challenges, including corruption, the urgent need to unbundle Eskom into separate entities for generation, transmission, and distribution to address the utility's substantial debt levels, frequent load shedding, an unstable grid network, exposure to high and volatile oil import prices, and limitations in the rural electrification program due to a lack of skills, resources, and technical experience at municipalities (Towards a sustainable rural electrification scheme in South Africa: Analysis of the Status quo - ScienceDirect).

2 Methodological approach for a GIS-based integration

As mentioned earlier the GIS-based approach to assess feasibility for microgrid in africa is considered a valueable approach signifying better decision making. In the following sections the work of transforming reliable data, validating it with experts and inserting it in a GIS model and applying it in a simulation will be presented.

2.1 Creating reliable data

To ensure the reliability of data for analysis, it is imperative to implement a systematic approach that focuses on key aspects of data collection, organization, normalization, and verification. This section discusses these steps in an academic context, emphasizing the importance of creating a robust foundation for data analysis.

The first step in improving data reliability is to enhance data collection practices. A meticulous selection of relevant data types specific to the suggested GIS approach. ves is essential. By identifying behaviors or factors that are most pertinent to the overall business, researchers can gather data that is highly applicable to their analyses. This targeted approach helps to streamline data collection efforts and ensures that the acquired data aligns with the research goals.

Once data collection practices are optimized, attention should be directed towards organizing the data effectively. Proper data organization facilitates data quality control and enhances the efficiency of subsequent analyses. A coherent and structured system for storing and managing the collected data is established. This system should adhere to established data management best practices, ensuring that data is easily accessible, well-documented, and capable of being efficiently manipulated for analysis purposes.

Normalization of data is another critical step towards achieving reliable analysis results. When data is collected from diverse sources, inconsistencies or errors in spelling, formatting, or naming conventions can arise. These inconsistencies can have a substantial impact on the accuracy and reliability of subsequent analyses. To address this, it is necessary to establish standardized norms for data representation and formatting. By enforcing consistency across the dataset, researchers can minimize discrepancies and ensure uniformity, thereby increasing the reliability of the data.

Data verification plays a vital role in bolstering data reliability. Verification involves cross-referencing the collected data against authoritative and reliable sources, such as official records or databases. This process confirms the accuracy and currency of the data, reducing the risk of misleading or erroneous analysis outcomes. Rigorous data verification procedures provide researchers with confidence in the integrity of the dataset and the subsequent analyses conducted on it.

By adhering to these systematic approaches and conducting comprehensive data quality checks, it is established a foundation of reliable data for analysis. The table III.1 shows the sources used to collect data for the different countries. Data senters such as World bank, Global Atlas and Energy Data are expirienced and reliable sources of relevant data.

Table III.1: Data Comparison

Parameter	**Kenya**	**Morocco**	**South Africa**
Major cities	Simplemaps.com	Simplemaps.com	geonames.org
Sub-region	Humanitarian Data Exchange	Humanitarian Data Exchange	Humanitarian Data Exchange
Population density	2019 Kenya Population and Housing Census	Haut-Commissariat au Plan du Royaume du Maroc	Datasets - openAFRICA
Water bodies	Humanitarian Data Exchange (humdata.org)	AmeriGEOSS Community Platform DataHub. (BETA)	stanford University
Existing transmission network	ENERGYDATA.INFO	worldbank.org	worldbank.org
Solar Potential	Global Solar Atlas	Global Solar Atlas	Global Solar Atlas
Wind potential	Global Wind Atlas	Global Wind Atlas	Global Wind Atlas
Expenditure data	2019 Kenya Population and Housing Census	Enquête nationale sur la consommation et les dépenses des ménages	Wazimap
Power Plants & substations	ENERGYDATA.INFO	Global Energy Observatory	Dept of Water & Sanitation South Africa
Existing & developing Microgrids	ENERGYDATA.INFO	earthengine	Data | World Resources Institute
Prices of selected Items	Jiji.co.ke	#NA	Gumtree: South Africa

2.2 Validity analysis using experts in the field

Due to restricted and outdated knowledge on the area available for common person, it is important to verify from in field experts. By doing so it increases the reliability of the results making it a better decision making option.

An interview was carried out with the goal of being enlightened in three areas:

- Unknown or hidden factors that effect microgrid operation.
- Parameter validation.
- GIS-based approach validation.

The candidates are field experts in the fields mentioned in table III.2. Candidates were informed on the thesis thematic pre-interview. The questions asked are given in list below but the conversation will not be limited to them as the conversation is dynamic:

1. Where do I gather reliable weather data from for African countries?
2. What are the differences between sub-Saharan countries and North African countries?
3. How do you model a microgrid?
4. What are the key factors of placing out a microgrid?
5. How do you determine the purchasing power of local communities?

6. Can you show me the map of Lolupe and Sungli? Is a microgrid feasible in these conditions?
7. How do you project the demand for a household?
8. What factors would attract investors to invest in microgrids in Africa?
9. What are the expenditures of a microgrid(Hidden)?
10. What are the main challenges of microgrid implementation in Africa?
11. Is it justified to compare different models?

Table III.2: Candidates for Validating data

Candidate	Expirience
Sisty Basil	Engineer in Elico NGO with experience from multiple African countries
Charles Ogalu	SESA Kisegi WeTu Head of Energy department
Mads Uhlin Hansen	CEO Kube energy business manager with a background in microgrid cost
Bjørn Thorud	Trønder Energi and experience from Multiconsult Solar expert
Endre Skolt	Co-founder of an investment firm that invests in African factories assembling and distributing Solar home systems (SHS)

2.3 Data integration using GISARC

The GIS program ArcMap 10.8 was used to integrate gathered data. The data collected was of three types;

- Vector data: This includes points, lines, and polygons that represent geographic features. Examples include shapefiles, geodatabases, and KML files.
- Tabular data: This includes attribute tables that contain non-spatial information about geographic features. Tabular data can be in formats like CSV (comma-separated values), Excel spreadsheets, or databases.
- GPS data: Global Positioning System (GPS) data collected from GPS devices or mobile apps can be imported into GIS software. This

data usually contains coordinates (latitude and longitude) and can be used to create point features.

The vector data Could easily be integrated into GisArc and modified to highlight the differences in values. They were already preposition at the correct coordinates of the country. The two main factors that included population density and expenditure capability score could not be assessed directly and need to be calculated either due to lack of information or outdated information. The different types of data can be seen in table III.3

Table III.3: Data types of parameter

Parameter	**Data type**
Major cities	CSV
Sub-region	Shapefile
Population density	Calculated Excel/CSV
Water bodies	Shapefile
Existing transmission network	Line vector
Solar potential	Shapefile
Wind potential	Shapefile
Expenditure data	Calculated Excel/CSV
Power Plants & substations	Point vector
Existing & developing Microgrids	Point vector
Prices of selected Items	Web service to Excel

To calculate the updated population density of the three SESA countries Census data was investigated. The census data offers detailed population on the sub-region of the countries. This population is then divided by the region area to access the population density as seen in equation III.1

$$Population/Area(km^2) = Populationdensity(p/km^2) \tag{III.1}$$

Calculating the Expenditure Capability Score done is done by applying Weighted Linear Combination on the given data. The census reports of Kenya and South Africa include a table reporting various owned household items in every sub-region as well as the division of rural and urban population in these areas. By integrating the prices of the items in tables III.4 and III.5 a weighted expenditure per sub-region develops for the respective areas.

Table III.4: Household items and their local prices in Kenya

Item	Price (Ksh)
Standalone Radio	5000
Desktop Computer/Laptop/Tablet	34000
Functional Television	15000
Analogue Television	7000
Internet	1500 /month
Bicycle	10000
Motorcycle	20000
Refrigerator	20000
Car	135000
Mobile Phone	12000
Tuk Tuk	70000

Table III.5: Household items and their local prices in South Africa

Item	Price (ZAR)
Cell phone	2500
Computer	3000
DVD player	100
Electric/gas stove	3000
Landline/telephone	100
Motor-car	255000
Radio	200
Refrigerator	4000
Satellite television	2500
Television	5000
Vacuum cleaner	500
Washing machine	2300

To start of it is important to categorise household types. Not every household can consume every item on the list. The items themselves can be classified with level of luxuriousity as seen in table III.6. The given item categories are then utilized to create three types of household classifications as shown in the list below. To allocate household items the "Urban-first distribution" approach is utilized. It involves initially allocating resources to the richest of the three household classes and

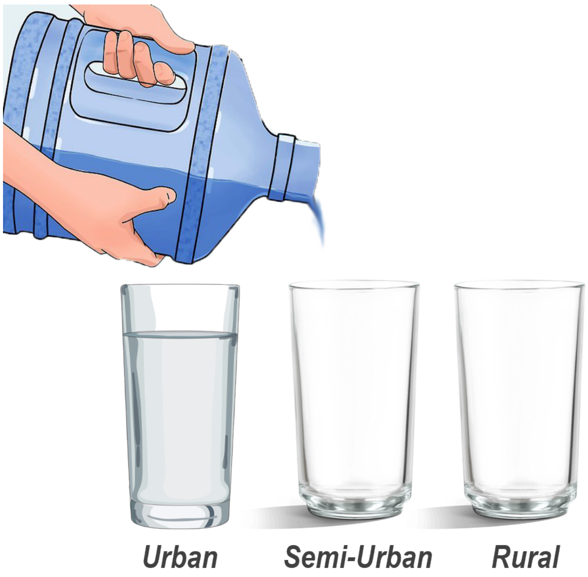

Figure III.4: Visual example of "Urban-first distribution" approach. The jug containing high luxioriousity household items is distributed first to all the urban households than if any remains it is distributed on the next household class.

then, if there are any remaining items, distributing them among the poorer groups as seen in figure III.4

Table III.6: Household items classification

Item	Luxuriosity
Landline/telephone	Low
Mobile	Medium/High
Radio	Low
DVD player	Low
Desk Top Computer/Laptop/Tablet	Low
Satellite television	High
Television	Medium
Internet	Medium/High
Electric/Gas stove	High
Refrigerator	High
Vacuum cleaner	High
Washing machine	Low/Medium
Bicycle	Medium
Motorcycle	High
Car	Low/Medium
Tuk Tuk	Low/Medium

Table III.7: Household items by Household Class

Urban Household	**Semi-Urban Household**	**Rural Household**
Washing machine	-	-
DeskTop/Laptop/Tablet	-	-
Vacuum cleaner	-	-
Advanced TV	Advanced TV	-
Electric/gas stove	Electric/gas stove	-
Internet	Internet	-
Motorcycle	Motorcycle	-
Car	Car	-
Refrigerator	Refrigerator	Refrigerator
Mobile	Mobile	Mobile
-	Satalite TV	Satalite TV
-	Radio	Radio
-	DVD player	-
-	bicycle	bicycle
-	-	Landline/ telephone

$$MSoI_x(HC_x) = I \cdot NoI_x \tag{III.2}$$

Firstly the expenditure per item or Money Spent on Item x is calculated using eq. III.2. $MSoI_x$ is given by the three Household Classes (rural, semi-urban and urban). NoT is the number of households with $item_x$. To derive the total amount of money spent given HC, a summation can be done from item 1 to x as seen in eq. III.3

$$MS(HC) = \sum_{i=1}^{x} MSoI_x \tag{III.3}$$

Currently a weighted accumulated expenditure is developed for each of the three household classes. To summarize this into one value for each region the equation for WLC is used.

$$ECscore(R) = \frac{\sum_1^3 MS(HC) \cdot H_a}{\sum H} \tag{III.4}$$

In the equation above (Eq.III.4), the WLC eq.II.1 is transformed to fit the purpose of making the expenditure capability score. $ECscore$ represents the expenditure for an average household in region R. The weighting factor is the number of households in class a divided by all the households in the region given by $\sum H$.

Morocco on the other hand does not have a specific list of owned items in households in subregions of the country. The most recent expenditure report was the *National survey on household consumption and expenditure 2013/2014* [8]. The report was on main region level and descripted a the "Average Annual Expenditure per Person" or "Dépense Annuelle Moyenne par Personne" (DAMP). DAMP translates into an indicator that represents the average amount of money spent per person in a year. In the context of the provided information about Morocco, the DAMP in 2014 was 15,876 Moroccan Dirhams (DH) [8]. The indicator can likewise be used as a measure of the standard of living and depict a picture of a region's average person's solvency. The table III.8 shows the expenditure capability of an average person in a specific region in Morocco.

Table III.8: Average Annual Expenditure per Person by region in Morocco

Moroccan sub-region	**DAMP**
Chaouia - Ouardigha	11547
Doukkala - Abda	11547
Fès - Boulemane	9679
Gharb - Chrarda - Béni Hssen	9300
Grand Casablanca	11547
Guelmim - Es-Semara	9697
Laâyoune - Boujdour - Sakia El Hamra	12569
Marrakech - Tensift - Al Haouz	10107
Meknès - Tafilalet	9679
Oriental	12110
Rabat - Salé - Zemmour - Zaer	9300
Souss - Massa - Draâ	10401
Tadla - Azilal	9407
Tanger - Tétouan	11817
Taza - Al Hoceima - Taounate	11817

A decision making tool based on the Analytic Hierarchy Process

Chapter IV

Results and discussion

1 Results from interview

1.1 Validity Status

The feasibility study on GIS-based microgrid implementation is considered valid based on the inputs from the following validators: Kube Energy, Charles Ogalu WeTu, Bjørn Thorud, Sisty Basil, and Endre Skolt. These validators provided valuable insights and expertise related to various parameters of the study. Here is a summary of their interviews and how their inputs contribute to the validity of the study:

It is important to note that while the validator's inputs enhance the validity of the study, the ultimate validation of the feasibility study relies on rigorous analysis, data accuracy, and comprehensive assessments specific to the study area.

1.2 Commonalities

- Demand Projection: Both Mads Uhlin Hansen and Bjørn Thorud emphasized the importance of accurately projecting the demand for households in order to ensure the feasibility and success of microgrid implementations. This is rather difficult to find, forcing the investors to have a cite visit even in the early feasibility tests.
- Importance of Solvency: Mads U. H., Charles Ogalu WeTu, and Bjørn T. all highlighted the significance of ensuring solvency and payment capabilities of customers to maintain the financial viability

of microgrid projects. They highlighted that solvensy data is hard found or not available in SSA, while most north African countries have a credit score on their citizens.

- Challenges in Regulatory Framework: Both Charles O. and Bjørn T. mentioned the challenges and limitations posed by the regulatory frameworks in terms of construction approval, application guidelines, and the need for supportive policies and frameworks. The non-existent or unoptimized framework causes long delays and project closing. An example that was provided suggested that the framework asks for submission of builders request, but the submission process is not defined. This causes confusion and unnecessary hinder.
- Local Stakeholder Engagement: Charles O., Bjørn T., and Sisty Basil emphasized the importance of engaging with local stakeholders throughout the microgrid implementation process to ensure community support and sustainable outcomes.
- Subsidies and Financing: Sisty B. and Endre Skolt discussed the need for subsidies and financing options to make microgrid projects financially viable and accessible, particularly in areas where the cost of electricity is significantly higher than the national grid.

1.3 Discrepancies/diverging argumentation's

- Cost Estimations: Mads U. H. provided specific cost estimations for batteries, diesel, and solar systems, while Charles Ogalu WeTu and Sisty Basil focused more on the overall cost considerations, including hidden factors such as transportation fee(grossly underestimated), battery explosions, social marketing, stolen land, difficulty in demand projection and fall off of customers.
- Technology and Lasting Solutions: Bjørn T. emphasized the importance of microgrid technologies working effectively and having long lifespans, while Sisty Basil discussed challenges related to the high cost and limited lifespan of batteries, suggesting the need for more

efficient and long-lasting solutions.

- Productive Use of Energy: Sisty Basil highlighted the importance of introducing productive use of energy programs to increase the value and demand for electricity, while this might add to the capex it will in the long term also increase income and hold a stable money flow.
- Market Reach and Scalability: Endre S. emphasized the importance of market reach and scalability for microgrid projects, focusing on team expertise, business models, and the ability to target larger markets, whereas other validators focused more on the specific challenges within their local contexts.

These discrepancies highlight the diverse perspectives and priorities among the validators, demonstrating the multifaceted nature of microgrid feasibility studies and the various factors that need to be considered for successful implementations. It is of value in adjusting the approach and obtaining more reliable results as seen in the next session. See Appendix A for detailed interviews.

2 Assessment of potential using GIS-integration

After integrating all data factors into a GIS model three main maps develop for each of the three subject countries. This section presents the most important findings from the results of analysis of cases. The three maps for population density, exacting power facilities and expenditure capability score are presented respectively.

The population density for each of the three countries is presented in figure IV.1 IV.2 IV.3. Compared to the public data achieves the population density maps are up to date. This can either be due to bad data publication strategies by the countries or no public access. The data from South Africa is 9 years old, which is enough time for drastic demographic changes to occur. It is there by a question of map reliability. Firstly all the three countries border to open water. Since the beginning of history settlements have settled close to water, indicating that the population near water will not change unless significant change in geographical structure of the countries. Secondly more developed countries such as South Africa have a well developed infrastructure causing the main population distribution trend to remain. Morocco and Kenya on the other hand have more updated data and are reliable.

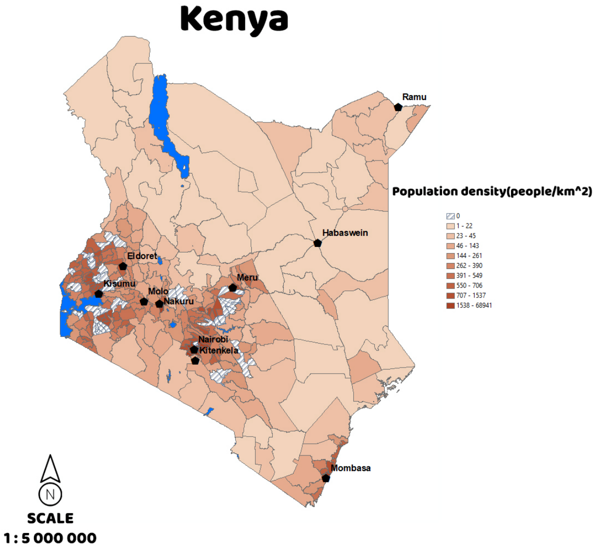

Figure IV.1: (2019)Population density in Kenya by sub-region. The 10 largest cities are marked to show relative data. Areas showing 0 population density have unconfirmed data and are negelected in this map due to time limitation.

The country comparison between the three selected countries suggests similar settlement trends, Although their political, economical and energy situation is different. Areas such as mid-north Kenya and north-west South Africa have experienced drought in the recent years due to climate change. This has forced settlements to domestically migrate to more suitable regions, often moving closer to larger cities. This indicates availability of land in less populated areas for large scale projects. The effects of drought also indicate that the current data on water bodies in the countries may verily be outdated. Thereby suggesting a site visit necessary as recommended by the validators.

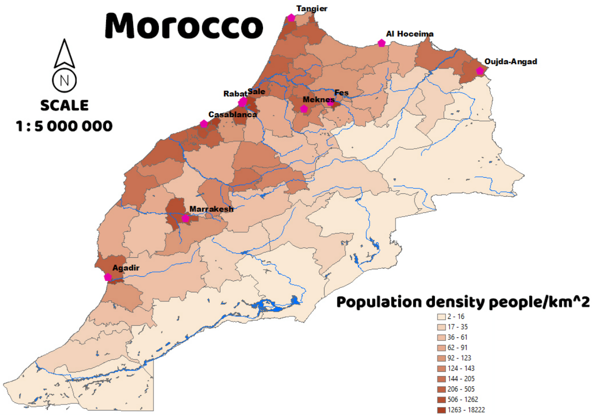

Figure IV.2: (2020)Population density in Morocco by sub-region. The 10 largest cities are marked to show relative data.

The population density maps were confirmed helpful for the feasibility study of microgrids in Africa by both state of praxis and validitor's. The feasibility study as mentioned by the validators often require presis measurements of the study area. Study areas are often smaller than what the map can differentiate. A more detailed map is required in comparison to the output maps to be able to use this in the final decision process. On the contrary the maps presented in this study are relatively updated and reliable and can be used in the early phases of feasibility study for better overall overview.

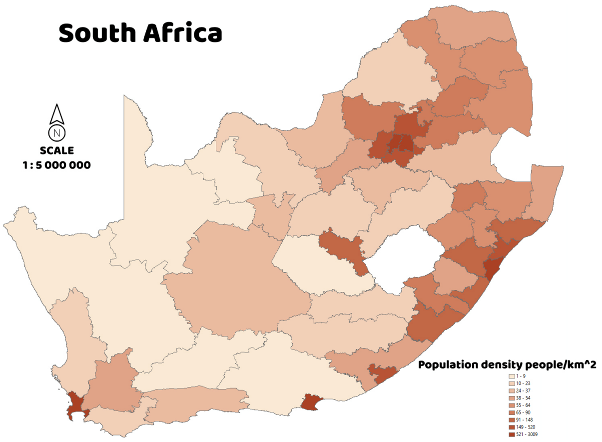

Figure IV.3: (2016)Population density in South Africa by sub-region. The 10 largest cities are marked to show relative data.

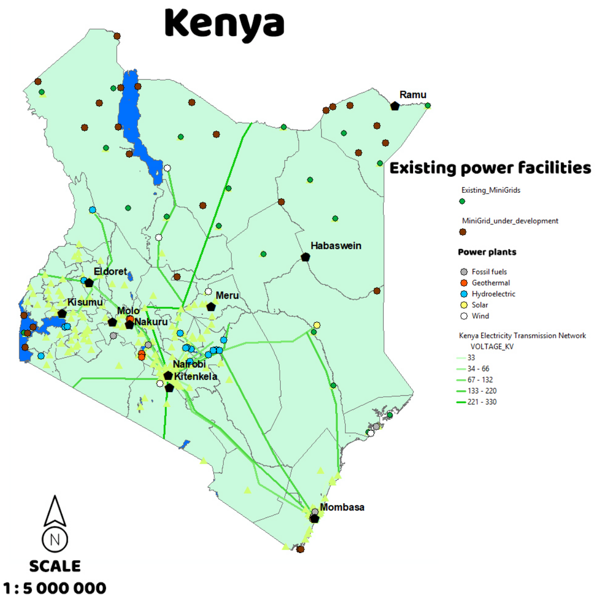

Figure IV.4: Map of Kenyan power facilities. Current infrastructure is displayed in terms of transmission network, power plants and existing and developing minigrids.

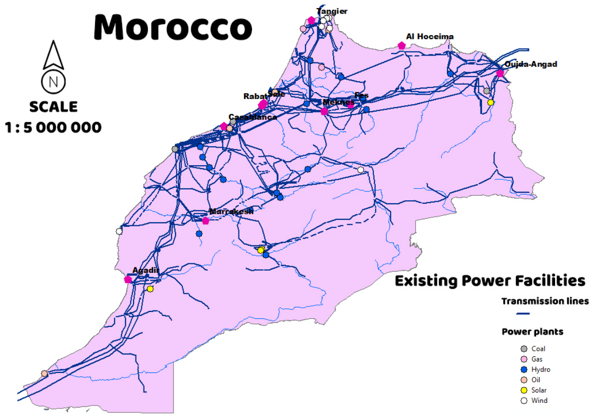

Figure IV.5: Map of Moroccan power facilities. Current infrastructure is displayed in terms of transmission network and power plants.

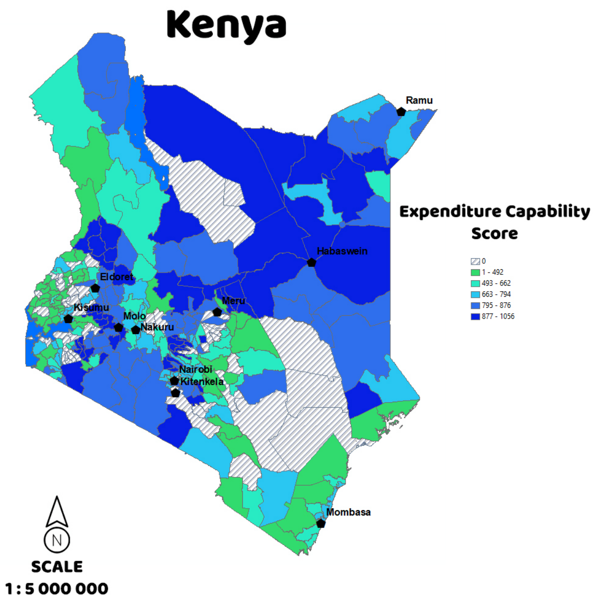

Figure IV.7: Expenditure Capability Score of sub-regions in Kenya. The 10 largest cities are marked to show relative data. Areas showing 0 EC-score have no data and are negelected in this study.

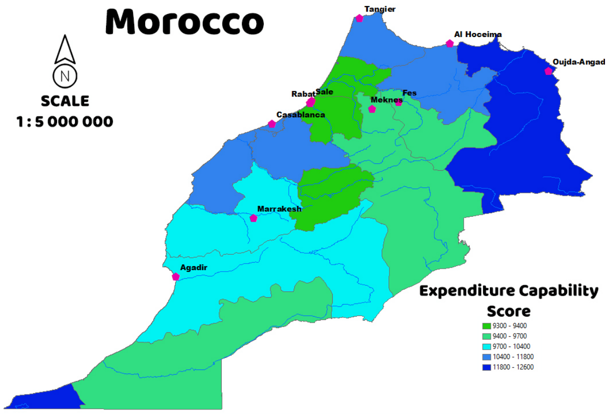

Figure IV.8: Expenditure Capability Score of sub-regions in Morocco. The 10 largest cities are marked to show relative data.

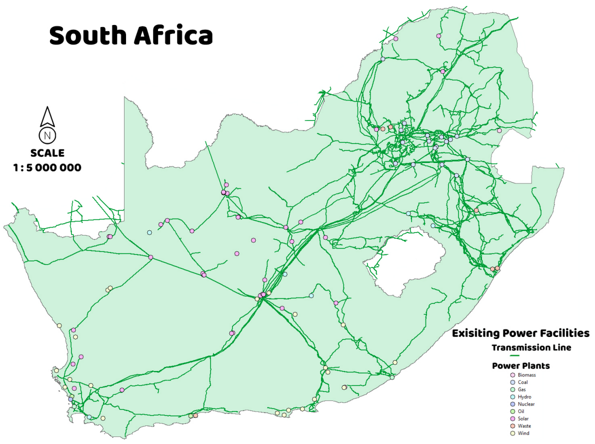

Figure IV.6: Map of South African power facilities. Current infrastructure is displayed in terms of transmission network and power plants.

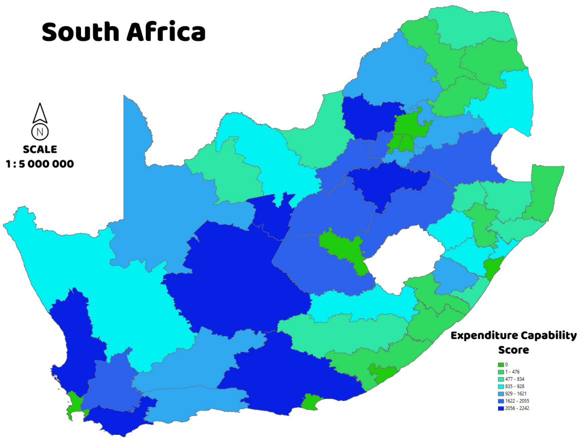

Figure IV.9: Expenditure Capability Score of sub-regions in South Africa. The 10 largest cities are marked to show relative data.

3 Enhanced decision making tool

EDM tool is created...

Chapter V

Conclusion and future work?

This Thesis can be concluded by reinterpret the defined research quetions; What are the key characteristics of successful minigrid systems for renewable energy uptake in Africa, and how can these be compared and improved through mathematical optimization models?

- Technical design: The minigrid system should be designed to meet the electricity demand of the community reliably and efficiently. This requires careful sizing of the renewable energy generation capacity, energy storage systems, and backup generators, as well as the appropriate selection of power electronics and control systems to ensure the stability and quality of the electricity supply.

- Economic viability: The minigrid system should be financially sustainable and provide affordable electricity to the community. This requires careful consideration of the initial capital investment, operating and maintenance costs, and revenue streams from electricity sales, as well as the potential for accessing financing and subsidies.

- Social acceptance: The minigrid system should be socially acceptable and integrated into the local community. This requires engagement and participation of the community in the design and operation of the system, as well as addressing any cultural or social barriers to adoption.

- Environmental impact: The minigrid system should have minimal environmental impact and promote sustainable development. This requires careful consideration of the carbon footprint, land use, and biodiversity impacts of the renewable energy sources, as well as the potential for promoting energy access and reducing poverty.

What are the economic, social, and environmental factors that influence the adoption of minigrid systems for renewable energy uptake in Africa, and how can these be modeled and evaluated using mathematical optimization?

The adoption of minigrid systems for renewable energy uptake in Africa is influenced by a complex interplay of economic, social, and environmental factors. These factors include energy poverty, unreliable grid infrastructure, high electricity costs, limited access to financing, environmental degradation, and climate change. Mathematical optimization techniques can be used to model and evaluate these factors, enabling policymakers and stakeholders to make informed decisions about the deployment of minigrid systems in Africa.

Economic factors are a key driver of the adoption of minigrid systems in Africa. High electricity costs, limited access to financing, and unreliable grid infrastructure can make grid-connected electricity unaffordable or unavailable to many people, particularly those in rural areas. Minigrid systems can provide a cost-effective alternative to grid-connected electricity, particularly in areas where the cost of extending the grid is prohibitively high. Mathematical optimization techniques can be used to model the economic viability of minigrid systems, taking into account factors such as the cost of renewable energy technologies, financing options, and revenue streams from energy sales.

Social factors also play a significant role in the adoption of minigrid systems in Africa. Energy poverty, which affects millions of people in

Africa, can have far-reaching social and economic consequences, including limited access to education, healthcare, and economic opportunities. Minigrid systems can provide reliable and affordable electricity to communities that are currently underserved by the grid, improving quality of life and supporting economic development. Mathematical optimization techniques can be used to model the social benefits of minigrid systems, such as improvements in education, healthcare, and economic activity.

Environmental factors are another important consideration in the adoption of minigrid systems in Africa. The use of renewable energy technologies can help to reduce greenhouse gas emissions, mitigate the effects of climate change, and promote sustainable development. However, the environmental benefits of minigrid systems can vary depending on factors such as the type of renewable energy technology used, the scale of the system, and the location of the system.

Mathematical optimization techniques can be used to model the environmental impacts of minigrid systems, taking into account factors such as carbon emissions, land use, and water use. Overall, mathematical optimization techniques can be a powerful tool for modeling and evaluating the economic, social, and environmental factors that influence the adoption of minigrid systems for renewable energy uptake in Africa. By taking a holistic approach to modeling, policymakers and stakeholders can make informed decisions about the deployment of minigrid systems, ensuring that they deliver maximum benefits to communities while also promoting sustainable development. How do the energy needs and profiles of different regions in Morocco, Kenya, and South Africa impact the design and implementation of minigrid systems for renewable energy uptake?

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Appendix A

Kube Energy Interview Summary During the interview, the following topics were discussed:

- Solar and Diesel: Kube Energy focuses on transitioning from diesel power to renewable solar energy. They operate in Kenya and provide additional power to UN hubs, benefitting the local community.
- Project Scale: Kube Energy works on projects ranging from 2 kilowatts (kW) to 3 megawatts (MW) in size.
- Factors Considered: When considering projects, Kube Energy takes into account factors such as having an anchor client, financial solvency, and large energy consumption.
- Production and Cost: Kube Energy aims to produce energy at 4 Kenyan shillings (kr) per kilowatt-hour (kWh), while the national grid costs 12 cents per kWh. A minimum usage of 10 kW per day is required, and the microgrid is connected to a larger private grid.
- Feasibility and Business Case: Kube Energy assesses the feasibility and develops a business case for each project. They consider factors such as the political regime and the level of development of the national grid in different regions. North Africa is considered to have a stronger regime and a better-developed national grid, making it more attractive for investment. In contrast, Sub-Saharan Africa faces challenges such as higher production costs and lower grid coverage.
- GDP Effect: The GDP of a region affects the expenditure on energy projects.
- Modelling Software: Kube Energy uses software tools like Homer (which covers 85% of the solution) for assessing energy use and helioscope for detailed analyses.
- Battery Costs: Batteries cost around $400-500 per kilowatt-hour

(kWh), accounting for approximately 50% of the project cost.

- Diesel Capex: The capital expenditure for diesel systems is estimated to be $270 per kilowatt-peak (kWp), which is considered relatively low.
- Solar O/M Cost: The operational and maintenance cost for solar systems is around $350 per kWp, which includes the inverter and constitutes 15-20% of the total cost.
- Payback Period: The payback period for Kube Energy's projects is approximately 5 years.
- Projecting Household Demand: Kube Energy considers factors such as energy needs, logging systems, and satellite images to project household demand.
- Attracting Investors: To attract investors for microgrid projects in Africa, Kube Energy emphasizes factors such as limited competition, presenting to investors, and ensuring favorable terms and conditions.
- Expenditures of Microgrid: The costs of microgrid projects are categorized into three types: development (time and money, rights/licenses), capital expenditure (logistics, commissioning, solar panels), and operational expenditure (diesel generators, maintenance, security).
- Challenges of Microgrid Implementation: Key challenges in implementing microgrids in Africa include assessing the payment capacity of customers, acquiring data from other countries, documenting ownership rights in the host country, and accurately projecting demand.
- Model Comparison: The justification for model comparison involves on-site visits, transportation costs, and the discrepancy of around 5-6 million kr, where an estimated 2 million kr resulted in an actual cost of 8 million kr.

Charles Ogalu WeTu Interview Summary:

During the interview, Charles Ogalu discussed the use of solar energy to provide three facilities. These facilities include water purification using a local lake, a pump powered by solar energy and batteries (lithium-ion), and a reverse osmosis system. He also mentioned the option to charge lanterns for a small fee of 70 cents using lead-acid batteries. Additionally, he talked about solar cooling systems being implemented in small communities and on mobility bikes, utilizing ice-based technology. He emphasized the productive usage of electricity, whether there is connectivity to the grid or not, and the need for feasibility studies to determine the appropriate system size for urban and rural areas, taking into account the environmental impact as well as socio-economic factors.

One question raised during the interview was about hidden costs and community engagement. Charles explained that onboarding customers and marketing incurred huge costs. He also mentioned the issue of not optimizing or underutilizing operations, leading to idle power that can be costly. He referred to the importance of relying on reliable and updated sources like the World Bank and IRENA for information. He also mentioned the option of leasing assets to reduce the high upfront costs, and the potential of a shared economy approach involving local stakeholders. Charles emphasized the need to communicate with customers from the start to the finish of a project and to be attentive to the local community's needs.

Charles discussed the impact of inflation and disruptions in the global supply chain, highlighting the significant problems they can cause. He mentioned that the cost of photovoltaic (PV) technology has decreased, but the level of energy access and finance access still need to be addressed. He also mentioned the importance of test beds to prove the technology's efficacy, although he noted that these are heavily subsidized and face challenges related to batteries, currency fluctuations affecting payback, and no guarantee of performance, as well as potential issues such as explosions and malfunctions that could increase costs.

When discussing the choice between lithium-ion and lead-acid batteries, Charles explained that while lithium-ion batteries are more expensive in terms of capital, they require less maintenance. On the other hand, lead-acid batteries have a cheaper startup cost but higher ongoing maintenance expenses.

Charles mentioned that a minimum of 500 to 5000 customers is required for such projects, and he referred to the KNBS national database as a source for determining the number of users.

The interview touched upon the issue of the monopoly of the national grid and the importance of behavior change, addressing income disparities, capacity building, and the potential bottleneck effect. Charles highlighted the negative long-term effects on the ecosystem caused by relying on diesel power.

Overall, the interview provided insights into the challenges and considerations related to implementing solar energy solutions, emphasizing the need for comprehensive planning and community involvement.