TECHNICAL ASSESSMENT OF LARGE-SCALE INTEGRATION OF SOLAR ELECTRIFICATION IN ENERGY SYSTEMS IN KENYA

BY
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A Thesis Submitted to the School of Engineering, Department of Manufacturing, Industrial Textiles Engineering in Partial Fulfillment of the Requirements for the award of Degree of Doctor of Philosophy in Industrial Engineering

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DECLARATION

Declaration by the Candidate

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DEDICATION

To the sacred memory of my beloved parents, Mr. and Mrs. Elijah Samoita—Your love was boundless, your strength quiet yet unwavering and your sacrifices—often silent—immeasurable.

You shaped the core of who I am and instilled in me the values that anchor my soul. Though you no longer walk beside me, your wisdom echoes through every step I take. This work is a tribute to your eternal legacy— a blossom nurtured by the seeds of your love and the depth of your devotion.

And to my precious children— May these pages stand as a beacon, a gentle reminder that no dream is too distant, no summit too high for hearts full of courage and minds lit with purpose. Let resilience be your guide, discipline your strength, and faith your constant flame.

Go forth with boldness. Embrace the virtue of hard work, uphold truth, and walk always in the light of integrity. The world awaits the excellence only you, can bring.

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ABSTRACT

Kenya has witnessed a significant increase in electricity demand, reaching 1.5 GW in 2022 compared to a production of 12.65 TWh. This growth is primarily driven by population expansion and industrialization. However, continued reliance on fossil fuels remains environmentally unsustainable. To address this, the Kenyan government has set a target of achieving 100% renewable energy integration by 2030, with a strong emphasis on solar and wind energy. With its abundant solar resources, Kenya has the potential to generate more solar power than its total electricity demand. This thesis investigates the feasibility and impact of large-scale integration of solar power systems into Kenya's energy mix. EnergyPLAN tool was employed to simulate hourly energy production and demand, enabling a comprehensive assessment of the technical, economic, and environmental implications. Cross-sectoral analysis was conducted to evaluate interdependencies and sectoral dynamics. A novel Whale Optimization Algorithm (WOA) based Maximum Power Point Tracking (MPPT) algorithm was developed in MATLAB and benchmarked against conventional methods, including Incremental Conductance, Fuzzy Logic, and Particle Swarm Optimization (PSO). Simulation results showed a 32% increase in solar power capacity—from 212.5 MW (6.8% of total generation) to 4,601 MW—at an annual cost of KSh 145.5 billion, compared to KSh 186.9 billion under the baseline scenario. With further solar power integration, optimal generation reached 10.01 TWh (39.56% of total), while renewable electricity output increased from 11.90 TWh to 19.76 TWh. CO_2 emissions dropped significantly from 0.134 Mt to 0.021 Mt, and total annual production costs decreased to KSh 134.3 billion. These findings demonstrate that optimized solar power integration offers substantial benefits in cost savings, emissions reduction, energy security, and system reliability. Sectoral Innovation System (SIS) analysis revealed that global cost declines primarily drive solar power adoption, with minimal local adaptation needed. The proposed WOA-based MPPT algorithm achieved a tracking efficiency of 99.95% with a steady-state error of 0.04%, outperforming PSO (99.7% efficiency, 0.2% error). Although PSO successfully tracked the global maximum power point, its dynamic response was inferior to that of the developed WOA-based MPPT system.

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SYMBOLS, ABBREVIATIONS AND NOTATIONS

AC0_NPU	Ant Colony Optimization algorithm with a New Pheromone Updating
ANN	Artificial Neural Network
BA	Bat Algorithm
BESS	Battery energy storage systems
BC	Bee Colony
CO_2	Carbon Dioxide
CHP	Combined Heat and Power
CAES	Compressed Air Energy Storage
CI	Computational Intelligence
CSP	Concentrated Solar power
CS	Cuckoo Search
DE	Differential Evolution
DMPPT	Distributed Maximum Power Point Tracking
EPRA	Energy and Petroleum Regulatory Authority
ESS	Energy Storage Systems
FIT	Feed-In-Tariff
FA	Firefly Algorithm
FLC	Fuzzy Logic Control
GWh	Giga Watt Hour
GMPP	Global Maximum Power Point
GMPPT	Global Maximum Power Point Tracking
GHG	Greenhouse Gas
GWO	Grey Wolf Optimization
HC	Hill-Climbing
HOMER	Hybrid Optimization of Multiple Energy Resources
HEP	Hydroelectric Power
IC	Incremental Conductance
IREK	Innovation and Renewable Electrification in Kenya
IPCC	Intergovernmental Panel on Climate Change

IEA	International Energy Agency
KPLC	Kenya Power and Lighting Company
KSh	Kenya Shillings
kW	Kilo Watt
LCPDP	Least Cost Power Development Plan
LCOE	Levelized Cost of Electricity
LEAP	Low Emissions Analysis Platform
MER	Market Economic Regulation
MPPT	Maximum Power Point Tracking
MW	Megawatt
MWp	Mega Watt Peak
MENA	Middle East and North Africa
MOE	Ministry of Energy
MAFSA	Modified Artificial Fish Swarm Algorithm
MPSO	Modified particle swarm optimization technique
NEMS	Next Energy Modeling System
NGO	Non-Governmental Organization
PSO	Particle Swarm Optimization
PSO–ANFIS	Particle Swarm Optimization-Adaptive Neuro Fuzzy Inference System
P&O	Perturb and Observe
P&O–ANFIS	Perturb and Observe- Adaptive Neuro Fuzzy Inference System
PtG	Power-to-Gas
PHES	Pumped Hydro Energy Storage
PV	Photo Voltaic
QCA	Qualitative Comparative Analysis
RES	Renewable Energy Source
RnD	Research and Development
SIS	Sectoral Innovation Systems
SWERA	Solar and Wind Energy Resource Assessment
SERC	Strathmore Energy Research Centre

TS	Tabu Search
TR	Technical Regulation
TWh	Terawatt-hour
TES	Thermal Energy Storage

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The urgent need to address and control climate change, ensure energy stability, and foster fair economic progress underscores the worldwide obligation to transition towards sustainable and renewable energy sources (RES) (Androniceanu & Sabie, 2022). Across the globe, countries are grappling with the twin dilemmas of fulfilling escalating energy needs while lessening the ecoloigical consequences of traditional energy sources (Yadav et al. 2020).

A significant global energy shift is underway to address climate change, driven by the Intergovernmental Panel on Climate Change (IPCC's) call for rapid adoption of REs (IPCC 2018) and the Paris Agreement's commitment to limit temperature rise (Agreement, 2015). Solar electrification is now central to national energy strategies (Nowotny et al., 2018a; Wilson et al., 2020), with solar power emerging as the best renewable option due to its cleanliness, abundance, and technological advancement (Sweeney et al., 2020).

Due to advancements in technology, reduced costs, and favorable policies, the worldwide solar energy sector has seen impressive expansion (Salvarli and Salvarli 2020). The accessibility and efficiency of solar energy have been improved due to the rapid evolution of solar technologies (Mohammad & Mahjabeen, 2023; Righini & Enrichi, 2020), i.e., thin-film solar cells, organic PVs, and tandem solar cell innovations that enhance the performance of solar energy systems (Wang et al., 2020; Xu et al., 2020).

Enhanced manufacturing methods, increased durability, and economies of scale have led to a significant drop in PV module costs (Benda and Černá 2020; Green 2016; Verlinden 2020). According to reports from the International Renewable Energy Agency (IRENA) and other researchers, there's been a consistent decrease in solar PV technology costs, making solar-generated electricity more competitive against conventional sources (IRENA 2020; Smith et al. 2021; Victoria et al. 2021). Moreover, the scalability of solar energy and advancements in energy storage systems (ESS) technology position PV energy as a crucial catalyst in the global shift toward a sustainable energy future (Saldarini et al. 2023; Zeng et al. 2020).

The decreasing cost of solar energy has driven its widespread adoption, achieving grid parity in many regions (Adeyemi-Kayode et al., 2023; Lu et al., 2021; Mu et al., 2021; Putranto et al., 2022; Zhang et al., 2020). Solar PV now costs around $2.40 to $3.60 per watt (IEA 2020) and is expected to decline further (IEA 2020; Jones-Albertus et al. 2018; Kabir et al. 2018; Moriarty & Honnery 2020; Timilsina et al. 2012). This reduction is due to improved manufacturing, economies of scale, competition, and government incentives (Dupont, Koppelaar, and Jeanmart 2020; Singh & Singh 2010; Timilsina et al. 2012).

Concerns about climate change have increased demand for clean energy (Jaiswal et al., 2022; Moustakas et al., 2020). Solar power, being emission-free, aligns with global efforts to reduce carbon footprints (Kim & Junghans 2023). This demand has driven the expansion of the solar sector, with businesses and governments prioritizing solar initiatives (Rauf et al. 2023). The solar sector also significantly contributes to job creation and economic development (Ram et al., 2020; Dai et al., 2016; IRENA, 2020), offering employment across the solar value chain from R&D to maintenance.

The main challenge of solar energy is its intermittent nature (Yin et al., 2020). However, the development of ESS technologies has mitigated this challenge (Mohamad et al., 2021; Olabi et al., 2021; Shaqsi et al., 2020) by the adoption of an optimal energy management system (Ullah et al., 2021). Therefore, enhances the reliability and dispatchability of solar power, hence, it is more consistent and dependable (Varzaneh et al., 2021). Kenya, like other developing nations, is faced with significant challenges in ensuring reliable access to electricity (Mugisha et al., 2021). Despite the recent progress, a considerable portion of the population, particularly in rural and remote areas, remains without reliable access to electricity (Boamah et al., 2021; Mugisha et al., 2021; Takase et al., 2021). The absence of energy accessibility constrains progress in economic growth, educational access, and impedes advancements in healthcare (Acheampong, Erdiaw-Kwasie, & Abunyewah 2021; Banerjee, Mishra, & Maruta 2021; World Bank 2021).

Historically, hydroelectric power (HEP) dominated Kenya's energy mix, comprising 52.1% of total electricity (Takase et al., 2021). However, HEP's susceptibility to climate shifts, affecting water availability, necessitates energy diversification (Dutta et al., 2023; In et al., 2022; World Bank, 2018). As a solution to these challenges, Kenya introduced Vision 2030 (Ndung'u et al., 2011; Parthasarathy et al., 2011), a long-term development roadmap aimed at transforming the country into a middle-income, globally competitive nation (Mwenzwa & Misati, 2014). Kenya's Vision 2030 focuses on economic, social, and political pillars, aiming for sustainable development (Mwenzwa & Misati, 2014; Ndung'u et al., 2011). The vision prioritizes a robust, diversified, and eco-friendly energy sector to spur economic growth and enhance living standards (Berggren & Österberg, 2017). It emphasizes universal electricity access, aligning with global renewable energy transition goals (Mwenzwa & Misati, 2014; Ndung'u et al., 2011; Owino et al., 2016).

The Kenya Renewable Energy Policy (The Energy Act, 2019), aims to boost domestic renewable energy growth, aligning with Vision 2030 goals (The Energy Act, 2019). Challenges like limited funds and regulatory hurdles slow implementation (George et al., 2019; Yaqoot et al., 2016). Overcoming these challenges requires a concerted effort from both the public and private sectors, along with strategic partnerships and international collaboration (IEA, 2020). The integration of solar electrification is a crucial economic strategy in Vision 2030 (Adenle, 2020; Boamah, 2020b). it aligns with the goals of diversifying the energy mix, enhancing energy access, and promoting environmental sustainability (Ndung'u et al., 2011) as shown in Figure 1.1. Large-scale solar projects can significantly advance Vision 2030's targets by expanding access and decreasing reliance on climate-sensitive energy (Schwarz & Glemarec, 2009).

The Vision 2030 acknowledges the correlation between energy deprivation and broader socio-economic progress (Singh & Inglesi-Lotz 2021), advocating for the adoption of renewable energy outlets, notably solar power, to tackle energy scarcity and foster a conducive setting for economic endeavors. These consequently result in poverty reduction and the realization of sustainable development goals (Bertheau, 2020; Kaygusuz, 2011; Nasir et al., 2022; Wang et al., 2020).

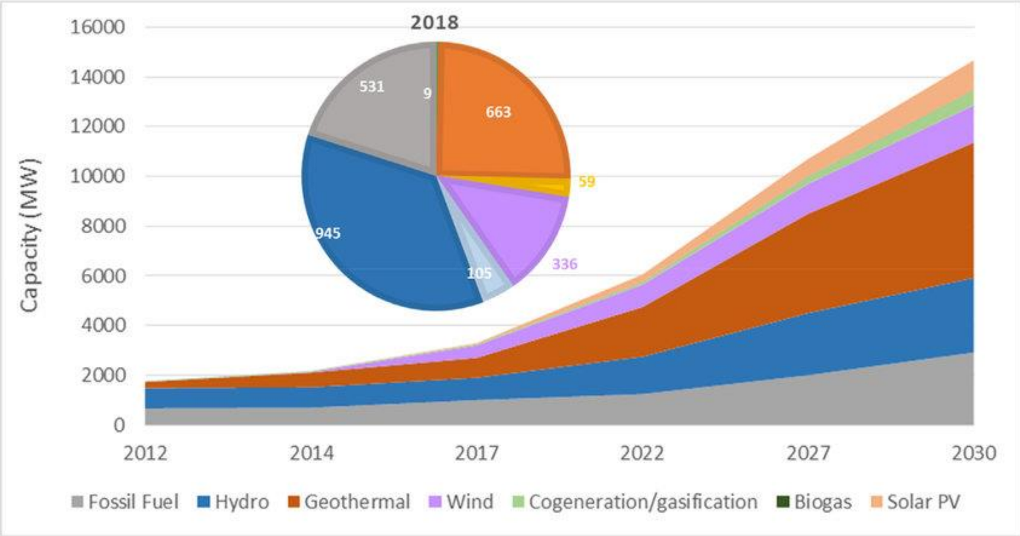


Figure 1.1: Installed electricity capacity (MW) in Kenya in 2018 and national targets for the energy mix in power generation until 2030 (Kenya's Vision 2030) (Moner-Girona et al., 2019)

Kenya's rapid economic growth drives increased energy demand (Mugisha et al., 2021a). To meet this, Kenya adopts a diverse, sustainable energy mix (Akrofi, 2021), with renewables contributing 81% of total generation in 2021. Efforts to reduce fossil fuel dependency promote environmental well-being (Elkadeem et al., 2019). Kenya heavily relies on HEP as a key component of its energy mix. The country has several major HEP plants, i.e., the Turkwel Dam and the Seven Forks dams, contributing 51.2% to the national grid (Takase et al., 2021).

HEP has the advantage of being a renewable and reliable source, but it is susceptible to climate variability, such as droughts (Berga, 2016; Wasti et al., 2022). Kenya is one of the leading geothermal producers in Africa (Elbarbary et al., 2022; Mangi, 2018). The Olkaria Geothermal Plant, located in the Rift Valley, is a flagship project and a major contributor to Kenya's energy mix (Elbarbary et al., 2022; Shi et al., 2021). Geothermal energy is considered a reliable and continuous source of power with minimal environmental impact (Shortall et al., 2015; Soltani et al., 2021). Recently, Kenya has heavily invested in wind energy initiatives, notably the Lake Turkana Wind Power project (Gregersen, 2022b), with a capacity of 310 MW is one of the largest in Africa and has added substantial capacity to the national grid (Alemzero et al., 2021; Gregersen, 2022b). Wind power contributes to diversifying the energy mix and reducing dependency on traditional sources (Gregersen, 2022b; Richard et al., 2020).

Thermal energy, primarily sourced from fossil fuels like coal, oil, and natural gas, continues to contribute to Kenya's energy combination (Al-Shahri et al., 2021; Elkadeem et al., 2019). However, the government is prioritizing reducing the share of thermal power to mitigate environmental concerns and address climate change (Mumbo et al., 2020). Lastly, Kenya has focused on expanding access to electricity in rural areas (Tesfamichael et al., 2020). The Last Mile Connectivity Project aims for universal electricity access, boosting living standards and economic growth (Kassem, Zane, & Uzor 2022). Kenya faces challenges like climate impact on HEP, financial constraints, and the need for renewable energy investment. These efforts aim to ensure a resilient energy future.

Kenya's equatorial position and high year-round solar irradiance make it ideal for solar energy (Rose et al., 2016). With vast, underutilized solar potential (Lei et al., 2019), comprehensive solar resource assessments using GIS and meteorological data are crucial (Sengupta et al., 2021; Choi et al., 2019). The Solar and Wind Energy Resource Assessment (SWERA) project highlights Kenya's solar resource distribution (World Bank, 2021), with many regions exceeding 4.5 $kWh/m^2/day$ (Elmi, 2018; Mohammed, 2017). This supports efficient solar power systems and sustainable electricity generation (Oloo et al., 2015), aiding off-grid and rural electrification (Mugisha et al., 2021). Regional solar irradiance variations are key for optimizing solar projects (George et al., 2019; Kiplagat et al., 2011).

Remote areas, often underserved by conventional grid infrastructure, can benefit significantly from decentralized solar systems (Alstone et al., 2015; Boamah, 2020a). These off-grid solutions not only address energy poverty but also contribute to achieving Kenya's electrification targets, as outlined in the Least Cost Power Development Plan (Bhattacharyya & Palit, 2021; Jeuland et al., 2023; Mugisha et al., 2021; Ulsrud & Saini, 2022). Furthermore, Kenya's solar potential extends to solar thermal technologies (Samoita et al., 2020; Takase et al., 2021). Solar water heating, in particular, has gained traction in residential and commercial applications (Doorga et al., 2022; Nanda et al., 2023). The high solar irradiance levels make solar thermal systems an effective and environmentally friendly alternative for meeting domestic hot water needs, reducing reliance on conventional electric or gas water heaters (Doorga et al., 2022; Mahato et al., 2020; Nanda et al., 2023; Sakthivadivel et al., 2021).

Harnessing solar energy in Kenya requires solutions for intermittency (Asiaban et al., 2021). Battery technology advancements and smart grid integration can enhance solar power reliability (Aznavi et al., 2020). Careful assessment of land use and environmental impacts is necessary (Cossu et al., 2021; Tawalbeh et al., 2021). Strategic land-use planning, adherence to environmental regulations, and community engagement are crucial for ensuring sustainable solar projects (Cossu et al., 2021; Formolli et al., 2022; Tawalbeh et al., 2021). Additionally, the disposal and recycling of solar panels at the end of their life cycle should be managed responsibly to minimize environmental impact (Ansanelli et al., 2021; Chowdhury et al., 2020).

Apart from the above-mentioned supporting factors, international cooperation and funding mechanisms play a vital role in unlocking Kenya's solar potential. Collaboration with international organizations, such as the World Bank and IRENA, facilitates the mobilization of financial resources and expertise for large-scale solar projects. Additionally, multilateral initiatives support the development of solar infrastructure, especially in regions where access to conventional financing may be challenging (IRENA, 2020)

1.2 Problem Statement

Kenya has made commendable progress in expanding electricity access, with national coverage rising from approximately 37% in 2013 to nearly 79% by 2023. However, significant disparities persist, particularly between urban and rural areas. Around 36% of households remain unconnected to the national grid, with the vast majority located in rural regions.

Even among connected households, less than half experience reliable electricity supply. This unreliability is largely due to high system losses, estimated at 23% in 2023, which contribute to frequent power outages and inefficiencies in electricity distribution.

Kenya's energy generation mix is predominantly renewable, with 85–90% of electricity generated from geothermal, hydro, wind, and solar sources. However, per capita electricity consumption remains low, at approximately 244 kWh annually. This figure is well below the global average and highlights the shallow depth of access, especially in rural areas where many still rely on traditional energy sources such as biomass and kerosene.

Several economic and structural barriers continue to hinder progress toward universal access. The high cost of extending the national grid to remote areas, coupled with expensive connection fees and electricity tariffs (averaging KSh 25.78–28.36 per kWh), makes electricity unaffordable for many low-income households.

These challenges pose a significant threat to Kenya's ambition of achieving universal, affordable, and sustainable electricity access by 2030. Moreover, they constrain the country's broader socio-economic development—impacting healthcare, education, agriculture, and industrial growth.

1.3 Justification

Given Kenya's significant energy challenges, research into the feasibility of accelerated integration of solar electrification in the country's energy system is crucial. The current reliance on non- REs like fossil fuels exposes Kenya to economic vulnerabilities due to price fluctuations and geopolitical tensions, while also contributing to environmental degradation and climate change. Solar energy, being abundant and renewable, presents an opportunity to diversify the energy mix, enhance energy security, and reduce greenhouse gas emissions. Accelerating solar electrification can help mitigate the adverse effects of reliance on fossil fuels, stabilize energy costs, and align Kenya with global environmental commitments such as the Paris Agreement (Djellouli et al., 2022; Takase et al., 2021).

The development and organization of the solar market in Kenya based on sectoral innovation systems is essential to address the logistical and financial challenges associated with extending grid infrastructure, especially in rural and remote areas. Currently, many rural communities face high costs and logistical barriers to accessing electricity, perpetuating socio-economic disparities and hindering development (Hansen & Xydis, 2020; Takase et al., 2021). A well-organized solar market can provide off-grid and mini-grid solutions, making electrification more feasible and affordable. By leveraging sectoral innovation systems, Kenya can foster local entrepreneurship, attract investments, and create a supportive policy environment that promotes the adoption of solar technologies. This approach can drive innovation, lower costs, and facilitate widespread access to electricity, thereby improving the quality of life and economic opportunities for all Kenyans.

Optimal solar capacity based on technical and economic analysis is critical for scaling up solar power generation in Kenya. Determining the right balance of solar capacity involves analyzing factors such as solar irradiance, grid integration capabilities, storage solutions, and economic viability. This analysis ensures that the deployment of solar power is both technically feasible and economically sustainable, maximizing the benefits of solar energy while minimizing costs and risks. By optimizing solar capacity, Kenya can efficiently allocate resources, enhance grid stability, and ensure a reliable supply of electricity. This strategic planning is essential for achieving long-term energy security, fostering economic growth, and reducing dependence on non- REs (Adedoyin et al., 2021; Opeyemi, 2021).

Developing an efficient and robust Maximum Power Point Tracking (MPPT) algorithm to improve solar power efficiency is fundamental to maximizing the potential of solar power generation in Kenya. MPPT algorithms ensure that solar panels operate at their maximum efficiency by continuously adjusting to changing environmental conditions such as shading, temperature, and irradiance. An improved MPPT algorithm can significantly enhance the performance and reliability of solar solar power systems, leading to higher energy yields and better economic returns on investment. This technological advancement is particularly important for Kenya, where maximizing the output of solar installations can directly contribute to addressing the energy deficit, improving the reliability of power supply, and supporting socio-economic development (Sai Shibu et al., 2020; A. Farzinfar et al., 2019). By focusing on enhancing solar PV efficiency, Kenya can make the most of its solar resources, ensuring a sustainable and resilient energy future.

1.4 Objectives

The main objective of this research is to investigate the viability and potential of large-scale integration of solar electrification in Kenya's energy mix.

1.4.1 Specific Objectives

i. To determine the feasibility of Accelerated Integration of Solar Electrification in Kenya’s Energy System
ii. To evaluate the development and organization of the solar market in Kenya based on sectoral innovation systems (SIS)
iii. To determine the optimal solar capacity based on technical and economic analysis in scaling up solar power generation
iv. To develop an efficient and robust MPPT algorithm to improve solar power efficiency

1.5 Significance of the Study

The significance of this thesis lies in its potential to drive transformative change in Kenya's energy landscape and beyond. By focusing on the feasibility and performance of large-scale integration of solar electrification, this research addresses several key issues of paramount importance.

Firstly, Kenya encounters difficulties in delivering consistent and economical electricity to its people, especially in distant and rural regions. Solar electrification presents a decentralized approach that has the potential to broaden electricity availability to marginalized communities, enhancing their standard of living and opening up economic prospects.

Secondly, with the global spotlight on the consequences of climate change, it is crucial to shift towards REs. Solar energy emerges as a viable, eco-friendly substitute for fossil fuels, diminishing carbon emissions and alleviating the negative repercussions of climate change. This research, by assessing the environmental advantages of solar power adoption, adds to worldwide endeavors aimed at tackling climate change.

Thirdly, incorporating solar power could drive economic expansion and generate job openings. By assessing the economic feasibility of solar power usage, this thesis can guide investment choices and foster the growth of a robust solar sector in Kenya. Moreover, by lessening dependence on imported fossil fuels, solar energy can bolster energy security and fortify resilience against external disruptions.

Fourthly, this research corresponds with multiple Sustainable Development Goals (SDGs), encompassing Affordable and Clean Energy (Goal 7), Industry, Innovation, and Infrastructure (Goal 9), Sustainable Cities and Communities (Goal 11), and Climate Action (Goal 13). Therefore, encouraging the uptake of solar power aids in advancing these overarching global development targets, fostering inclusive and sustainable progress. Finally, the study's outcomes will offer data-driven suggestions for advancements and inform policymakers, empowering them to craft efficient policies and regulatory structures to facilitate the incorporation of solar energy within Kenya's energy infrastructure.

By fostering an enabling environment for renewable energy deployment, technologists and policymakers can accelerate progress toward national energy targets and contribute to global sustainability goals. Furthermore, this thesis promotes creativity within renewable energy technology, expanding the limits of MPPT algorithms and clearing the path for future progress in optimizing solar power generation and energy storage.

1.6 Scope of Study

This research investigates the integration of solar power in Kenya’s energy systems, focusing on grid-connected systems. The study employs a multidisciplinary approach, combining techno-economic modeling, Sectoral Innovation Systems (SIS) analysis, and algorithmic optimization to assess the feasibility and impact of solar power deployment. The study is geographically confined to Kenya, with a focus on regions targeted by national initiatives such as Vision 2030 roadmap (Parthasarathy, V. A. and Anandaraj, 2011).

The analysis utilizes energy data from 2020 to 2024 as a baseline, with projections extending to 2030. This timeframe allows for the examination of current trends and the exploration of future energy transition pathways under various scenarios.

The study employs the EnergyPLAN system planning tool to simulate scenarios aiming for up to 100% renewable electricity penetration. This tool incorporates grid infrastructure expansion, and dispatch optimization to model Kenya's unique energy landscape.

The Sectoral Innovation Systems component examines the policy frameworks, institutional capacities, market mechanisms, and research and development dynamics that influence solar power deployment in Kenya. Qualitative methods, including stakeholder interviews and document analysis, are employed to gather insights.

Concurrently, the study develops a Whale Optimization Algorithm (WOA)-based Maximum Power Point Tracking (MPPT) controller, customized to Kenyan solar irradiance and temperature profiles. Performance metrics, such as convergence speed, tracking efficiency, and robustness under partial shading, are evaluated through high-fidelity simulations and pilot-scale experiments.

1.7 Limitations of the Study

This thesis is limited to the integration of grid-connected solar power systems within Kenya's existing energy infrastructure. As such, it does not address off-grid solar energy solutions, including mini-grids and solar home systems, which play a critical role in expanding energy access to remote and underserved regions. Additionally, the scope of this research excludes battery systems, which are essential for mitigating the mismatch between solar energy generation and demand patterns, and for improving grid reliability and system efficiency.

By focusing exclusively on grid-connected solar power systems, the study provides an in-depth analysis of their integration challenges and opportunities within the national grid. However, this narrow scope may limit the ability to assess the broader spectrum of solar energy solutions available in the country. The omission of off-grid systems and energy storage components may overlook key technical, economic, and policy considerations that are vital for a comprehensive understanding of Kenya’s solar energy landscape.

Future research that incorporates these aspects would be instrumental in offering a more holistic perspective on the deployment of solar energy technologies and their role in achieving sustainable energy access and security in Kenya

1.8 Thesis Structure

This thesis is outlined as shown in Figure 1.2.

Chapter 1: Introduction

This chapter introduces Kenya’s electricity context, states the research problem and objectives, and explains the study’s significance and scope. It ends with a roadmap guiding the reader through the thesis structure.

Chapter 2: Literature Review

It synthesizes existing research on electrification and solar power in Kenya, organized by themes. This chapter critiques prior studies, highlights gaps, and links them to the research objectives.

Chapter 3: Methodology

This chapter details the research design, data collection methods, and analytical approaches related to solar electrification and innovation systems.

Chapter 4: Results & Discussion

Empirical findings are presented on PV techno-economic performance, innovation systems evaluation, MPPT development, and renewable pathways. Each result is interpreted in context, connecting analysis to research objectives.

Chapter 5: Conclusions & Recommendations

This final chapter summarizes main findings, draws conclusions, discusses implications for theory and policy, acknowledges limitations, and outlines directions for future research. It emphasizes how this research fills identified knowledge gaps.

The thesis concludes with References and Appendices.

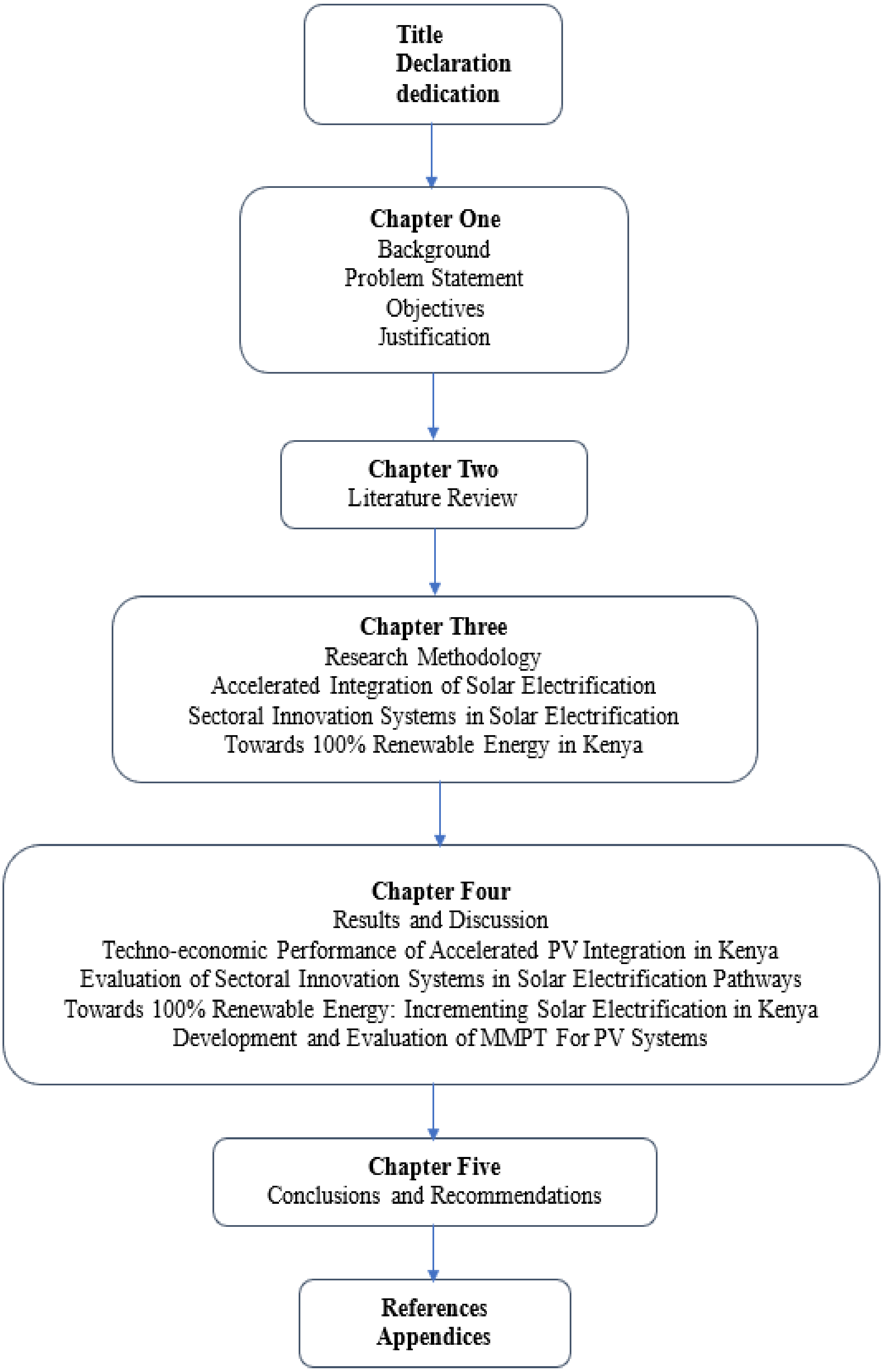


Figure 1.2: Structure of Thesis

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Kenya has made significant progress in expanding its electricity generation capacity and harnessing RES to meet growing power demands. The country has actively diversified its energy mix, drawing from a range of sources including hydroelectric, geothermal, wind, solar, and thermal power. These efforts align with Kenya’s broader goal of achieving energy sustainability and resilience (Elmer et al., 2018).

As of 31st December 2022, Kenya's total installed electricity generation capacity stood at 3,321.3 MW, sourced from a blend of technologies as shown in Table 2.1 (EPRA, 2022).

Notably, renewable sources such as geothermal, hydropower, wind, and solar account for a significant share of the energy mix, reflecting the country's commitment to clean energy.

Table 2.1: Power Capacity as of 31st December 2022 (EPRA, 2022a).

Technology	Total Installed Capacity (MW)	% Share of the country’s energy mix
Hydropower	838.9	25.26%
Geothermal	950.0	28.60%
Thermal	689.9	20.77%
Wind	436.1	13.13%
Solar	212.5	6.40%
Co-generation	2.0	0.06%
Imports	200	6.02%
Total	**3,321.3**	**100%**

In comparison to the country's electricity generation capacity, the national electricity demand in 2022 reached 1.5 GW (EPRA, 2022).

2.2 Overview of Electricity Capacity in Kenya

2.2.1 Wind Power

Wind power is a growing source of electricity in Kenya. Although it currently constitutes a relatively small portion of the national energy mix, accounting for only 13.13%, there is significant potential for expansion. Kenya is actively pursuing additional wind power projects as part of its broader strategy to meet its growing energy demands and transition towards a more sustainable and renewable energy future. This commitment is in line with global trends that emphasize the reduction of carbon emissions and reliance on fossil fuels.

The northern and north-eastern regions of Kenya, in particular, have substantial wind energy potential due to their consistently high wind speeds throughout the year. Figure 2.1 illustrates the wind speed distribution across the country, highlighting areas with strong wind energy prospects. The nation's overall wind energy potential is estimated to exceed 3,000 MW, with the possibility of expanding installed capacity to more than 5,000 MW by 2030 (IRENA and AfDB, 2022). This suggests that with the right policies, investments, and infrastructure developments, Kenya could harness a significant amount of wind energy to supplement its energy needs.

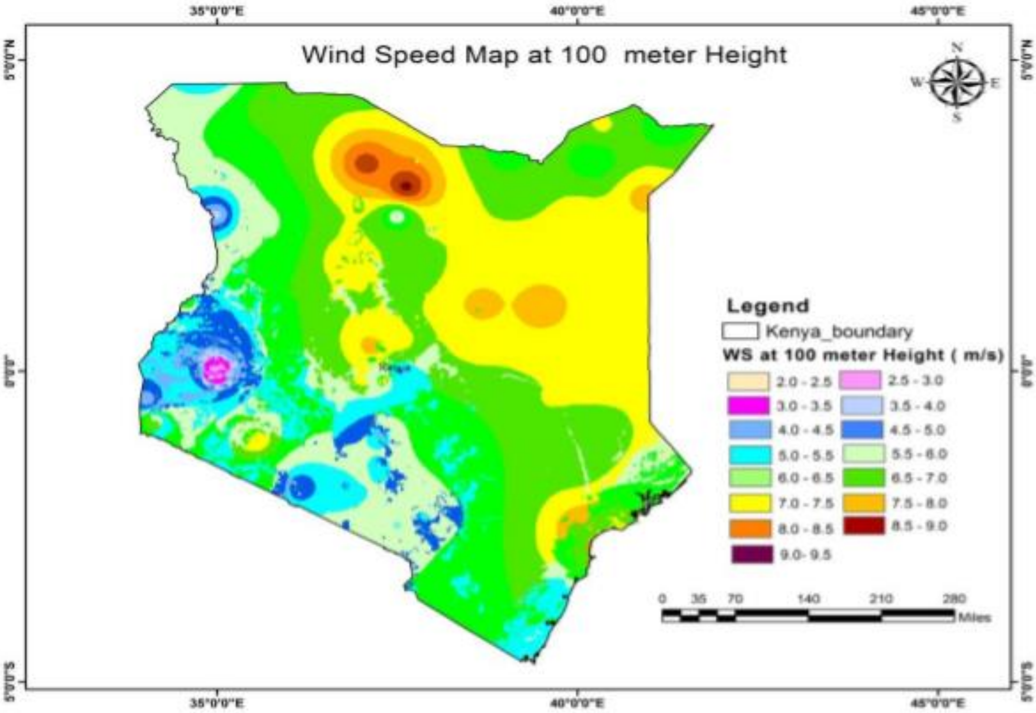


Figure 2.1: Wind Speed Map (Ministry of Energy & petroleum, 2025)

Kenya's wind energy potential is supported by favorable wind conditions, with approximately 73% of the country experiencing wind speeds of at least 6 meters per second at a height of 100 meters above the ground. Within this, an expansive area covering 28,228 square kilometers enjoys wind speeds ranging from 7.5 to 8.5 meters per second, while an additional 2,825 square kilometers experience even stronger winds, ranging from 8.5 to 9.5 meters per second (EPRA, 2022). These figures underscore the suitability of Kenya’s terrain for wind energy generation, particularly in the arid and semi-arid regions where land use conflicts are minimal compared to more densely populated areas.

Expanding wind power in Kenya presents numerous economic, environmental, and social benefits. From an economic perspective, wind energy reduces dependence on expensive fossil fuel imports, thereby lowering the overall cost of electricity generation. Since Kenya relies on hydroelectric power, which is susceptible to variability due to changing weather patterns, wind power provides a crucial alternative that enhances energy security and stability. Moreover, increased investment in wind energy creates job opportunities in various sectors, including manufacturing, installation, maintenance, and research and development.

Environmentally, wind power is a clean and renewable source of energy that significantly reduces greenhouse gas emissions. Kenya has committed to reducing its carbon footprint as part of its obligations under the Paris Agreement on climate change. Wind energy plays a critical role in achieving this goal by replacing fossil fuel-based power generation with a sustainable alternative. Furthermore, wind farms have a relatively low environmental impact compared to other energy generation methods, as they do not require large amounts of water for operation and do not produce hazardous waste.

Socially, wind power projects contribute to community development through corporate social responsibility initiatives and revenue-sharing agreements with local communities. The LTWP project, for instance, has invested in infrastructure, education, and healthcare facilities in the surrounding areas. Such projects can significantly improve the livelihoods of residents in remote and underserved regions, fostering socio-economic development alongside energy generation.

Despite the promising potential of wind energy in Kenya, several challenges hinder its widespread adoption and implementation. One of the primary obstacles is the high initial cost of wind power infrastructure. The cost of wind turbines ranges from $1,200 to $2,000 per kW of installed capacity (Vasquez et al., 2018). This requires substantial capital investment, which may be challenging for both the government and private investors, especially in a developing economy. Additionally, securing financing for wind projects can be complex, particularly when dealing with international lenders and navigating regulatory frameworks.

Another significant challenge is the need for grid upgrades and improved interconnection facilities. Many of the regions with high wind energy potential, such as northern Kenya, are located far from the national grid. Developing the necessary transmission infrastructure to integrate wind power into the existing grid is costly and requires long-term planning. In some cases, the intermittent nature of wind energy poses challenges for grid stability, necessitating investments in energy storage solutions or hybrid systems that combine wind with other renewable sources such as solar or hydropower.

Land acquisition and environmental concerns also present hurdles to wind power expansion. While wind farms typically require less land compared to other forms of renewable energy, they must be strategically located to minimize disruptions to local communities and wildlife. Some stakeholders have raised concerns about the impact of wind farms on bird populations and migratory patterns. Proper environmental assessments and mitigation measures must be undertaken to address these issues and ensure sustainable development.

Policy and regulatory frameworks play a crucial role in determining the success of wind energy projects in Kenya. While the government has made significant strides in promoting renewable energy through policies such as the Energy Act of 2019 and feed-in tariffs for wind power, there is still room for improvement. Streamlining the licensing process, providing incentives for investors, and enhancing public-private partnerships can accelerate the growth of the wind energy sector. Additionally, addressing bureaucratic challenges and ensuring transparency in project approvals will create a more conducive environment for investment.

Looking ahead, the future of wind power in Kenya appears promising. The government has outlined ambitious plans to increase renewable energy capacity, with wind playing a significant role. Several new wind projects are in the pipeline, including the Kipeto Wind Power Project (100 MW) in Kajiado County and the Meru Wind Farm (80 MW). These projects will further enhance Kenya’s renewable energy portfolio and contribute to achieving the country’s Vision 2030 goals.

Advancements in wind energy technology are also expected to drive growth in the sector. Improvements in turbine efficiency, energy storage solutions, and smart grid integration will enhance the reliability and cost-effectiveness of wind power. Additionally, ongoing research and development efforts aim to explore offshore wind energy potential along Kenya’s coastline, which could further diversify the country’s energy sources.

In conclusion, wind power presents a viable and sustainable energy solution for Kenya. While the sector faces challenges such as high initial costs, grid infrastructure limitations, and regulatory hurdles, the potential benefits outweigh these obstacles. By investing in wind energy, Kenya can reduce its reliance on fossil fuels, enhance energy security, create employment opportunities, and contribute to global climate change mitigation efforts. With continued government support, private sector involvement, and technological advancements, wind power will play an increasingly vital role in Kenya’s energy future.

2.2.2 Solar power

Kenya has significant potential for harnessing solar energy, receiving solar radiation of approximately 5 kWh/m²/day on average throughout the year (Samoita et al., 2024). This high solar energy potential provides an opportunity for increased renewable energy utilization across the country. The daily solar energy potential for each month in Kenya is depicted in Figure 2.2 and Figure 2.3, which illustrate the distribution and variations in solar radiation received across different regions throughout the year. The availability of consistent solar radiation positions Kenya as an ideal location for large-scale solar power generation and off-grid solar energy solutions.

According to several reports, about 188,284 square kilometers, representing approximately 32.4% of Kenya's total land area, were projected to receive solar energy in the range of 5.0 to 5.5 kWh/m²/day. This suggests that nearly one-third of the country has substantial potential for harnessing solar power efficiently. In addition, an estimated 154,185 square kilometers, equating to 26.5% of Kenya's total land area, was identified to receive solar energy ranging between 5.5 and 6.0 kWh/m²/day. This category represents another considerable portion of land with viable solar energy potential, reinforcing the country's ability to tap into solar energy as a major renewable power source.

Furthermore, an area covering approximately 58,800 square kilometers, corresponding to 10.1% of the total land area in Kenya, experiences solar radiation ranging from 6.0 to 6.5 kWh/m²/day. This makes these regions among the most promising in terms of solar energy viability, as they receive significantly high amounts of solar radiation. Such areas are especially suitable for large-scale solar farm projects or industrial solar applications, which require a reliable and abundant solar resource.

At the top of the solar energy potential classification, a smaller but crucial portion of land about 4,230 square kilometers, which accounts for 0.7% of Kenya's total land area was identified as receiving solar radiation exceeding 6.5 kWh/m²/day. These high-radiation zones are particularly advantageous for specialized solar energy projects that demand maximum solar exposure to optimize energy generation efficiency. Investing in solar projects in these areas could yield high returns due to the exceptional solar energy availability.

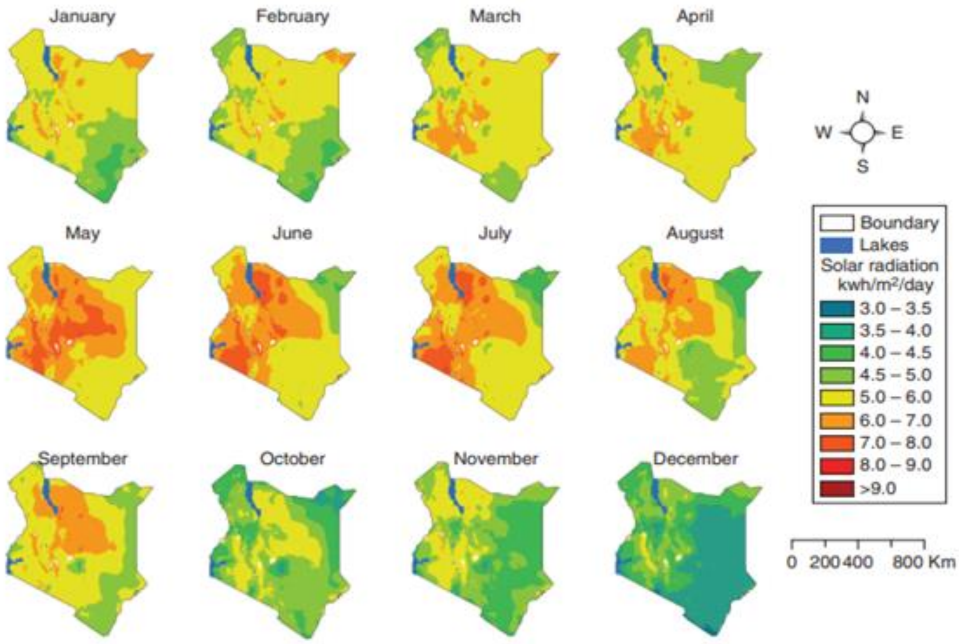


Figure 2.2: Spatial distribution of Daily Solar Potential in Kenya (Rotich et al., 2024a)

Conversely, in the lowest solar energy potential category, approximately 176,170 square kilometers, or 30.3% of Kenya’s land area, were forecasted to receive less than 5 kWh/m²/day of solar radiation (Rotich et al., 2024a). These regions have lower solar energy potential and may require additional technological innovations, such as high-efficiency solar panels or hybrid renewable energy systems, to make solar power generation feasible and productive. Despite their lower radiation levels, these areas still contribute to the overall national solar energy potential, as advancements in photovoltaic technology continue to improve efficiency and performance even in regions with moderate solar exposure.

According to (Rotich et al., 2024a), approximately 70% of Kenya's total land area possesses an annual solar energy potential that exceeds 5 $kWh/m^2/day$. More precisely, around 32.4% of the country's land receives an average annual solar potential within the range of 5.0 to 5.5 $kWh/m^2/day$. Meanwhile, roughly 26.5% of Kenya's total land area falls within the 5.5 to 6.0 $kWh/m^2/day$ category for average annual solar energy potential. These figures highlight Kenya's robust solar energy capabilities, which, if fully exploited, could significantly contribute to the country's energy security and economic growth.

Additionally, more than 10.8% of Kenya's land area has the capacity to receive over 6 $kWh/m^2/day$ of solar radiation. These high-potential zones, where solar radiation is anticipated to surpass 6 $kWh/m^2/day$, are mainly concentrated in specific geographic regions. Among the most prominent high-radiation zones are the elevated ridges of the Rift Valley, where the combination of high altitude and clear atmospheric conditions contributes to enhanced solar energy reception. Furthermore, areas east of Lake Turkana, particularly around Marsabit, have been identified as solar energy hotspots due to their geographical and climatic conditions. These locations present excellent opportunities for deploying large-scale solar energy projects, given their superior solar energy potential.

The distribution of these high-potential solar regions across the country suggests that targeted investments in solar energy infrastructure could significantly enhance electricity generation, transmission, and accessibility. Such investments would not only ensure a steady supply of renewable power but also promote sustainable energy solutions for Kenya's growing population. Additionally, the expansion of solar power infrastructure would contribute to reducing reliance on fossil fuels, lowering carbon emissions, and addressing energy poverty in various parts of the country.

Investing in solar energy in Kenya is particularly beneficial for rural and off-grid communities, which currently experience limited access to electricity. Many remote areas in Kenya remain unconnected to the national electricity grid, relying on expensive and unsustainable energy alternatives such as kerosene lamps and diesel generators. By harnessing the abundant solar resources available in these regions, solar power can offer an affordable, clean, and reliable energy solution to improve living standards, support economic activities, and foster sustainable development.

The growing interest in solar energy investments in Kenya has led to various government initiatives and policy frameworks aimed at promoting renewable energy development. The Kenyan government, through institutions such as the Ministry of Energy and the Energy and Petroleum Regulatory Authority (EPRA), has implemented policies to encourage the adoption of solar energy. These policies include incentives for solar energy investors, tax exemptions on solar equipment, and the establishment of regulatory guidelines for solar power projects. Such measures are instrumental in attracting both local and international investors to Kenya’s renewable energy sector.

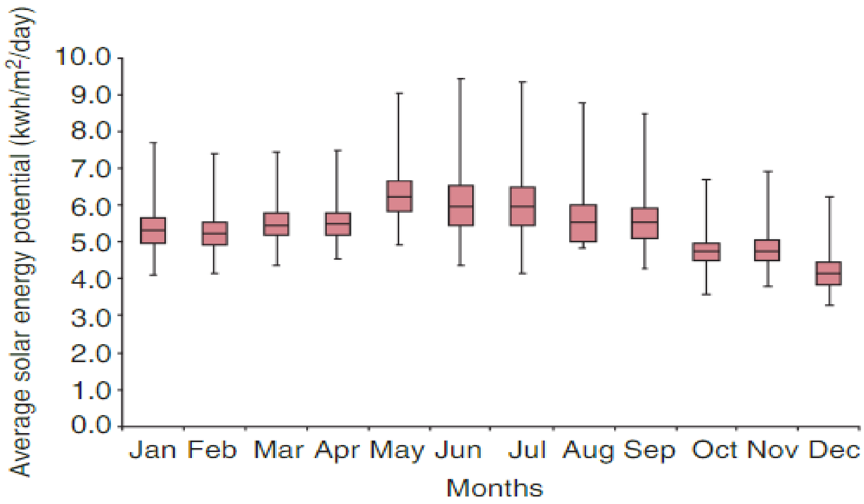


Figure 2.3: Solar Potential in Kenya averaged per month across the year (Rotich et al., 2024a)

In addition to government efforts, several private sector players and international organizations have been actively involved in promoting solar energy adoption in Kenya. Various solar energy projects, including grid-connected solar farms and off-grid solar home systems, have been successfully deployed in different parts of the country. These projects have played a crucial role in demonstrating the feasibility and benefits of solar power in Kenya, thereby encouraging further investments and expansion in the sector.

Despite the vast potential and growing investments in solar energy, several challenges still hinder the full realization of Kenya's solar energy capacity. Some of the primary challenges include the high initial costs of solar energy systems, limited technical expertise, and inadequate infrastructure for large-scale solar integration into the national grid. Addressing these challenges requires a multi-faceted approach involving policy support, financial incentives, capacity building, and infrastructure development.

Moreover, research and innovation in solar energy technologies are essential to enhancing the efficiency and affordability of solar power solutions. Continued advancements in photovoltaic technology, energy storage systems, and smart grid integration will be critical in maximizing Kenya’s solar energy potential. Collaborations between research institutions, universities, and industry stakeholders can facilitate knowledge transfer, technological advancements, and the development of tailored solar energy solutions for Kenya’s unique energy needs.

Lastly, Kenya's substantial solar energy potential presents a unique opportunity for sustainable and clean energy development. With approximately 70% of the country’s land area receiving an annual solar energy potential exceeding 5 kWh/m^2/day, solar power has the potential to play a significant role in meeting Kenya’s energy demands. The distribution of high-radiation areas, particularly in the Rift Valley and around Marsabit, highlights key zones for large-scale solar investments. By leveraging this potential, Kenya can enhance electricity access, promote economic growth, reduce carbon emissions, and achieve energy sustainability. Strategic investments, supportive policies, and technological innovations will be vital in unlocking the full benefits of solar energy for the country’s future.

2.2.3 Hydro Electric Power (HEP)

Hydropower (HEP) remains one of the largest sources of electricity in Kenya, playing a crucial role in the country’s energy mix. The nation's reliance on hydropower is evident from the total installed hydropower capacity, which stood at 838.9 MW as of 2022 (KNBS 2023). This capacity has contributed significantly to Kenya's electricity supply, with HEP plants accounting for approximately 30% of the total annual electricity generation (KNBS 2023). The hydropower plants currently in operation vary in size and design, with some being large-scale plants equipped with reservoirs, while others consist of smaller run-of-river installations. Among the operational plants, eight major power stations with reservoirs have individual capacities exceeding 10 MW, making them instrumental in maintaining stability in the national grid.

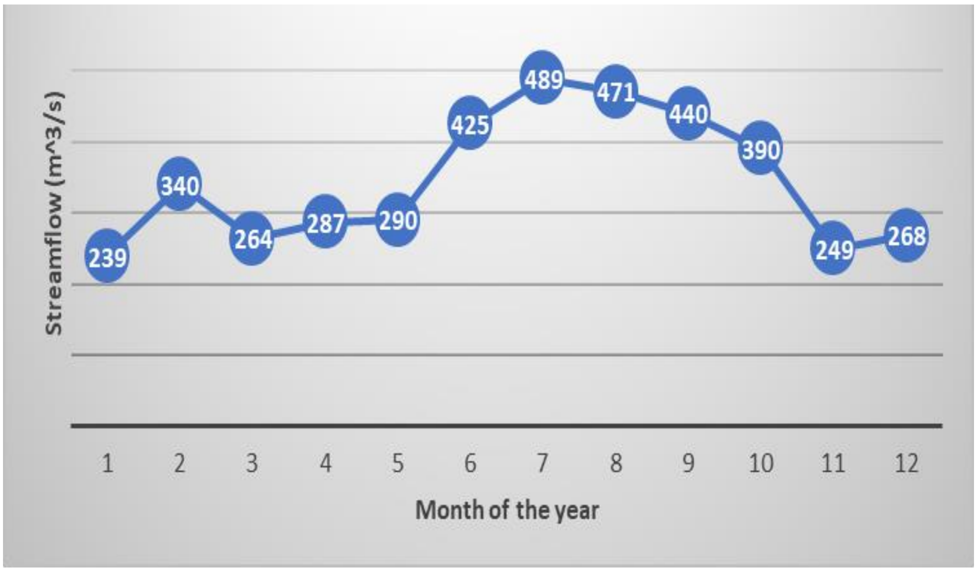


Figure 2.4: Water inflow to hydro dams in Kenya (Musyoka, Wambua, and Mutua 2018)

Despite the prominence of large-scale hydropower plants, it is important to acknowledge the significant role played by small-hydro resources. A considerable portion of the total hydropower potential in Kenya stems from smaller rivers, which are crucial for small-hydro generation. These smaller rivers have been instrumental in expanding the country's RES, particularly in remote regions where grid connectivity remains limited. According to the Kenya National Bureau of Statistics (KNBS 2023), at least half of the nation’s total hydropower potential is attributed to small hydro resources. Such decentralized hydropower solutions have proven beneficial in improving energy access, fostering rural electrification, and enhancing energy security.

Kenya has substantial hydropower potential, estimated at around 6,000 MW. Of this total, small-hydro potential alone is projected to be slightly above 3,000 MW, making it a significant contributor to the overall renewable energy landscape in the country.

The hydropower potential in Kenya is geographically distributed across five major drainage basins: Mt. Kenya, the Mau Complex, the Aberdare Ranges, the Cherangani Hills, and Mt. Elgon (Samu, Poyrazoglu, & Fahrioglu 2019). These catchment areas provide crucial water inflows necessary for hydropower generation. Figure 2.4 illustrates the water inflow rates into the major dams, highlighting seasonal variations that influence electricity production.

Year	Installed Capacity (MW)	Generation (GWh)
2010	820 MW	3.6
2012	820 MW	4.26 (peak)
2015	825 MW	3.2
2018	826 MW	3.1
2020	826 MW	3.0
2022	860 MW	3.04
2023	870 MW	2.67
2025 (*estimated)*	950 MW	2.8–3.2 *(projected)*

Figure 2.5: Evolution of HEP 2010-2025, Kenya (KenGen, 2025)

One of the defining characteristics of HEP generation is its strong correlation with precipitation patterns. The availability of water directly impacts the generation capacity of hydropower plants, meaning that higher precipitation levels result in increased electricity output, whereas lower precipitation levels lead to a decline in generation. According to Samoita et al. (2020), peak power generation typically occurs during the long rainy season, which extends from June to September. Conversely, lower power generation is observed during drier periods, which typically fall between January and April, as well as in December. This seasonal variability in hydropower generation necessitates the integration of other energy sources, such as geothermal, wind, and solar power, to ensure a stable electricity supply throughout the year.

Over the years, climatic variations have had a profound impact on Kenya's hydropower sector. In particular, decreasing levels of rainfall and rising temperatures have resulted in reduced inflow rates into reservoirs such as the Masinga Dam, one of the country's major hydropower reservoirs. This decline in water inflows has led to a reduction in hydropower generation, affecting the overall electricity supply and creating an increased dependency on alternative sources of power. Additionally, rising temperatures pose a significant threat to the floral biodiversity within hydropower catchments. Warmer temperatures can lead to changes in vegetation cover, potentially leaving soil exposed to erosion agents such as wind and heavy rainfall (Musyoka et al., 2018).

Table 2.2: HEP Storage Capacity in Kenya (Samu et al., 2019)

Power Station	Head (m)	Storage Capacity (GWh)
Wanjii Power Station	115	94.87
Masinga dam	49	33.26
Kamburu	82	72.58
Kindaruma	32	25.57
Kiambere	105.5	139.61
Turkwel	365	561.46
Gitaru	136	126
Tana HEP station		67.7
Gogo	20	18.91
Sondu Miriu	196.9	330
Sangoro		106.2
Total		**1,576.16**

One of the major consequences of increased erosion in catchment areas is the accumulation of sediments in reservoirs. When large quantities of sediment settle in dams, they gradually reduce the storage capacity of the reservoirs. This sedimentation process not only decreases the amount of water available for power generation but also impairs the overall operational efficiency of the dams. As the reservoirs lose their capacity to store sufficient amounts of water, the reliability of hydropower generation diminishes, leading to increased fluctuations in electricity output. Furthermore, the accumulation of sediments increases the need for regular maintenance and dredging activities, which can be both costly and time-consuming.

In addition to sedimentation, Kenya's hydropower sector has also faced challenges posed by extreme climatic events such as droughts and floods. Historical data indicates that the country has experienced prolonged dry spells, which have significantly impacted hydropower generation. Notably, severe droughts were recorded in 2000/2001 and 2009/2010, leading to critically low water levels in reservoirs (Musyoka et al., 2018). During these periods, power generation from hydropower plants declined sharply, necessitating increased reliance on fossil fuel-based power generation to meet electricity demand. On the other hand, excessive rainfall and flooding events have also posed challenges to hydropower infrastructure. Heavy rainfall can lead to dam overflow, increasing the risk of structural damage and necessitating emergency spillway releases to prevent catastrophic failures. Figure 2.5 presents data on historical drought periods and their corresponding impacts on hydropower generation.

Despite the crucial role that hydropower plays in Kenya's electricity sector, the industry faces several significant challenges. One of the primary challenges is the growing impact of climate change on water resources. Changes in rainfall patterns and increasing temperatures have made hydropower generation less predictable, affecting the stability of electricity supply. Additionally, climate-induced variability in water availability has underscored the need for improved water management strategies to optimize hydropower generation.

Another major challenge confronting the hydropower sector is the substantial financial investment required for developing large-scale hydropower projects. The construction of dams, reservoirs, and related infrastructure involves high capital costs, which can be a limiting factor in expanding hydropower capacity. Moreover, securing funding for hydropower projects often requires significant financial backing from government agencies, international donors, and private investors. The long gestation periods associated with hydropower development also present economic risks, particularly in cases where project timelines are extended due to regulatory, environmental, or social considerations.

Beyond financial constraints, the environmental and societal ramifications of hydropower projects also present challenges to the sector. Large-scale hydropower projects often involve the displacement of local communities, leading to socio-economic disruptions. The relocation of populations to make way for dam construction can result in the loss of traditional livelihoods, changes in land use patterns, and conflicts over compensation. Additionally, the alteration of natural river ecosystems due to damming can have far-reaching ecological consequences, including the disruption of aquatic habitats and the reduction of downstream water availability.

To address these challenges, Kenya has been exploring various strategies to enhance the resilience and sustainability of its hydropower sector. One approach has been the promotion of small-hydro projects, which require lower capital investments compared to large-scale hydropower plants. Small-hydro installations also have a lower environmental footprint and can be developed in remote areas to improve energy access. Furthermore, there has been an increasing emphasis on integrated water resource management, which involves the sustainable use and conservation of water resources to optimize hydropower generation.

Additionally, the diversification of Kenya's energy mix has been a key strategy in mitigating the risks associated with hydropower variability. The country has been investing in alternative RES such as geothermal, wind, and solar power to complement hydropower generation. Geothermal energy, in particular, has emerged as a reliable baseload power source that is not dependent on weather conditions, making it a crucial component of Kenya's energy future.

Generally, hydropower remains an essential pillar of Kenya's electricity sector, contributing significantly to national energy security. However, the sector faces various challenges, including climate change impacts, financial constraints, and environmental concerns. Addressing these challenges requires a multi-faceted approach that includes improved water resource management, investment in small-hydro projects, and the diversification of the country's energy mix. By implementing these strategies, Kenya can enhance the sustainability and resilience of its hydropower sector, ensuring a stable and reliable electricity supply for future generations.

2.2.4 Geothermal Power

Geothermal power remains the most important and rapidly growing source of electricity in Kenya, with significant potential for further expansion and development. As a RES, geothermal power has become a crucial component of Kenya's energy mix, helping to meet the country's increasing electricity demand while reducing reliance on fossil fuels. Unlike other energy sources, geothermal power provides a stable and reliable supply of electricity, making it an essential part of Kenya's strategy for energy security. The country's location along the East African Rift System gives it access to abundant geothermal resources, positioning Kenya as a leader in geothermal energy production in Africa.

One of the key advantages of geothermal power over other electricity sources in Kenya is its reliability. Unlike solar and wind energy, which depend on weather conditions, geothermal power is available around the clock, regardless of seasonal or climatic variations. This ensures that Kenya's power grid remains stable and can support industries, businesses, and households without major disruptions. Additionally, geothermal power is considered an affordable energy source in the long term. While the initial investment costs are relatively high, operational and maintenance costs are low compared to thermal power plants, which require continuous fuel supply. The affordability of geothermal power makes it an attractive alternative to fossil fuels, contributing to a reduction in electricity costs for consumers and businesses.

Another significant advantage of geothermal power is its low carbon footprint. As the world shifts towards cleaner energy sources to combat climate change, Kenya has positioned itself at the forefront by prioritizing geothermal power development. Unlike coal and diesel-fired power plants, which emit large amounts of greenhouse gases, geothermal power plants produce minimal emissions. The use of geothermal energy helps Kenya reduce its dependence on fossil fuels, thereby decreasing carbon emissions and contributing to global efforts to combat climate change. The environmental benefits of geothermal energy further align with Kenya's commitment to sustainable development and its adherence to international climate agreements.

Beyond its contribution to electricity generation, geothermal power development has had notable economic benefits for Kenya, particularly in communities surrounding geothermal plants. One of the most important economic benefits is job creation. The construction, operation, and maintenance of geothermal power plants require skilled and unskilled labor, providing employment opportunities for local communities. Many people benefit from direct employment in the geothermal sector, while others find work in related industries, such as transport, construction, and equipment supply. The increase in job opportunities has led to improved livelihoods for many Kenyans.

Additionally, infrastructure development in areas surrounding geothermal power plants has enhanced economic growth and improved living standards. Geothermal projects often lead to the construction of better roads, schools, hospitals, and other essential facilities, benefiting both the workers and the local communities. These infrastructural developments not only support the geothermal industry but also promote regional development by attracting further investment in businesses and industries that rely on stable electricity supply.

Geothermal power plants in Kenya operate using a combination of advanced technologies and strategic operational approaches to ensure reliable and efficient electricity generation. Typically, geothermal plants run in base-load mode, meaning they generate electricity at a constant rate, regardless of fluctuations in electricity demand. This operational strategy makes geothermal power an essential foundation for Kenya's electricity grid, ensuring a steady supply of energy without major interruptions.

The process of generating geothermal electricity in Kenya involves several critical stages. First, steam is extracted from underground geothermal reservoirs by drilling deep wells into the earth's crust. The steam is then channeled through a network of pipes to the power plant, where it is directed into a steam turbine generator. The high-pressure steam spins the turbine, which is connected to a generator that produces electricity. After passing through the turbine, the steam is cooled and condensed back into water, which is then reinjected into the underground reservoirs to sustain the geothermal system.

To ensure efficient and reliable operation, geothermal power plants in Kenya are designed to optimize the flow of steam from the reservoirs to the turbines. This involves the use of sophisticated control systems that regulate the pressure and flow of steam to maximize energy output while preventing damage to equipment. Monitoring systems are also implemented to detect any abnormalities or performance fluctuations within the plant. These technologies enhance operational efficiency and contribute to the longevity of geothermal power plants, ensuring a stable supply of electricity for years to come.

Despite the rapid growth and success of geothermal power in Kenya, the sector faces several challenges that need to be addressed for sustained development. One of the most significant challenges is the high initial capital investment required for geothermal projects. The process of identifying viable geothermal sites, drilling wells, and constructing power plants involves substantial financial resources. Due to these high upfront costs, many investors are hesitant to commit to geothermal projects without government incentives or financial support.

Another challenge is the technical complexity associated with drilling and maintaining geothermal wells. Drilling deep into the earth's crust to access geothermal reservoirs is a sophisticated and costly process that requires specialized expertise and advanced equipment. In some cases, geothermal wells may experience reduced steam output over time, necessitating additional drilling or reinjection strategies to maintain productivity. These technical difficulties pose risks to geothermal project developers and can affect the long-term viability of power plants.

Moreover, geothermal power operations can have environmental and social impacts on local communities. Land acquisition for geothermal projects may lead to the displacement of communities or affect traditional land use patterns. Additionally, geothermal activities can cause minor seismic disturbances, which may raise concerns among local populations. Ensuring that geothermal projects are implemented in a socially and environmentally responsible manner is crucial to maintaining public support and minimizing negative impacts.

To address these challenges and support the continued expansion of geothermal power in Kenya, the government has implemented various strategies. One of the most notable initiatives is the establishment of the Geothermal Development Corporation (GDC), a state-owned entity tasked with spearheading geothermal resource exploration and development. The GDC plays a vital role in reducing financial risks for investors by undertaking preliminary exploration and drilling activities before handing over viable sites to private developers. By assuming these risks, the government encourages more investment in the geothermal sector, facilitating faster project implementation.

Additionally, the Kenyan government has invested in capacity building and manpower training to strengthen the country's expertise in geothermal energy development. The training of engineers, geologists, and technicians ensures that Kenya has the skilled workforce needed to sustain its growing geothermal industry. Furthermore, research and development initiatives are being promoted to improve geothermal exploration techniques, enhance efficiency, and develop innovative solutions to overcome technical challenges.

In conclusion, geothermal power is a cornerstone of Kenya's electricity sector, providing a reliable, affordable, and environmentally friendly energy source. The advantages of geothermal power, including its ability to operate continuously, its cost-effectiveness in the long run, and its low carbon footprint, make it an essential component of Kenya's energy strategy. Moreover, the economic benefits associated with geothermal development, such as job creation and infrastructure growth, have positively impacted surrounding communities. However, challenges such as high initial investment costs, technical complexities, and social and environmental concerns must be carefully managed to ensure the sustainable growth of the sector. Through government initiatives such as the Geothermal Development Corporation and capacity-building programs, Kenya is working towards overcoming these challenges and further solidifying its position as a leader in geothermal energy production in Africa. As the country continues to harness its geothermal potential, it is well on its way to achieving energy security, economic prosperity, and environmental sustainability.

2.2.5 Thermal Power Plants

Thermal power plants, which are powered by diesel and gas, represent a significant and prospective source of electricity generation in Kenya. These plants play a crucial role in complementing the country's energy mix by providing reliable and dispatchable power, particularly during peak demand periods or when other RES, such as hydro and solar, are insufficient. The utilization of thermal power is essential in ensuring grid stability, given the intermittent nature of some RES.

Thermal power plants generally operate by employing turbines and generators to produce electricity. The primary fuel sources, which include diesel and natural gas, are used to drive the turbines. These turbines, in turn, convert the thermal energy produced from the combustion of fuel into mechanical energy, which is then transformed into electrical energy through a generator. One of the key aspects of modern thermal power plants is their ability to utilize exhaust heat efficiently. In many plants, the waste heat generated from the turbine's exhaust is captured and used to produce steam. This steam is subsequently used in a secondary process to generate additional electricity through a combined cycle operation. This combined cycle technology significantly enhances the efficiency of thermal power plants by utilizing the available energy more effectively, thereby improving overall power generation while reducing fuel consumption per unit of electricity produced.

The significance of thermal power plants in Kenya's electricity generation landscape is evident from their role in providing additional capacity to the national grid. These plants are particularly crucial during times of high electricity demand, such as peak hours in the morning and evening, as well as during periods of reduced generation from other sources. Kenya's energy mix consists of various renewable and non-renewable sources, with geothermal, hydro, wind, and solar contributing a substantial share of the total electricity generated. However, these sources are not always sufficient to meet the country's growing energy demands, especially during extreme weather conditions that may affect hydroelectric generation. As a result, thermal power plants serve as a reliable backup, ensuring that the grid remains stable and that electricity supply is not interrupted (Simiyu et al. 2014).

In 2022, condensing power plants fueled by diesel and gas played an important role in Kenya’s electricity sector. These plants provided additional capacity to the grid, helping to maintain a balance between supply and demand. Condensing power plants are designed to maximize efficiency by cooling and condensing steam back into water after it has passed through the turbine, enabling the water to be reused in the power generation process. This process helps conserve resources and improves the overall sustainability of thermal power generation. Despite their reliance on fossil fuels, thermal power plants remain an essential component of Kenya’s energy sector, as they provide a stable and reliable electricity supply that supports economic growth, industrial development, and household consumption.

The integration of thermal power plants into Kenya's energy system has both advantages and challenges. On the positive side, these plants offer a dependable source of electricity that can be dispatched as needed, unlike renewable sources that depend on environmental conditions. They are also capable of providing consistent power output, which is crucial for industries that require stable electricity supply, such as manufacturing and processing industries. Additionally, thermal power plants can be constructed relatively quickly compared to some renewable energy projects, making them a viable option for meeting urgent electricity demands.

However, there are also challenges associated with the use of thermal power plants in Kenya. One of the primary concerns is the environmental impact of burning fossil fuels, which contributes to greenhouse gas emissions and air pollution. The combustion of diesel and natural gas releases carbon dioxide (CO_2) and other pollutants into the atmosphere, which can have adverse effects on air quality and contribute to global climate change. To mitigate these environmental impacts, there is growing interest in adopting cleaner technologies, such as natural gas-fired power plants with lower emissions, as well as exploring the potential for carbon capture and storage (CCS) solutions.

Another challenge is the cost of fuel, which can be a significant factor in the overall operational expenses of thermal power plants. The price of diesel and natural gas fluctuates based on global market conditions, and this variability can affect the cost of electricity production. In some cases, higher fuel costs may lead to increased electricity tariffs for consumers, making it more expensive for households and businesses to access reliable power. To address this issue, Kenya has been exploring options to diversify its energy mix further by increasing investments in RES, such as geothermal, wind, and solar power.

Despite these challenges, thermal power plants continue to play a vital role in Kenya’s electricity supply strategy. Their ability to provide emergency power during shortages makes them an indispensable asset in the country's energy infrastructure. Additionally, ongoing efforts to improve the efficiency of thermal power generation through advanced technologies, such as combined cycle systems and waste heat recovery, are helping to reduce fuel consumption and minimize environmental impacts.

In conclusion, thermal power plants fueled by diesel and gas represent an essential component of Kenya’s electricity generation system. They provide a reliable source of power that supports the national grid, especially during times of high demand or when renewable sources are insufficient. While there are environmental and economic challenges associated with thermal power generation, advancements in technology and efforts to transition towards cleaner energy solutions are helping to improve sustainability in the sector. As Kenya continues to expand its energy infrastructure, the role of thermal power is likely to evolve, with a greater emphasis on efficiency and reduced emissions to ensure a balanced and sustainable energy future.

2.2.6 Biomass Cogeneration

Biomass cogeneration power is a significant source of electricity in Kenya, contributing substantially to the country's energy mix. This form of energy generation primarily involves the simultaneous production of electricity and useful heat from biomass resources, a process that enhances efficiency and sustainability. In Kenya, biomass cogeneration is largely driven by the sugar industry, where several sugar mills have adopted this technology to generate power. These mills produce both sugar and electricity, utilizing sugarcane waste, known as bagasse, as the primary fuel source (ERC, 2019a). By leveraging bagasse, these mills efficiently generate electricity to meet their internal energy demands while also supplying surplus power to the national grid, thereby contributing to the overall energy supply in the country.

The use of biomass cogeneration in Kenya has grown over the years due to its economic and environmental benefits. As a byproduct of sugar production, bagasse provides an abundant and cost-effective fuel source, reducing the reliance on fossil fuels and minimizing waste disposal issues. By converting this agricultural waste into a valuable energy resource, sugar mills can lower operational costs while promoting sustainable energy production. Additionally, the process significantly reduces greenhouse gas emissions by utilizing biomass that would otherwise decay and release carbon dioxide and methane into the atmosphere. This aligns with Kenya's commitment to environmental sustainability and climate change mitigation under international frameworks such as the Paris Agreement.

The role of biomass cogeneration in Kenya is further reinforced by government policies and initiatives aimed at promoting renewable energy. The Kenyan government has actively supported the development of biomass energy through favorable regulatory frameworks, incentives, and investment opportunities. The Energy and Petroleum Regulatory Authority (EPRA), formerly known as the Energy Regulatory Commission (ERC), has implemented policies that encourage independent power producers (IPPs) to invest in biomass cogeneration projects. This has led to increased private sector participation, fostering innovation and efficiency in the sector (ERC, 2019a). By providing a conducive environment for investment, the government aims to enhance energy security and diversify Kenya's energy sources.

One of the key advantages of biomass cogeneration is its ability to provide stable and reliable electricity. Unlike some RES such as solar and wind, which are intermittent and weather-dependent, biomass cogeneration offers a more consistent and predictable energy supply. This reliability is crucial for industries that require uninterrupted power to maintain production efficiency. Sugar mills, for instance, rely heavily on continuous energy to power their operations, and biomass cogeneration ensures a steady supply of electricity without dependence on external sources. Furthermore, the integration of biomass cogeneration into Kenya's power grid helps stabilize energy availability, particularly in rural areas where access to electricity is limited.

The economic impact of biomass cogeneration extends beyond the sugar industry. The expansion of this energy source has created numerous employment opportunities, ranging from technical jobs in power generation facilities to roles in the collection, transportation, and processing of biomass feedstock. By stimulating economic activities within local communities, biomass cogeneration contributes to rural development and poverty reduction. Additionally, the surplus electricity generated by sugar mills is often sold to the national grid under power purchase agreements (PPAs), generating additional revenue for the industry. This financial boost enables further investment in technological advancements and capacity expansion, ensuring the long-term viability of biomass cogeneration in Kenya.

Despite its numerous benefits, biomass cogeneration in Kenya faces several challenges that need to be addressed to maximize its potential. One of the primary challenges is the seasonal nature of sugarcane production, which affects the availability of bagasse. Since sugar mills operate in cycles based on sugarcane harvesting seasons, the consistency of biomass fuel supply fluctuates, impacting power generation. To mitigate this issue, some mills have adopted strategies such as storing bagasse during peak production periods to ensure a continuous energy supply. Additionally, exploring alternative biomass sources such as agricultural residues, wood waste, and energy crops could enhance the sustainability of cogeneration systems.

Another challenge is the high initial capital investment required for biomass cogeneration infrastructure. Establishing a cogeneration plant involves significant costs related to equipment, technology, and grid integration. While government incentives and private sector investments have helped alleviate some financial barriers, further support is needed to enhance affordability and accessibility. Financial institutions can play a crucial role by offering favorable loan facilities and funding mechanisms tailored to renewable energy projects. Additionally, international partnerships and collaborations could provide technical expertise and financial assistance to accelerate the growth of biomass cogeneration in Kenya.

The efficiency and performance of biomass cogeneration systems also depend on technological advancements and innovation. Continuous research and development (R&D) are essential to improving the efficiency of biomass conversion processes, optimizing energy output, and reducing operational costs. Advancements in combustion technologies, gasification, and biogas production can enhance the overall effectiveness of biomass cogeneration plants. Furthermore, digitalization and automation can improve monitoring and control systems, ensuring optimal performance and maintenance of cogeneration facilities. Encouraging knowledge-sharing and capacity-building initiatives within the sector will foster innovation and skill development, ultimately enhancing the sustainability of biomass energy production.

In addition to technological and economic considerations, policy and regulatory frameworks play a critical role in shaping the future of biomass cogeneration in Kenya.

The government must continue to refine and implement policies that support the integration of biomass energy into the national grid. This includes streamlining licensing procedures, ensuring fair tariff structures for biomass-generated electricity, and addressing regulatory barriers that may hinder investment. A transparent and predictable policy environment will attract more investors and promote the expansion of biomass cogeneration projects.

Furthermore, public awareness and community engagement are crucial in promoting the adoption of biomass cogeneration. Many stakeholders, including farmers, industrial players, and local communities, may not fully understand the benefits and potential of biomass energy. Educational campaigns, workshops, and stakeholder consultations can enhance awareness and encourage participation in biomass energy initiatives. By fostering a culture of sustainability and energy consciousness, Kenya can create a supportive ecosystem for biomass cogeneration and other REs.

Looking ahead, biomass cogeneration is poised to retain its significance as a vital source of electricity in Kenya. The increasing demand for renewable energy, coupled with the government's commitment to energy diversification, suggests that biomass cogeneration will continue to play a key role in the country's energy landscape. As Kenya strives to achieve its Vision 2030 goals and transition to a low-carbon economy, biomass cogeneration offers a viable solution to meeting energy needs while promoting environmental conservation and economic development (ERC, 2019a).

Moreover, regional and international collaborations can further enhance the growth of biomass cogeneration in Kenya. Partnerships with international organizations, research institutions, and development agencies can facilitate knowledge exchange, funding, and technology transfer. Lessons from successful biomass cogeneration projects in other countries can be adapted to Kenya's context, optimizing efficiency and scalability. Strengthening regional energy cooperation within East Africa could also create opportunities for cross-border electricity trade, enhancing energy security and economic integration.

In conclusion, biomass cogeneration power remains a significant and promising source of electricity in Kenya. Driven by the sugar industry and supported by government policies, this RES contributes to energy security, economic growth, and environmental sustainability. Despite challenges such as seasonal fuel supply, high initial investment costs, and technological limitations, continued efforts in policy development, innovation, and stakeholder engagement can unlock the full potential of biomass cogeneration. By fostering a conducive environment for investment and research, Kenya can position itself as a leader in biomass energy production, paving the way for a more sustainable and resilient energy future (ERC, 2019a).

2.2.7 Imported Power

Kenya increasingly depends on electricity imports to address domestic power deficits and ensure grid stability. In 2025, imported electricity accounted for over 10% of the national supply, up from just 2% in 2022 (Africa Energy Council, 2025).

The bulk of imported electricity—approximately 85%—is sourced from Ethiopia via the 500 kV Sodo–Moyale–Suswa transmission line, which enables Kenya to access up to 400 MW of power (Africa Energy Council, 2025). This interconnection has become a vital component of Kenya's base-load capacity, particularly during peak demand periods or when domestic generation is constrained.

Uganda supplies roughly 15% of Kenya's electricity imports through the Bujagali–Tororo–Lessos interconnector. This line is designed for a maximum transfer capacity of 1,200 MW and extends from the Bujagali Hydropower Station in Uganda to Tororo at 220 kV over approximately 127 km, before transitioning to 400 kV through Eldoret and terminating in Lessos, Kenya (Africa Energy Council, 2025).

Kenya also imports electricity from Tanzania via the Isinya–Singida interconnector, a 400-kV double-circuit transmission line with a total length of approximately 507 km—comprising 96 km within Kenya and 414 km within Tanzania. This line has a designed transfer capacity of up to 2,400 MW, offering substantial potential for future energy exchange within the framework of the Eastern Africa Power Pool (EAPP) (Africa Energy Council, 2025).

2.3 Integration of Solar Electrification

Developed countries are shifting towards relying on REs as their primary resource to fulfill energy requirements due to their capability to tackle concerns related to climate change (Hansen et al., 2015). As advancements in economically advanced nations have contributed to cost reductions, low and middle-income countries are also showing a growing interest in RES.

Until 2008, the majority of countries had not integrated solar power technology into their electricity generation portfolios (Rose et al., 2016). One factor contributing to this situation is that solar power technology was not cost-competitive in comparison to other REs such as wind power, as well as when compared to electricity generation relying on fossil fuels.

In general, fossil fuel-based technologies have dominated installations over solar power technology on a worldwide scale. However, mounting concerns regarding the continual rise in greenhouse gas emissions have prompted governments to implement planning practices and policies. (Østergaard & Sperling, 2014) as well as subsidies favoring RES

(Adam & Apaydin, 2016). These concerns, alongside declines in the cost of PV technology, have led to a simultaneous increase in adoption and technological advancements.

Over the last decade, there has been a notable and continuous decrease in the cost of PV systems, typically ranging from $1,200 to $2,000 per kW installed (Lang et al., 2016), depending on the system size and specific project requirements. Primarily due to swift technological advancements encouraged by government subsidies (Lang et al., 2016). Between 2006 and 2013, installed costs witnessed an annual average reduction of 16%. By the first quarter of 2017, the standard cost of solar PV in typical rooftop setups had dropped to KSh 249,772 per kWp from its initial figure of over KSh 8,200,000 per kWp in 2006 (Kausar et al., 2014). At the same time, advancements in PV technology led to an enhancement in efficiency from 15% to 30% (*Fukushima Renewable Energy Institute*, 2014). As of 2024, the cost of solar PV systems in Kenya generally ranges from KSh 128,900 to KSh 193,350 per kW installed, depending on the scale and specific project requirements.

The decreasing module expenses along with rising efficiencies have led to a compounded reduction in the electricity costs derived from PV modules. As a result, PV has become notably more competitive on a global scale, leading to a substantial increase in the cumulative capacity of PV technology (Q. Xu et al., 2016).

The development has been inconsistent worldwide. In the study carried out by Tazi et al. (2018), an evaluation was conducted to analyze the present situation and future prospects of REs in Morocco. Morocco exhibits exceptional potential for the utilization of solar PV technology, with promising opportunities also existing for wind power—a sector already embraced within the country. The study assessed the challenges and barriers in the advancement of REs along with the national strategy for ensuring energy security and how these challenges will be addressed, employing the time series method. Findings indicated that by 2030, wind and solar power could be integrated without encountering transit constraints concerning their utilization.

Kenya, on the other hand, is neither as ambitious nor as successful in terms of PV development despite good solar radiation. Data show that the total installed solar power capacity in Kenya was only about 50.25 MWp as of 2019 (ERC, 2019b). As of 2024, data statistics show that the total installed solar power capacity in Kenya is approximately 200 Megawatts (MW) (Alghanem & Buckley, 2024). This capacity is marginal compared to the total installed power production capacity of approximately 5,000 MW in Kenya as shown in Figure 2.6.

In Kenya, it is anticipated that solar power will experience a 15% annual growth rate (ERC 2019), primarily due to declining prices, making solar power increasingly competitive. However, this growth remains relatively modest compared to its potential, with many developments focusing on off-grid systems. For such purposes, consumers not only desire cost savings but also value the notion of independence (Karakaya & Sriwannawit, 2015) – a motivating factor observed in places like Denmark is the willingness of solar power owners to invest in expensive storage systems to enhance their electricity self-sufficiency (Marczinkowski & Østergaard, 2018).

Although a 15% yearly rise might appear substantial in various contexts, it falls short of facilitating a swift transition, given that such a growth pace would necessitate numerous decades for implementation. Moreover, the concurrent rise in income and urbanization is driving up fossil fuel consumption in Kenya (Kwakwa et al., 2018) this demand needs to be counteracted by heightened utilization of RES. Additionally, there was a 3.6% upsurge in peak electricity demand between 2018 and 2019, with projections indicating a peak increase from 1802 MW in 2018 to 15,000 MW by 2030 (ERC, 2019a).

More RES development is thus needed and any barriers have to be overcome. The Kenyan electricity generation mix as given in Figure 2.6. shows that fossil fuels only provided approximately one-quarter of the electricity while hydropower and geothermal had even more significant shares of approximately 30% each. Thus, Kenya is heavily supplied by RES as it is. Kenya has a high potential for the use of geothermal energy, with the potential to increase from currently about 200 MW up to 10 GW (Ogola et al., 2012).

However, the utilization of geothermal energy encounters various obstacles, such as escalating investment costs, heightened challenges in resource exploration and expansion, conflicts over land use, insufficient expertise, and substantial investments required for grid infrastructure due to the considerable distances between geothermal sites and existing load centers (Phillips, 2016a). In Kenya, HEP primarily exists in the form of hydroelectric plants utilizing dams, making their electricity production vulnerable to drought conditions.

This leads to suboptimal resilience and direct power cuts (Lai & McCulloch, 2017). Pumped hydro storage has the potential to enhance flexibility by allowing surplus energy from wind and solar power to be stored for future usage. This collaboration could bolster Kenyan hydropower, rendering it more resilient during dry periods.

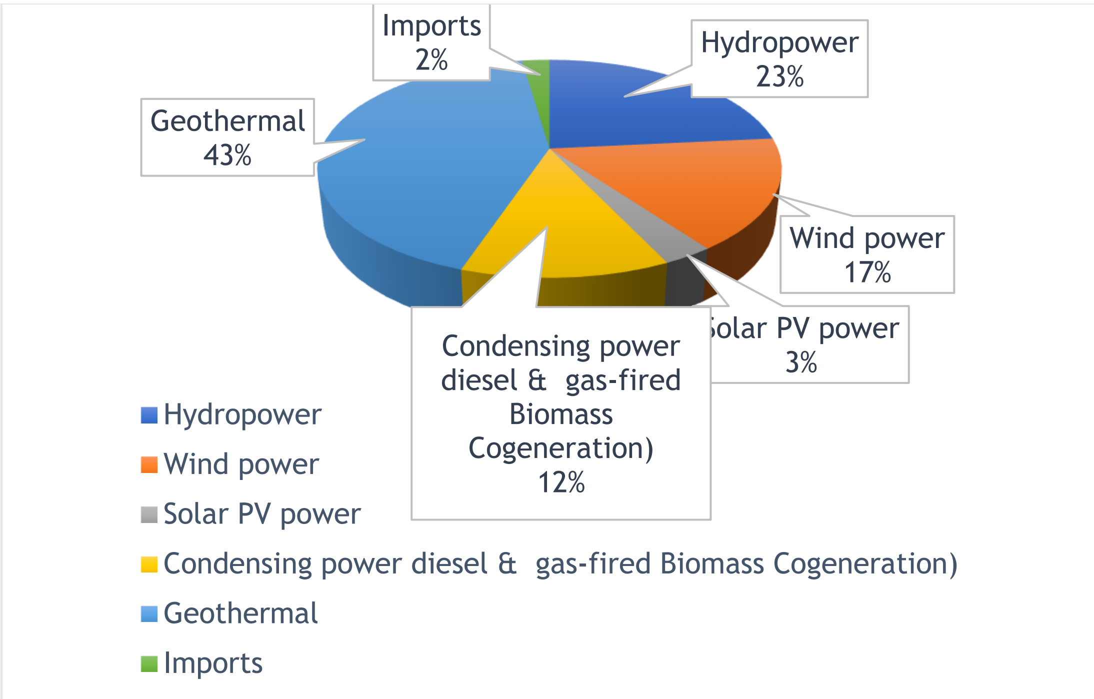


Figure 2.6: Kenyan electricity production mix shares in 2022. Based on data from (KNBS, 2022)

Furthermore, due to their lengthy development processes, both hydropower and geothermal projects may not be sufficient to address the anticipated production shortfall. Consequently, alongside other limitations, the electricity grid in Kenya frequently experiences power interruptions. On average, homes and businesses connected to the grid encounter around six outages per month, each lasting roughly five hours (Ramirez, 2016).

The financial impact of power disruptions is estimated at approximately 7.1% of the revenue generated by power distribution firms. Consequently, these outages bear a substantial economic burden on businesses, as noted by Ramirez (2016), consequently affecting Kenyan society as a whole.

Due to its proximity to the equator, Kenya possesses significant potential for solar power solar energy generation, benefiting from abundant solar radiation (Lai & McCulloch, 2017). The abundant sunshine in Kenya, coupled with its extensive rural population, encourages the adoption of solar power energy. As per (Rotich et al., 2024b), roughly 70% of Kenya's land area has the capacity to receive around 5 kWh/m^2/day consistently throughout the year, with an average yearly radiation of 6.98 kWh/m^2.

A literature survey on the integration of solar power in the electricity generation mix reveals, however, that the focus is predominantly on Europe and the United States of America (Johannsen et al., 2020). Little attention has been paid to emerging economies such as Kenya where electricity production and demand are expected to grow considerably in the coming years. Besides, there is room for adopting an infrastructure capable of meeting the future power demands using RES from the outset given the resource availability notably solar power (Johannsen et al., 2020).

No study has emphasized the opportunities and challenges of solar solar power generation in regions with existing hydropower. Studies on solar power in Kenya tend to prioritize providing electricity access to remote areas rather than focusing on grid-connected projects (Johannsen et al., 2020). This restricts the examination of interactions with hydroelectric power. So far, the only instances where off-grid analyses have been conducted are viability studies conducted in South Africa (Samoita et al., 2020) and an assessment concentrating on the advancement of small-scale electricity distribution networks (Sharma et al., 2014).

Despite the demonstrated large potential for solar power utilization, estimated at approximately 23,046 terawatt-hours (TWh) per year, given its high solar insolation levels averaging 4-6 kWh/m^2/day and vast land areas suitable for solar energy development, current exploitation is still limited, and projections show a modest growth that may not even match the increase in electricity and general energy consumption

(Alghanem & Buckley, 2024). Also, a predominant focus in the existing studies on Kenya is on the potential of solar power as a source of renewable energy from a technical perspective with a particular focus on stand-alone applications.

While other nations, particularly those more economically advanced, are already pursuing greater utilization of solar power, even in regions with less favorable solar conditions than Kenya, the country itself lags behind in this endeavor. To fully harness its potential, a comprehensive examination of the opportunities and challenges in integrating solar power into Kenya's electricity generation mix is essential. Therefore, this research aims to assess the possibilities and obstacles associated with incorporating solar power technology into Kenya's electricity generation mix.

Obstacles to the widespread adoption of renewable energy technologies, including solar power technology, are observed globally and are documented similarly across various studies, with minor variations specific to countries or technologies. (Child, Haukkala, & Breyer 2017b) Son and colleagues classified the primary obstacles to the adoption of renewable energy technologies into six groups: "market failures/imperfections, market distortions, economic and financial challenges, institutional barriers, technical obstacles, and social, cultural, and behavioral factors."

Child, Haukkala, & Breyer (2017a) highlighted certain obstacles, including restricted information accessibility, a preference for traditional energy sources, financial constraints, the absence of externalities in decision-making, insufficient training, and societal non-acceptance. Hvelplund & Djørup (2019) suggested that ownership acts as both a barrier and a motivator for the progress of energy technologies. However, the evaluation conducted by Samoita et al. (2020) found limited evidence regarding the influence of ownership as either a hindrance or an opportunity. There is some anecdotal evidence regarding the types of actors adopting solar power technology in Kenya, particularly in off-grid applications.

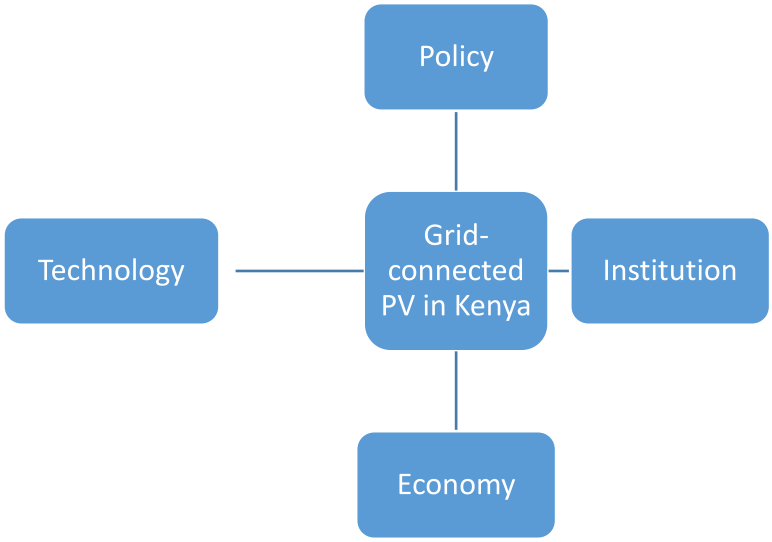


Figure 2.7: Analytical framework for assessing barriers and opportunities for increased integration of solar power in Kenya. ***Source: Author***

Furthermore, it's important to recognize that not all barriers identified by Child et al. (2017a) are pertinent or applicable within the Kenyan context. As a result, these barrier categories and opportunities for success were reviewed and adjusted to ensure their relevance in the Kenyan context. Consequently, the spectrum of barriers impeding the adoption of solar power was classified into technological, economic, institutional, and policy categories, as illustrated in Figure 2.7. This classification serves as the analytical framework.

2.4 Barriers to Increasing Integration of Solar Power in Kenya

The introduction of solar power technology in Kenya during the 1970s was largely enabled by donor support, especially in the 1980s when solar power systems were contributed to facilities like off-grid health clinics (Phillips, 2016b) As solar power was implemented in rural off-grid regions, it became evident that there was a broader market for this technology beyond health clinics and off-grid missions (Rotich et al., 2024a)

During the span of two years, from 2000 to 2002, the proportion of households acquiring solar power systems rose from 20% to 40% of the total annual purchases. Nonetheless, the advantages derived from these solar solar power systems primarily benefited the rural middle class (Kirubi et al., 2009a). Consequently, poorer rural households were overlooked in terms of accessing subsidized solar power systems (Simiyu et al., 2014b).

Over time, prioritizing wealthier rural areas enabled the solar solar power industry to become financially sustainable without depending on external funding or subsidies. Particularly in the 2000s, attention shifted towards the middle-income bracket, driven by declining solar power system costs and the middle class's growing interest in television (Kirubi et al., 2009b). These progressions have resulted in the widespread installation of numerous solar power systems (Tigabu et al., 2017).

Nevertheless, the majority of progress in Kenya has occurred through stand-alone (off-grid) systems, which remain disconnected from the national grid. Consequently, the utilization of Solar Home Systems has been predominant in Kenya's solar power market, recognized as the most successful off-grid solar market among developing economies (Rolffs et al., 2015a).

2.4.1 Technological Barriers

Despite significant advancements in solar power technology over recent decades, literature continues to identify various technical barriers to its widespread adoption. The quality of solar power systems remains paramount for successful integration into modern energy infrastructure. Ensuring high-quality solar power systems involves multiple aspects, including appropriate design, installation, operation, and maintenance. However, achieving this level of quality is often hindered by several challenges that persist despite technological advancements.

A critical obstacle is the lack of sufficient knowledge regarding solar power systems, which may lead to improper usage and an inability to maintain the systems effectively (Karakaya & Sriwannawit, 2015b). This gap in knowledge can stem from inadequate training for technicians, a lack of awareness among potential users, and limited accessibility to educational resources on solar power system maintenance. When solar power systems are installed and operated by individuals or organizations with insufficient expertise, the likelihood of system failures increases. Poor installation practices, improper sizing of components, and lack of adherence to standard operating procedures can result in suboptimal performance or premature degradation of solar power systems.

Such issues contribute to a broader problem—negative perceptions regarding the reliability and effectiveness of solar power technology. If users experience frequent breakdowns, poor energy output, or high maintenance costs due to improper installation and operation, they may develop unfavorable opinions about the technology. These perceptions can, in turn, deter potential customers from embracing solar power systems. Negative experiences, particularly in regions where awareness of solar power technology is still developing, may lead to skepticism and reluctance to invest in solar energy solutions. Overcoming this challenge requires concerted efforts in training, awareness campaigns, and capacity building to ensure that both technical professionals and end-users are well-equipped to handle solar power systems efficiently.

In Kenya, a significant technological hurdle for solar power implementation has been the absence of energy storage systems (Munro et al., 2016). The intermittent nature of solar energy means that energy storage is crucial for ensuring a stable and reliable power supply. Without effective storage solutions, solar energy cannot be fully harnessed, as excess energy generated during peak sunlight hours may go unused if there is no means to store it. The lack of adequate storage infrastructure has made it difficult for solar power systems to provide consistent power, particularly in off-grid areas where backup energy sources are limited. This challenge underscores the importance of developing and deploying suitable energy storage technologies to complement solar power installations.

However, given Kenya's heavy dependence on reservoir/dammed hydroelectric power, the adoption of solar power -based pumped storage hydropower presents a potentially more adaptable solution to address the variability in residual production (demand minus non-dispatchable power production). Pumped storage hydropower functions by using excess electricity generated by solar power systems to pump water to a higher elevation during periods of surplus generation. This stored energy can then be released to generate hydroelectric power when solar energy is insufficient, thereby providing a stable and dispatchable energy source. This hybrid approach combines the advantages of both solar and hydroelectric power, offering a feasible alternative to battery-based storage systems.

Battery storage solutions also exist, but the accompanying initial cost remains high, although it has been declining over time. The cost of battery storage typically ranges from KSh 38,670 to KSh 64,450 per kWh of storage capacity for grid-connected systems (Werner & Breyer, 2012). This high upfront cost has been a significant barrier to widespread adoption, particularly in developing countries where financial constraints may limit investment in energy storage solutions. While advancements in battery technology and economies of scale have contributed to cost reductions, further innovations are needed to make battery storage more affordable and accessible.

Given the economic constraints associated with battery storage, research has pointed to the need to explore the development of hybrid systems that combine solar solar power with hydropower as a viable alternative option (Werner & Breyer, 2012). Hybrid energy systems offer the advantage of increased reliability and flexibility, as they leverage multiple energy sources to ensure a consistent power supply. In Kenya, integrating solar power with existing hydropower infrastructure could provide a cost-effective and sustainable solution for addressing energy storage challenges. This approach aligns with global trends in renewable energy integration, where hybrid systems are increasingly being explored to enhance grid stability and energy security.

The storage requirement for solar power systems is, of course, dependent on both the composition of the rest of the electricity system and the share of solar power in the overall energy mix. When solar power systems represent less than 10% of total generation capacity, they can typically be integrated into the grid without significant technical issues. However, as the share of solar power increases beyond 30% of total generation capacity, the demands on energy system flexibility become significantly higher. The variability and intermittency of solar power necessitate the implementation of advanced energy management strategies, grid modernization efforts, and enhanced storage solutions to maintain system stability.

Mathiesen et al. (2015) identified three phases in the implementation of renewable energy systems (RES). The first stage, known as the introduction phase, involves the initial deployment of RES technologies, where they only marginally replace production based on fossil fuels. At this stage, the integration of renewables into the grid is relatively straightforward, as conventional power sources can still compensate for variability.

The second phase involves the extensive integration of variable renewables into the energy system, introducing greater complexity and raising concerns about grid stability. As the share of renewable energy increases, grid operators must implement sophisticated demand-response mechanisms, advanced forecasting techniques, and enhanced grid management strategies to accommodate fluctuations in energy supply and demand. This phase requires significant investment in energy storage, grid flexibility measures, and regulatory frameworks to support large-scale renewable integration.

The third phase represents a fully renewable energy scenario, where the majority of the energy supply is derived from renewable sources. At this stage, sophisticated storage and conversion technologies become essential to maintaining energy system balance over time. Solutions such as large-scale battery storage, hydrogen storage, power-to-gas technologies, and smart grid innovations play a crucial role in ensuring a stable and reliable energy supply. Achieving this level of renewable penetration requires comprehensive policy support, substantial infrastructure investments, and continued technological advancements.

Currently, the Kenyan national electricity system, like many others globally, is in the second phase, where challenges associated with large-scale renewable integration have not yet fully emerged. However, as Kenya continues to expand its SOLAR POWER capacity and move towards greater renewable energy adoption, it is inevitable that the country will enter this phase. Preparing for this transition requires proactive measures to address storage limitations, enhance grid flexibility, and develop supportive regulatory policies.

A concentrated emphasis on solar power will inevitably lead Kenya into the phase where large-scale integration challenges become more pronounced. To mitigate potential issues, it is crucial to invest in research and development efforts focused on improving solar power system efficiency, developing cost-effective storage solutions, and enhancing grid infrastructure. Additionally, capacity-building initiatives aimed at training professionals, raising public awareness, and fostering collaboration between stakeholders will be essential for ensuring the successful integration of solar power technology into Kenya's energy landscape.

While significant progress has been made in solar power technology over recent decades, various technical barriers continue to hinder its widespread adoption. The lack of sufficient knowledge, the absence of energy storage solutions, and the high initial costs of battery storage remain key challenges. However, innovative approaches such as hybrid solar power -hydropower systems offer promising alternatives for addressing these barriers. As Kenya advances towards greater renewable energy integration, strategic investments in storage technologies, grid modernization, and capacity-building initiatives will be crucial for ensuring a stable and sustainable energy future. By proactively addressing these challenges, Kenya can harness the full potential of solar power technology and contribute to a more resilient and sustainable energy system.

2.4.2 Economic Barriers

The integration of solar power systems into the energy mix has been hindered by several economic challenges, with the most significant being the substantial initial investment required for installation. This financial burden has made banks reluctant to finance such projects, viewing them as high-risk investments. The high construction costs associated with solar power systems, compounded by the relatively new nature of the technology, have led financial institutions to perceive renewable energy ventures, including solar power, as riskier than traditional energy sources. As a result, loans for solar power projects often come with higher interest rates, making it more difficult for utilities or developers to justify such investments. Despite significant reductions in solar power costs in recent years, these lingering perceptions about the costs of adopting solar energy continue to present a major barrier to its widespread adoption (Energy, 2018).

Historically, the high upfront costs of solar power installations have made the technology less accessible, especially in developing regions. The capital-intensive nature of solar power systems has created challenges for utilities and private developers, limiting the number of projects initiated. However, in recent years, substantial efforts have been made to assess the economic viability of solar power ER across various global regions. Studies and research initiatives have focused on determining the cost-effectiveness of solar power systems when compared to conventional forms of energy generation. A study conducted in the Middle East and North Africa (MENA) region, for instance, found that rooftop solar power systems could rival other traditional energy-generating methods in the region (Werner & Breyer, 2012b). This conclusion highlighted the potential for solar power to emerge as a competitive alternative to conventional energy sources, especially in regions with abundant sunlight.

Despite these promising findings, the pace of progress has not always lived up to expectations. The cost-effectiveness of solar power in certain regions has yet to reach the levels anticipated in early studies. In the Kenyan context, however, research has confirmed the feasibility of solar power as a competitive energy solution. A report by Da Silva et al. (2015) conducted a levelized cost of energy (LCOE) assessment, which showed that solar power, when integrated with other REs, can compete favorably against non-REs. This finding is significant, as it suggests that solar power can provide a cost-competitive alternative to traditional fossil fuels in a developing country setting like Kenya.

Despite the high levels of solar insolation experienced in Kenya, the adoption of solar power for grid-connected systems has remained limited, primarily due to the prohibitive upfront investment costs. Most solar power applications in Kenya have been in the form of off-grid solutions, such as solar lanterns, which are more affordable for rural communities but provide only limited power. The reluctance to invest in large-scale grid-connected solar power systems has also been attributed to the high capital expenditure required to set up such infrastructure. The initial cost of grid-connected solar power systems, which can be as high as several thousand dollars for residential systems, remains a significant barrier for many potential users (Republic of Kenya, 2014).

However, recent trends indicate that the costs associated with solar power systems are decreasing, making the technology increasingly viable in regions like Kenya. Over the past decade, the price of solar power panels has dropped significantly, from approximately KSh 902.30 per watt in 2010 to under KSh 128.90 per watt in recent years (Aris & Shabani, 2015). This dramatic price reduction has made solar power a more attractive energy source compared to traditional diesel generators, which are expensive to operate and maintain. In regions like Kenya, where the cost of electricity generation is high, especially in remote areas, solar power has emerged as a cost-effective solution for energy access. The declining price of solar power panels, combined with increasing demand for cleaner energy alternatives, has created a favorable environment for the adoption of solar power, both in off-grid and grid-connected applications.

Despite the falling prices of solar power, the comparison between the cost of solar power and conventional fossil fuels remains a significant barrier to the widespread adoption of solar energy in Kenya. For utility companies and individual investors, the initial investment required to deploy large-scale solar power systems without an effective energy storage solution is perceived as financially risky. This is particularly true for the national utility company, Kenya Power and Lighting Company (KPLC), as well as independent power producers (IPPs), who are concerned about the financial implications of integrating solar power into the national grid. The absence of cost-effective energy storage solutions for solar power further complicates the situation. Solar power is intermittent, meaning it is only available when the sun is shining. Without adequate storage, the electricity generated by solar power systems cannot be used during times of low sunlight, such as at night or on cloudy days. This intermittency poses a challenge to maintaining grid stability and reliability.

The challenge of intermittency has led some stakeholders to view large-scale solar power projects as a potential burden on grid infrastructure. The need for backup power sources, such as batteries or diesel generators, adds to the cost of solar power systems. As a result, both KPLC and IPPs have expressed concerns about the financial feasibility of integrating solar power into the national grid without significant investments in energy storage technology (Rolffs et al., 2015). The cost of energy storage systems, which are necessary to ensure a continuous supply of electricity from solar power, remains high, further complicating the economic viability of large-scale solar power projects.

To address these challenges, several stakeholders have proposed various solutions to facilitate the integration of solar power into the energy mix. One potential solution is the sale or leasing of energy storage systems to offset the high upfront costs of solar power WER installations. By offering financing options for both solar power systems and storage solutions, developers and utilities can make solar energy more affordable for a wider range of consumers. This approach could be particularly effective in developing countries like Kenya, where access to affordable financing is often a major constraint. Another option is to establish service partnerships with individual investors, allowing them to participate in solar energy projects through shared ownership or leasing arrangements. This model has been successfully implemented in some regions and could provide a viable alternative for individuals and businesses who wish to invest in solar energy but are unable to afford the high upfront costs.

As the solar energy market continues to evolve, it is expected that installation costs will continue to decrease, making solar power a more accessible and attractive option for consumers. One way to accelerate this process is through the implementation of national-level training and certification programs for solar power installers. By ensuring that installers are well-trained and certified, the quality of installations can be improved, and installation costs can be reduced. Such programs would also create job opportunities in the growing solar energy sector, further boosting the local economy. In Kenya, such initiatives are already underway, with organizations such as the Kenya Renewable Energy Association (KEREA) working to promote the adoption of solar energy through training, certification, and awareness campaigns (Rotich et al., 2024a).

In conclusion, while the initial economic barriers to solar power adoption in Kenya remain significant, there are growing indications that these challenges can be overcome. As the cost of solar power continues to decrease, and with the implementation of financing options, storage solutions, and training programs, solar power has the potential to become a key component of Kenya's energy mix. The government, utilities, developers, and investors must continue to collaborate to create an enabling environment for the widespread adoption of solar power, which will not only reduce the country's dependence on fossil fuels but also contribute to its long-term energy security and sustainability.

2.4.3 Institutional Barriers

The institutional barriers vary largely and are here grouped into four categories namely; grid access, RnD programs, university linkages, and policy experience from other African nations.

2.4.3.1 Grid access

In Kenya, the national electricity grid, which is primarily managed by the monopoly Kenya Power and Lighting Company Limited (KPLC), presents significant challenges for new connections of solar power systems. The process of connecting a new solar power system to the grid is both lengthy and complex, involving up to fourteen licensing steps that must be navigated by those looking to invest in solar power generation. This highly bureaucratic procedure, which includes obtaining approvals from multiple regulatory bodies and fulfilling numerous technical requirements, often acts as a significant deterrent to potential investments in solar power generation (Lai & McCulloch, 2017).

The role of Kenya Power and Lighting Company in managing the national electricity grid is crucial, as it holds a monopoly over the distribution and retail of electricity in the country. While KPLC is tasked with ensuring the reliability and stability of the grid, its dominance in the sector also means that it has significant control over the process by which new generators, including those using REs like solar power systems, can connect to the grid. The process, however, is far from streamlined. It involves multiple steps that are required to ensure compliance with both technical and regulatory standards. These steps can be cumbersome, time-consuming, and at times confusing, especially for new investors unfamiliar with the intricacies of the process.

The licensing and approval process for new solar power systems typically starts with the submission of an application, which is reviewed by KPLC to assess whether the proposed system meets the necessary technical and safety standards. Once this preliminary review is complete, applicants must then go through various stages, including the signing of agreements, submission of detailed technical designs, and conducting feasibility studies to ensure the proposed system will integrate seamlessly with the existing grid infrastructure.

One of the key hurdles in this process is the requirement for multiple approvals from different government bodies and regulatory agencies. For instance, approvals may be required from the Energy and Petroleum Regulatory Authority (EPRA), the National Environmental Management Authority (NEMA), and local government authorities. Each of these agencies has its own set of requirements and documentation that need to be submitted, adding to the complexity of the process. In addition to these approvals, there are also technical studies and assessments that must be conducted to ensure that the new solar power system will not overload or destabilize the grid.

The complexity of this process is compounded by the fact that it is not always clear to investors what exact documentation is required at each stage, or how long each approval process will take. In some cases, there may be delays in receiving feedback from the relevant agencies, leading to further uncertainty. This uncertainty, combined with the long timelines involved, often makes it difficult for investors to accurately estimate the costs and timeframes for connecting a new solar power system to the grid. As a result, many potential investors may be discouraged from pursuing solar power projects, opting instead to explore other, more straightforward investment opportunities in other sectors.

Moreover, the costs associated with meeting the various licensing and approval requirements can also be prohibitive. Investors must factor in the costs of technical studies, environmental impact assessments, and other assessments required by the relevant authorities. These costs, in addition to the potential delays and administrative hurdles, create a financial burden that may be too much for some investors, particularly those in the early stages of establishing their businesses or seeking to enter the market. While Kenya has made significant strides in promoting renewable energy, particularly solar power, through policies such as the Feed-in Tariff (FiT) and net metering schemes, the process for connecting new solar power systems to the national grid remains a significant barrier. The lengthy and complex licensing process can dissuade potential investors from pursuing solar power generation projects, ultimately limiting the growth and development of the solar energy sector in the country.

This situation is not unique to Kenya. Across many developing countries, the regulatory environment and grid connection process for renewable energy systems are often seen as obstacles to the growth of the sector. However, addressing these challenges is crucial if Kenya is to fully capitalize on its renewable energy potential, particularly in the solar sector. Streamlining the connection process, reducing unnecessary bureaucratic hurdles, and providing clearer guidelines for investors could go a long way in encouraging more investments in solar power generation.

In conclusion, the challenges associated with connecting new solar power systems to the national grid in Kenya are significant and multi-faceted. The lengthy and complex licensing process, coupled with the involvement of multiple regulatory bodies and agencies, creates a barrier to entry for many potential investors. This complexity, in turn, acts as a deterrent to the growth of the solar power sector, limiting the country’s ability to expand its renewable energy capacity. Addressing these challenges through regulatory reforms and streamlined processes could help unlock the full potential of solar power in Kenya and encourage greater investment in the sector (Lai & McCulloch, 2017).

2.4.3.2 Research and Development

Internationally, China has firmly established itself as a global leader in solar technology, emerging as a dominant force in the solar power industry (Tian & Zhao, 2013). China's commitment to advancing solar technology is evident in its substantial investment in research and development (R&D). By the early 2000s, China had made impressive strides in solar energy, establishing a robust infrastructure to support innovation. Specifically, by 2001, the country had established thirty research institutes and universities dedicated to the collaborative advancement of materials utilized in solar power cells, positioning China as a major player in the global solar energy market (Zhao et al., 2012). This focused effort has helped China drive technological improvements in solar power technology, such as enhancing the efficiency of solar cells and reducing manufacturing costs. Additionally, China’s commitment to scaling solar energy production is demonstrated by its large domestic and international solar power manufacturers.

Several Chinese companies have emerged as leading figures in solar power equipment, driving the industry by undertaking multiple key responsibilities. These companies are involved in a comprehensive range of activities, including system design, technology research and development, component manufacturing, sales, and after-sales services. This vertically integrated approach has been a key factor in China's dominance of the global solar power market, as it allows for cost-effective production and efficient technological advancements. By focusing on enhancing their technological capabilities, Chinese firms have managed to reduce the costs associated with solar energy production, making it more accessible to a broader market globally. This success has further consolidated China's position as a global leader in the renewable energy sector.

In contrast, Kenya's experience with solar energy and its reliance on renewable energy technologies presents a different challenge. In Kenya, the majority of solar power companies have been involved in supporting the government's rural electrification initiatives, aiming to expand access to electricity in underserved regions (Elmer & Brix, 2014a). While these efforts have made significant progress in improving access to electricity in rural areas, there are notable gaps in technological development within the industry. One of the key shortcomings in Kenya’s solar power sector is the lack of substantial investment in research and development. Many of the country's solar companies allocate minimal resources to R&D, failing to reinvest a portion of their annual earnings back into enhancing their technological capabilities. This lack of focus on innovation means that Kenyan companies are less competitive in the global solar market and have fewer opportunities to improve the efficiency and reliability of their solar systems (Marigo et al., 2020). This approach has significant implications for the long-term sustainability and growth of the solar sector in Kenya.

Investing in non-renewable energy infrastructure presents a significant obstacle to the development and expansion of renewable energy technologies. When a country directs resources toward non-RES, such as fossil fuels, it diverts valuable financial and technical resources away from clean energy solutions, thus hindering innovation in the renewable energy sector (Li et al., 2022). This diversion of funds signifies a missed opportunity not only for improving energy security but also for creating jobs, fostering economic growth, and ensuring the long-term viability of the energy industry. By prioritizing non-renewable resources, Kenya is inadvertently delaying the transition to a more sustainable and environmentally friendly energy infrastructure, which could otherwise provide substantial benefits to the country in terms of energy access, economic growth, and environmental protection.

Kenya's heavy reliance on finite energy resources underscores the need to transition to RES in order to ensure long-term energy stability and sustainable economic growth. The adoption of renewable energy solutions, particularly solar energy, is crucial to reducing the country’s dependence on fossil fuels and mitigating the negative effects of climate change. Solar energy, being abundant and readily available in Kenya due to the country's geographical location, presents a promising alternative to conventional energy sources. By focusing on a diversified, low-carbon energy mix, Kenya can reduce its environmental impact and increase its resilience to the challenges posed by climate change (Guilhot, 2022). This transition would help protect the environment, promote economic prosperity, and ensure a sustainable future for generations to come.

Kenya's rapid economic growth and urbanization have placed significant pressure on the country's energy infrastructure. The growing demand for energy, driven by a combination of factors, presents a complex challenge for policymakers, energy providers, and other stakeholders. The expansion of industries such as manufacturing, construction, and services has led to an increased need for energy to sustain economic growth (Rafique et al., 2022). Industries require reliable and affordable electricity to power machinery, production lines, and facilities, which has significantly contributed to the heightened energy demand in Kenya (Bogdanov et al., 2021). As the economy continues to industrialize, it is expected that this demand will only continue to grow, necessitating significant investments in energy infrastructure and production capacity.

Urbanization is another key factor contributing to the growing energy demand in Kenya. As the population becomes increasingly concentrated in urban centers, energy consumption patterns change, with higher energy needs in metropolitan areas. Rapid urbanization places considerable strain on existing energy infrastructure, which may not be adequately prepared to meet the increasing demand for electricity (Bakirtas & Akpolat, 2018). As more people migrate to cities in search of better employment opportunities and living conditions, the demand for energy in urban areas continues to rise. This requires the expansion and modernization of the energy grid, as well as investments in new technologies and generation capacity to ensure reliable electricity supply.

Technological advancements and the growing adoption of electronic devices have also contributed to increased per capita energy consumption in Kenya. The widespread use of mobile phones, computers, household appliances, and other electronic devices has led to an exponential increase in energy demand. These devices consume electricity for their operation, and their growing presence in Kenyan households and businesses has resulted in a higher overall demand for power (Kahouli et al., 2022). As the adoption of digital technologies continues to rise, it is anticipated that energy consumption will further increase, placing additional pressure on Kenya's energy systems (Ren et al., 2021).

Government initiatives aimed at improving access to electricity for underserved populations have also contributed to the rise in energy demand. As part of its rural electrification efforts, the Kenyan government has worked to expand the national grid and provide electricity to remote and rural communities (Avedi, 2020). These efforts are essential for improving the living conditions of underserved populations but come with the challenge of meeting the rising energy needs in these areas. As more people gain access to electricity, their energy consumption patterns will evolve, increasing the overall demand for power (Avedi, 2020; Joshi & Yenneti, 2020; Khaleel & Chakrabarti, 2020). Electrification programs are crucial to improving access to energy but must be accompanied by investments in infrastructure and generation capacity to ensure that the energy supply can meet the growing demand.

The increasing standard of living in Kenya, coupled with rising disposable incomes, has also led to greater energy usage in both commercial and residential settings. As people’s purchasing power increases, they demand more modern appliances, such as air conditioning units, refrigerators, lighting systems, and electronic devices, all of which contribute to higher energy consumption (Verma et al., 2021). As the middle class continues to expand in Kenya, the energy needs of both households and businesses will continue to rise, placing additional strain on the national grid.

The transportation sector, which is heavily dependent on fossil fuels, is another significant contributor to overall energy demand in Kenya. As the country continues to urbanize and industrialize, the demand for transportation services including private vehicles, public transport, and freight—has escalated (Neves et al., 2017). This increased demand for mobility translates to higher energy consumption, particularly in the form of petrol and diesel for vehicles. As Kenya seeks to modernize its transportation infrastructure, there will be a need to invest in alternative energy sources, such as electric vehicles, to reduce the sector's dependence on fossil fuels (Pietzcker et al., 2014).

Addressing the growing energy demand in Kenya presents both challenges and opportunities. If left unchecked, the rising demand for energy could lead to supply shortages, slower economic growth, and social inequalities. However, by taking proactive steps to manage energy consumption and implement efficient energy solutions, Kenya can harness the potential of renewable energy and ensure long-term energy security. A balanced approach is required—one that considers economic growth, environmental sustainability, and social equity in shaping the country's energy future.

Kenya's current energy landscape is dominated by non-renewable sources, such as fossil fuels, which contribute to various environmental challenges. These challenges are compounded by the country's vulnerability to the negative effects of climate change, including droughts, floods, and unpredictable weather patterns (Njogu, 2020). These environmental concerns emphasize the urgent need for a transition toward cleaner, more sustainable energy solutions, such as solar electrification. The burning of fossil fuels for energy production releases greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH4), and nitrous oxide (N_2O), which contribute to global warming and climate change (Lipman & Delucchi, 2002; Siddik et al., 2021). These gases have serious consequences for Kenya's agricultural sector, water resources, and biodiversity, with far-reaching implications for food security and sustainable development (Muigua 2021; Ntinyari and Gweyi-Onyango 2020).

In addition to GHG emissions, the combustion of fossil fuels produces harmful pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM), all of which contribute to air pollution (Hannun and Razzaq 2022; Yang et al. 2021). The adverse health effects of air pollution are well-documented, including respiratory diseases, cardiovascular problems, and premature death (Manisalidis et al.

2020). The detrimental impact of fossil fuel combustion on both the environment and public health underscores the urgency for Kenya to prioritize renewable energy solutions that can reduce reliance on fossil fuels and improve air quality.

Additionally, Kenya's reliance on biomass, including firewood and charcoal, for cooking and heating exacerbates environmental degradation. Unsustainable harvesting of these biomass resources leads to deforestation, soil erosion, and the loss of biodiversity, further contributing to environmental degradation (Danlami, 2018; Duguma et al., 2020; Okoko, 2018). Furthermore, the extraction, refinement, and transportation of fossil fuels can result in water pollution through spills, leaks, and runoff. This contamination of water sources jeopardizes ecosystems, drinking water supplies, and aquatic life, with far-reaching implications for human health and livelihoods (Danlami, 2018; Duguma et al., 2020; Okoko, 2018).

Kenya’s vulnerability to the effects of climate change presents additional challenges, particularly in terms of food security, water availability, and the displacement of communities (Abdikadir, 2021; Kalele et al., 2021). The adoption of solar electrification can mitigate some of these challenges by reducing greenhouse gas emissions, promoting sustainable development, and supporting climate change adaptation efforts. By shifting toward cleaner energy sources, Kenya can contribute to global climate action and fulfill its commitments under the Paris Agreement.

To successfully integrate solar power into Kenya's energy systems, the country must engage in strategic planning, investment, and policy support. While Kenya is blessed with abundant solar resources due to its geographical location, effective utilization of these resources requires overcoming significant technical challenges. For instance, the current algorithms used for Maximum Power Point Tracking (MPPT) in solar power systems are often inadequate in optimizing solar energy capture. These traditional MPPT algorithms fail to adapt to environmental factors such as intermittent cloud cover, shading, and variations in solar radiation, leading to inefficiencies in solar energy generation (Belhachat & Larbes, 2018; Kumar et al., 2023). This limitation hampers the widespread adoption of solar electrification, as systems that rely on these algorithms may not achieve optimal performance, resulting in underutilization of available solar resources.

To maximize the potential of solar power in Kenya, it is essential to develop more advanced MPPT algorithms that can dynamically adjust to changing environmental conditions. By improving the efficiency of solar energy capture and maximizing the output of solar power systems, Kenya can enhance its efforts toward achieving widespread solar electrification and reducing its dependence on non- RES.

2.4.3.3 University-Industry Linkages

Higher education institutions are central to the growth and evolution of both national and regional innovation ecosystems. Universities are at the heart of research, development, and technological advancements, often pioneering scientific progress that transcends borders. As innovation hubs, universities play an indispensable role in nurturing creative thinking, advancing scientific inquiry, and driving solutions to complex societal challenges (Osman, 2012a). In recent years, an increased focus has been placed on the role of higher education institutions in contributing to innovation, particularly with regard to their impact on economic progress. Their ability to generate knowledge, foster innovation, and translate research into real-world applications positions universities as fundamental drivers of national and regional development. This is particularly true in countries like Kenya, where universities have made substantial contributions to the growth of RES and the broader energy sector.

In the context of Kenya, universities have long been important players in the country's National Innovation System, actively participating in efforts to develop and implement renewable energy solutions. The transition to renewable energy is a critical priority for Kenya, driven by both environmental concerns and the need to enhance energy security and economic growth. Kenya's universities have been at the forefront of this transition, engaging in research and development, training skilled professionals, and fostering collaborations with industry stakeholders to drive the adoption of renewable energy technologies.

A prime example of such contributions is the Strathmore Energy Research Centre (SERC), established in 2012. SERC has emerged as a leader in advancing renewable energy technologies across Africa, particularly in the field of solar energy. The center has been instrumental in developing innovative research initiatives aimed at promoting renewable energy solutions, focusing on projects that are sustainable, affordable, and scalable. SERC's commitment to supporting the renewable energy sector is evident in its diverse activities, which range from providing specialized training to technicians, to conducting cutting-edge technical research that addresses the most pressing challenges in the energy sector.

One of SERC's core strengths lies in its ability to train highly skilled technicians who are proficient in solar power technology, including installation, maintenance, and servicing. This is particularly important in the context of Kenya’s growing demand for solar energy solutions, especially in rural areas where the electricity grid is often inaccessible. By equipping local technicians with the skills needed to install and maintain solar power systems, SERC is contributing not only to the proliferation of solar technology but also to the sustainability of these systems. The training programs offered by SERC have empowered countless individuals with the expertise needed to support the growing solar energy market in Kenya and beyond.

Moreover, SERC's focus on fostering awareness of renewable energy technologies is also a key aspect of its mission. Through various outreach programs, community engagement initiatives, and partnerships with government agencies, the center has worked to increase public understanding of the benefits and potential of renewable energy. By raising awareness about the advantages of clean energy solutions, SERC is helping to create a more favorable environment for the adoption of renewable energy technologies, which is essential for the widespread implementation of solar power across the region.

SERC’s commitment to innovation is also reflected in its collaborations with industry partners and stakeholders. The center works closely with energy companies, government agencies, and international organizations to promote the development and deployment of renewable energy solutions. Through these partnerships, SERC is helping to bridge the gap between research and practical applications, ensuring that the knowledge generated within academic institutions is translated into real-world solutions. By connecting academia with industry, SERC is playing a pivotal role in advancing Kenya's energy sector and contributing to the country's broader development goals.

In addition to SERC, Maseno University’s Center for Research on New and Renewable Energies (CNRRE) has also made significant contributions to the promotion and application of renewable energy technologies in Kenya. Established with the goal of conducting research on various forms of renewable energy, CNRRE has become a leading institution in advocating for the utilization of RES, particularly in rural areas.

The center's work spans multiple RES, including bio-energy, geothermal, solar, and wind energy, with a strong emphasis on exploring local solutions that can address the energy needs of remote and underserved communities.

CNRRE has been instrumental in advancing the application of renewable energy technologies in rural areas, where access to electricity is limited. In these regions, traditional energy sources are often expensive and unreliable, and renewable energy presents a more sustainable and cost-effective solution. By focusing on the local context, CNRRE is working to identify renewable energy solutions that are both technically feasible and economically viable for rural communities. This includes exploring the use of solar energy for off-grid electrification, as well as the potential for harnessing wind and geothermal energy to power rural industries and households.

The center's research efforts are not limited to the technical aspects of renewable energy; CNRRE is also committed to understanding the socio-economic and environmental implications of renewable energy adoption. Through its interdisciplinary approach, CNRRE is investigating how renewable energy can contribute to poverty alleviation, job creation, and environmental sustainability. By combining technical expertise with a deep understanding of local communities and their needs, the center is helping to design renewable energy solutions that have a lasting and positive impact on society.

Maseno University, like Strathmore University, recognizes the importance of cultivating a new generation of energy professionals who are equipped to address both the local and global challenges of the energy sector. The university’s energy technology programs are specifically designed to produce graduates who are not only skilled in the technical aspects of renewable energy but also capable of navigating the complex policy, economic, and social dimensions of energy systems. These programs are essential in preparing students for the challenges and opportunities that lie ahead in the renewable energy sector.

By fostering collaboration between academia and industry, Maseno University is creating a robust ecosystem for the development and adoption of renewable energy technologies. The university’s partnerships with government agencies, NGOs, and private sector companies are helping to create a favorable environment for the deployment of renewable energy solutions. These collaborations are essential for accelerating the transition to a more sustainable energy future in Kenya and throughout the region.

The role of universities in Kenya’s renewable energy landscape is not limited to research and education; they are also active participants in the development of policies and strategies that support the growth of the renewable energy sector. Through their engagement with policymakers, universities are helping to shape the direction of Kenya’s energy policy, ensuring that it aligns with the country’s long-term sustainability goals. For example, universities are actively involved in providing input on the implementation of Kenya’s Vision 2030, which includes the promotion of renewable energy as a key pillar of the country’s development strategy.

In addition to their involvement in policy development, universities also play a critical role in the implementation of energy projects. Through their research centers and collaborations with industry partners, universities are actively contributing to the design and implementation of renewable energy projects across Kenya. These projects often serve as pilot initiatives that demonstrate the viability and benefits of renewable energy technologies, helping to build confidence among stakeholders and encouraging the wider adoption of these solutions.

Kenyan universities, such as Strathmore University and Maseno University, are also helping to foster an entrepreneurial spirit within the renewable energy sector. By supporting students and researchers in developing their own renewable energy startups and initiatives, universities are contributing to the growth of a vibrant clean energy sector. This entrepreneurial focus is essential for driving innovation and ensuring that Kenya remains at the forefront of renewable energy development in Africa.

The collaboration between universities, government agencies, and industry stakeholders is essential for accelerating the transition to renewable energy in Kenya. Through their research, training, and policy advocacy, universities are providing the knowledge and expertise needed to drive the widespread adoption of renewable energy technologies. This collaboration is also critical for ensuring that renewable energy solutions are tailored to the unique needs and circumstances of Kenya and its communities.

The future of renewable energy in Kenya is closely tied to the continued efforts of universities and their role in driving innovation. As the country works to expand its renewable energy capacity and meet its energy demands, universities will continue to play a crucial role in shaping the future of the energy sector. By conducting cutting-edge research, developing new technologies, and fostering collaboration between academia, industry, and government, universities are helping to pave the way for a more sustainable, resilient, and prosperous energy future in Kenya.

Kenyan universities are designing their energy technology programs with a clear objective: to produce individuals who are equipped to tackle the complex energy challenges facing both Kenya and the world. These programs are designed to provide students with the technical skills, problem-solving abilities, and entrepreneurial mindset needed to succeed in the rapidly evolving renewable energy sector. By focusing on both the local and global dimensions of energy challenges, universities are preparing the next generation of energy professionals to lead the transition to a more sustainable energy future.

Lastly, the role of higher education institutions in promoting renewable energy and driving innovation cannot be overstated. Universities in Kenya, through their research centers, educational programs, and collaborations with industry and government, are making significant contributions to the development and adoption of renewable energy technologies. Their efforts are helping to shape the future of the energy sector, both locally and regionally, and are critical to the achievement of Kenya’s long-term energy and development goals. Through continued investment in research, education, and innovation, Kenyan universities will remain at the forefront of the renewable energy revolution, playing a key role in building a sustainable and resilient energy future for the country and the broader region.

2.4.3.4 Policy Experience

The African continent is known for its vast solar energy potential due to its abundant sunshine, which makes it one of the most promising regions globally for solar energy generation. Over recent years, solar energy, especially through solar power technology, has become an increasingly viable option for electricity generation in various regions across Africa. The growth of solar power technologies, which harness the sun's energy and convert it into electrical power, has proven particularly significant for rural electrification, off-grid solutions, and large-scale energy production (Elmer & Brix, 2014b). Kenya, like many other African nations, has embraced solar power as a primary solution to address the energy deficit in remote, off-grid areas where extending national grid connections has traditionally been difficult or economically unfeasible.

However, one country that stands out in terms of its early recognition of solar energy's potential for large-scale electricity generation is Morocco. Unlike many African countries, which initially focused on small-scale or decentralized applications, Morocco made significant investments in large-scale solar projects and has positioned itself as a leader in solar energy development within the continent. Morocco’s ambitious strategy has sought to diversify the country’s energy sources, reduce reliance on imported fossil fuels, and reduce greenhouse gas emissions, all while fostering a more sustainable and resilient energy infrastructure. Morocco’s achievements with large-scale solar power initiatives have garnered international attention and serve as a model for other African countries.

A notable example of Morocco's proactive approach to solar energy integration is a project where solar and wind energy technologies were combined to create a 500 MWp solar power plant. This innovative project was spearheaded by Attari, Elyaakoubi, and Asselman (2016), who sought to maximize the renewable energy potential of the region by capitalizing on both solar and wind resources to ensure a more stable and reliable power generation capacity. This kind of integrated approach to renewable energy generation underscores Morocco's vision for a sustainable energy future and offers insights into how other African nations can blend different renewable sources to address their power needs.

In contrast, Rwanda’s adoption of solar energy has been somewhat more gradual but equally significant. In 2015, Rwanda was still in the early stages of adopting solar power, with an emerging interest from both the government and the private sector in using solar power technology for rural electrification. At that time, there were approximately eight companies operating in Rwanda, mostly funded by international donors, which were focused on installing solar systems in government institutions. According to Hansen et al. (2015), these efforts laid the foundation for a growing market in the country, as private households began to show increased interest in adopting solar power systems to meet their energy needs. The authors noted that there was a notable rise in the number of installations and a corresponding increase in the adoption of solar energy in Rwanda during the mid-2010s, signaling a shift toward more widespread use of renewable energy.

Although Rwanda had been a latecomer to solar power compared to some of its African counterparts, it quickly became a leader in terms of grid connections in East Africa, surpassing both Kenya and Tanzania in this regard (Hansen et al., 2015). This achievement is a testament to Rwanda's strong commitment to expanding access to electricity for its population, including rural communities that had previously been underserved by the national grid. The country's success in grid connections is particularly noteworthy given that Rwanda, like many other African countries, faces challenges related to population density, geographic distribution, and infrastructure limitations that make the expansion of the grid a complex and costly endeavor.

However, despite Rwanda's significant progress in improving grid access, it has also witnessed impressive growth in off-grid solar power systems, especially in rural areas, since 2009. As reported by Kirubi et al. (2009b), the implementation of solar power systems in off-grid rural areas has been a key factor in improving electricity access for households and small businesses in remote regions of the country. This shift toward off-grid solar solutions has been particularly critical in a country like Rwanda, where providing electricity to the rural population is often more cost-effective and efficient through decentralized systems rather than extending the national grid to distant areas.

This surge in off-grid solar adoption can be attributed to the strong policy direction that has been set by the Rwandan government, particularly through the Rwandan Vision 2020. As noted by Nygaard et al. (2015a), this long-term national development plan emphasizes the importance of renewable energy technologies as part of the country's broader economic and social development goals. By focusing on solar power as a key component of Rwanda's energy future, Vision 2020 has facilitated the development of a supportive regulatory environment, the mobilization of international investment, and the creation of local partnerships that have collectively contributed to the widespread adoption of solar energy.

In addition to Vision 2020, Rwanda's Monetary Growth and Poverty Reduction policy plays a crucial role in furthering the integration of solar energy into the country's energy mix. As outlined by Nygaard et al. (2015b), this policy encourages the collaboration of the Rwandan government with private sector actors to promote the distribution and sale of solar power systems, particularly to rural households and small enterprises. By establishing a regulatory framework that fosters the rapid integration of solar technologies, the government has made it easier for private companies to introduce innovative, affordable solar solutions. This collaborative approach has also led to the creation of various financial mechanisms and incentives that make it easier for Rwandans to access and adopt solar technology.

The lessons learned from Rwanda's experiences with solar power and rural electrification offer valuable insights that can be used to inform policy and strategy development in Kenya. Much like Rwanda, Kenya faces similar challenges with providing electricity access to rural populations, particularly in remote regions that are far from the national grid. By looking to Rwanda's example, Kenya could accelerate the adoption of solar power and other renewable energy technologies through a combination of favorable policies, public-private partnerships, and investment in infrastructure that supports off-grid solutions.

Moreover, the successes of both Morocco and Rwanda can serve as valuable blueprints for other countries in Africa that are seeking to improve energy access and transition to a more sustainable energy future. In particular, Morocco's large-scale solar projects demonstrate the potential for solar power technologies to contribute to national energy needs, while Rwanda's focus on off-grid solar solutions shows how smaller-scale systems can be deployed in rural areas to meet local needs. Both approaches are crucial for addressing Africa's diverse energy challenges, and they offer lessons that can be applied to various national contexts across the continent.

Africa's abundant solar resources, coupled with advancements in solar power technology, provide a unique opportunity for the continent to leapfrog traditional energy infrastructure and move directly into renewable energy solutions. While countries like Morocco have embraced large-scale solar initiatives, others, such as Rwanda, have focused on decentralized, off-grid systems to ensure that rural populations can benefit from clean and reliable electricity. The experiences of both Morocco and Rwanda highlight the importance of sound policy, regulatory frameworks, and public-private partnerships in driving the adoption of solar energy. These experiences offer valuable lessons for other countries, including Kenya, in fostering the development and integration of solar power technologies to meet growing energy demands while promoting environmental sustainability and economic growth.

2.4.3.5 Political Barriers

Effective policy measures play a crucial role in facilitating the widespread adoption of solar power technology, which is increasingly seen as a key solution to addressing energy access and sustainability challenges globally. The adoption of solar power systems can significantly reduce reliance on fossil fuels, mitigate environmental impacts, and enhance energy security, particularly in regions where the electrical grid infrastructure is inadequate or non-existent. However, the successful adoption and integration of solar power systems depend heavily on the stability and coherence of the policies that support such technologies. Policies that lack consistency or stability, such as sudden subsidy removals or inconsistent regulatory frameworks, can create significant barriers to the adoption of solar power technologies. In many cases, these disruptions discourage both potential investors and consumers from embracing renewable energy options, as they introduce uncertainty into the market and undermine long-term planning efforts. To encourage the adoption of solar power systems, effective policy measures must ensure a stable and predictable environment that supports both short-term adoption and long-term investments in the renewable energy sector (Hansen et al., 2015).

Kenya, like many countries in sub-Saharan Africa, has recognized the importance of integrating renewable energy technologies into its energy mix to address its growing energy demand and to promote environmental sustainability. Several policy measures have been put in place by the Kenyan government to promote the use of solar power technology, and to create an enabling environment for solar energy solutions. These policies are designed to address the various barriers that hinder the large-scale deployment of solar power systems, particularly in rural and off-grid areas where energy access remains a challenge. Key policies implemented in Kenya include the

Kenya Rural Electrification Master Plan, a Feed-in Tariff (FiT) initiative, and the Vision 2030 development plan. These policies, while essential in promoting solar power adoption, have encountered challenges in terms of coordination and implementation, which have hindered the desired growth of the solar power sector.

The Kenya Rural Electrification Master Plan (Borah et al., 2014) is a strategic policy document designed to address the electrification challenges in rural areas, where access to electricity is limited. The plan emphasizes the need for solar power solutions in off-grid and remote areas of the country, given the high potential for solar energy in Kenya. By prioritizing solar power for rural electrification, the government seeks to expand energy access, reduce dependency on biomass for cooking, and improve the quality of life for rural populations. The implementation of the Kenya Rural Electrification Master Plan has been accompanied by initiatives aimed at providing financing mechanisms, such as subsidies and low-interest loans, to support the adoption of solar power technology in rural areas.

In addition to the rural electrification plan, the Kenyan government introduced the Feed-in Tariff (FiT) policy, which was initially launched in 2008 (Republic of Kenya, 2014b). The FiT policy allows independent power producers (IPPs) to sell electricity generated from renewable sources, including wind, hydro, and solar, to the national grid at a guaranteed price. This policy was designed to create a stable market for renewable energy, particularly for smaller-scale projects, by offering long-term contracts that provide a secure revenue stream for investors. The FiT has played a pivotal role in attracting both domestic and foreign investment in Kenya’s renewable energy sector, as it reduces the financial risks associated with renewable energy projects.

In 2012, the FiT policy was updated to include solar power, allowing solar energy producers to benefit from the same incentives that were extended to wind and hydro producers. The incorporation of solar power into the FiT policy was a significant step towards enhancing the role of solar power systems in Kenya’s energy mix. The government’s support for entrepreneurs interested in investing in solar power technology, especially through the FiT, has been a critical element in encouraging the development of solar projects and increasing the capacity of grid-connected solar power systems. Furthermore, Kenya’s Vision 2030, a long-term development blueprint, underscores the importance of renewable energy in achieving sustainable economic growth and social development. Vision 2030 envisions a future where Kenya becomes a middle-income country, and energy plays a central role in achieving this goal. The integration of renewable energy technologies, including solar power, is seen as a key enabler of this vision, particularly in rural development and industrialization efforts.

While these policies are commendable in their intentions, their implementation has not been without challenges. One of the major obstacles to the widespread adoption of solar power technology in Kenya is the lack of effective coordination between the various government agencies and stakeholders involved in the energy sector. The implementation of renewable energy policies often requires collaboration between the Ministry of Energy and Petroleum, the Rural Electrification Authority, local governments, the private sector, and international development partners. However, poor coordination among these stakeholders has led to inefficiencies and delays in the roll-out of solar power projects. In some cases, the implementation of policies has been inconsistent or entirely lacking, particularly in remote and rural areas where the need for solar power is most urgent (Hansen et al., 2015).

Additionally, the allocation of investments in the renewable energy sector, including solar power projects, is often influenced by political considerations rather than technical assessments. As a result, investments may be channeled into projects that align with the political interests of powerful stakeholders, rather than those that offer the greatest potential for economic and environmental benefits. Large-scale solar power projects, in particular, are major infrastructure initiatives that typically involve multiple stakeholders, including government agencies, private investors, and international organizations. These projects are often deeply intertwined with political dynamics, as politicians seek to secure funding and political support for initiatives that align with their agendas. The involvement of multiple stakeholders with competing interests can lead to lengthy negotiations and delays, preventing the timely deployment of solar power projects.

Despite these challenges, there have been notable successes in Kenya’s renewable energy sector, particularly in the development of large-scale solar power projects. For example, the 50 MW Garissa Solar power Plant, which was commissioned in 2018, is one of the largest solar power plants in East Africa. This project was developed under the government’s FiT policy and has played a significant role in increasing the share of solar energy in Kenya’s national grid. Similarly, the government has continued to promote decentralized solar systems, such as solar home systems and mini-grids, to provide electricity to rural households and small businesses. These efforts have helped to improve energy access in off-grid areas, thereby contributing to the achievement of Kenya’s energy access goals.

However, as Elmer et al. (2018) note, the promotion of renewable energy in Kenya is not solely driven by environmental concerns or the desire to mitigate climate change. Instead, the primary motivation is the need to extend electricity access to as many people as possible, as quickly as possible. This urgency is driven by the country's growing population and the need to support economic growth and development. In many instances, the focus on rapid electrification has led to tensions between the goals of "growth," "inclusiveness," and "sustainability." While increasing the number of people with access to electricity is a priority, it is equally important to ensure that the energy supplied is sustainable and does not exacerbate environmental degradation.

The conflicting objectives of growth, inclusiveness, and sustainability can create challenges in the design and implementation of renewable energy policies. For example, the expansion of electricity access may be prioritized over the environmental impact of the energy sources used, leading to the adoption of solutions that are not necessarily the most sustainable in the long term. This tension is particularly evident in the case of large-scale infrastructure projects, such as hydroelectric dams and coal-fired power plants, which may be more politically feasible but are not as environmentally friendly as solar power or wind energy. As such, policymakers in Kenya must carefully balance the competing demands of development and sustainability to ensure that the adoption of renewable energy technologies, such as solar power, contributes to the country's long-term energy and environmental goals.

While Kenya has made significant strides in promoting the adoption of solar power technology through a range of policy measures, challenges remain in ensuring the effective implementation of these policies. The instability of incentives, poor coordination, and political influences on investment allocation have all played a role in limiting the growth of the solar power sector in Kenya. Nevertheless, the country's efforts to integrate renewable energy into its energy mix are commendable, and the continued development of policies that prioritize sustainability, inclusiveness, and growth will be essential in realizing the full potential of solar power technology in

Kenya. By addressing the existing challenges and improving policy coordination, Kenya can position itself as a leader in the adoption of solar power technology in Africa, contributing to the achievement of its energy access and sustainability goals.

2.5 Solar Energy Storage Solutions

Efficient energy storage options like batteries, pumped hydro storage, and thermal energy storage address the intermittent nature of solar power generation. These storage systems allow for the collection and utilization of solar energy during times of limited sunlight or increased demand, enhancing the stability and dependability of the grid.

2.5.1 Pumped Hydro Storage

Transitioning from fossil fuel-based electricity generation to RES such as solar power systems necessitate the incorporation of storage or flexibility mechanisms to manage the intermittency inherent in these sources. RES, particularly solar and wind, are inherently variable, as their generation depends on weather conditions and time of day. This variability poses challenges for grid stability and reliability, making energy storage systems essential for balancing supply and demand. However, batteries, which are commonly used for energy storage, face significant constraints. They are unable to provide extended storage capacity spanning multiple hours or discharge over prolonged durations. Additionally, batteries have a finite lifespan, beyond which their performance cannot be assured. This limitation makes them less suitable for large-scale, long-duration energy storage needs. Furthermore, batteries demand considerable housing space to accommodate their substantial power output, which can be a logistical challenge in densely populated or geographically constrained areas.

Pumped Hydro Energy Storage (PHES) offers a viable solution to these challenges. PHES involves the transfer of water's gravitational potential energy from a lower reservoir to a higher one, functioning as a controllable reservoir to supply turbines as needed (Lund et al., 2011a). This method of energy storage is highly efficient and scalable, making it one of the most reliable options for grid-scale energy storage. PHES stands as the most extensive type of grid energy storage currently accessible, constituting approximately 95% of all active and monitored storage systems (Williams, 2016a). Its widespread adoption is a testament to its effectiveness in managing the intermittency of RES.

The initial PHES systems were put into operation in the Alpine regions of Switzerland, Austria, and Italy during the 1890s. These early systems laid the groundwork for the development of modern PHES facilities, which have since become a cornerstone of energy storage infrastructure worldwide. Globally, the installed capacity of PHES now exceeds 181 GW, with around 29 GW located in the United States (Lund et al., 2011b). This significant capacity highlights the importance of PHES in the global energy landscape. Modern PHES facilities boast a cycle efficiency of approximately 80% (Schlecht & Weigt, 2015; Williams, 2016b), enabling surplus electricity from base-load power sources like coal or nuclear, as well as from variable REs, to be stored for later use during periods of increased demand. This high efficiency makes PHES an attractive option for integrating renewable energy into the grid.

The reservoirs employed in PHES systems are typically smaller in size compared to conventional hydroelectric dams with similar power capacity, and their operational periods often span less than half a day. This compact design allows for greater flexibility in site selection and reduces the environmental impact compared to traditional hydroelectric projects. Chile, for example, possesses abundant solar and wind resources, which are progressively utilized to substitute fossil fuel-based generation. The assessment focused on the repercussions of extensively integrating these variable REs for grid-scale electricity storage (Maximov et al., 2019a). This research devised a cost-centered linear optimization model for the Chilean electricity system to examine and enhance different scenarios involving REs generation, transmission, and energy storage up to 2050. The findings indicated that in the baseline scenario, which involves retiring aging coal plants without introducing new coal and large hydro generation, the gap in generation could be bridged by solar power, concentrated solar power, and flexible gas generation, resulting in a 78% decrease in carbon dioxide emissions. Incorporating solar power for on-grid storage boosts the solar solar power proportion, consequently leading to a 6% reduction in operational and investment expenses by 2050 (Maximov et al., 2019b). These results underscore the potential of PHES to facilitate the transition to a low-carbon energy system.

Switzerland has emerged as a frontrunner in power storage within Europe, leveraging its unique geographical advantages to develop advanced energy storage solutions (Limpens & Moret, 2019). The country benefits from its mountainous terrain, abundant snow, and glaciers, which provide ideal conditions for the advancement of hydro technology. Switzerland's HEP generation is highly developed and mature, making it a key player in the European energy market. Consequently, Switzerland plays a crucial role in providing backup supply to the Western European electric power system and serves as a means of storing reserve power (Lang et al., 2016; Schlecht & Weigt, 2015). Effective power management and storage are essential for Switzerland to achieve a fully renewable energy-based system. The country employs two primary hydro storage systems: PHES and hydro systems utilizing natural inflows to reservoirs, which are then utilized to power turbines as needed. These systems enable Switzerland to balance supply and demand, ensuring grid stability even with high levels of renewable energy penetration.

The growing presence of REs in Australia's electricity blend is driving a shift away from reliance on fossil fuels. Research conducted by Generation (2016) concentrated on the South West Interconnected System in Western Australia, simulating various scenarios with high penetration of renewables including wind, solar power, and PHES. These scenarios were assessed using a chronological dispatch model that focused on technologies already extensively deployed, i.e., exceeding 150 GW. The findings revealed that achieving 100% penetration of wind and solar power electricity is feasible while maintaining grid stability, albeit with the inclusion of PHES. Moreover, integrating PHES enables a RES share exceeding 90% while still maintaining competitive electricity supply costs. These results highlight the critical role of PHES in enabling high levels of renewable energy integration while ensuring grid reliability and affordability.

A study conducted by Canales, Jurasz, & Beluco (2020) utilized the Hybrid Optimization of Multiple Energy Resources (HOMER) software to simulate a PHES system and a geothermal plant on Ometepe island, Nicaragua. This island was selected due to its access to wind, solar, and geothermal resources, along with the presence of an inactive volcano with a crater that could function as the upper reservoir for the PHES system. Various system setups were illustrated, and the outcomes indicated that PHES technology can fulfill the base load demand of the system. This consequently lowers the necessary installed capacity of alternative power resources and reduces both storage needs and surplus electricity generation. The study demonstrates the versatility of PHES in integrating multiple RES and optimizing energy systems in remote or resource-constrained areas.

Zimbabwe, like many African nations, depends on power imports to satisfy its energy requirements, posing a threat to the country's energy security. Various studies have been undertaken to evaluate the viability of hybrid power generation systems, integrating intermittent sources like solar power energy, with or without storage, to optimize both technical and economic feasibility. An example of such research, conducted by Al-ghussain et al. (2020), compared the technological and economic aspects of standalone wind or solar power systems with hybrid solar power /wind systems. The hybrid setup prioritized the optimization of intermittent energy sources. Findings indicated that the levelized cost of electricity (LCOE) was equal to or lower than the local grid tariff. Additionally, the research highlighted that integrating REs would enhance energy security and decrease reliance on imported energy. These findings are particularly relevant for countries like Zimbabwe, where energy security is a pressing concern.

In Zimbabwe's Manicaland province, the Osborne dam on the Odzi River is the site for the construction of a 2,000 MW PHES plant, accompanied by a 300 MW solar power plant. This marks the country's inaugural endeavor of this nature, aimed at offering grid support during peak hours when existing capacity is insufficient. Zimbabwe experiences peak electricity demand for approximately 8.5 hours daily (Makonese, 2018; Profile, 2016). The integration of PHES with solar power generation in this project represents a significant step toward enhancing the country's energy security and reducing its reliance on imported power. By leveraging its natural resources, Zimbabwe can develop a more resilient and sustainable energy system.

Based on the preceding information, PHES emerges as a well-established and proven technology for large-scale energy storage. With strategic coordination, countries like Kenya could achieve greater integration of solar solar power by leveraging hydropower to offset fluctuations in solar power output. This approach would result in fewer interruptions in electricity supply, as it relies on both solar and hydroelectric power. By combining these RES with PHES, Kenya can enhance its energy security, reduce its carbon footprint, and ensure a stable and reliable electricity supply for its population. The successful implementation of PHES in various regions around the world demonstrates its potential to play a pivotal role in the global transition to renewable energy.

2.5.2 Thermal Energy Storage

Solar energy, which is a clean and abundant renewable resource, holds immense potential for addressing the world's growing energy needs (Rose et al., 2016). As the global demand for energy continues to rise, solar energy offers a sustainable and environmentally friendly solution that can help mitigate dependence on fossil fuels and reduce greenhouse gas emissions. The sun emits an enormous amount of energy daily, and harnessing even a fraction of this energy can significantly contribute to meeting the world's electricity and thermal energy requirements.

solar power and concentrated solar power (CSP) systems are two primary technologies used to harness solar energy (Alami et al., 2023; Sharma et al., 2022). These two technologies differ in their methods of capturing and converting solar radiation into usable energy. solar power systems, which are widely deployed in residential, commercial, and industrial applications, directly convert sunlight into electricity using semiconductor materials. This technology has seen rapid advancements in recent decades, leading to higher efficiencies and lower costs. CSP systems, on the other hand, utilize mirrors or lenses to focus solar radiation onto a receiver, where the concentrated heat is used to generate steam and drive turbines for electricity production. Unlike solar power systems, CSP has the added advantage of incorporating thermal energy storage (TES), allowing for electricity generation even when sunlight is unavailable (Sharma et al., 2022).

Both solar power and CSP technologies have witnessed significant advancements, leading to cost reductions and increased efficiency over the years (Islam et al., 2018; Sharma et al., 2022). Continuous research and development have improved solar panel efficiency, durability, and affordability, making solar energy more competitive with conventional fossil fuel-based power generation. Innovations in CSP technology, such as advanced receiver designs and improved thermal storage solutions, have further enhanced its viability as a large-scale RES. However, despite these advancements, one of the primary challenges hindering the widespread adoption of solar power is its inherent intermittency due to variations in weather and daylight hours (Wu et al., 2022). Unlike fossil fuel plants, which can operate continuously, solar power generation fluctuates based on sunlight availability. This intermittency poses challenges for grid stability and energy reliability, particularly in regions where solar energy penetration is high.

TES emerges as a promising solution to mitigate this intermittency, offering a reliable means of storing solar energy for use during periods of high demand or low sunlight (Sadeghi, 2022). By storing excess solar energy in the form of heat, TES enables solar power plants to provide a steady and controllable energy supply, thus enhancing grid integration and reducing the reliance on backup fossil fuel generators. TES systems function by capturing and storing the heat energy produced by solar collectors during periods of maximum sunlight (Alva et al., 2018). This stored heat can then be released on demand to generate electricity or provide heating and cooling, effectively extending the availability of solar power beyond daylight hours (Alva et al., 2018).

Several TES technologies exist, including molten salt, phase change materials, and thermal storage in rocks or concrete (Alva et al., 2018; K. El Alami et al., 2020; Junaid et al., 2021). Each of these technologies has unique characteristics that influence their performance, efficiency, and economic feasibility. Phase change materials (PCMs), for instance, store and release thermal energy through phase transitions, allowing for high energy density storage. Thermal storage in rocks or concrete involves storing heat within solid materials, which can be used for building heating applications or industrial processes. Among these options, molten salt stands out as a particularly promising solution due to its high energy density, excellent thermal properties, and proven reliability in utility-scale solar power plants (Bernagozzi et al., 2019; Diez et al., 2021; Magnusson et al., 2020).

In CSP systems, molten salt serves dual roles as a heat transfer fluid in solar collectors and a thermal storage medium in insulated tanks (Arias et al., 2022; Bonk et al., 2018; Ding & Bauer, 2021). This dual functionality enhances the efficiency of CSP plants by minimizing heat loss and ensuring continuous energy production. The ability to store heat in molten salt allows CSP plants to generate electricity continuously, even after sunset or during cloudy periods, thus enhancing grid stability and reliability (Bonk et al., 2018). Unlike solar power systems, which require battery storage to mitigate intermittency, CSP with TES offers a more cost-effective and scalable solution for large-scale renewable energy deployment.

Research has reported that integrating TES in solar power plants can significantly enhance their capacity factor and dispatchability, making them more competitive with conventional power sources (Codd et al., 2020; Liu et al., 2022; C. Wang et al., 2022; Zurita et al., 2021). The capacity factor, which represents the ratio of actual energy output to the maximum possible output, is a critical parameter in evaluating the performance of power plants. A study by Gutiérrez, Haro, and Gómez-Barea (2021) highlights the potential of TES to increase the capacity factor of CSP plants from around 30% to over 70%, substantially improving their economic viability and contribution to grid stability. This increase in capacity factor makes CSP with TES a more attractive option for utilities seeking reliable and dispatchable RES.

Additionally, the ability to deliver consistent and predictable power output reduces grid instability caused by fluctuations in solar generation, thereby enhancing grid reliability (Shafiullah et al., 2022). The integration of TES allows solar power plants to provide firm capacity, meaning they can supply electricity on demand, similar to conventional power plants. This capability is particularly valuable in regions with high renewable energy penetration, where grid operators must balance supply and demand in real time. By smoothing out variations in solar power output, TES helps prevent voltage fluctuations, frequency deviations, and other grid stability issues.

TES also provides environmental advantages by decreasing the requirement for backup fossil fuel power plants and reducing greenhouse gas emissions linked to energy generation (Achkari & El Fadar, 2020). The ability to store and dispatch solar energy reduces reliance on natural gas and coal-fired power plants, which are often used as backup sources during periods of low solar generation. By displacing fossil fuel generation, TES contributes to lowering carbon emissions and mitigating climate change. Furthermore, the widespread adoption of TES can facilitate higher penetration of solar energy into the grid, accelerating the transition toward a low-carbon energy system (Aghahosseini et al., 2023; Ryland & He, 2024).

Beyond its environmental benefits, TES offers economic advantages by improving the cost-effectiveness of solar power plants. The ability to store and utilize excess solar energy reduces curtailment, where surplus generation is wasted due to grid constraints. This maximization of solar energy utilization enhances the return on investment for solar projects, making them more financially viable. Moreover, TES enables solar power plants to participate in energy markets by providing ancillary services such as frequency regulation and peak shaving, further enhancing their economic value.

The role of TES extends beyond electricity generation to various industrial and residential applications. In industrial settings, TES can provide process heat for manufacturing, reducing reliance on fossil fuel-based heating systems. In residential and commercial buildings, TES can be integrated into heating, ventilation, and air conditioning (HVAC) systems to improve energy efficiency and reduce peak electricity demand. By enabling the efficient use of thermal energy, TES contributes to energy conservation and cost savings across multiple sectors.

Solar energy is a crucial component of the global renewable energy transition, offering a clean and abundant energy source that can help meet the world's growing energy demands. However, the intermittency of solar power presents challenges for grid integration and reliability. TES addresses these challenges by providing a reliable means of storing and dispatching solar energy, enhancing the capacity factor and economic viability of solar power plants. Among various TES technologies, molten salt has emerged as a leading solution due to its high energy density and proven effectiveness in CSP applications. By enabling continuous and predictable power generation, TES enhances grid stability, reduces dependence on fossil fuels, and supports the transition to a sustainable energy future. As research and development in TES continue to advance, its role in the global energy landscape will become increasingly significant, paving the way for a cleaner and more resilient energy system.

2.5.3 Battery Energy Storage

Battery energy storage systems (BESS) are essential in addressing solar intermittency, as they can store excess solar energy generated during peak periods and release it as required. This capability improves grid stability and reliability, thereby enhancing the overall integration of solar energy generation on a large scale. Figure 2.8 shows a hybrid energy storage system to improve the RES intermittent.

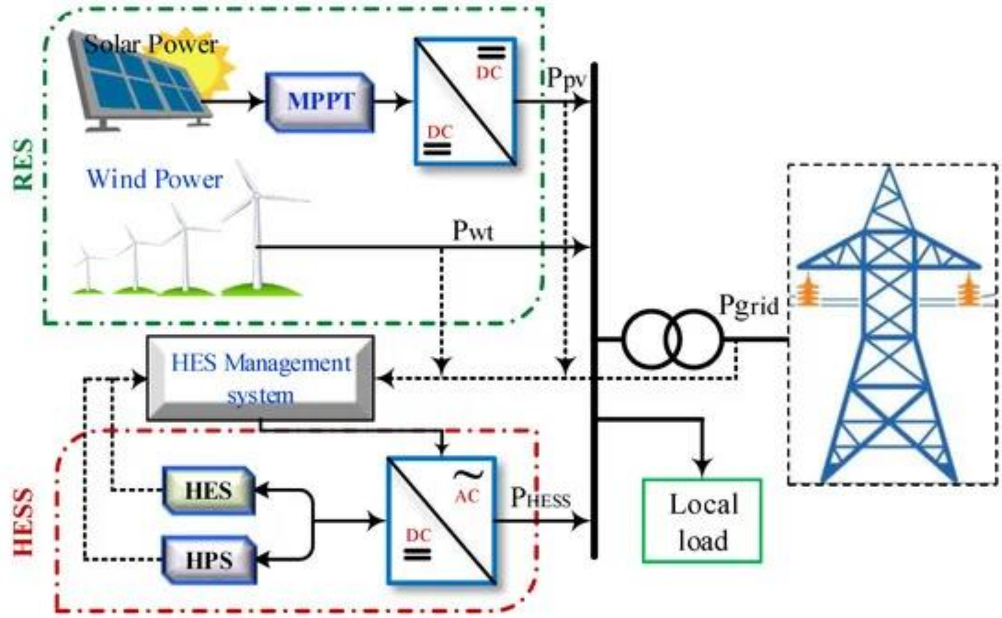


Figure 2.8: Intermittence Improvement of Renewable Systems using BESS
(Atawi et al., 2022)

BESS technology plays a very critical role in smoothing out the variability of solar power generation (Tee et al., 2020) by storing excess energy produced during peak sunlight hours, batteries enable the utilization of solar power during times of low or no sunlight, effectively overcoming the intermittency issue (Tee et al., 2020). This capability reduces the reliance on traditional backup power sources and enhances the integration of solar energy into existing electricity grids. Studies have expressed that one of the main advantages of BESS is its flexibility and scalability (Eskandari et al., 2022; Hannan et al., 2021). Batteries come in various sizes and configurations, allowing for deployment at different scales, from residential and commercial applications to utility-scale installations. Tesla's Powerwall and Powerpack, for instance, offer residential and commercial-scale storage solutions (Hasan et al., 2023), the Hornsdale

Power Reserve in South Australia showcases the capability of utility-scale battery storage to stabilize grids and facilitates the integration of renewable energy on a large scale (Lal et al., 2021).

Moreover, advancements in BESS, such as improvements in energy density, cycle life, and cost reductions, continue to enhance the viability and effectiveness of BESS (Lawder et al., 2014; Ogunniyi & Pienaar, 2017). Advancements in materials science, manufacturing techniques, and system design play a vital role in creating battery storage solutions that are both cost-effective and highly efficient. These innovations are pivotal in propelling the shift towards a cleaner and more robust energy environment (Amici et al., 2022).

Policy support and market incentives further accelerate the deployment of battery energy storage systems (Sani et al., 2020). Governments around the globe are enacting measures to encourage the uptake of energy storage technologies, such as offering subsidies, tax incentives, and making regulatory adjustments (Gandhok & Manthri, 2023; Sani et al., 2020; Sioshansi et al., 2012). These measures create a favorable environment for investment in BESS infrastructure, fostering innovation and market growth (Faunce et al., 2018).

2.6 Potential for Solar Power Integration into Kenya's Energy System

The need for electrical power has been escalating swiftly, with an annual growth rate averaging 6%, primarily fueled by population expansion and industrial development (Nowotny et al., 2018b). Furthermore, according to a report by the (EIA 2016), global energy demand is forecasted to surge by 48% over the next 28 years. With the unsustainable nature of fossil fuels becoming evident, many nations are pivoting their energy sectors towards REs (Sharew et al., 2021).

Presently, there's a notable rise in the utilization of REs for electricity generation, driven by the pursuit of sustainability, improved power quality, and enhanced reliability, owing to escalating demand (Sharew et al., 2021). Kenya's national strategy to increase electricity accessibility from below 25% in 2010 to 40% by 2030 which was revised to 2022 to accelerate the achievement of this goal (EIA, 2016b; Ndung'u et al., 2011). Thus, bolstering both public and private investments in coal, extensive geothermal, and gas-powered plant initiatives (ERC, 2011). Nevertheless, these endeavors entail substantial initial capital outlays, and historically, the Sub-Saharan Africa (SSA) region has witnessed minimal investment in its power sector (Wimmler et al., 2015). Thus, there's a pressing need to explore an alternative approach, focusing on gradual investments in utility-scale solar power.

Research indicates that Kenya has the capacity to produce a greater amount of electricity from solar power than the total annual consumption from the national grid (Sarkodie & Adom, 2018). Despite this potential, solar power hasn't been fully utilized in comparison to other REs like geothermal and wind (Roche & Blanchard, 2018; Ulsrud et al., 2015).

Boosting investments in utility-scale solar power holds appeal for SSA nations for multiple reasons. Primarily, solar power installations boast short construction periods, and their scalability enables incremental investments over time, offering energy system planners an advantage in mitigating uncertainty regarding load growth. Consequently, this helps in reducing investment risks (Y. Li & Liu, 2018; Rose et al., 2016).

Another benefit of solar power is its ability to be built near load centers, which eliminates the need for expensive investments in transmission infrastructure (Rose et al., 2016). Additionally, solar power plants can serve as substitutes for costly diesel power plants, thus lowering total production costs, provided that other REs can offset solar power's intermittency (Lei et al., 2019). Nonetheless, the primary challenge facing solar power power generation remains its intermittent nature (Cavallo, 2001).

Increased research attention has been devoted to assessing the effects of intermittent REs on both short-term system operations and long-term capacity expansion planning (Fosnight, 2010). In the realm of short-term system operations, challenges arise from the variability and uncertainty in solar power output, posing obstacles to its integration (Fosnight, 2010). Osman (Osman, 2012b) provided an extensive analysis detailing the impacts of intermittent RES on system stability, operating reserves, market prices, and the cycling of thermal power plants.

During low penetration levels, solar power generation can replace and supplement costly generators, consequently decreasing average production costs (Lei et al., 2019). Nevertheless, as penetration levels rise, there's a corresponding increase in the expense of cycling conventional thermal plants and utilizing storage solutions like pumped hydro or batteries to mitigate ramping rates and enhance the response to system disturbances (Arbabzadeh et al., 2019).

Furthermore, in systems equipped with reservoir hydropower capacity, coordinated management of both solar power and hydro generation is essential to minimize the cycling of thermal generators and overall peak loads (Acker & Kammen, 1996; Ondraczek, 2014). Determining the optimal penetration levels of intermittent RESs has also garnered considerable interest, with much research focusing on the development of long-term planning models such as multistage stochastic optimization and dynamic optimal methods, among others (Franco & Salza, 2011; Golari et al., 2017; Kim et al., 2020).

According to Baurzhan and Jenkins (2016), the integration of solar power is restricted by the ramping constraints of current generators, highlighting the importance of aligning intermittent generation with demand. Consequently, the level of intermittent renewable energy penetration, viewed as a constraint on flexibility, must be considered in conventional planning procedures (Denholm et al., 2008). (Wogrin et al. 2014) proposed the notion of system states in lieu of load levels to depict market outcomes and system costs in a chronological and precise manner. Conversely, when the system possesses ample flexible generation capacity, a net load duration curve is utilized to strategize the generation mix (George et al., 2019; Hansen et al., 2015).

According to the Kenyan government, the primary obstacle hindering the widespread adoption of solar power is its high initial costs (Da Silva et al., 2015). Consequently, it hasn't been included as a viable resource in the latest long-term power system plan spanning from 2011 to 2031 (Da Silva et al., 2015). Nonetheless, these conclusions relied on outdated cost analyses from the US and Europe dating back to 2005 (Sisternes, 2014). However, recent advancements in technology have led to a decrease in solar module prices (Candelise et al., 2013; Dobrotkova et al., 2018). Studies indicate that economic assessments based on obsolete data tend to overstate the implementation costs of solar power (Child et al., 2017d, 2020). (Lai and McCulloch 2017) and (Olson 2014) have estimated the Levelized Cost of Electricity (LCOE) for solar power - connected to the grid. Furthermore, these investigations have also highlighted that solar power holds a competitive advantage over currently utilized fossil-based power plants.

Moreover, Rose et al. (2016) reported comparable findings regarding price evaluations across various global markets. However, comparisons of Levelized Cost of Electricity (LCOE) neglect to incorporate the synergies between solar generation and demand, or the impact of integrating new technologies on the operational modes of existing plants

(Lai & McCulloch, 2017). Lai and McCulloch (2017) introduced an LCOE framework that considers the integration and variable costs associated with intermittent renewables.

An alternative approach involves eschewing comparisons based on the Levelized Cost of Electricity in favor of estimating the savings achieved through increased utilization of REs. This method would involve employing site-specific solar data along with current tariff rates to calculate the avoided energy costs (Lai & McCulloch, 2017; Olson, 2014). Moreover, when considering different levels of solar power penetration, time blocks, and load duration curves, it is advisable to refrain from relying solely on cost metrics (Rose et al., 2016).

Furthermore, there has been considerable emphasis on research into forecasting the time-dependent variability of solar irradiation. This focus stems from the considerable challenges associated with accurately predicting both short and long-term trends in solar power as an energy source, compounded by the impacts of climate change (Xu et al., 2019).

Additionally, solar power generation suffers from low conversion efficiency, making it unreliable for consistent production. Furthermore, it presents challenges related to low inertia and harmonic issues stemming from the conversion of direct current (DC) to alternating current (Nduka & Pal, 2017). Moreover, the obstacles associated with integrating REs are further compounded by limited electricity access, which stands at less than 50%, and instances where demand exceeds supply (Aliyu et al., 2013; Okonkwo et al., 2021). Implementing significant technological changes, such as energy storage systems, electric vehicles, and optimized solar power setups, is crucial for effective RES integration (Okonkwo et al., 2021).

Despite the noted constraints, researchers have formulated policies and strategies aimed at assisting various regions in achieving their renewable energy objectives. These efforts aim to enhance energy accessibility and realize the environmental advantages linked with Res, such as reducing carbon footprints (Porubova & Bazbauers, 2010). As far as the authors are aware, there is currently no literature exploring the transition of Kenya's existing energy system to rely entirely on solar power within any specified timeframe. This thesis shifts immediate attention to the electricity supply situation in Kenya, emphasizing the significant dependence of both industrial and domestic demand on the country's available energy resources.

Therefore, it is imperative to devise a sustainable strategy for decarbonizing the energy system, aiming to mitigate carbon emissions linked to industrial processes and food production. The primary aim of this newly introduced study is to assess the impact of varying levels of solar power penetration on production costs and system operations within the Kenyan electricity generation framework. This evaluation will encompass both the current year under a business-as-usual scenario and an accelerated solar power scenario.

The study aims to address several specific objectives: evaluating the impacts of substantial solar power penetrations, particularly when coordinated with hydro generation; determining the value of solar power within the context of Kenya's energy landscape; and quantifying the operational costs associated with solar power's interaction with other power plants. By doing so, this research intends to offer a novel approach to estimating the potential value of emerging technologies for future energy generation mixes. Additionally, it seeks to assess current feed-in-tariff (FIT) policies, thereby providing valuable insights into capacity expansion strategies concerning intermittent REs.

2.6.1 Knowledge Gap and Contribution

The gap in existing research encompasses various dimensions, notably the absence of studies that specifically examine the rapid integration of solar electrification within the energy systems of Kenya. While there are studies on solar electrification or Kenya's energy systems individually, there is limited research explicitly examining the potential for rapid integration of solar power into Kenya's broader energy infrastructure.

Therefore, there is a need to examine existing policies and regulations regarding solar electrification in Kenya. This could include an analysis of how current policies facilitate or hinder the accelerated adoption of solar energy, as well as potential policy recommendations to promote faster integration.

Assessing the technical feasibility of integrating solar electrification at an accelerated pace within Kenya's energy systems is another research gap. This could involve evaluating factors such as the scalability of solar technologies, grid compatibility, storage solutions, and the infrastructure required for widespread adoption.

Consequently, bridging these research gaps has the potential to offer valuable perspectives on both the opportunities and hurdles linked with incorporating solar electrification into Kenya's energy systems. This, in turn, could enhance the quality of policymaking and decision-making processes by providing more informed insights.

2.7 A Disaggregated Perspective on Solar Electrification Pathways

Among other nations worldwide, Kenya is confronting critical power decisions (Takase et al., 2021). Given the low rate of rural electrification and a significant portion of the population lacking access to electricity, the primary focus of the government is to enhance production capacity and attain universal energy access, aiming for 100% coverage (Moner-Girona et al., 2019).

The current electricity infrastructure relies heavily on hydropower, but there's a strong emphasis on prioritizing the expansion of RESs, notably wind and solar power. This commitment is evident in national initiatives like the National Development Strategy Vision 2030 and the rural electrification master plan (Boliko & Ialnazov, 2019; Moner-Girona et al., 2019). Kenya's fast-evolving energy system requires strategic decisions on prioritizing and deploying various technologies (Das et al., 2020). The current policy frameworks have facilitated a combination of government and private sector initiatives in energy development (Eitan et al., 2019; Maulidia et al., 2019).

SIS provides insight into the factors that impact innovation within and across sectors (U. E. Hansen et al., 2018a). The SIS approach focuses particularly on pinpointing the distinctive characteristics of industrial advancement within specific sectors (U. E. Hansen et al., 2018a; Malerba & Nelson, 2011). Sectorally, there is a growing focus on the renewable energy industry and its growth (Hansen et al., 2018a).

Innovation systems techniques are increasingly being utilized to analyze development challenges globally (Adebowale et al., 2014; Lundvall & Lema, 2014) and the sectoral systems view emphasizes the relevance of knowledge, learning, and potential building in the process of innovation (Malerba, 2005). The SIS approach assumes that the features of an industry or sector strongly influence the process of innovation (Hansen et al., 2018a). Innovation within an industry is an ongoing evolution that transforms its framework and limits over time (Chirumalla, 2021).

Despite the notable differences among various low-carbon technologies, both solar power and wind energy, as overarching technology categories, hold equal importance (Tönjes et al., 2020). Thus, comprehending these differences in sectoral structures aids in uncovering processes that might otherwise remain undocumented (Stephan et al., 2021). Hence, each of these technological systems' subcategories may be better suited to being regarded as independent units of study. Malerba (2002) defined SISs to encompass both new and old goods for specialized needs, as well as the agents involved in their design, manufacturing, and sale.

This thesis employs a detailed analysis to examine innovation trends within major industries. Hence, it differentiates between small-scale mini-grids and large-scale power plants utilizing solar and wind technologies. Mini-grids are off-grid systems providing electricity capacities ranging from 0.2 kW to 2 MW, serving multiple households, whereas large-scale power plants, owned by utilities or private operators, possess capacities exceeding 15 MW and are grid-connected (Pedersen, 2016). As a result, Kenya hosts four separate Sustainable Innovation Systems (SISs) characterized by distinctive sector-specific innovative attributes, namely solar-powered mini-grids, wind-powered mini-grids, large-scale solar power plants connected to the grid, and large-scale wind power plants connected to the grid. Based on the study by Malerba and Nelson (2011) a three-dimensional approach (Knowledge and technologies, Institutions, and Actors and networks) is used to analysis of these four sectors.

The knowledge and technology aspect centers on the specific knowledge foundations within a sector, influenced by interactions among enterprises and organizations (Malerba, 2005). These knowledge-based dimensions vary by sector, encompassing tacit know-how, craftsmanship, practical expertise, codified knowledge, and formal research and development (Asheim & Coenen, 2005). Therefore, acquiring and transferring knowledge across sectors can be challenging. Institutions in a sector include the infrastructure and framework conditions that foster innovation (Edsand, 2019; Hansen et al., 2018a). Institutions can be formal or informal, including rules, regulations, and standards, as well as conventions, habits, and routines formed through repeated encounters among players (Hansen et al., 2018a). These institutional elements dictate how actors engage and interact, shaping the learning processes that result in the accumulation of knowledge and capabilities (Hansen et al., 2018a; Malerba, 2005).

The actors and networks within SISs include both companies and non-firm players that collaborate to drive learning and innovation in certain areas (Malerba & Nelson, 2011). Kern (2015) showed that the primary limitation of the innovation systems approach is identified as its lack of political engagement. Examining politics as pervasive throughout all facets and operations of innovation systems suggests that prioritizing certain sectors over others isn't solely a technical choice but also mirrors political preferences. Consequently, endeavors like large-scale solar and wind energy initiatives are intricate and involve multiple stakeholders with conflicting interests, necessitating discussions across various levels (Newell et al., 2014). Additionally, in Newell et al. (2014) the conflicts arising from the pursuit of multiple objectives such as growth, inclusivity, and sustainability were outlined. Therefore, it's crucial to analyze the renewable energy industry and its components to delve deeper into the breakdown of trends within the subcategories of solar power (Chen & Chen, 2021). Hence this introduced study aims to provide a disaggregated view of innovation dynamics with the specific objectives of Analyzing the structure and dynamics of innovation systems within key sectors relevant to solar electrification. To identify the key actors, their roles, and interactions within each sectoral innovation system. To assess the influence of policies, regulations, and market mechanisms on sectoral innovation trajectories, and to explore the implications of sectoral interactions on overall solar electrification pathways. This allows for upcoming research to concentrate on the political elements that impact the comparative advantages and disadvantages of the renewable energy sector.

2.7.1 Knowledge Gap and Contributions

Research on disaggregated perspectives of sectoral innovation systems in solar electrification pathways typically focuses on examining the dynamics, actors, and factors influencing innovation within specific segments or components of the solar electrification value chain. While this area of study has seen significant attention in recent years, there are still several gaps that warrant further investigation:

Many existing studies provide insights into sectoral innovation systems at a national or regional level, but there is a lack of research focusing on the dynamics of innovation systems in localized contexts, such as rural communities or urban slums. Understanding the specific challenges and opportunities faced by different localities can inform more tailored innovation strategies.

Research in this area often stems from disciplines such as engineering, economics, or innovation studies. However, there is a need for more interdisciplinary approaches that integrate insights from fields like sociology, anthropology, or political science to provide a comprehensive understanding of the socio-technical aspects of solar electrification pathways. While some studies analyze the roles of key actors such as governments, businesses, and Non-Governmental Organizations (NGOs) in driving innovation, there is a limited understanding of the complex networks and power dynamics among these actors. Investigating how different actors collaborate, compete, or exert influence within innovation systems can offer valuable insights for policy and practice.

Additionally, while technological innovations are often the focus of research in this area, there is a need to broaden the scope to include non-technological innovations such as business models, financing mechanisms, or policy frameworks. Exploring how these innovations interact and shape the evolution of sectoral innovation systems can provide a more holistic understanding of solar electrification pathways.

Numerous current studies offer glimpses of innovation systems at specific moments, yet there's a deficiency in longitudinal research that traces the progression of these systems over time. Longitudinal studies can help identify patterns, trends, and critical junctures in the development of sectoral innovation systems and shed light on their long-term sustainability and resilience.

Lastly, knowledge sharing and learning are essential components of innovation systems, there is limited research on how knowledge flows, networks and learning processes operate within the context of solar electrification pathways. Understanding how knowledge is generated, transferred, and absorbed among different actors can inform strategies to accelerate innovation and diffusion processes.

Addressing these research gaps can contribute to a deeper understanding of the dynamics of sectoral innovation systems in solar electrification pathways and provide valuable insights for policymakers, practitioners, and researchers working towards sustainable energy transitions.

2.8 Incrementing Solar Electrification in Kenya

Recently, Kenya has been experiencing rapid economic growth, leading to an increase in electricity demand from about 6,000 GWh in 2010 to over 12,000 GWh in 2020, with peak demand rising from around 1,200 MW to 2,200 MW currently (KNBS, 2023). However, the country's electricity generation is dominated by thermal and HEPs. Thermal power plants are expensive to run and have a significant negative environmental impact whereas HEPs are susceptible to unreliable precipitation patterns

(KNBS, 2023). Kenya also depends on electricity imports, which makes it vulnerable to price fluctuations and frequent power outages.

Moreover, a notable segment of the populace, particularly in rural regions, lacks electricity access, with rates standing at 65% (KNBS, 2023b). In response to these challenges, the Kenyan government has established a goal of attaining 100% of the nation's electricity from REs by 2030, emphasizing the augmentation of solar and wind power (IRENA and AfDB 2022). Solar power emerges as a pivotal RES to accomplish this objective.

Africa possesses significant potential for harnessing solar energy, owing to its plentiful solar resources and the imperative to extend electricity access to millions across the continent. Several African countries, including Morocco, South Africa, and Egypt, have made significant progress in increasing their share of solar power generation, South Africa, Egypt, and Morocco have the largest installed solar generation capacity at 57%, 16%, and 7% respectively (IRENA and AfDB 2022).

Despite good solar conditions in Kenya, solar integration has been slow. In general, there are challenges regarding the incorporation of solar energy into the grid both in terms of energy system flexibility for accommodating the variability of solar power and in terms of supportive policies and regulatory frameworks to promote the technology’s adoption (Cruz et al., 2018). Kenya's limited adoption of solar power technology can be attributed to a combination of challenges, including difficulties in integrating solar power into the grid due to inadequate energy system flexibility (Samoita et al., 2020).

The country faces obstacles in accommodating the variability of solar power, as well as a lack of supportive policies (Samoita et al., 2020). Factors such as the cost of solar infrastructure and a potential lack of awareness among consumers and businesses further contribute to the modest development of solar power in Kenya (Amankwah-Amoah, 2015). Several studies have been conducted on the potential for solar power in Kenya's energy mix. A study by Oloo, Olang, & Strobl (2016), and Samoita et al. (2020) assessed the potential of solar power systems to provide electricity in rural areas of Kenya. Samoita et al. (2020) reported that such systems were a cost-effective and reliable source of electricity for off-grid communities. A separate investigation conducted by Moner-Girona et al. (2019) assessed the viability of incorporating solar energy into Kenya's grid system, concluding that, with conducive policies and regulatory structures, solar power technology could emerge as a cost-effective and dependable electricity source for the nation. Additionally, a study by Wambui et al. (2022b) offers a socio-techno-economic evaluation of electricity development prospects in Kenya, employing the Low Emissions Analysis Platform (LEAP) and the Next Energy Modeling System (NEMS).

In line with Kenya's Least Cost Power Development Plan (LCPDP) spanning from 2017 to 2037, the research was in accordance with the country's overarching objectives, seeking to provide direction to the energy sector regarding opportunities for expanding generation, targets for transmission infrastructure, and resource needs.

The LCPDP acts as a revised blueprint, considering the Feed-in Tariff policy and highlighting the energy-related components of the Big 4 Agenda program. The Ministry of Energy (MOE) establishes policy directives, while regulatory standards are outlined by the Energy and Petroleum Regulatory Authority (EPRA). Their investigation includes an extensive load projection, information on ongoing generation initiatives, and a growth plan covering the period from 2025 to 2037.

Research indicates the existence of four distinct electricity development scenarios for Kenya, which encompass a Business-as-Usual scenario, a least-cost scenario, a Sustainable Development Scenario, and a Carbon Mitigation Scenario (Kehbila et al., 2021; Wambui et al., 2022a). The occasions are assessed based on a range of socio-economic, technical, and environmental indicators, including greenhouse gas emissions, energy security, and affordability. Generally, these studies indicated that the feasibility of the scenarios depended on a complex interplay of factors.

The Least Cost Scenario highlighted the possibility of achieving significant cost savings without compromising environmental sustainability Scenario (Kehbila et al., 2021; Wambui et al., 2022a). The Sustainable Development Scenario presented the potential alignment between economic growth and environmental preservation, fostering a harmonious relationship between these aspects (Ouedraogo, 2017).

The Carbon Mitigation Scenario showcased the possibility of achieving significant decreases in greenhouse gas emissions while upholding energy security (Ouedraogo, 2017; Xavier, 2022). A report by González-García et al. (2022) indicated that a pathway incorporating 98.7% RES and a battery energy system is not only feasible but also offers substantial advantages for energy planning.

The alignment between REs and ESSs presents a promising approach, demonstrating advantages such as cost-effectiveness, decreased CO_2 emissions, heightened reliability, and bolstered security for Kenya's future power system (Smdani et al., 2023; Zhu et al., 2024). Overall, Kenya has the potential for becoming a progressive and sustainable energy producer. Both Hansen et al. (2018) and Samoita et al. (2020) looked into barriers to solar power in Kenya. Samoita et al. (2020) found that while there are technical barriers, most other barriers can be overcome. Additionally, Elmer et al.

(2018) focused on the diffusion of large and small-scale systems, finding that these must be addressed differently. Regarding Sub-Saharan Africa, Ghana has significant solar power potential due to its proximity to the Equator, which provides it with abundant sunlight throughout the year. Sulley et al. (2022) conducted research evaluating the viability of a grid-connected solar power /wind hybrid system to fulfill standard commercial energy demands in Kumasi, Ghana.

The study applied a simulation approach to model the performance of the hybrid system and evaluate its economic viability, considering factors such as capital costs, operating costs, and the LCOE. However, Sulley et al. (2022) did not explicitly incorporate energy efficiency analysis in their analysis.

The research concluded that combining solar power and wind turbines in a hybrid system can offer a dependable and consistent electricity supply, alongside proving economically feasible. Aghahosseini, Bogdanov, & Breyer (2020) investigated the possibility of attaining complete reliance on REs (RES) in the Middle East and North Africa (MENA) region by 2030. Their focus encompassed the power sector, non-energy industrial gas, and seawater desalination sectors.

The research examined three scenarios, varying in regional grid interconnection and sector integration: Region, Area, and Integrated. solar power and wind energy emerge as the most competitive and abundant REs, comprising over 90% of generation capacity in all scenarios. To tackle REs variability, energy storage, surplus generation, and grid enhancements are employed. Battery storage is used in conjunction with solar power to address this variability.

Moreover, the research suggested incorporating a comprehensive transmission network spanning a large area to mitigate the variability of solar power and wind resources throughout the region. Additionally, (Aghahosseini et al. 2020) underscored the significance of storage technologies in handling the variability of REs. Furthermore, the study indicated that an interconnected power system results in decreased demand for energy storage capacities, encompassing large-scale batteries, Compressed Air Energy Storage (CAES), and gas storage. However, Pumped Hydro Energy Storage (PHES) remains relatively unaffected.

The research emphasizes the significance of Power-to-Gas (PtG) technology, wherein water electrolysis capacities are expanded in the Integrated scenario to fulfill the increased gas demand for the non-energy industrial gas sector. Battery storage supplements solar power by offering a solution for daytime electricity supply. In comparison to a business-as-usual approach, a 100% REs-powered system proves to be 55–69% more cost-effective, considering both economic and environmental considerations (Aghahosseini et al., 2020b).

Given the interconnected issues of climate change and energy shortages in Africa, Oyewo et al. (2022) advocated for a transition toward sustainable development. They introduced a novel techno-economic energy modeling tool capable of delineating the pathways in high geospatial and full hourly resolution for Africa, encompassing the entirety of the energy system.

The study illustrates that a REs-based approach is not only aligned with climate goals but also yields a less expensive system framework compared to other alternatives. Specifically, the REs-based approach, especially incorporating solar SOLAR POWER-battery hybrid systems and electrolyzers, is deemed both climate-compatible and more economically viable than alternative routes. (Oyewo et al., 2022b; Traber et al., 2023).

Solar power is recognized as the most economically efficient technology, and the solar-centric energy system is characterized as cost-competitive, aligned with climate objectives, and less reliant on politically volatile nations (Oyewo et al., 2022b). The REs-based strategy implies that Africa possesses both the energy and land resources necessary to pursue clean and economically competitive energy solutions (Ofélia de Queiroz et al., 2024). Sterl (2021) evaluated the recent scientific findings on integrating RES into African power grids to expand electricity access, minimize costs, and reduce fossil fuel emissions.

The study emphasizes enhanced cross-border transmission and storage solutions, such as batteries and PtG. Model-based studies suggest that leveraging complementarities between RES and interconnections within Africa's power networks, coupled with substantial storage deployment, could effectively fulfill rising power needs with environmentally friendly electricity (Sterl, 2021b). Tsuma and Kibaara (2022) presented an assessment of the techno-economic tools available for power systems with REs penetration in Kenya. The document offers an outline of the existing level of REs adoption in Kenya and addresses the necessity for dependable and effective techno-economic instruments to facilitate the advancement and incorporation of REs into the national grid.

Tsuma and Kibaara (2022) presented the techno-economic tools available for REs planning such as EnergyPLAN (Lund et al., 2021a), EnergyPRO (Poul Alberg Østergaard, Andersen, and Sorknæs 2022), H2RES (Goran Gašparović a, Goran Krajačić a, Neven Duić a 2014), RetScreen (RETScreenExpert 2022), Times (Loulou et al. 2021) and Homer (Homer Energy, 2019). Abdulganiyu (2017) used EnergyPLAN to examine the potential for RES development in Tanzania by modeling and analyzing the feasibility of RES in the existing energy systems. The findings indicate that

Tanzania holds substantial potential for the development of REs (RES), particularly in the realms of solar and wind energy. Salah, Eltaweel, and Abeykoon (2022) conducted a comprehensive review of the potential for REs exploitation in Egypt, as well as the challenges and opportunities associated with this. The study applied EnergyPLAN to evaluate the feasibility of integrating REs into Egypt's energy system.

Similarly, Chouder et al. (2013) conducted an optimization study for achieving a 75% RES integration by 2050 in Algeria using EnergyPLAN to model and evaluate different scenarios. The study employed a multi-objective cuckoo search algorithm to optimize the energy mix for Algeria and identify the best pathway toward achieving the renewable energy target.

A case study on the potential role of electric vehicles in Nigeria's energy transition was presented by Dioha et al. (2022) using EnergyPLAN to simulate different scenarios and to assess the impact on the electricity grid. In Kenya, EnergyPLAN has been applied by (Abdulganiyu 2017) to model and evaluate different REs scenarios, for the years 2030 and 2050. This thesis identified regulatory constraints and technological challenges as the main barriers that hinder the uptake of REs.

From previous literature, it is evident there is a lack of comparable scenario research works looking into countries with similar climates and similar potential energy resources, especially with the high temporal resolution required for adequately analyzing REs-based energy systems. The objective of this thesis therefore is to thoroughly analyze the potential of solar power to meet the dynamic electricity demand in Kenya from a technical and economic standpoint. This is a novel study that provides a national simulation of the large-scale incorporation of REs into Kenya's electricity combination. This thesis also provides an in-depth analysis of Kenya's current energy mix and scaling up of solar power generation and proposes the optimal solar capacity that is technically and economically feasible using EnergyPLAN. 2022 is chosen as a year of reference.

2.8.1 Knowledge Gaps and Contributions

From the literature, many studies generally discuss the capability of renewable energy in Kenya, but it happens that there is limited research reported on opportunities and specific challenges related to the implementation of large-scale integration of solar power in the Kenyan context. This includes factors such as policy barriers, financing constraints, technical limitations, or social acceptance issues.

A thorough examination is required to explore the incorporation of REs into Kenya's current energy grid, along with the challenges related to maintaining grid stability and reliability. Understanding the effective integration of renewable energy alongside conventional sources to address fluctuating demand patterns is vital for realizing a sustainable energy transition.

Studies highlight the environmental benefits of renewable energy adoption, but there is a gap in research focusing on the social and economic impacts of transitioning towards 100% renewable energy in Kenya. This could include examining issues such as job creation, income distribution, energy access for marginalized communities, and the overall socioeconomic transformation brought about by renewable energy deployment.

Therefore, addressing these research gaps will contribute to a more comprehensive understanding of the opportunities and challenges associated with achieving 100% renewable energy in Kenya

2.9 MPPT Techniques for Solar Power Systems

The adoption of Solar power systems is increasing due to their low cost, availability, and sustainability in addition to being the most promising REs (Kanwal et al., 2020). Despite the numerous advantages of solar power, its efficiency is still low compared to other conventional energy sources (Al-Shahri et al., 2021).

This variability arises because the active power output of solar power systems fluctuates based on factors such as operating temperature, solar irradiance, and weather conditions, including partial shading. These variations occur due to the non-linear nature of solar power cell characteristics (Bhattacharyya et al., 2020; Yap et al., 2020).

The complex interaction between power output and solar power input parameters results in suboptimal power generation. Hence, to enhance generation efficiency, researchers have focused on Maximum Power Point Tracking (MPPT), which aims to optimize operation towards the maximum power point (MPP) (Yung et al., 2019). MPPT methods are typically divided into two categories: conventional hill-climbing (HC) MPPT and dynamic MPPT. Conventional HC MPPT techniques, like perturb and observe (P&O) and incremental conductance (IC), have been utilized to track optimal conditions consistently and mitigate intermittency (Ibrahim et al., 2019).

However, studies have established that solar power outputs many peaks (global MPP (GMPP) and several local peaks due to intermittency and partial shedding (S. Bhattacharyya et al., 2020; Yap et al., 2020). MPPT ensures that the solar panels operate at their maximum efficiency regardless of varying environmental conditions like shading, temperature, and solar irradiance (Almutairi et al., 2020a). Therefore, the MPPT technique must determine the real maximum (Correa-Betanzo et al., 2019), As a result, MPPT has evolved into algorithms based on evolutionary, heuristic, and metaheuristic techniques, with the goal of tracking global peaks rather than local ones. This shift is because conventional HC MPPT techniques struggle to track global peaks, especially amidst rapid changes in solar irradiance (Chen et al., 2017). The MPPT techniques can be categorized as given in Figure 2.9 below.

Traditional techniques for Maximum Power Point Tracking (MPPT) in solar power systems encompass Perturb and Observe (P&O), Incremental Conductance (IC), Hill Climbing (HC), fixed voltage, fractional short-circuit current, fractional open-circuit voltage, scanning and tracking of the current-voltage (I-V) curve, Fibonacci search method, Global MPPT (GMPPT) segmentation search, and extremum seeking control (Yap et al., 2020).

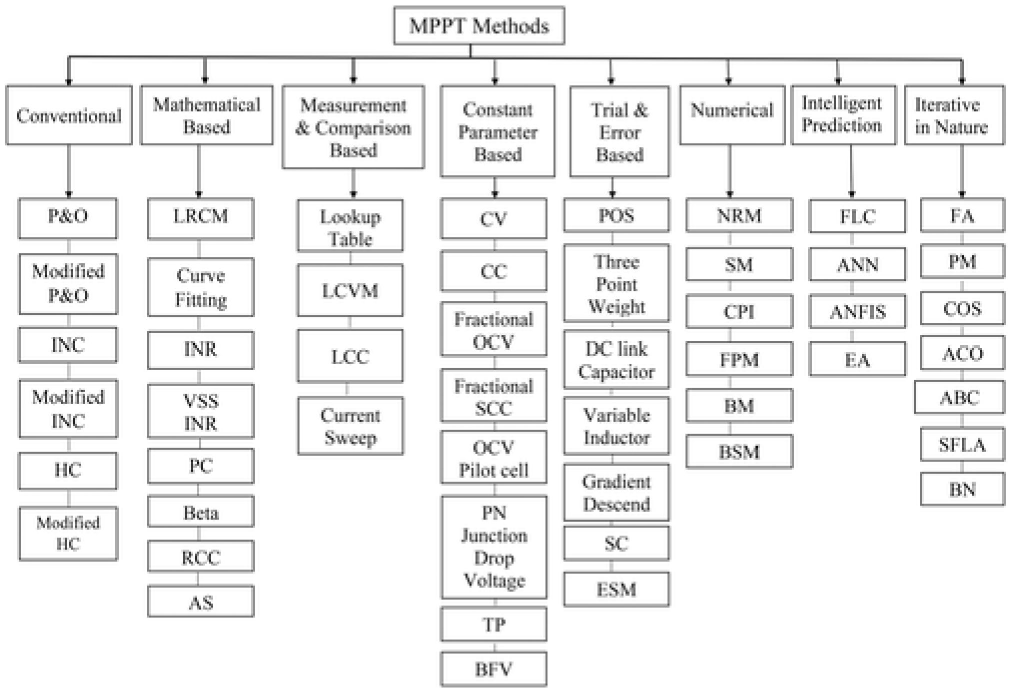


Figure 2.9: The Classification of MPPT methods (Podder et al., 2019)

The combination of optimization techniques with MPPT aims to address the limitations of standard HC MPPT such as trapping at local MPP and incorrect perturbation direction, steady-state error, and lack of adaptive, robust capabilities (Zhang et al., 2019). Typically, current optimization-driven MPPT methods rely on sensory data, such as solar irradiance, input voltage, and input current, to anticipate and approximate the Global Maximum Power Point (GMPP) across the nonlinear traits of solar power cells (Yap et al., 2020).

Algorithm optimization in MPPT improves convergence speed and transient responsiveness due to its sophisticated, learning rate, and digitalized system (Yap et al., 2020). Algorithm optimization MPPTs are also known as bio-inspired MPPT, computational intelligence (CI)-based MPPT, contemporary MPPT, or soft-computing MPPT. These methods incorporate artificial neural networks (ANN), particle swarm optimization (PSO), differential evolution (DE), Tabu search (TS), firefly algorithm (FA), Cuckoo search (CS), fuzzy logic control (FLC), and hybrid algorithms (Aouchiche et al., 2018; Raj & Samuel, 2022).

Choudhury and Rout (2015) and Zhou et al. (2015) utilized the Fuzzy Logic Control (FLC)-based Global Maximum Power Point Tracking (GMPPT) algorithm, achieving superior tracking accuracy and speed compared to Perturb and Observe (P&O). (Belhachat and Larbes 2017) addressed various shading scenarios by introducing an Adaptive Neuro-Fuzzy Inference System (ANFIS), demonstrating effective GMPP attainment. Additionally, (Kheldoun et al. 2016) proposed a heuristic approach employing the golden section optimization algorithm for GMPPT, while Huynh et al. (2013) presented a dynamic Particle Swarm Optimization (PSO) algorithm.

Modified particle swarm optimization technique (MPSO) by Sakthigokulrajan and Ravi (2017) who reported that once MPP is reached the system has a reduction in steady-state oscillation. modified artificial fish swarm algorithm (MAFSA) by Mao et al. (2016). Bat algorithm (BA) (Kaced et al., 2017). Bee Colony-based MPPT algorithm

(BC) (Soufyane Benyoucef et al., 2015). Grey Wolf Optimization based MPPT technique (GWO) by Mohanty, Subudhi, and Ray (2015) outperformed P&O and improved PSO. Ant Colony Optimization algorithm with a New Pheromone Updating strategy (ACO_NPU MPPT) by Titri et al. (2017).

Research has indicated that employing a Distributed Maximum PowerPoint Tracking (DMPPT) setup offers a viable solution in terms of both stability and efficiency (Femia et al., 2008), and fault diagnosis (Solórzano & Egido, 2013). The DMPPT configurations have also been presented to be based on hybrid (perturb and observe-adaptive neuro-fuzzy inference system (P&O–ANFIS) and particle swarm optimization-adaptive neuro-fuzzy inference system (PSO–ANFIS) techniques (Muthuramalingam & Manoharan, 2014).

As solar energy becomes increasingly integrated on a large scale, enhancing the efficiency of solar power systems across varying conditions is essential. Hence, this research introduces a Global Maximum Power Point Tracking (GMPPT) algorithm aimed at addressing partial shading challenges. The proposed algorithm utilizes a whale optimization algorithm to optimize power output at the boost converter, aiming for efficient and effective solar power system tracking while ensuring stability and speed.

2.9.1 Summary of Knowledge Gaps

Extensive review of literature reveals critical knowledge gaps in the development, application, and integration of technologies that support efficient solar power utilization—particularly in the areas of Maximum Power Point Tracking (MPPT) and solar energy storage systems (ESS). Although MPPT algorithms are widely used to optimize energy extraction from solar panels, their performance under dynamic, real-world conditions remains insufficiently explored. In parallel, the coordination between energy harvesting and storage has not been thoroughly addressed, despite its central importance in ensuring reliability and energy continuity, especially within off-grid and hybrid energy systems.

A key limitation lies in the scarcity of systematic evaluations of MPPT algorithms under realistic environmental conditions such as fluctuating irradiance, variable temperatures, partial shading, and electrical disturbances. Many existing studies are based on controlled or idealized environments, which do not reflect the operational variability of actual solar power systems. Consequently, current literature offers limited insights into the responsiveness, adaptability, and long-term reliability of these algorithms when deployed across different geographic and climatic contexts.

Furthermore, the practical integration of advanced MPPT techniques—particularly those leveraging metaheuristic optimization or machine learning—is hindered by several technical challenges. These include hardware compatibility issues, increased computational demands, and limited scalability. Without resolving these challenges, the potential benefits of intelligent tracking algorithms cannot be fully realized in real-world solar energy applications.

Closely related to the optimization of energy generation is the integration of solar energy storage systems. While technologies such as lithium-ion batteries and pumped hydro storage are increasingly considered essential in solar electrification, their combined operation with MPPT-controlled solar power systems is not yet well documented in literature. Studies that explore the co-optimization of generation and storage are rare, despite the fact that such coordination is vital for mitigating power fluctuations, reducing curtailment, and enhancing system resilience—particularly in regions with underdeveloped grid infrastructure.

Additionally, there is a lack of comprehensive comparative research assessing different combinations of MPPT algorithms and energy storage configurations. Few studies have examined how storage technology selection, control logic, or charging strategies influence the performance of MPPT algorithms. These interactions are likely to have significant implications for overall system efficiency, cost, and reliability, especially in decentralized and rural electrification contexts.

To address these knowledge gaps, future research should prioritize both simulation and field-based validation of advanced MPPT algorithms in conjunction with various energy storage systems. Comparative studies that evaluate a range of optimization techniques—such as the Whale Optimization Algorithm (WOA), Particle Swarm Optimization (PSO), and artificial neural networks—across different operational conditions and system architectures will be instrumental in identifying effective and scalable solutions.

In conclusion, addressing the interconnected gaps in MPPT optimization and solar energy storage integration is essential for the advancement of reliable, adaptive, and sustainable solar power systems. Improved algorithmic control, when paired with intelligent storage strategies, can significantly enhance energy reliability, system efficiency, and cost-effectiveness. These advancements are particularly critical for countries like Kenya, where abundant solar resources and rising energy demand intersect with infrastructural and economic challenges. A holistic, context-specific approach that integrates technical innovation with system-level coordination will be vital in supporting Kenya’s renewable energy ambitions and broader energy access goals.

A summary of research gaps in the reviewed literature is presented in Table 2.3.

Table 2.3: Summary of Knowledge Gaps

Thematic area	Study	Results	Research Gap	Reference
Feasibility of Accelerated Integration of Solar Electrification in Kenya's Energy System	Integration of solar power systems into power networks: a scientific evolution analysis	Integration of solar power into grids is feasible with existing technologies. solar power integration can reduce greenhouse gas emissions and dependence on fossil fuels.	Need for more research on grid integration strategies, including storage and demand-side management. Lack of standardized policies and regulations for solar power integration.	(Elomari et al., 2022)
	Techno-economic potential assessment of mega scale grid-connected solar power plant in five climate zones of Pakistan	Pakistan has high solar irradiance, making large-scale solar power deployment feasible. Solar solar power can help alleviate energy shortages and reduce reliance on imported fuels.	Lack of comprehensive data on solar resource assessment and site suitability. Need for financial incentives and supportive policies to attract investment in solar solar power projects.	(Ahmed et al., 2021)
	Highly renewable energy systems in Africa: Rationale, research, and recommendations	Africa has abundant RES, including solar, which can provide sustainable electricity access. Accelerated deployment of renewables requires investment in infrastructure, capacity building, and policy reforms.	Limited access to financing for renewable energy projects in Africa. Insufficient coordination among stakeholders and policymakers to implement renewable energy initiatives effectively.	(Oyewo et al., 2023)
	Feasibility Study of Integrating a 120MW solar power Plant into the Jamaica Power Grid	Solar power can contribute to reducing electricity costs and dependence on imported fossil fuels in the Caribbean.	Lack of data on electricity demand patterns and grid infrastructure in the Caribbean. Need for tailored financing mechanisms and capacity-building	(Nelson, 2019)

		Challenges include high initial costs, grid stability concerns, and limited technical expertise.	programs for solar power deployment.	
The development and organization of the solar market in Kenya based on sectoral innovation systems (SIS)	Exploring innovation in developing countries	Identified key actors, institutions, and interactions shaping the solar market in Kenya. Highlighted the importance of policy frameworks, technological innovation, and market dynamics in fostering solar market growth.	Lack of comprehensive analysis on the role of informal actors and networks in the solar market. Limited understanding of the influence of cultural and socio-economic factors on solar market development.	(Gregersen & Trischler, 2014)
	Review of solar power policies, interventions and diffusion in East Africa	Evaluated the effectiveness of policy interventions, such as feed-in tariffs and tax incentives, in stimulating solar market expansion. Identified policy gaps and implementation challenges hindering the full realization of the solar market's potential.	Limited empirical evidence on the long-term impacts of policy interventions on solar market sustainability. Need for a more nuanced analysis of policy interactions within the broader innovation system context.	(Hansen et al., 2015)
	Assessing the opportunities and challenges facing the development of off-grid solar systems in Eastern Africa: The cases of Kenya, Ethiopia, and Rwanda	Examined patterns of technological innovation and diffusion in off-grid solar solutions, including pay-as-you-go (PAYG) models and solar home systems. Identified barriers to innovation adoption and opportunities for collaborative research and development.	Insufficient exploration of end-user perspectives and preferences influencing technology adoption. Limited consideration of ecosystem dynamics beyond technological aspects, such as financing and distribution networks.	(Mugisha et al., 2021b)

Optimal solar capacity based on technical and economic analysis in scaling up solar power generation	Optimal sizing of residential solar power and battery system connected to the power grid based on the cost of energy and peak load	Identified optimal solar capacity based on electricity demand, roof area, and economic criteria. Economic analysis showed potential cost savings over the system lifetime.	Limited focus on residential buildings; more studies needed for commercial and industrial sectors. Lack of consideration for variability in solar irradiance and its impact on optimal sizing.	(Khah et al., 2023)
	Sizing approaches for solar solar power -based microgrids: A comprehensive review	Reviewed various methods for determining optimal solar power system size, including economic indicators Highlighted the importance of considering load profile and energy storage options in sizing.	Limited discussion on the integration of solar power systems with grid infrastructure and smart grid technologies. Insufficient exploration of the impact of policy incentives and regulatory frameworks on optimal sizing decisions.	(Mathew et al., 2022)
	Techno-economic analysis of solar solar power and solar power thermal systems using exergy analysis	Conducted a techno-economic analysis to optimize solar power system size for different applications. Identified cost-optimal system sizes for residential, commercial, and utility-scale applications. Highlighted the importance of considering levelized cost of electricity (LCOE) in sizing decisions.	Lack of consideration for real-world variability in energy demand and solar resource availability. Limited discussion on the role of energy storage and grid integration in optimizing solar power system size. Need for sensitivity analysis to assess the robustness of optimal sizing recommendations under different scenarios.	(Abdul-Ganiyu et al., 2021)
Robust MPPT algorithm to improve	Modified grey wolf optimization for global maximum power point tracking	Proposed a modified Grey Wolf Optimizer (GWO) algorithm for MPPT in solar power systems,	Limited experimental validation; further real-world testing needed.	(Motamarri et al., 2021)

solar solar power efficiency	under partial shading conditions in solar power system	showing improved convergence speed and accuracy compared to conventional methods.		
	A novel hybrid MPPT technique for solar solar power applications using perturb & observe and fractional open circuit voltage techniques	Developed a novel hybrid MPPT algorithm combining P&O and Fractional Order (FO) control techniques, achieving higher efficiency under partial shading conditions.	Evaluation limited to specific shading scenarios; need for broader testing under various environmental conditions.	(Murtaza et al., 2012)
	An adaptive neuro-fuzzy inference system (ANFIS) model for wire-EDM	Proposed an Adaptive Neuro-Fuzzy Inference System (ANFIS) for MPPT, demonstrating superior performance under dynamic weather conditions.	Lack of comparison with other state-of-the-art MPPT techniques; need for benchmarking against existing algorithms.	(Çaydaş, Hasçalık, & Ekici, 2009)
	A novel MPPT algorithm based on particle swarm optimization for solar power systems	Investigated the application of Particle Swarm Optimization (PSO) in MPPT, showing enhanced tracking accuracy and stability over conventional methods.	Limited analysis of algorithm robustness under various solar power system configurations; further examination of algorithm performance in diverse setups required.	(Koad, Zobaa, & El-Shahat, 2016)

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the research methodology employed to achieve set objective, focusing on the integration solar power systems into Kenya's energy mix. The approach combines both technical and systemic analyses to provide a comprehensive evaluation of the factors influencing solar electrification. A blend of simulation tools and analytical frameworks has been used to ensure a rigorous and multi-dimensional investigation.

To assess the economic and technical viability of strategies aimed at accelerating solar energy deployment, the study adopts a methodological framework centered on the use of EnergyPLAN simulation tool. EnergyPLAN enables the modelling of Kenya's energy system under various policy and technology scenarios, allowing for the evaluation of potential outcomes in terms of energy cost, emissions, and renewable energy penetration.

In parallel, a Sectoral Innovation Systems (SIS) analysis is conducted to examine the institutional, technological, and market dynamics that shape the development and diffusion of solar power technologies in Kenya. This qualitative component identifies key actors, policies, and structural conditions that either support or hinder solar electrification efforts.

The study further involves a detailed simulation process in EnergyPLAN, where multiple scenarios are constructed to explore the implications of different solar deployment pathways. These scenarios are designed to test the effects of varying levels of investment, regulatory support, and technological adoption on the national energy system.

In addition to systemic modelling, a technical performance analysis is carried out using a MATLAB-based simulation. This simulation incorporates a Whale Optimization Algorithm to enhance the effectiveness of a Maximum Power Point Tracking (MPPT) strategy. The goal is to assess how intelligent optimization techniques can improve the efficiency and reliability of solar power systems under fluctuating environmental conditions.

Overall, this methodology integrates both macro-level energy system modelling and micro-level technical optimization, offering a robust framework for understanding and advancing solar power integration in Kenya.

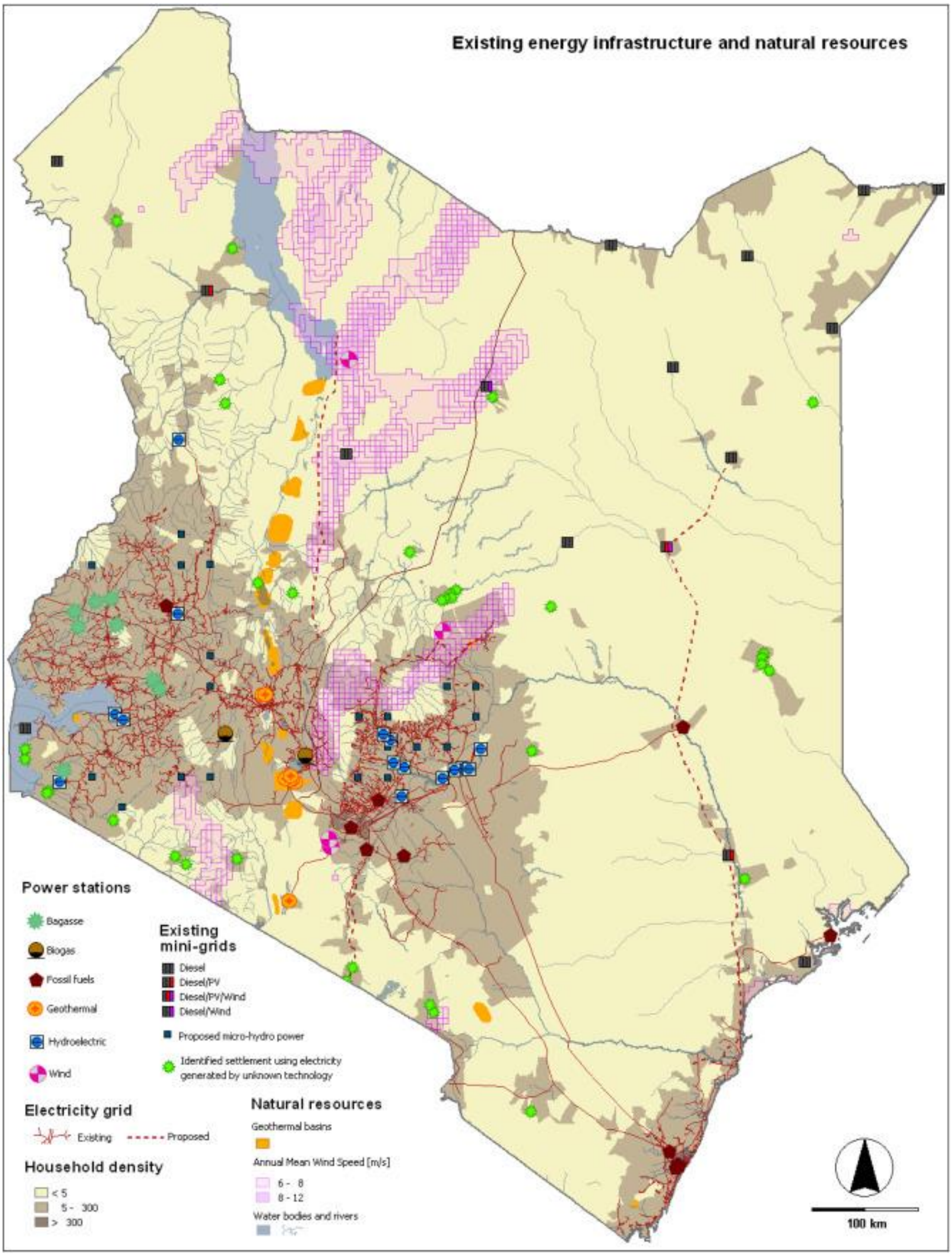


Figure 3.1: Existing energy infrastructure in Kenya, potential energy sources, and population density (Moner-Girona et al., 2019)

3.2 Techno-Economic Performance of Accelerated solar power Integration in Kenya

This goal sought to assess the impact of varying levels of solar power integration on production expenses and system functionalities within the Kenyan electricity generation framework, comparing the present year (under normal business conditions) with an accelerated solar power scenario. The layout of the existing energy infrastructure is shown in Figure 3.1.

3.2.1 Energy Resource Potential in Kenya

Kenya, a swiftly advancing country in East Africa, has been prioritizing the expansion of its energy mix to satisfy its increasing energy needs, bolster energy reliability, and mitigate greenhouse gas emissions (Moner-Girona et al., 2019). As of 2021, Kenya's energy blend encompasses a range of resources, comprising fossil fuels, renewable energy, and emerging technologies as shown in Figure 3.1 (Moner-Girona et al., 2019; Mugisha et al., 2021). In 2021, Kenya had a total of 53 power stations, comprising hydroelectric (15), fossil fuels (14), geothermal (10), bagasse (8), wind (4), and biogas (2) (Moner-Girona et al., 2019; Takase et al., 2021).

This research aimed to utilize the EnergyPLAN simulation tool to model and simulate the consequences of fast-tracking solar power integration into Kenya's electricity composition. Ensuring minimal electric grid stabilization is a crucial concern requiring attention in any power system integrating intermittent RES. Therefore, it is imperative to uphold grid stability by maintaining consistent frequency and voltage levels. In Kenya's energy landscape, grid stability relies on non-intermittent electricity sources like HEP, geothermal, and thermal electric power. This research is pioneering within Kenya's context because it provides a scientific analysis on an hourly basis, elucidating the technical and economic repercussions of expediting solar power integration into the nation's generation mix while considering grid stability (curtailment).

3.2.2 Overview and Simulation Using EnergyPLAN

EnergyPLAN offers a comprehensive framework for evaluating the feasibility of solar power generation within Kenya's energy mix. The tool can incorporate various factors such as economic and environmental aspects. Designed to simulate and model extensive integration of RES and significant technological shifts in energy systems, EnergyPLAN provides a versatile platform for analysis (Lund et al., 2015). Figure 3.2 outlines the overall structure of EnergyPLAN.

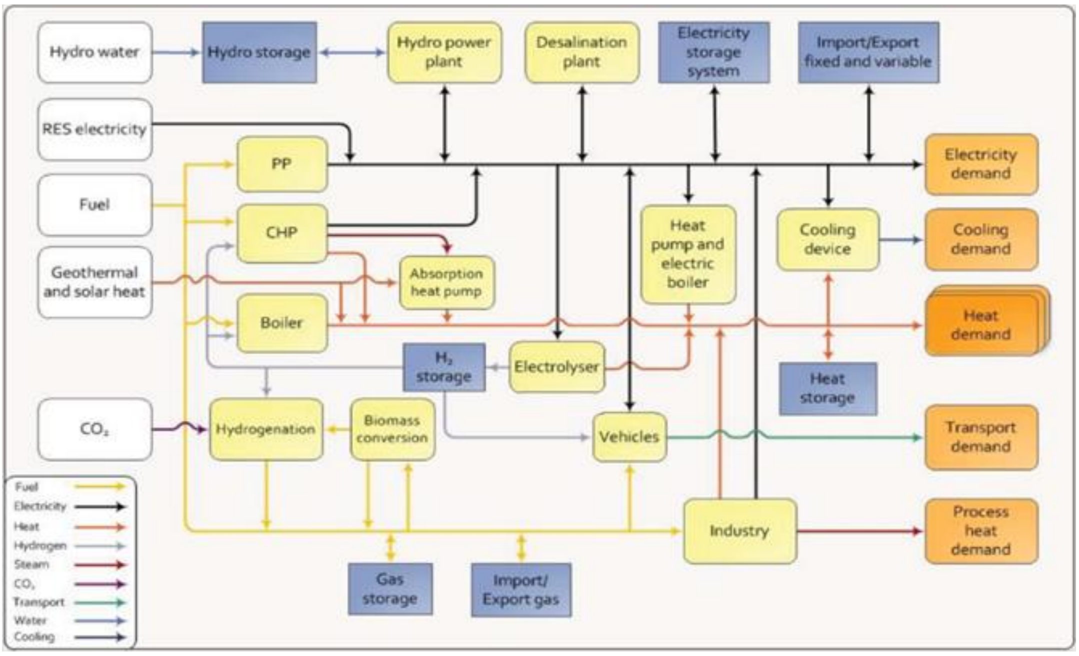


Figure 3.2: Conceptual Diagram of EnergyPLAN (Lund et al., 2015)

EnergyPLAN considers the transportation, heat, and hourly interactions among electricity and industrial systems (Bellocchi et al., 2020; Lund et al., 2015).

The electricity market is characterized by several key components, including the hourly electricity price, maximum transmission capacity, and price elasticity in the electricity exchange. When assessing socioeconomic costs, we consider various factors such as fuel and fuel handling expenses, fixed and variable operation and maintenance costs, electricity import and export, annualized investment costs using a discount rate, and carbon dioxide emission expenses (Lund et al., 2015; Østergaard, Lund, et al., 2022).

The tool operates at an aggregated level, meaning that individual energy plant sources are not modeled separately. Instead, all plants within the same category are represented as one entity (Lund et al., 2015). Consequently, it is also a copper-plate model, as there are no internal restrictions (Helistö et al., 2019; Lund et al., 2015) in, e.g., the electricity grid. The software can model the entire energy systems thus including (Lund et al., 2021) e.g., transportation and district heating systems, however, these facilities are not exploited in this work.

EnergyPLAN operates with two general classes of regulation strategies (Prasad et al., 2014): technical and economic. Technical strategies aim exclusively to minimize fuel usage while in the economic regulation strategy, power producers will also be optimized against the electricity market (Prina et al., 2019). In this thesis, a technical regulation strategy was applied to identify possible pathways.

Additionally, economic costs may also be calculated with the technical regulation strategy. Due to the aggregation property of EnergyPLAN, all solar power systems are aggregated into one. Additionally, solar power is prioritized by EnergyPLAN, thus in general, the technology will be allowed to be produced according to availability (Østergaard, Lund, et al., 2022). All dammed HEPs are modeled as one, with the same efficiency and drawing on the same reservoir (Chahine, 2018; Lund et al., 2015; Østergaard, Lund, et al., 2022).

Data on existing HEPs is a key input in EnergyPLAN's modeling of hydro. This includes information on the capacity, efficiency, and output of HEPs in the region being modeled (Chahine, 2018; Lund et al., 2015; Østergaard, Lund, et al., 2022). Cost data is also a key input in modeling hydro, including investment costs and operation and maintenance (Chahine, 2018; Lund et al., 2015; Østergaard, Lund, et al., 2022).

EnergyPLAN prioritizes HEP to minimize fossil fuel usage of the system (Noorollahi et al., 2023). Additionally, it is used for balancing other RESs limited by reservoir capacity and inflow (Noorollahi et al., 2023). Fossil fuel plants are the least prioritized and only applied in hours when RES are inadequate in supply (Noorollahi et al., 2023).

For grid stability reasons, EnergyPLAN can though be instructed to require a certain minimum production from ancillary service-providing units such as units based on synchronous generators (Matos, 2021; Warwick, 2002). Fuel consumption is determined by considering the fuel mixes of various plant types and how these plants operate (Chahine, 2018; Lund et al., 2015; Østergaard, Lund, et al., 2022).

EnergyPLAN identifies optimal system configurations through hourly calculations within a specified time frame demand (Okonkwo et al., 2021; Østergaard, 2015) as presented in Figure 3.3

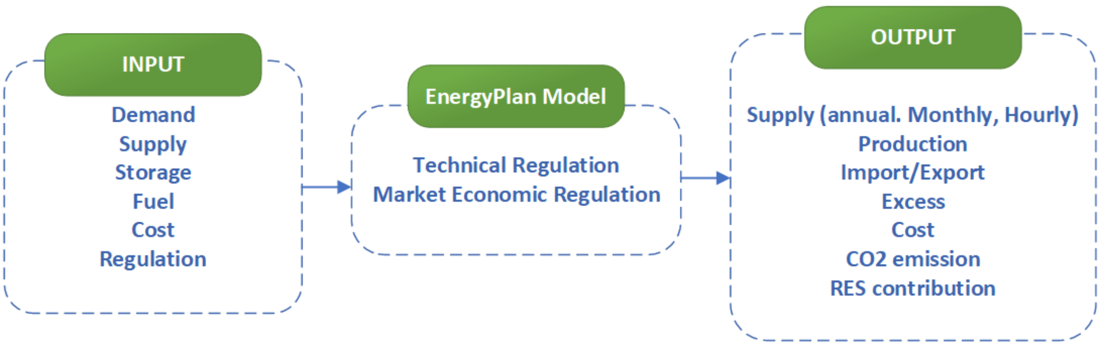


Figure 3.3: Simulation layout of the EnergyPlan simulation tool

The primary sources of electric power in Kenya's energy infrastructure include hydro, geothermal, and variable RES such as solar and wind. The annual supply calculation for each source is outlined in Table 3.1 below by Equations 3.1 to 3.3

Table 3.1: The simulation equations for the primary electric energy supply in Kenya's energy infrastructure.

Energy source	Simulation Equations
Geothermal power (E_g)	$E_g = \left(\frac{F_g * C_g * d_g}{Max(d_g)}\right)$ (3.1)
Where F_g is the correction factor between production and capacity, C_g is the capacity of the geothermal power electricity generator (MW), and d_g is the distribution of electricity production between 8784-hour values	
Hydropower (E_h)	$E_h = Max\left[E_{h(av)}, (W_h - S_h) * \mu_h\right]$ (3.2)
Where, $E_{h(av)}$ is the average hydroelectricity production, W_h is the annual water input, S_h is the water storage capacity, and μ_h is the efficiency of the generator	
Variable Renewable Energy (E'_r)	$E'_h = \left(\frac{E_r}{[1 - F_r * (1 - E_r)]}\right)$ (3.3)
Where E_r is the individual RES capacity, and $F_r$is the correction factor of RES production	

Furthermore, EnergyPLAN has the capability to model and simulate the extensive integration of RES and significant technological shifts in energy systems, rendering it a suitable option for this examination. The investment, fixed operation, and maintenance costs were simulated using Equation 2.4, which considers input capacity, unit price, interest rate, and equipment lifetime.

$$Ai_s = \left(\frac{I_s * i}{1 - (1 + i)^n}\right) \tag{3.4}$$

Where Ai_s is the annual cost of investment of the energy source s, I_s is the total investment of each production unit s, i is the interest used for socio-economic evaluation, and n is the lifetime of the investment. For economic simulation, specified hourly price distribution (P_{in}) was used to compute the market prices (P_M) based on Eq. 3.5. Where F_m is the multiplication factor and F_a is the addition factor.

$$P_M = P_{in}(F_m + F_a) \tag{3.5}$$

The EnergyPLAN tool was designed to simulate and model the functioning of existing energy and power markets. It enables the selection of generation sources for electricity and energy supply based on their minimal marginal production costs.

EnergyPLAN also accounts for the hourly interactions between electricity and heat systems. For example, a combined heat and power (CHP) unit can utilize thermal storage capacity while generating electricity. Factors such as price elasticity in the electrical exchange, maximum transmission capacity, and hourly electricity price are incorporated to represent the external electricity market.

The annualized investment expenses, factored in with a discount rate, are combined with costs related to CO_2 emissions, energy import and export, fixed and variable operation and maintenance, as well as fuel and fuel handling expenses, to calculate the socioeconomic costs.

This thesis utilized the EnergyPLAN tool to assess Kenya's energy system, focusing on the technical and economic impacts of integrating solar power and investing in the country's energy mix. Two regulatory strategies were employed: Technical Regulation (TR) and Market Economic Regulation (MER).

Table 3.2: Criteria for Analysis: Warnings and Corrective Measures

Criteria	Definition
EG warning (Crit 1)	There is surplus electricity generated once the annual demand has been satisfied. Solution: A progressive reduction in solar power supply capacity until an optimal technical resolution is reached.
PI warning (Crit 2)	The output from the solar power system is inadequate to fulfill the yearly demand. Solution: Enhance the generation capacity of the Solar power system until an optimal level is reached.
No EG warning and PI warning (Crit 3)	The annual power supply meets the yearly demand. Solution: Slightly decrease the power plant capacity until an optimal economic solution is attained.
Both PI warning and EG warning (Crit 4)	There is a surplus of electricity supply alongside unmet demand. Solution: Increase the capacity of power plants while reducing the solar power capacity.

The TR strategy aimed to optimize the generation process by minimizing excess electricity production and fuel consumption. Meanwhile, MER was employed to analyze the potential for electricity exchange in various scenarios, aiming to meet energy demands at the lowest marginal costs. Initially, solar power was analyzed independently, followed by examining other combinations. Additionally, thermal power plants were incorporated as energy sources to ensure system stability.

The optimized outcomes are derived from both TR and MER approaches. This analysis applied four criteria outlined in Table 3.2, focusing on Power Plant Input (PI) and Excess Electricity Generation (EG) to ensure optimal power generation. Figure 3.4 illustrates the process simulation (optimization) of the aforementioned four criteria and the actions taken to meet these criteria. It's important to note that intermittent RES are fully utilized before the demand is fulfilled by other energy resources.

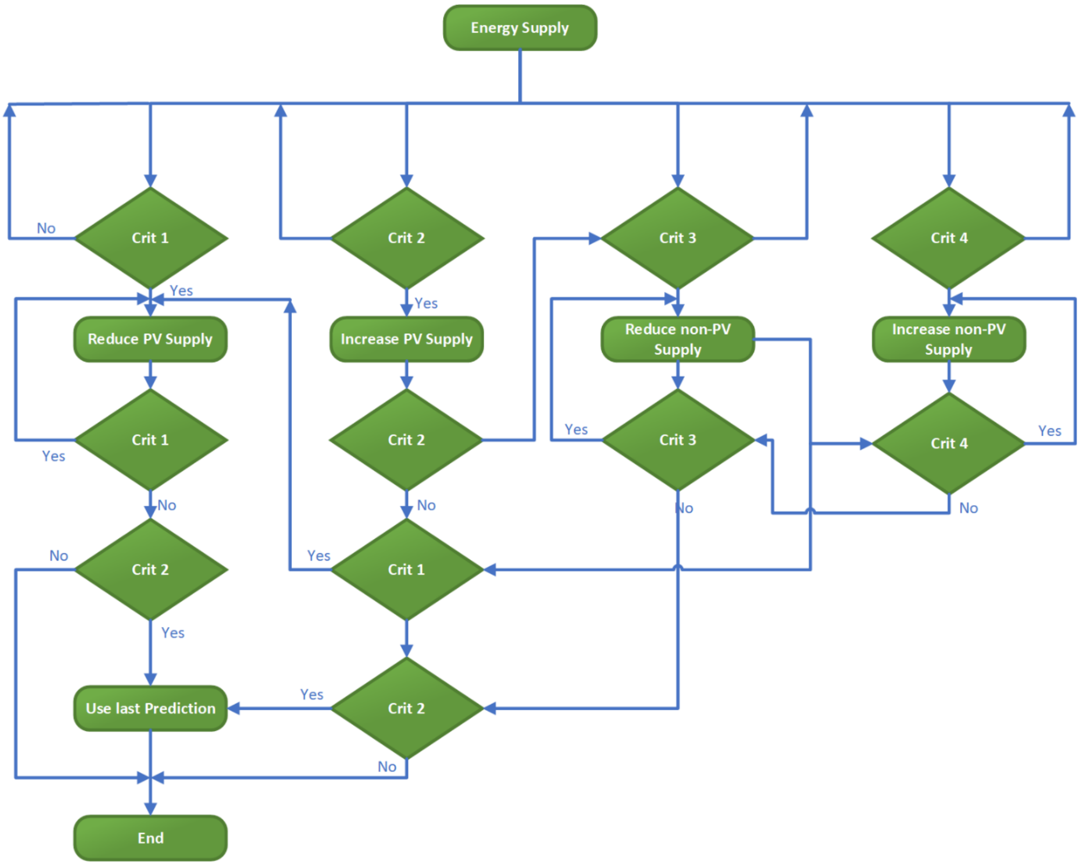


Figure 3.4: Process simulation (optimization) flowchart

3.2.3 Research Model and Data

This thesis introduces an approach to enhance the integration of solar power into Kenya's electricity grid, considering its impacts on system stability and CO_2 reduction across economic and technical dimensions. The analysis of solar power energy sources was conducted at hourly intervals to offer insights into its performance when integrated with other energy sources like HEP, wind, geothermal, and thermal on an annual basis.

The data utilized in this thesis encompassed hourly electricity demand for a year, hourly electricity generation per sector for a year, technology unit cost, efficiency of individual power plants, and their capacities. These data were sourced from the Energy Regulatory Commission and the Kenyan Ministry of Energy (Ministry of Energy, 2021).

This thesis assessed two distinct case scenarios: Scenario 1, which reflects the present year or business as usual and serves as the baseline. Scenario 2 represents accelerated solar power integration, depicting a hypothetical scenario for the year 2030 with an estimated demand of 25.28 TWh (International Energy Agency, 2022). The technical and economic performance concerning the current electricity demand is assessed and juxtaposed with the reference year (Scenario 1). Hourly distribution profiles for the demand and various energy production technologies were obtained from a Kenyan Model.

All configurations are tailored to match Kenya's energy system characteristics. Nevertheless, the technological solutions derived can be implemented in any country or region with similar potential for wind and solar power, HEP, and geothermal energy as Kenya's.

3.3 Evaluation of Sectoral Innovation Systems in Solar Electrification Pathways

This component of the study forms part of the broader research initiative**,** Innovation and Renewable Electrification in Kenya (IREK)**,** which ssought to examine how solar technologies are integrated into Kenya's renewable energy transition. The project applied the Sectoral Innovation Systems (SIS**)** framework to assess the interplay of actors, institutions, and technological dynamics shaping solar electrification in the country (Gregersen, 2022a).

3.3.1 Study Area Definition

The study was conducted in Nairobi County**,** Kenya's capital and primary economic hub, located at approximately 1.2921° S latitude and 36.8219° E longitude**, c**overing 696 square kilometres. Nairobi is a cosmopolitan and demographically diverse urban center, with a population exceeding 4.7 million (Owuor, 2019). Its rapid population growth is driven by both natural increase and rural-to-urban migration (Neubert & Stoll, 2020).

Economically, the city functions as Kenya's administrative, industrial, and financial nucleus, home to multinational corporations, government ministries, financial institutions, and international agencies (Littlewood & Kiyumbu, 2018; Warui, 2021). Given its infrastructural concentration and diversity of stakeholders, Nairobi provides a suitable setting for analyzing innovation systems in solar electrification.

3.3.2 Data Collection

A mixed-methods approach was employed to collect both qualitative and quantitative data from key stakeholders and documentary sources relevant to solar electrification.

Qualitative data was obtained primarily through semi-structured interviews with actors across the solar value chain—including technology developers, manufacturers, policymakers, distributors, financiers, and end-users. A snowball sampling strategy was used to expand the participant pool by leveraging existing networks of initial respondents.

To supplement interview data, policy documents, industry reports, and organizational publications were reviewed to capture formal regulatory and institutional contexts.

Quantitative data was gathered through structured surveys, aimed at documenting innovation activities, investment flows, market trends, and regulatory impacts across sectors. Survey instruments were customized for specific actor categories and pre-tested for validity and reliability, following the methodological approach outlined by Vishwakarma, Nema, and Sangle (2018). A sample questionnaire is provided in **Appendix 1**.

3.3.3 Cross-Sectoral Analysis

The collected data was analyzed using a combination of qualitative and comparative methods to synthesize sectoral insights and identify cross-cutting patterns, opportunities, and constraints.

- **Thematic Analysis** was conducted to extract recurring issues, challenges, and strategies emerging across sectors. This enabled the identification of shared institutional bottlenecks and innovation opportunities in solar deployment (Salm et al., 2021).
- **Comparative Analysis** was used to contrast sectoral innovation systems in terms of actor roles, policy environments, enabling conditions, and innovation trajectories. This helped to surface best practices and transferable lessons for broader application (Isaksen et al., 2018; Cinar et al., 2019).
- **Network Analysis** mapped the relationships and interactions among stakeholders within and between sectors. This approach identified key actors, influence structures, knowledge flows, and collaboration dynamics that underpin innovation diffusion and adoption (Vogel et al., 2022; Watkins et al., 2018).
- **Qualitative Comparative Analysis (QCA)** was employed to systematically assess the combinations of institutional and technological factors that lead to successful innovation outcomes (e.g., market adoption or regulatory approval). QCA enabled the identification of necessary and sufficient conditions for success across diverse sectoral contexts (Hanckel et al., 2021; Verweij & Trell, 2019).

By integrating these analytical techniques, the study offers a comprehensive understanding of how sectoral dynamics influence the innovation and diffusion of solar technologies in Nairobi. The findings contribute to policy recommendations for enhancing cross-sectoral coordination, addressing institutional gaps, and accelerating Kenya's transition to renewable electrification.

3.4 Towards 100% Renewable Energy: Incrementing Solar Electrification in Kenya

This section outlines the application of the EnergyPLAN model in analyzing energy system scenarios with the objective of evaluating the feasibility of large-scale integration of RES into Kenya's electricity mix—specifically focusing on the expansion of solar power generation.

The primary aim is to assess the technical viability and implications of increasing solar power penetration within the national energy system. EnergyPLAN serves as a robust simulation tool for modelling and analyzing various energy transition scenarios, enabling the evaluation of energy balances, emissions, system costs, and other key performance indicators. The model is utilized to construct and compare multiple scenarios, each reflecting different levels of solar power integration.

To ensure relevance and contextual accuracy, the analysis begins with a comprehensive review of Kenya's current energy mix, with 2022 selected as the base year. This provides a snapshot of the existing energy infrastructure and informs the development of realistic and data-driven scenarios. The reference year also serves as a benchmark for measuring the potential impact of increased solar power deployment.

Scenario development involves incrementally scaling up solar power capacity within the constraints of the national energy system as modeled in EnergyPLAN. This step is critical to identifying the optimal level of solar power penetration that is technically feasible and aligned with national energy objectives. Through this approach, the study explores how Kenya can transition toward a more sustainable, low-carbon electricity sector, ultimately contributing to the long-term goal of achieving a 100% renewable energy system.

3.4.1 Energy System Scenario Analyses

This section describes the approach used to develop and analyze energy system scenarios for assessing the potential integration of solar power generation into Kenya's national electricity grid. The analysis is grounded in empirical data collected from diverse and reputable sources, including the Kenya Power and Lighting Company (KPLC)**,** the International Energy Agency (IEA)**,** and insights obtained through expert interviews. Key data inputs include electricity demand, total installed generation capacity, and electricity generation disaggregated by fuel type.

To establish a robust understanding of Kenya's current energy landscape, a longitudinal analysis was performed, covering a twelve-year period. This involved evaluating historical trends in electricity demand, installed capacity, and generation by technology, thereby providing a comprehensive picture of the country's energy mix and its evolution over time.

Based on this analysis, a reference scenario was constructed using 2022 as the baseline year. This reference scenario serves as a critical foundation for subsequent modelling activities. It represents the status quo of Kenya's power system and provides a benchmark against which the effects of increased solar integration can be measured.

The simulation process was carried out using the EnergyPLAN model, chosen for its capability to perform detailed energy system analyses with high accuracy. The model enabled the systematic evaluation of various solar power deployment scenarios, with a particular focus on identifying the optimal solar power generation capacity that is both technically viable and economically reasonable within the context of Kenya's energy infrastructure.

To determine this optimal capacity, a series of simulations were run by varying the input values for installed solar power capacity from 100 MW to 10,000 MW**.** Each simulation run allowed EnergyPLAN to calculate key performance metrics, including system balance, energy production, fuel consumption, and CO_2 emissions**.** Through iterative refinement, the model identified the capacity range that achieved the best balance between increased renewable energy penetration and system reliability and cost-effectiveness.

This scenario-based approach not only illustrates the feasibility of scaling up solar power generation but also demonstrates the flexibility of EnergyPLAN in evaluating diverse pathways toward a more sustainable and decarbonized electricity system in Kenya.

3.4.2 Reference Scenario Development

This section outlines the development of the reference scenario for Kenya's electricity sector as of the year 2022**,** forming the baseline for all subsequent modelling and scenario analysis. The reference scenario is essential for capturing the current status of electricity generation, demand, storage capabilities, and economic conditions, thereby providing a realistic foundation upon which alternative energy futures—particularly those involving increased solar penetration—can be evaluated.

The following key components were considered in the development of the reference scenario:

3.4.2.1 Power Generation

This component includes an inventory of the current power generation technologies in operation within Kenya, encompassing thermal power plants, hydroelectric power (HEP) stations, geothermal facilities, wind farms, and solar power systems. While thermal and hydroelectric sources have traditionally dominated Kenya's electricity supply, recent developments indicate a growing shift toward other RES, particularly solar energy, given the country's abundant solar irradiance and untapped potential for solar power deployment. The scenario also accounts for the technical and infrastructural capacity to support additional solar installations.

3.4.2.2 Energy Demand

An assessment of national electricity demand was conducted for the reference year 2022, using available data from government reports and utility providers. The scenario also incorporates projections for future demand—specifically for the year 2030—to align with Kenya's development goals and anticipated population and economic growth. According to the Ministry of Energy and Petroleum (2015), electricity demand in Kenya is expected to rise steadily due to industrialization, urbanization, and improved access to electricity. Within this context, solar power presents a viable option to supplement future demand while reducing reliance on fossil fuels.

3.4.2.3 Energy Storage

The reference scenario considers dam-based hydroelectric storage as the primary mechanism for balancing supply and demand, particularly to mitigate the intermittency associated with solar power generation. In regions where the transmission and distribution infrastructure are limited or underdeveloped, energy storage plays a crucial role in maintaining system stability. Hydropower reservoirs, which currently exist in

Kenya's energy system, are utilized not only for generation but also as a strategic balancing resource.

3.4.2.4 Economic Parameters

The economic dimension of the reference scenario includes an analysis of energy production costs for different generation technologies. Conventional sources such as thermal have relatively high intitial investment costs, while the cost of solar power has been declining due to technological advancements and favorable investment conditions. Economic inputs also consider fuel prices, particularly the costs associated with imported fossil fuels used in thermal generation. These factors are summarized in Table 3.3, which provides a comparative overview of generation costs across technologies.

Table 3.3: System Energy Costs for Reference Scenario Based on EPRA (2022) Data

Annual Costs (Billion KSh)	Total	Variable	Breakdown
Fuel ex. Gas exchange		11	
Coal			0
FuelOil			0
Gasoil/Diesel			0
Petrol/JP			0
Gas handling			11
Biomass			0
Food income			0
Waste			0
Gas Exchange costs		243	
Marginal operation costs		93	
Electricity exchange		20	
Import			38
Export			18
Bottleneck			0
Fixed imp/exp			0
CO_2 emission costs		43	
Variable costs	62.44		
Fixed operation costs	37.77		
Annual Investment costs	89.40		
TOTAL ANNUAL COSTS	189.77		

Parts of the energy system that have not been included in the analysis in the Kenyan context include microgrids. These are localized power grids capable of functioning autonomously from the main grid. While they may be pertinent for certain regions or communities, they are not applicable to Kenya's national energy system. The optimal scenario developed in this thesis aims to provide a realistic and achievable scenario for optimizing solar power generation in Kenya's electricity generation mix.

3.4.3 Electricity Demand

The total electricity demand in Kenya in 2022 was 12,985.4 GWh (KNBS, 2023b). Demand for each sector is provided in Table 3.4. Losses are significant and alleviating measures are important, in this thesis same level of losses in both the reference and future scenarios have been maintained.

Transmission and distribution losses are attributed to resistance losses, and also to an aging and inefficient transmission and distribution network, as well as illegal power connections, poor metering, and inefficient reading of power meters. In 2022 losses accounted for 29.5% of the total generated power (KNBS, 2023b).

Table 3.4: Electricity Demand in Kenya by Sector, 2022

Sector	Demand (GWh)	Percentage (%)
Domestic and Small Commercial	4,291.5	33.04
Large & Medium (Commercial and Industrial)	4,958.2	38.18
Street Lighting	94.2	0.73
Rural Electrification	664.5	5.12
Transmission and distribution losses	2,955.7	22.76
Power Exports	21.3	0.17
Total demand	**12,985.4**	**100**

Source: Kenya National Bureau of Statistics (KNBS), 2023b

To boost system efficiency, KPLC has implemented various measures to mitigate losses. These measures encompass the redistribution and balancing of electrical loads to mitigate technical losses, along with increased scrutiny of customer metering installations to ensure their reliability, promptly followed by necessary corrective actions. Additionally, strategies include the implementation of smart metering technology, a crackdown on unauthorized connections, and the adoption of live line technology in network maintenance, thereby reducing both planned and unplanned outages (Power, 2022).

Table 3.5: Electricity Production for Kenya 2010 – 2022 (Ritchie, H., Roser, M. 2022)

Year	Production (TWh)
2010	7.22
2011	7.58
2012	8.09
2013	8.69
2014	8.37
2015	9.87
2016	9.69
2017	10.7
2018	11.25
2019	11.49
2020	11.75
2021	11.83
2022	12.65

3.4.4 Electricity Production

Over the period spanning from 2010 to 2022, Kenya's overall power production profile exhibited a notable trajectory of growth, as depicted in Table 3.5. The recorded values in TWh for each year reveal a consistent upward trend, showcasing an expansion in the country's power generation capacity from 7.22 TWh in 2010 to 12.65 TWh in 2022.

This increase of approximately 5.43 TWh over the 12 years, reflecting a growth of around 75%, suggests a concerted effort to meet the escalating energy demands within the nation. This upward trend implies several noteworthy impacts. Firstly, the consistent growth in power production aligns with the necessity to cater to the rising energy demands driven by factors such as population growth, urbanization, and industrial development. In 2022, geothermal generation was the largest source of electricity, accounting for 43.6% of total electricity generated. This was followed by HEP at 24.0% while solar contributed only 3%.

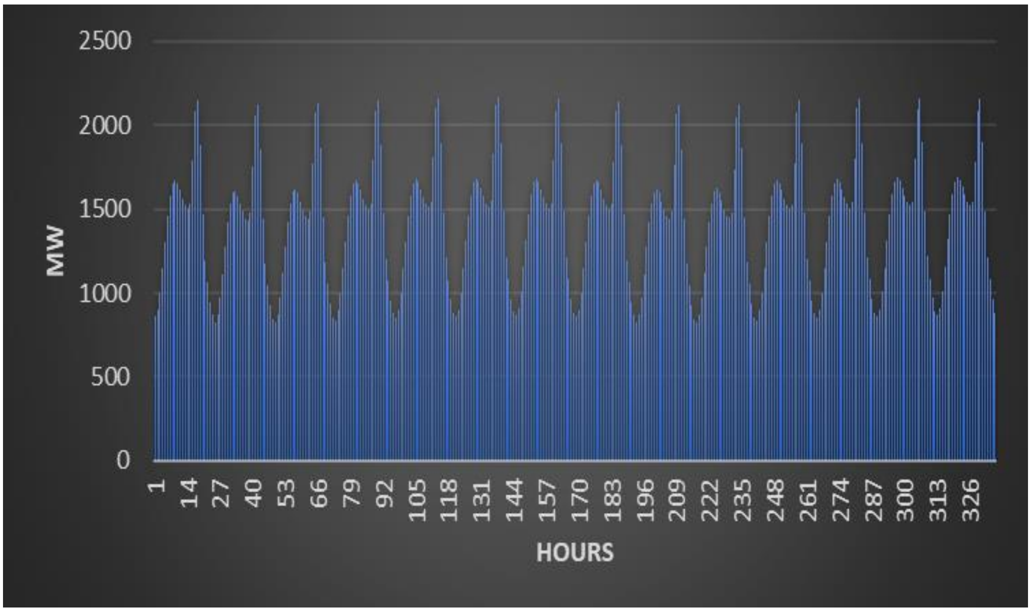


Figure 3.5: Sample two weeks' of electricity demand for Kenya made using data from (KNBS 2023)

The hourly production and demand profile become an important consideration for the development of the reference and the optimal RES scenarios using EnergyPLAN. Hourly distribution profile files for solar, hydro, wind, and the demand for Kenya in the year 2022 were obtained from (KNBS 2023) and (Abdulganiyu 2017).

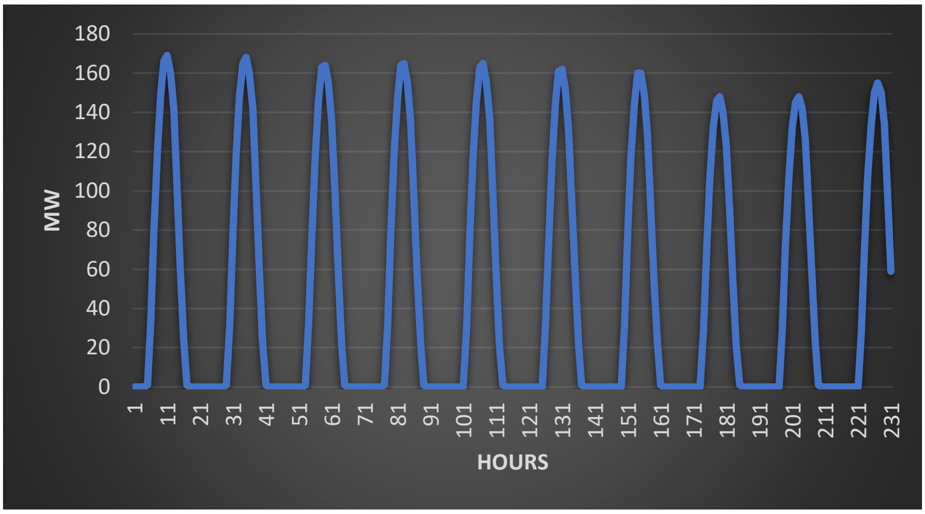


Figure 3.6: Sample two weeks' of solar electricity production for Kenya made using data from (KNBS 2023)

The number of values in the annual production and demand distribution profile will depend on the time resolution of the data. In this thesis data is presented in hourly intervals, hence there are 8,784 values for the entire year for every distribution file as EnergyPLAN models a leap year.

Analyzing the hourly production and demand distribution profiles allows for a better understanding of the energy system's dynamics throughout the year. It offers insights into fluctuations in electricity generation and consumption patterns, which are vital for optimizing the integration of solar power into the broader energy mix.

Distribution profiles help identify periods of high and low energy demand, as well as times when renewable power generation is most abundant. This information can be utilized to optimize the dispatch and scheduling of different energy sources, including solar, hydro, and wind, to meet the fluctuating electricity demand.

Figures 3.5 and 3.6 provide a sample of two weeks' hourly cumulative demand and production respectively. The distribution profiles shown in Figure 3.7 shows absolute values. The same time series are used as relative weights for other penetration of wind and solar power.

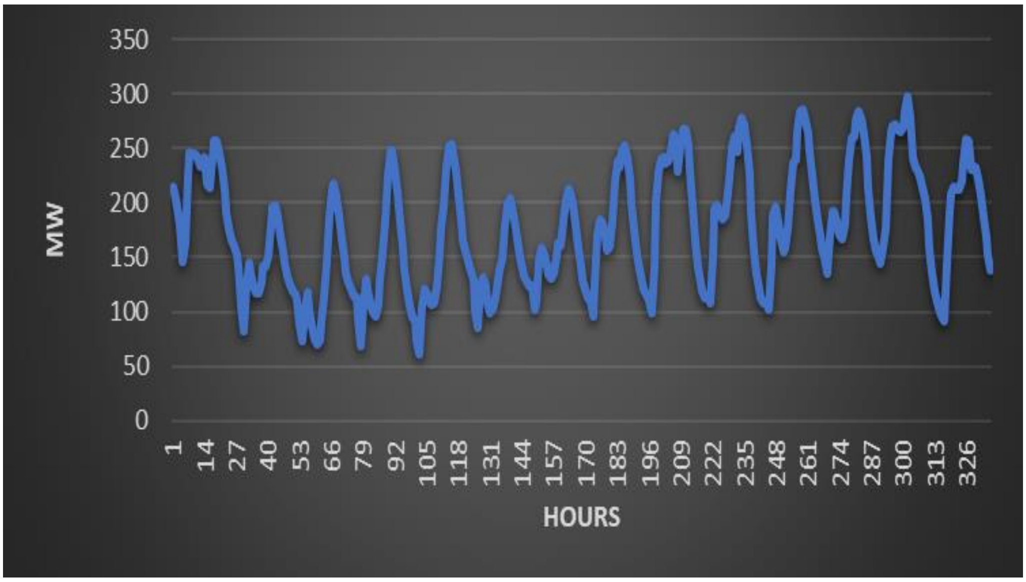


Figure 3.7: Sample two weeks' wind power production for Kenya made using data from (KNBS 2023)

3.5 Development and Evaluation of Whales Optimization Algorthm-Based MPPT for Solar Power Systems

This section presents methodology for development and evaluation of a Whale Optimization Algorithm (WOA)-based Maximum Power Point Tracking (MPPT) (Percin & Caliskan, 2023). The aim is to enhance the performance and efficiency of solar power systems. The motivation for this objective stem from the growing global emphasis on renewable energy integration and the need for robust MPPT algorithms capable of handling the dynamic and nonlinear behavior of solar power systems under real-world conditions.

The methodology is structured into three primary stages: algorithm design and implementation, simulation setup, and performance validation. These stages collectively ensure a rigorous investigation of the WOA-based MPPT's capability under varying environmental influences, with an emphasis on maintaining system stability and maximizing energy extraction.

3.5.1 Algorithm Design and Implementation

The WOA-based MPPT algorithm is implemented in MATLAB R2021a (The MathWorks Inc., Natick, MA), leveraging its computational power and simulation flexibility. The core objective of the algorithm is to iteratively identify the optimal duty cycle for a DC-DC converter, which interfaces the solar power system array with the electrical load. The duty cycle directly influences the operating voltage of the solar power array, thereby controlling the power output.

By dynamically adjusting the duty cycle in response to changing environmental parameters such as solar irradiance, temperature variations, and shading, the algorithm ensures that the solar power system operates consistently at or near its Maximum Power Point (MPP). The nonlinear and time-varying nature of solar power characteristics makes the MPPT problem well-suited for metaheuristic optimization methods, among which WOA offers significant advantages due to its balanced exploration and exploitation capabilities.

3.5.1.1 Whale Optimization Algorithm Fundamentals

The Whale Optimization Algorithm is a bio-inspired metaheuristic algorithm that models the unique bubble-net feeding behavior of humpback whales (Almutairi et al., 2020b). The algorithm mimics whales' hunting strategies, capturing their ability to encircle prey, perform spiral bubble-net attacks, and execute random searching movements to avoid local optima. The WOA combines global and local search tactics through the following behavioral phases (Almutairi et al., 2020b):

- **Encircling Prey:** This mechanism simulates whales moving toward the best-known solution, which, in this context, corresponds to the duty cycle yielding the highest solar power power output. This phase promotes convergence by guiding the candidate solutions (whales) toward promising regions of the search space, narrowing the range of possible duty cycle values over successive iterations.
- **Bubble-Net Attacking:** Once the algorithm identifies a promising candidate solution, it employs a logarithmic spiral updating technique to mimic the whales' bubble-net attack. This phase enhances the local search capability by fine-tuning the solution around the best candidate, improving the precision of convergence to the true MPP.
- **Random Search:** To maintain population diversity and prevent premature convergence, a probabilistic decision-making process randomly switches between shrinking encircling and spiral updating mechanisms. When a random number is below 0.5, the algorithm performs shrinking encircling to exploit known good regions; otherwise, it performs spiral updating to explore the search space more broadly.

During each iteration, candidate solutions representing duty cycle values are updated based on these mechanisms. A clip function is employed to restrict updated duty cycles within safe and feasible operational bounds of the DC-DC converter, thus ensuring system reliability and avoiding invalid control signals. The developed WOA-based MPPT algorithm in MATLAB is provided in Appendix II.

3.5.1.2 Power Evaluation Function

Central to the optimization process is the power evaluation function, which quantitatively assesses the fitness of each candidate duty cycle solution. This function accepts a duty cycle value as input and computes the corresponding power output using a detailed mathematical model of the solar power system.

The solar power model integrates key physical and environmental parameters, including:

- **Solar Irradiance:** Varying levels of sunlight intensity directly affect the current generation capacity of the solar power cells.
- **Temperature Variations:** Temperature influences the voltage and current characteristics of the solar power modules.
- **Internal System Losses:** Realistic simulation includes factors such as series and shunt resistances, conversion inefficiencies, and wiring losses.

By accounting for these elements, the power evaluation function produces accurate estimates of instantaneous power output under realistic operating conditions. This fitness value guides the WOA as it iteratively searches for the duty cycle maximizing solar power output.

3.5.2 Simulation Environment

The simulation environment is carefully constructed to replicate practical solar power system operation and test the robustness of the proposed MPPT algorithm. The setup comprises the following components:

- **Photovoltaic Module:** A standard solar power module with well-characterized electrical parameters was used as the energy source.

- **DC-DC Boost Converter:** Serving as the interface between the solar power module and the electrical load, the converter's duty cycle controls the operating voltage of the solar power module.
- **Resistive Load:** A fixed load simulating a typical electrical consumer was connected downstream of the converter.

To emulate real-world operating conditions, environmental inputs—namely solar irradiance and ambient temperature—were systematically varied throughout the simulation. These variations included:

- **Rapid Fluctuations:** Sudden changes in irradiance mimicking passing clouds or transient shading events.
- **Partial Shading:** Simulated by reducing irradiance on part of the solar power array, representing common scenarios in urban or obstacle-rich environments.
- **Temperature Dynamics:** Simulated changes in ambient temperature affecting solar power output characteristics.

This comprehensive simulation framework allows for a realistic and rigorous evaluation of the MPPT controller's dynamic response and steady-state performance.

The developed WOA-based MPPT is benchmarked against three conventional MPPT algorithms:

Fuzzy Logic Controller (FLC): Known for its robustness in nonlinear systems without needing an explicit mathematical model.

- **Particle Swarm Optimization (PSO):** A well-established metaheuristic optimization technique leveraging swarm intelligence.

- **Incremental Conductance (INC):** A widely used classical MPPT method based on the derivative of the power-voltage characteristic.

All algorithms are tested under identical environmental profiles to ensure fairness and consistency in comparative evaluation.

3.5.3 Performance Metrics

To rigorously assess the effectiveness of the WOA-based MPPT controller, seven key performance indicators (KPIs) were selected, providing a multifaceted evaluation of both transient and steady-state behaviors:

- **Overshoot:** Measures the extent to which the power output exceeds the MPP during transient responses, indicating potential instability or aggressive tuning.
- **Peak Power:** The highest power level attained during the tracking process, reflecting the controller’s capability to maximize energy capture.
- **Extracted Power:** The total energy harvested over the simulation period, integrating performance over time.
- **Rise Time:** Time taken for the output power to reach a significant percentage (typically 90%) of the MPP following a disturbance.
- **Settling Time:** Duration required for the power output to stabilize within a predefined tolerance band around the MPP.
- **Steady-State Error:** The residual deviation between the steady-state power output and the true MPP, indicating tracking accuracy.
- **Efficiency:** Ratio of the extracted power to the theoretical maximum possible energy under given environmental conditions, measuring overall algorithm effectiveness.

These KPIs are derived from detailed time-domain simulation data and allowed for a comprehensive understanding of the MPPT controller’s performance across a variety of operating scenarios.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and interprets the key findings of the study in relation to the research objectives. The discussion is structured into four main sections, each corresponding to a core component of the research methodology.

The first section presents the results of the technical and economic performance assessment of accelerated solar electrification in Kenya, highlighting the viability and implications of increased solar power deployment. The second section offers a disaggregated analysis of solar electrification pathways**,** examining sector-specific dynamics and institutional influences. The third section explores the outcomes of incrementing solar integration within Kenya's national energy mix, focusing on the potential impact of scaling up solar power capacity. The final section discusses the results from the simulation and evaluation of the WOA-based Maximum Power Point Tracking (MPPT) system for solar power systems, with emphasis on its performance, efficiency, and adaptability.

Together, these sections provide a comprehensive analysis of the technological, economic, and institutional dimensions of solar energy adoption in Kenya, offering insights into the opportunities and challenges associated with the transition toward a more sustainable energy future.

4.2 Tech-Economic Evaluation of Accelerated Solar Electrification

The highest electricity demand in Kenya was recorded at 2,056.67 MW in June 2022, as illustrated in the demand profile depicted in Figure 4.1. The installed capacity of the country's power plants stood at 3,074.34 MW, with geothermal and HEP being the predominant energy sources, contributing 39.15% and 26.47% respectively.

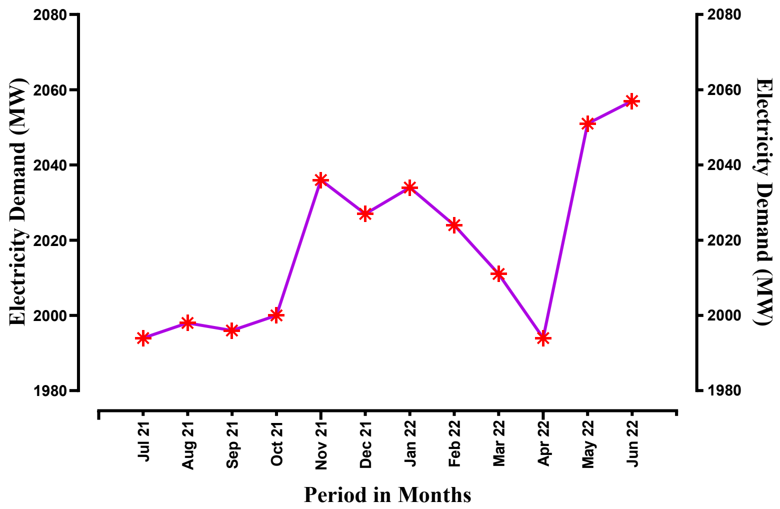


Figure 4.1: Annual Electricity demand profile in Kenya (2021 – 2022).

Wind and solar power sources collectively contributed 16.22% and 2.47%, respectively, as outlined in Table 4.1. The electrical energy generated, delivered to the national grid during peak demand in June 2022, amounted to 12,652.74 GWh.

In Kenya's energy system, a total of 285.51 GWh of electrical energy was curtailed during the period from 2021 to 2022. The highest curtailed energy occurred in November 2021, with 24,457 MWh from wind sources, and in June 2022, with 46,604 MWh from geothermal sources, as illustrated in Figure 4.2.

Table 4.1: Contribution to energy generation by Source in Kenya (2021 – 2022).

Energy source	Installed Capacity (MW)	Generation Capacity (GWh)	Contribution (%)
Hydro	837.58	3,348.71	26.47%
Thermal	646.32	1,647.75	13.02%
Wind	435.5	2,052.26	16.22%
Geothermal	949.13	4,953.15	39.15%
Bagasse/Biogas	2	0.38	0.00%
Imports	-	337.50	2.67%
Solar	170	312.99	2.47%
Off-grid	33.81	-	-
Total	**3,074.34**	**12,652.74**	**100%**

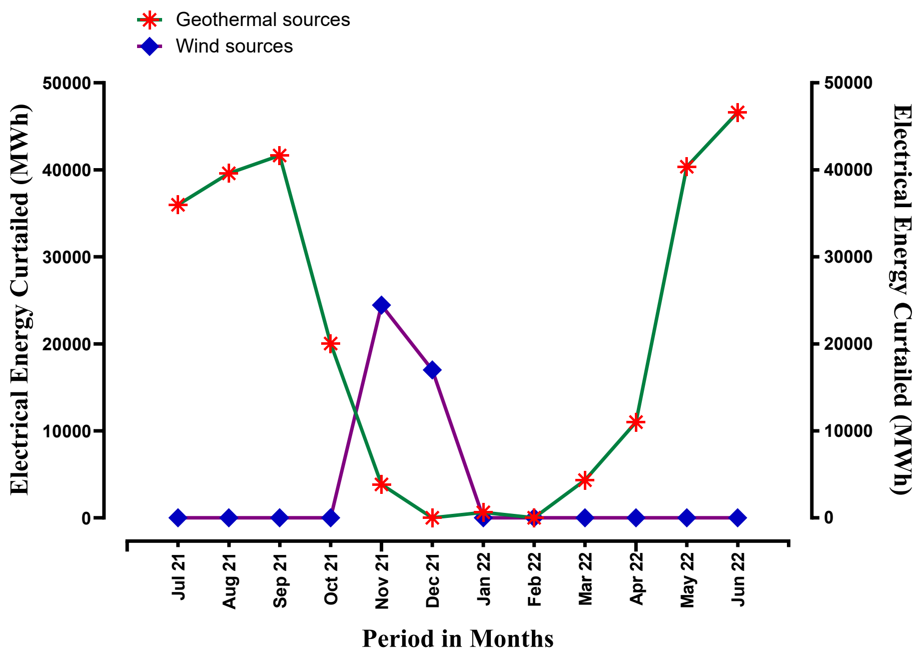


Figure 4.2: Annual Electricity curtailment in Kenya (2021 – 2022).

4.2.1 Scenario 1: Current Solar Power Integration

In the business-as-usual Scenario 1 (Reference case), all electrical energy within Kenya is generated from geothermal, HEP, wind, solar, thermal sources, and imports, as depicted in Table 4.1. The reference model was developed using technological inputs, followed by the inclusion of fuel, investment, and operation and maintenance (O&M) costs to conduct the energy system's socio-economic analysis. Table 4.2 outlines the cost assumptions for energy system components in the Technical Regulation (TR)-based analysis.

Table 4.2: Cost assumptions for energy system components.

Production Type	Parameters	Unit	Value
Large Power plant	Capex	KSh /kWh	990
	Lifetime	Years	20
	Opex fixed	% of investment	3.05
Wind	Capex	KSh /kWe	2400
	Lifetime	Years	20
	Opex fixed	% of investment	2.09 %
solar power - Ground-mounted	Capex	KSh /kWe	1150
	Lifetime	Years	30
	Opex fixed	% of investment	0.6 %
solar power - Rooftop	Capex	KSh /kWe	1200
	Lifetime	Years	30
	Opex fixed	% of investment	1 %
Hydropower - Run of the river	Capex	KSh /kWe	2750
	Lifetime	Years	50
	Opex fixed	% of investment	1.5 %
Geothermal Electricity	Capex	KSh /kWe	4550
	Lifetime	Years	20
	Opex fixed	% of investment	3.48%

Based on the reference model (Table 4.3), River Hydro exhibited the highest Estimated Production of 4.07 TWh per year, followed by Wind at 1.09 TWh per year, and finally Solar at 0.3 TWh per year among the variable renewable electricity generation systems. Geothermal served as the primary power plant.

Table 4.3: Production Per Sector for Scenario 1.

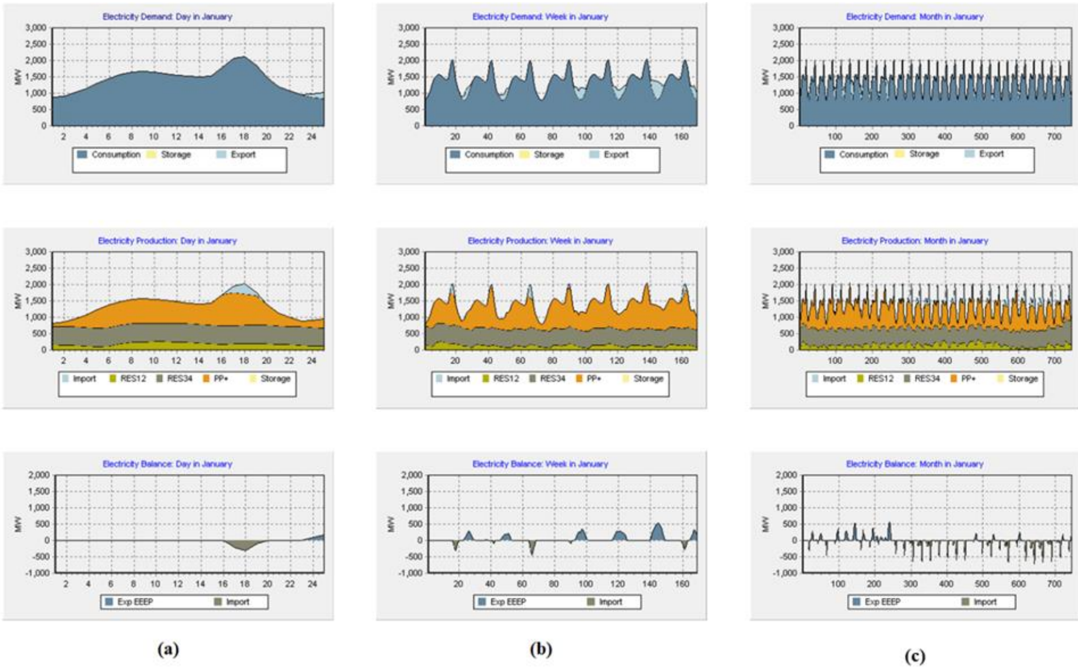
Variable Renewable Electricity			
Energy Source	**Estimated Production (TWh/Year)**	**Estimated post-correction Production (TWh/Year)**	**Estimated Capacity Factor**
Wind	1.90	1.90	0.50
Solar	0.30	0.30	0.20
River Hydro	4.07	4.07	0.55
Central Power Plants			
Power Plant	**Annual production (TWh/Year)**		
Geothermal	1.97		

A significant portion of the total power generated is derived from hydroelectric and geothermal power plants, with a smaller fraction originating from solar and wind energy sources. Furthermore, power imports are utilized to fulfill daily energy requirements, as illustrated in Figure 4.2. The monthly average demand per energy source is detailed in Table 4.4.

Table 4.4: Annual Average Demand Values.

Energy Source	Annual Average (MW)	Annual Max (MW)	Total for one Year (TWh)
Wind	217	408	1.9
River Hydro	464	828	4.07
solar power	34	137	0.3
Thermal	424	648	3.73
Geothermal	224	940	1.97
Off-grid	11	34	0.1
Import	84	1053	0.74

It was determined that electrical energy is imported to balance monthly electricity requirements. However, during off-peak hours, there is less demand for electricity than available supply, as depicted in Figure 4.2. It's important to note that balancing and storage systems were not considered in this analysis.



RES12 – Wind and Solar PV Renewable Energy Source
RES34 – River Hydro
PP+ – Geothermal and Hydro Power
Exp-EEEP – Exportable Excess Electricity Production
Exp-CEEP – Critical Excess Electricity Production

Figure 4.3: Electricity Energy profile in Kenya in Scenario 1, (a) A Day in January 2022, (b) A week in January 2022, and (c) Month of January 2022

Table 4.5: The Socio-Economic Analysis results based on Annual Costs of Investment and Annual Costs of Fixed O&M.

Production Type	**Total Investment Cost (Billion KHSs.)**	**Annual Costs (Billion KSh /Year)**	**Annual Costs (Billion KSh /Year)**
		Investment	**Fixed O&M**
Large Power Plants	102.80	6.85	3.20
Interconnection	509.60	22.08	5.02
Renewable Energy			
Wind	72.95	4.87	2.13
solar power	26.65	1.52	0.15
Hydro River	350.75	13.71	7.01
Geothermal	657.78	44.17	22.85
Total		**93.21**	**40.46**

The purpose of this socio-economic analysis is to determine the costs related to the technical simulation. The results of the socio-economic analysis are presented in Table 4.5. It was established that the overall cost for running and maintaining the energy system, even while some power units are not operating was KSh 40.36 billion /Year (Fixed O&M Sum Annual Costs) and investment Sum Annual Costs as KSh 93.21 billion /Year.

The study found that the annual costs for running and maintaining the energy system, even with some power units idle, are KSh 40.36 billion for fixed operation and maintenance, and KSh 93.21 billion for investments. These high annual costs imply that a significant portion of these expenses will likely be passed on to consumers in the form of higher electricity prices. Efficient management and reduction of these costs are crucial to prevent substantial increases in the price of electricity charged to consumers.

4.2.2 Scenario 2: Accelerated Solar- Solar Power Integration

Scenario 2 illustrates the grid performance with accelerated solar power integration, utilizing the process simulation (optimization) depicted in Figure 4.2. Figure 4.4 illustrates the energy flow applied by EnergyPLAN for Scenario 2. The Technical Simulation (TR) relied on the technical capabilities of the components within the energy system. The optimal capacity of solar power based on Technical Simulation was determined to be 5703 MW. Kenya's equatorial location has ensured abundant solar resources within the country, making solar power a readily available energy option. Figure 4.4 displays the simulated optimal energy generation in Scenario 2.

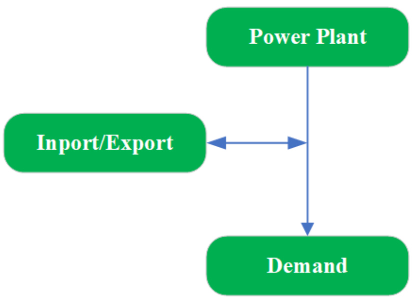


Figure 4.4: Schematic of energy flow by EnergyPLAN.

Under Scenario 2, the electrical energy generated from solar power amounted to 10.01 TWh, approximately 39.56% of the total energy generated. Moreover, accelerated solar power integration was found to reduce emission levels.

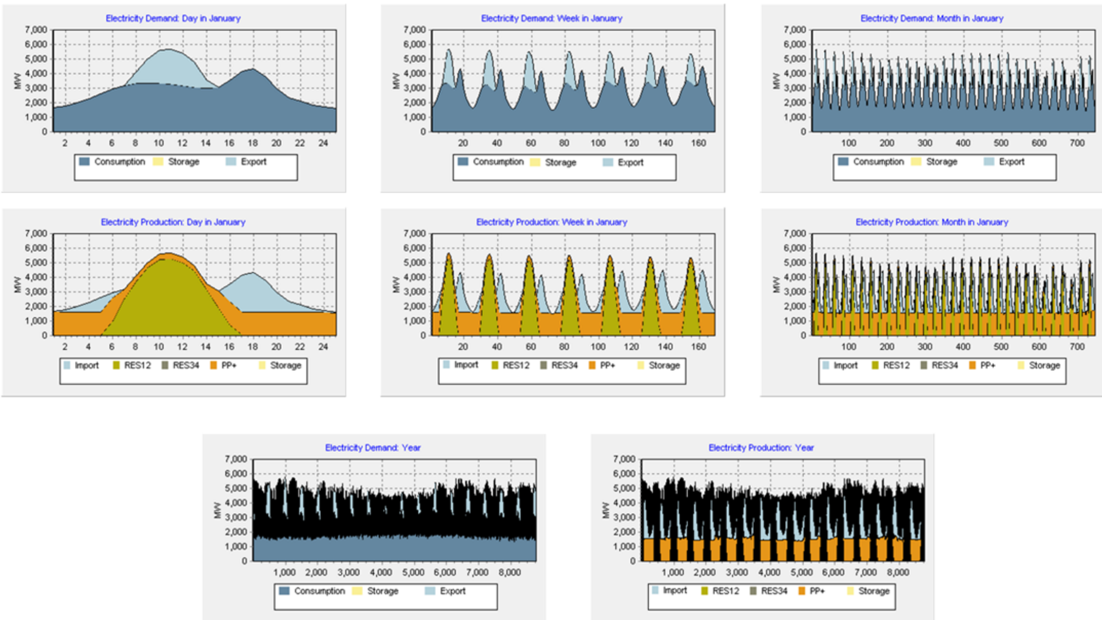


Figure 4.5: Simulated Electricity Energy Profile in Kenya in Scenario 2.

In Table 4.6, CO_2-equivalent emissions decreased to 0.021 Mt (Scenario 2) from 0.134 Mt (Scenario 1), while the RES electricity produced increased to 19.76 TWh/year (Scenario 2) from 11.90 TWh/year (Scenario 1). Additionally, based on technical simulation, the total annual cost incurred in the energy system to increment solar power up to an optimal level was established to be KSh136.31 billion.

Table 4.6: Carbon emissions and share of Renewable Energy.

	Scenario 1	**Scenario 2**
CO_2-equivalent emissions	0.134 Mt	0.021 Mt
RES electricity produced	11.90 TWh/year	19.76 TWh/year

Rather than focusing solely on minimizing fuel usage, the Market Economic Simulation (MER) was devised to align supply and demand. This simulation entailed two primary steps: firstly, calculating the short-term marginal cost of producing electricity for each power-producing unit, and secondly, selecting the least-cost combination of production units to meet the demand. Through this Market Economic Simulation, the optimal capacity of solar power obtained was 4394 MW, which will supply 30.54% of the total electricity generated at 7.72 TWh. Additionally, the total annual cost incurred in the energy system to increment solar power up to an optimal level was calculated to be KSh 139.96 billion.

To enhance the contribution of solar power energy, it's proposed that solar power mini-grids be interconnected into a unified grid to optimize technical efficiency(Rotich et al., 2024a). Furthermore, a system-level analysis of Kenya's power infrastructure conducted by (Rose et al., 2016) indicated that a rapid integration of solar power could surpass the Feed-in Tariff (FIT) payments, based on various energy generation combinations for 2012. Considering the scope of rural electrification in Kenya, research suggests that RES hold promise in meeting energy demands, with solar power mini-grids capable of supplying electricity to approximately 17% of the nation's population (Samoita et al., 2020).

The Market Economic Simulation and Technical Simulation conducted to expedite the integration of solar power both demonstrated instances where supply surpassed demand at certain times of the year, leading to the export of excess electricity, as illustrated in Figure 4.3. Additionally, the emissions linked with Scenario 2 decreased with the rise in the proportion of RES.

The current electricity cost is KSh 25.89 per kWh when compared to Scenario 2 This encourages investment into RES as viable alternatives. Additionally, the total investment cost annual cost for solar power in Scenario 2 is the lowest at KSh. 1.52 billion /Year this is due to the large-scale investment and research in solar power technologies that have increased its market competitiveness and thus lowers the overall cost of the system.

Studies have reported that the cost of solar power systems has been declining at an average of 16% per annum from KSh 761,500 per kWp in 2006 to KSh 249,772 per kWp in 2017 (Kausar et al., 2014; Lang et al., 2016). From 2023 to 2024, the cost of solar power systems is expected to continue its downward trajectory, potentially reaching around KSh 105,087 per kWp, reflecting an average annual decline of 16% from 2017 (Alghanem & Buckley, 2024). Finally, the rapid integration and greater adoption of solar power also rely on the effectiveness of solar power technology, including its generation efficiency (Aguirre et al., 2021), improved solar tracking systems (Hafez et al., 2018; Romero et al., 2021), solar concentrators (Álvarez Romero et al., 2021), efficient energy storage (Mshkil & Alwan, 2022), and energy management systems (Boostani et al., 2023; Molamohamadi & Talaei, 2022).

4.3 Evaluation of Solar Electrification Pathways

4.3.1 Solar Power Market Status and Trends in Kenya

The following sections will offer established perspectives on the advancement of market growth in Kenya, encompassing both the mini-grid and large-scale market segments for solar power technologies. It was established that various technologies, each with unique characteristics, contribute to broader pathways for the development trajectories seen in both decentralized mini-grid systems and projects connected to the main power grid.

4.3.1.1 Solar Mini-Grids

Presently, Kenya hosts eight solar-powered mini-grid stations under state ownership, comprising one wind-solar-diesel hybrid and seven solar-diesel hybrids, as detailed in

Table 4.7. These solar-powered mini-grids, managed by the Rural Electrification Authority (REA) and operated by Kenya Power (KP), collectively possess an installed capacity of 0.51 MW, as indicated in Table 4.8.

Table 4.7: Mini-grids owned and operated by KPLC in Kenya in 2015 (U. E. Hansen et al., 2018a)

Mini-grid	Type	Nominal capacity (kW)	Effective capacity (kW)	Number of Consumers
Elwak	Hybrid Solar	740	610	802
Habaswein	Hybrid Solar and Wind	760	542	1015
Hola	Hybrid Solar	1220	660	1956
Lodwar	Hybrid Solar	2740	1480	2380
Mandera	Hybrid Solar	2350	1480	4000
Merti	Hybrid Solar	250	170	436
Mfangano	Hybrid Solar	520	390	120
Takaba	Hybrid Solar	244	244	300

Comprehensive details regarding state-owned solar-powered mini-grids in Kenya are generally scarce. However, it's noteworthy that European enterprises specializing in essential solar technology components for mini-grid systems, along with related engineering and consultancy services, are actively involved in the Kenyan market, particularly with significant representation from German firms. Notable among these are companies such as Energiebau Solarstromsysteme, Donauer Solartechnik, and Juwi AG, which supply various components including panels/modules, inverters, controllers, and batteries. These international entities typically maintain close partnerships with local project developers in Kenya, evidenced by collaborations with companies like Harmonic Systems Ltd., Dreampower (a local subsidiary of an Italian firm), and Solar Works Ltd., engaging in diverse project initiatives.

Table 4.8: Installed capacities of wind and solar in existing mini-grids in Kenya (Hansen, 2018)

Station	**County**	**Installed solar power capacity (kW)**
Elwak	Mandera	50
Habaswein	Wajir	30
Hola	Tana River	60
Lodwar	Turkana	60
Mandera	Mandera	300
Merti	Isiolo	10
Mfangano	Homabay	0
Total		**510**

Numerous indigenous assembly plants are present, such as Ubbink East Africa Ltd., providing solar power panels with capacities ranging from 13 to 240 Wp. Furthermore, the market receives support from local battery manufacturers and suppliers like Chloride Exide Ltd. (Byrne, 2011; Ockwell & Byrne, 2016). However, the main focus of the local industry is on serving the Kenyan market with regard to domestic solar systems and smaller-scale solar applications designed for individual households (Ockwell & Byrne, 2016).

As a result, it appears that a significant portion of the key system components used in solar-powered mini-grids in Kenya are sourced internationally, mainly from reputable European or American companies through local sales outlets and wholesale distributors (Hansen et al., 2018a).

In Kenya, there is ongoing construction of an additional fifteen state-owned mini-grids, powered by solar energy, with a cumulative capacity of 2 MW (U. E. Hansen et al., 2018a). Furthermore, nine additional solar-powered mini-grids, totaling a capacity of 1.8 MW, are currently in the development stage. These systems are designed as hybrid setups, incorporating both solar and diesel components into existing diesel-fired plants. Moreover, there are twenty-five more plants in the preliminary proposal phase, with a combined capacity of 5.6 MW. Recently, the Rural Electrification Authority (REA) has issued a tender call for the establishment of 25 additional solar-powered mini-grids (Kohsri et al., 2018).

Donor organizations actively contribute to the progress of solar-powered mini-grids in Kenya by providing financial support for specific projects. For example, the KfW Development Bank and GIZ, operating through the German development agency, are engaged in the development of approximately 26 new solar-powered mini-grids, with a primary emphasis on solar-diesel hybrids (Sema, 2020).

Likewise, direct investments from the Department for International Development (DfID) and the World Bank contribute to the creation of new solar-powered mini-grids, including those initiated as part of the Kenya Off-grid Solar Access Project (KOSAP) (Ituru et al., 2018), recently launched. Furthermore, the Spanish embassy has offered financial support for the development of five new hybrid mini-grids that integrate solar, wind, and diesel technologies.

Several other projects funded by donors are in progress, including the Kitonyoni mini-grid, supported by DfID, which operates as a cooperative-based solar-diesel hybrid system with a capacity of 13.5 kWp. The United Nations Industrial Development Organization (UNIDO) is financing the Olosho Oibor mini-grid, which is a community-based hybrid system integrating solar, wind, and diesel technologies with a capacity of 10 kWp. Additionally, GIZ is providing support for two solar-diesel hybrid mini-grids: the Talek Power mini-grid (50 kWp) and the Strathmore University solar hybrid system (10 kWp) (Babayomi et al., 2023; Gollwitzer et al., 2018).

Numerous private companies are involved in offering commercial solar-powered mini-grid systems in Kenya, with notable players such as Powerhive East Africa Ltd., PowerGen, and Talek (Ituru et al., 2018). Since 2012, these foreign-owned companies have managed the installation of roughly twenty to thirty solar-powered mini-grids, with capacities ranging from 1.4 kW to 10 kW, with a few larger systems at 20 kW and 50 kW.

Noteworthy is the fact that two of these enterprises have obtained formal operational licenses, while one has secured funding to establish an additional one hundred mini-grids (Harrington, 2016a; Max & Berman, 2018). Initial pilot phases have been conducted by these entities, with current endeavors focused on substantial expansion across Kenya (Max & Berman, 2018).

The components of these solar-powered mini-grids mainly come from well-known suppliers in Europe or the United States, either obtained directly or through external channels. It's worth noting that SteamaCo has introduced an advanced metering system, which has been incorporated into several solar-powered mini-grid installations in Kenya, along with related software services.

4.3.1.2 Large-scale, Grid-Connected Solar Power Projects

Presently, Kenya boasts the operation of five solar power plants integrated into the national grid. These installations include a 575 kWp facility located within the United Nations compound in Nairobi, a 60 kWp plant at the SOS Children's Village in Nairobi, a 100 kWp installation at Kenyatta University, a 72 kWp system established at a flower farm, and finally, a 1 MWp facility at a tea-processing facility (Ockwell et al., 2018).

While the first three plants primarily received funding from international donors, the last two were financed by the owners of the respective industrial facilities. The existing plants were seemingly delivered as turnkey solutions by foreign total system suppliers, working in partnership with local consultancy firms and installation contractors (U. E. Hansen et al., 2018a).

For example, the plant mentioned earlier was executed by the German company Energiebau Solarstromsysteme GmbH, serving as the turnkey provider in collaboration with the Kenyan-based entity SolarWorks. SolarWorks managed the procurement of essential components mainly from European suppliers, including modules from Schott Solar and Kaneka, and inverters from SMA Solar Systems (Moner-Girona et al., 2019).

Similarly, the second plant was built by the UK-based company Arun Construction Services, in partnership with the local firm Azimuth Power, using modules from Centrosolar AG and inverters from SMA Solar Systems (Moner-Girona et al., 2019). Regarding the fifth plant, the tea farm owner enlisted the services of the UK-based company SolarCentury to oversee the project, which involved the importation of critical components. This was done in collaboration with Kenyan-based companies East African Solar Ltd. and Azimuth Power (Moner-Girona et al., 2019).

Another significant contribution to Kenya's solar power infrastructure is the plant at Strathmore University, with a capacity of 0.6 MW. This facility entered into a Power Purchase Agreement (PPA) in 2015 and has recently started operations. In this project, Kenyan companies Questworks and ReSol have been engaged as the total system provider and installation contractor, respectively. Crucial components for the project were sourced from European and Chinese suppliers, including panels from JinkoSolar and inverters from Solaredge.

In general, the participation of more local businesses in those projects seems mostly limited to hiring local technicians and engineers for construction and involving local contractors for maintenance once the projects are operational (Moner-Girona et al., 2019).

Table 4.9: Projects approved by the ERC to be developed under the feed-in tariff system (ERC, 2015)

Technology	No. of applications	Proposed capacity (MW)	Approved capacity (MW)	Percentage (%)
Wind	1	50.00	50.00	11.8
Hydro	0	0.00	0.00	0.0
Small Hydro	13	85.95	85.95	20.3
Geothermal	0	0.00	0.00	0.0
Solar	3	120.00	120.00	28.4
Biogas	6	167.30	167.30	39.5
Co-generation	0	0.00	0.00	0
Total	**23**	**423.25**	**423.25**	**100**

Numerous projects of considerable magnitude are currently in progress within Kenya, as part of the feed-in tariff framework, which presently extends a tariff rate of US$ 0.12/kWh to project developers (ERC, 2015) (Table 4.9. Note that the list only involves projects for which expressions of interest (EOI) have been approved by the FIT evaluation committee).

Prominent among these undertakings include the Samburu project (40 MW), the Garissa project (50 MW), the Greenmillenia Energy project (40 MW), the Nakuru project (50 MW), the Kopere Solar Park project (17 MW), the Witu Solar power project (40 MW), and the Alten Kenya Solar farm project (40 MW) (U. E. Hansen et al., 2015; IREK, 2015).

Primarily managed by foreign technology suppliers and companies specializing in comprehensive Engineering, Procurement, and Construction (EPC) contracts in the energy sector, such as Stimaken and Martifier Solar, these initiatives have a commonality: they have not advanced beyond initial expressions of interest, and feasibility studies towards securing financial closure and Power Purchase Agreement

(PPA) endorsements. Developers of these projects regularly face challenges in securing financing and achieving financial closure (Dinnewell, 2014; Eberhard et al., 2016).

Consequently, despite commencing project planning and preparatory efforts as early as 2012, progress on the ground remains sluggish, with the majority of these endeavors yet to enter the construction or operational phases (Eberhard et al., 2016; ERC, 2015). Significant financial backing for numerous of these projects comes from diverse donors and development institutions, including the World Bank and the German development agency.

In the market, there's considerable momentum surrounding small-scale solar-powered mini-grid systems. This momentum is clear from the active involvement of private operators of mini-grids and various donors who are participating in both operational and potential hybrid greenfield mini-grid projects (Duby & Engelmeier, 2017).

Conversely, the landscape concerning large-scale solar endeavors shows minimal advancement in practical implementation. The existing projects are notably modest in scale, with larger initiatives predominantly in the developmental phase. Subsequent sections will delve into a comparative analysis of these trends vis-à-vis the distinctive attributes of the four disaggregated SISs.

4.3.2 Size and Shape of Wind and Solar Sectoral Innovation Systems

In this section, an analysis is undertaken to delineate the distinct features of the four SISs. Employing the SIS framework, an analysis is conducted to elucidate the three key dimensions namely, the knowledge base, involved actors, and institutional framework within the solar sector, considering the varying scales and configurations of projects.

Referring to the market dynamics mentioned earlier, the following descriptions of system characteristics aim to enable discussions on the potential differences in the effectiveness of the four SISs in promoting the uptake and spread of solar power technologies within Kenya's context.

4.3.2.1 Sectoral Innovation System Characteristics of Solar Mini-Grids

The formulation of solar-powered mini-grids in Kenya relies extensively on a diverse knowledge base sourced from various disciplines, prominently leveraging foreign expertise. Specifically, for state-owned solar-diesel hybrid projects, expertise in turnkey contracting is imperative. Key technological competencies required from total system suppliers predominantly involve plant design, key component procurement management, and plant construction and commissioning.

Due to the lack of this particular skill set among local suppliers in Kenya, European companies with significant expertise in turnkey contracting and related engineering responsibilities play a leading role in the development scene. Although the domestic industry has developed technical proficiency in solar home systems, local suppliers of essential components like panels and batteries appear to be less involved in the progress of solar-powered mini-grids (Byrne, 2011).

Foreign private companies involved in the commercial provision of solar-powered mini-grids in Kenya predominantly rely on engineering expertise to continuously innovate and improve their systems. Furthermore, they incorporate insights from the telecommunications sector to develop business models, especially those utilizing pay-as-you-go (PAYG) systems designed for underserved customers in rural, off-grid areas.

These models incorporate IT and software solutions, data analysis, optimization systems, as well as smart metering and monitoring technologies (Harrington, 2016b). These companies frequently engage with private investors, including philanthropic foreign investors, establishing collaborative networks and forging connections with foreign investors, headquarters, and component suppliers in Europe and the US.

Various initiatives funded by the government and donors aimed at hybridizing existing diesel-fired mini-grids significantly affect the favorable environment for the development of solar-powered mini-grids in Kenya. However, the current regulatory framework for rural electrification, which mainly focuses on traditional grid-extension programs, continues to influence the development of commercial solar-powered mini-grids, leading to prolonged approval and negotiation processes for project developers. Despite these efforts, solar mini-grid developers face ongoing challenges, particularly in accessing financing and ensuring project affordability, as the higher production costs of small-scale energy generation often burden consumers. The inadequacy of policy frameworks to accommodate innovative energy generation and distribution models is apparent, with grid owners and operators advocating for improved regulation regarding tariffs, integration, standards, licensing, and the potential for subsidy schemes (Harrington, 2016b).

4.3.2.2 Sectoral Innovation System Characteristics of Grid-Connected Solar Power Projects

The increase in large-scale solar power plants in Kenya is mainly driven by the significant decrease in costs related to solar panel technology. The current projects in Kenya indicate that the designs for these large-scale facilities are mostly standardized globally, requiring only minimal modifications in design and construction to adapt to local conditions.

The establishment of solar power plants in Kenya heavily depends on foreign expertise, especially in turnkey project delivery. Notably, European firms with significant experience in turnkey plant engineering, component procurement, and project commissioning have partnered with local consultancy firms to carry out the current projects.

The progress of large-scale solar power plants in Kenya demands a deeper comprehension of Engineering, Procurement, and Construction (EPC) contracting, along with the organizational capacities necessary for overseeing extensive infrastructure projects. Consequently, international contractors and technology suppliers with the necessary technical expertise and managerial capabilities are involved in the planning and implementation of these projects.

They also provide additional expertise in areas like Power Purchase Agreement (PPA) negotiations, legal matters, and intricate engineering tasks. While current solar power plants have had industrial users and donor entities as project sponsors, upcoming larger-scale initiatives involve direct participation from international investors, including development banks and donor organizations. However, progressing large-scale solar projects face challenges in securing financing from foreign investors, primarily due to concerns about whether feed-in tariffs are sufficient to significantly attract foreign investments (Hansen et al., 2015).

4.3.3 Sub-Sectoral Dynamics Across Size and Shape

Analyzing the distinctive attributes of sectoral innovation systems within various market segments and technological domains underscores the importance of assessing the comparative characteristics of distinct sub-sectors within the solar power firms in Kenya. Subsequently, the subsequent sections of this thesis scrutinize the three dimensions delineated in Malerba's SIS framework (Malerba, 2005) across the four delineated sub-sectors, as outlined in Table 4.10.

4.3.3.1 Differences and Similarities Between Knowledge Bases

In terms of knowledge, it's clear that each of the four SISs, as well as their interactions, harbors distinct knowledge bases. Malerba (2005) emphasized the crucial role of knowledge and technology in bringing the issue of sectoral boundaries to the forefront of analysis.

These disparities underscore the necessity for a detailed sectoral analysis, particularly concerning SIS magnitude (Stephan et al., 2017). This need becomes evident when examining large-scale wind and solar projects, both of which share similarities in terms of project size, with the involvement of EPC contractors and turnkey suppliers in both technologies.

Table 4.10: Summary of sectoral innovation system dimensions across sectors.

Sectoral Innovation	Solar Mini-Grids	Large-Scale Solar
Knowledge and Technologies	1. Engineering-based knowledge 2. Telecom expertise (mobile payment schemes, PAYG models) 3. Smart metering and monitoring systems 4. Data management and software optimization tools 5. Consultancy and donor experience	6. Engineering-based knowledge 7. Experience in turnkey contracting 8. Experience in EPC contracting and planning of large-scale plants 9. Knowledge system design integration and operation
Actors and Networks	10. European turnkey contractors 11. Local engineering and consultancy firms 12. Private suppliers of mini-grids owned by foreign expatriates 13. Foreign investors (direct plant investments and equity investments) 14. Foreign component suppliers 15. Examples of cooperatives and community-based solar mini-grids	16. International EPC contractors 17. Technology suppliers 18. International investors, including development banks and donors 19. Industrial users
Institutions	20. State and donor support for hybridization of existing diesel-fired mini-grids 21. Significant funding from foreign investors	22. Feed-in tariff for wind-power projects 23. Financial support from donors and development banks

The confluence of global sectoral characteristics is where many enabling factors within this dimension are found, as international entities have entrenched themselves in the Kenyan market. Noteworthy is the apparent disconnection of domestic actors, despite possessing technical prowess and accumulated knowledge, especially within the domestic solar industry for home systems.

Limited information is available regarding the involvement of local suppliers in solar or wind projects. Additionally, differences exist in the knowledge base dimensions across the solar and wind mini-grid sectors concerning the participation of various actors.

In the wind mini-grid sector, informal learning and knowledge sharing are prevalent, whereas the solar mini-grid sector tends to rely on engineering-oriented knowledge, with significant involvement from private entities and international donors. The solar-powered mini-grid sector exhibits a high level of specialization, with business models and software customized for distinct PAYG customer segments.

4.3.3.2 Differences and Similarities between Actors and Networks

Within the framework of actor-network theory, foreign entities exert influence within the realms of expansive wind and solar mini-grid installations as well as large-scale solar projects. However, the involvement of foreign industry actors in wind mini-grid initiatives remains notably limited, with predominance instead being held by domestic small-scale industry players alongside non-governmental organizations (NGOs) and donor entities focusing on small-scale developmental endeavors.

While universities participate in practical applied research within scientific endeavors, this engagement doesn't lead to structured R&D within the domestic industry. This underscores a noticeable lack of private suppliers specializing in wind-powered mini-grid technologies.

In contrast, the solar mini-grid sector enjoys a wide range of private suppliers, foreign investors, component providers, and turnkey contractors. In both large-scale wind and solar projects, the influence of leading companies in the global industry, especially in the wind sector, as well as international engineering, procurement, and construction (EPC) contractors, is apparent.

Local community actors are visibly involved in both large-scale wind projects and solar mini-grid installations; however, there is limited evidence of community engagement within wind mini-grid initiatives. In the context of large-scale solar projects, users mainly include major industrial entities. In the sphere of large-scale wind projects, the participation of national policymakers and governmental agencies is notable, particularly through direct negotiations with project developers concerning power purchasing agreements.

4.3.3.3 Differences and Similarities Between Institutions

When examining the institutional aspect of the SISs, notable similarities emerge in the utilization of feed-in tariffs and power purchasing agreements in large-scale solar and wind projects. Small-scale solar projects primarily rely on state and donor support for hybridizing existing diesel-fired mini-grids.

Despite a shared drive to hybridize mini-grids due to the rising operational costs of diesel systems, the solar mini-grid sector differs significantly in terms of stakeholders and networks, receiving more attention from international donors compared to wind mini-grids.

The solar mini-grid market presents a favorable environment, facilitating the development of a commercial market for providing electricity services to rural areas, representing an unprecedented private-sector-led approach to rural electrification in Kenya and East Africa.

A significant number of operating businesses are founded by foreign expatriates who bring considerable expertise in various fields such as business ventures, engineering, renewable energy consultancy, telecommunications, and donor organizations. As a result, these enterprises bring elevated levels of technical proficiency, organizational skills, and management systems into Kenya, combined with insights into energy usage and local community needs acquired over time (Rolffs et al., 2015b).

However, a shared challenge remains in both wind and solar mini-grid sectors regarding the lack of a regulatory framework for commercial mini-grid development. Bilateral negotiations between companies and relevant government agencies, especially regarding operational licenses and approval of end-user tariffs, are often challenging and time-consuming (ESMAP, 2016).

The prolonged negotiation process is partly due to the differing objectives of government agencies and private operators. Private companies typically propose a commercial tariff significantly higher than the universal tariff provided by the government through conventional grid-extension efforts aimed at supporting rural electrification. Regulatory authorities often hesitate to accommodate private operators employing business models that rely on low connection fees and high usage rates.

Securing funding for RE projects faces a significant hurdle due to ambiguous policy signals and ongoing discussions about potentially introducing new incentive structures and regulatory frameworks. Since the revision of the feed-in tariff system in 2012, various alternative models, such as auction systems, competitive bidding, and net metering for smaller grid-connected projects, have been under consideration.

4.4 Incrementing Solar Power Electrification in Kenya’s Energy Mix

4.4.1 Reference Scenario Validation

To validate the simulation tool and simulation process, simulation results are compared with measured data obtained from EPRA. The variation between measured data and simulation results is 0.22 %, this shows that the simulation process closely matches actual data hence validating the software and simulation process.

Table 4.11: Comparison of Simulation and Measured Data made using data from (EPRA, 2022b)

Production Mode	Actual (TWh)	Simulation (TWh)	Variation (TWh)
HEP	3.04	3.04	0.00
Wind power	2.14	2.14	0.00
Solar power	0.383	0.38	0.003
Condensing power	1.58	1.57	0.01
Geothermal	5.52	5.55	-0.003
Import	0.316	0.34	-0.024
Export	-0.021	-0.015	-0.006
Net Supply	12.98	13.005	-0.028
Variation Percent			**0.216**

4.4.1.1 Analysis of Seasonal Operation

Sample weekly demand and production are given in Figure 4.6. Throughout this week, demand was always higher than production. High electricity demand is experienced during working hours in the morning when industrial operations are busiest. Electricity demand peaks towards evening hours when most of the domestic consumers get to their homes and turn on appliances. During nighttime electricity demand is relatively constant and low since industrial operations, service industry, and domestic use are minimal.

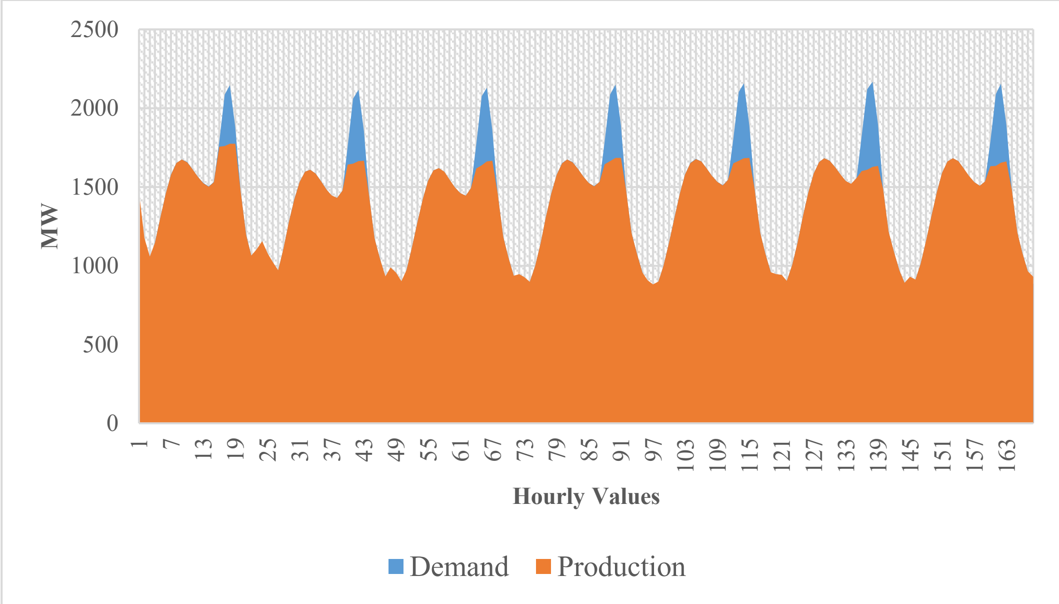


Figure 4.6: Sample Weekly Electricity Demand & Production for 2022 (EPRA, 2022b; KNBS, 2023b)

Table 4.12 shows the 2022 Electricity Production in Kenya split on technologies. From Table 4.12, Solar and wind energy account for just 20% of the total electricity produced in a day, while thermal, geothermal, and HEP account for about 91% of the total electricity produced. Imports accounted for about 5% of the total electricity produced.

This demand is met with domestic electricity supply and supplemented with power imports from Uganda's HEP power stations in Jinja and Ethiopia. This shows a good prospect and justification to scale up solar power production to replace thermal, hydropower, and imported electricity for the reasons earlier highlighted in this thesis.

Table 4.12: Electricity Production in Kenya in 2022 per Technology (KNBS, 2023b)

Production mode	Actual 2022 (GWh)
Hydropower	3,039.9
Wind power	2,143
Solar power	383.7
Condensing power diesel and gas-fired and Biomass Cogeneration)	1,585.2
Geothermal	5,517.5
Import	316.0
Export	21.3
Domestic Supply	**12,985.4**

Electricity demand and production for a typical month for the reference year are presented in Figure 4.7. For this sampled month, peak demand was on the 21st day. Throughout the month, the actual consumption of electricity exceeds production hence the justification for the need to explore newer sources of electricity supply to plug this demand.

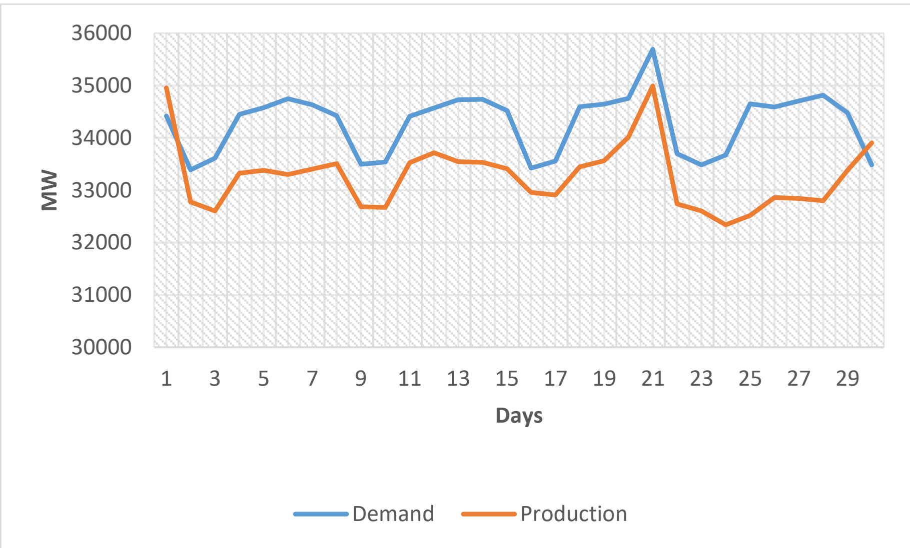


Figure 4.7: Monthly Electricity Demand and Production for 2022 (EPRA, 2022b; KNBS, 2023b)

4.4.1.2 Economics of the Reference Scenario

For the reference scenario, the overall annual expenses accrued within the system for electricity production is KSh189.77 billion as captured in Table 4.13.

This cost encompasses various components, including KSh 1.672 Billion for natural gas exchange, while other fuel sources such as coal, fuel oil, gasoline/diesel, petrol/JP, biomass, food income, and waste incur no expenses. Natural gas exchange accounts for an additional cost of KSh37.0 billion, and marginal operation costs stand at KSh14.16 billion. The electricity exchange component involves a total cost of KSh. 3.05 billion, comprising KSh5.79 billion for imports, KSh2.74 billion for exports, and zero costs for bottleneck and fixed import/export. CO_2 emission costs contribute KSh6.55 billion to the total. Variable costs, encompassing diverse factors, amount to KSh 62.44 billion, while fixed operation costs and annual investment costs reach KSh37.77 billion and KSh89.40 billion, respectively.

Table 4.13: System Energy Costs for the Reference Scenario

ANNUAL COSTS (BILLION KSh)	TOTAL	VARIABLE	BREAKDOWN
Fuel ex. gas exchange		11	
Coal			0
FuelOil			0
Gasoil/Diesel			0
Petrol/JP			0
Gas handling			11
Biomass			0
Food income			0
Waste			0
Gas Exchange costs		243	
Marginal operation costs		93	
Electricity exchange		20	
Import			38
Export			18
Bottleneck			0
Fixed imp/exp			0
CO_2 emission costs		43	
Variable costs	62.44		
Fixed operation costs	37.77		
Annual Investment costs	89.40		
TOTAL ANNUAL COSTS	**189.77**		

Table 4.14 provides data on CO_2 gas emissions for the reference scenario measured in metric tons (Mt).

The emissions are categorized into two segments: total CO_2 emissions and corrected CO_2 emissions. Total CO_2 emissions for the reference year scenario are recorded at 1.514 Mt, representing the unadjusted carbon dioxide output resulting from our energy operations.

Table 4.14: CO_2 emissions for the reference scenario

ANNUAL CO_2 EMISSIONS (Mt)	
CO_2 emission (total)	1.514
CO_2 emission (corrected)	1.647

To provide a more precise assessment of our environmental impact, the table also presents corrected CO_2 emissions, which stand at 1.647 Mt. These corrected emissions consider relevant fuel adjustments, offering a more accurate reflection of the carbon footprint associated with energy activities. Table 4.15 presents RES metrics, showing the RES portion of primary energy supply (PES), the RES portion of electricity production, and the yearly RES electricity production, measured in TWh/year.

The RES share of PES for the reference scenario in 2022 is at 58.4%, indicating a significant portion of the primary energy supply is sourced from renewable sources. Simultaneously, the RES share of electricity production stands at 71.3%, underscoring the dominance of RE in our electricity generation portfolio. The annual RES electricity production for the reference year scenario is 9.04 TWh/year.

Table 4.15: Reference Scenario share of RES

SHARE OF RES	
RES share of PES	58.4%
RES share of elec. prod.	71.3%
RES electricity prod.	9.04 TWh/year

4.4.2 Incremental Solar Power Integration Scenarios

This subsection examines the gradual increase of solar power integration into Kenya's electricity mix and assesses its impact on grid stability, the associated costs, and the proportion of carbon dioxide emissions.

4.4.2.1 20% Solar Power Integration Scenario

To increment solar energy capacity and establish a sustainable and renewable energy landscape, the first step focuses on achieving a 20% increase in solar power capacity. To realize this objective, generated solar capacity is increased to 2,879 MW through serial calculations in EnergyPLAN up from the initial 212.5 MW, as indicated in Table

2.1. As of 2022, solar power contributed only 0.384 TWh, representing approximately 3% of the total domestic power supply, as outlined in Table 4.12.

Solar power capacity of 2,879 MW yields annual solar energy production of 5.06 TWh which has the potential to provide 20% of total electricity demand. For this output to be realized, the total annual cost incurred is KSh 307.19 billion as shown in Table 4.16.

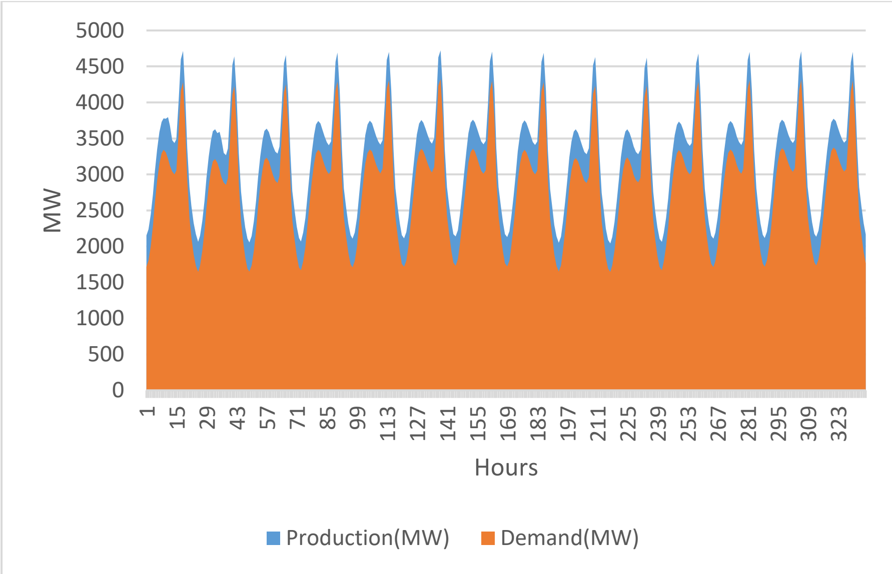


Figure 4.8: Two Weeks' Demand & Production for 20% Solar Power Increase Scenario

It's important to acknowledge that solar power integration of such magnitude impacts grid stabilization. According to the obtained simulation results in EnergyPLAN for this scenario, the grid stabilization measure stands at 100%.

Table 4.16: System Electricity Costs for 20% Solar Power Increase Scenario

ANNUAL COSTS (BILLION KSh)	TOTAL	VARIABLE	BREAKDOWN
Fuel ex. gas exchange		18	
Coal			0
Fuel Oil			0
Gasoil/Diesel			0
Petrol/JP			0
Gas handling			18
Biomass			0
Food income			0
Waste			0
Gas Exchange costs		392	
Marginal operation costs		98	
Electricity exchange		429	
Import			429
Export			1
Bottleneck			0
Fixed imp/exp			0
CO_2 emission costs		70	
Variable costs	153.37		
Fixed operation costs	40.66		
Annual Investment costs	113.31		
TOTAL ANNUAL COSTS	**307.19**		

This indicates that the electrical grid's stability and reliability are maintained, allowing for the seamless integration of the increased solar energy capacity with the existing infrastructure. To provide a comprehensive overview of the operational dynamics within the 20% solar power increase scenario, Figure 4.8 presents a depiction of the demand and supply curves spanning two weeks. Production exceeds demand for this duration which affirms that this scenario is satisfactory.

Table 4.17: Annual CO_2 Emissions for 20% Solar Power Increase Scenario

ANNUAL CO_2 EMISSIONS (Mt)	
CO_2 emission (total)	2.446
CO_2 emission (corrected)	5.223

Table 4.17 presents an overview of the annual CO_2 emissions, both total and corrected, expressed in metric tons (Mt) obtained from the EnergyPLAN simulation for this scenario. It incorporates import/export adjustments to accurately determine the carbon footprint associated with energy production. Table 4.18 displays RES metrics, such as the RES portion of primary energy supply (PES), the RES portion of electricity production, and the yearly RES electricity production, measured in TWh/year.

Table 4.18: Share of RES for 20% solar power increase scenario

SHARE OF RES	
RES share of PES	55.8%
RES share of elec. prod.	54.4%
RES electricity prod.	13.76 TWh/year

4.4.2.2 Optimal Solar Power Integration Scenario

In this subsection, simulation results are provided for the optimal solar power generation scenario. The technical simulation relies on the technical capabilities of the components within the energy system. The deficit between demand and supply is fulfilled as long as the power-generating units can meet the requirements. Solar power can be boosted to 4,601 MW in this scenario to supply 31.96% of the total electricity generated. This was achieved by running a series of serial simulations, where the input is defined as a series of different solar power units, and the output as the total cost for the referenced Energy system, under the Technical Simulation option.

For this scenario, the total annual cost incurred to optimize solar power production is KSh138.14 billion as shown in Table 4.19. Compared with the reference scenario whose cost is KSh 189.77 billion, the optimal scenario is economical besides supplying additional electricity from RES that will replace thermal sources.

Table 4.19: System Electricity Costs for Optimal Scenario

ANNUAL COSTS (BILLION KSh)	TOTAL	VARIABLE	BREAKDOWN
Fuel ex. Natural gas exchange		5	
Coal			0
Fuel Oil			0
Gasoil/Diesel			0
Petrol/JP			0
Gas handling			5
Biomass			0
Food income			0
Waste			0
Natural gas Exchange costs		113	
Marginal operation costs		88	
Electricity exchange		377	
Import			29
Export			428
Bottleneck			21
Fixed imp/exp			0
CO_2 emission costs		20	
Variable costs	23.15		
Fixed operation costs	42.49		
Annual Investment costs	128.69		
TOTAL ANNUAL COSTS	**147.73**		

Recognizing the significance of incorporating such a substantial solar power energy capacity, it is crucial to consider and ensure that grid stability is maintained. As indicated by the output data from EnergyPLAN for this scenario, the grid stabilization measure remains at an optimal 100%.

Table 4.20: Annual CO_2 Emissions for Optimal Scenario

ANNUAL CO_2 EMISSIONS (Mt)	
CO_2 emission (total)	2.446
CO_2 emission (corrected)	5.223

This outcome underscores the fact that the stability and dependability of the electrical grid are upheld, facilitating the smooth assimilation of the augmented solar energy capacity into the existing infrastructure which forms the basis for the upper limit of solar power penetration in the system. Table 4.20 presents the annual CO_2 emissions data, measured in metric tons (Mt). These emissions are classified into two categories: total CO_2 emissions and corrected CO_2 emissions. The total CO_2 emissions stand at 1.934 Mt, reflecting the raw output of carbon dioxide generated as a result of energy operations. Table 4.20 also includes corrected CO_2 emissions, which account for import/export adjustments.

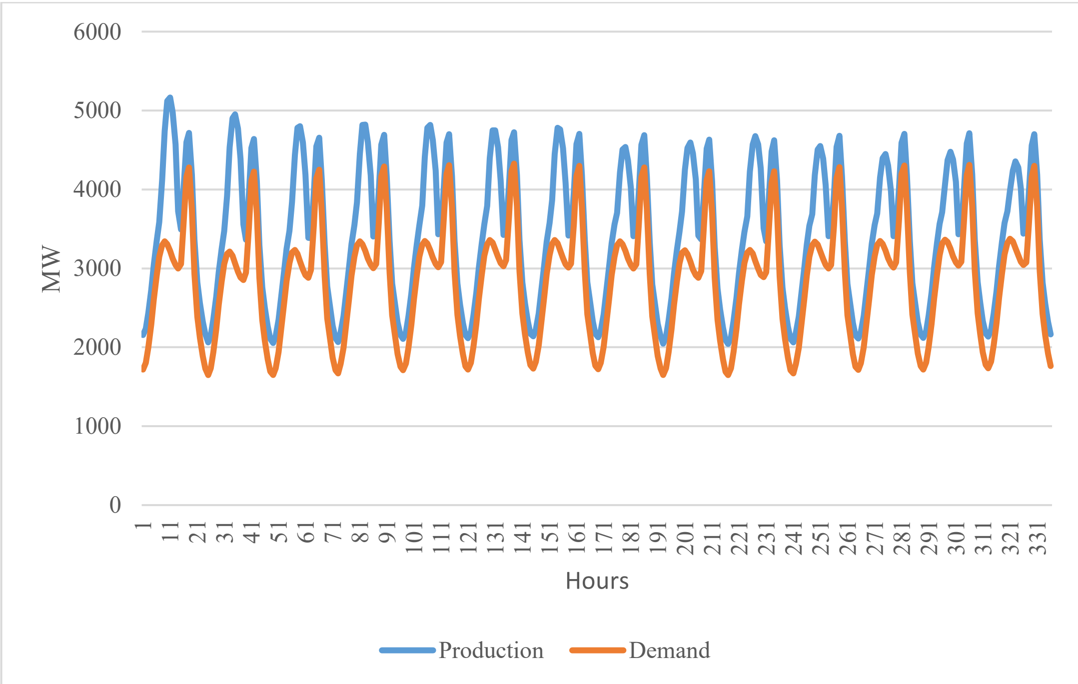


Figure 4.9: Two Weeks' Demand & Production for Optimal Scenario

Table 4.21 presents RES metrics within the optimal scenario for solar power integration, including the RES share of PES, the RES share of electricity production, and the annual RES electricity production measured in TWh/year.

Table 4.21: Share of RES for the optimal scenario

SHARE OF RES	
RES share of PES	65.8%
RES share of elec. prod.	66.5%
RES electricity prod.	16.82 TWh/year

Two weeks' operation of the optimal scenario gives results shown in Figures 4.9 and 4.10. Production exceeds demand for this scenario throughout the two weeks and the electricity system is stable.

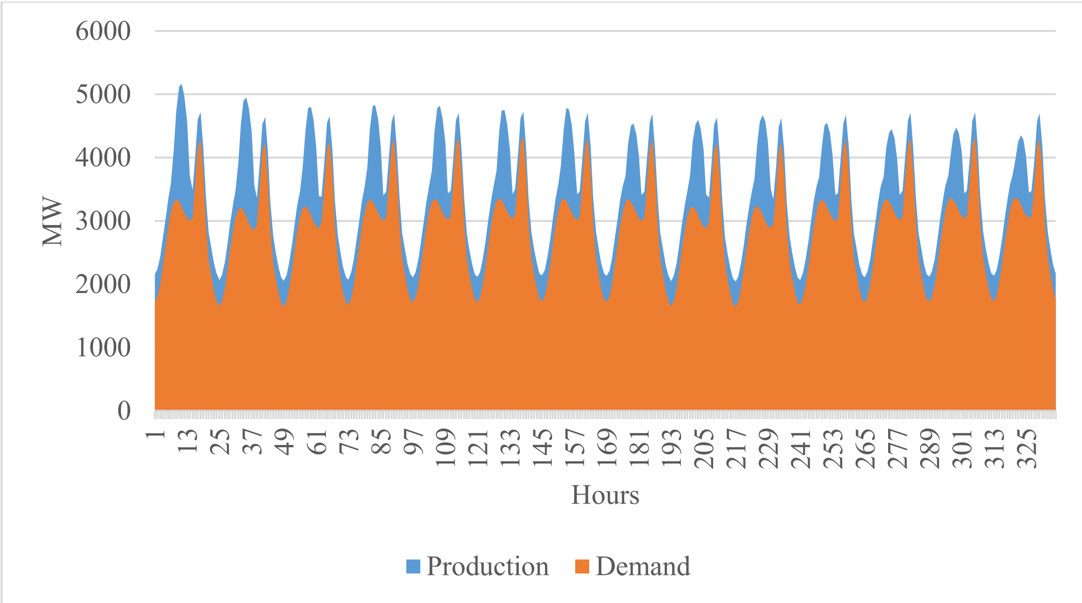


Figure 4.10: Two Weeks' Demand & Production for Optimal Scenario

4.5 Evaluation of Developed WOA Algorithm-based MPPT System

4.5.1 Solar Power System Simulation Model

The objective of this thesis is to test and validate the WOA-based MPPT algorithm by comparative analysis. Figure. 4.11 represents a 35-kW solar power -grid-connected system used for analysis.

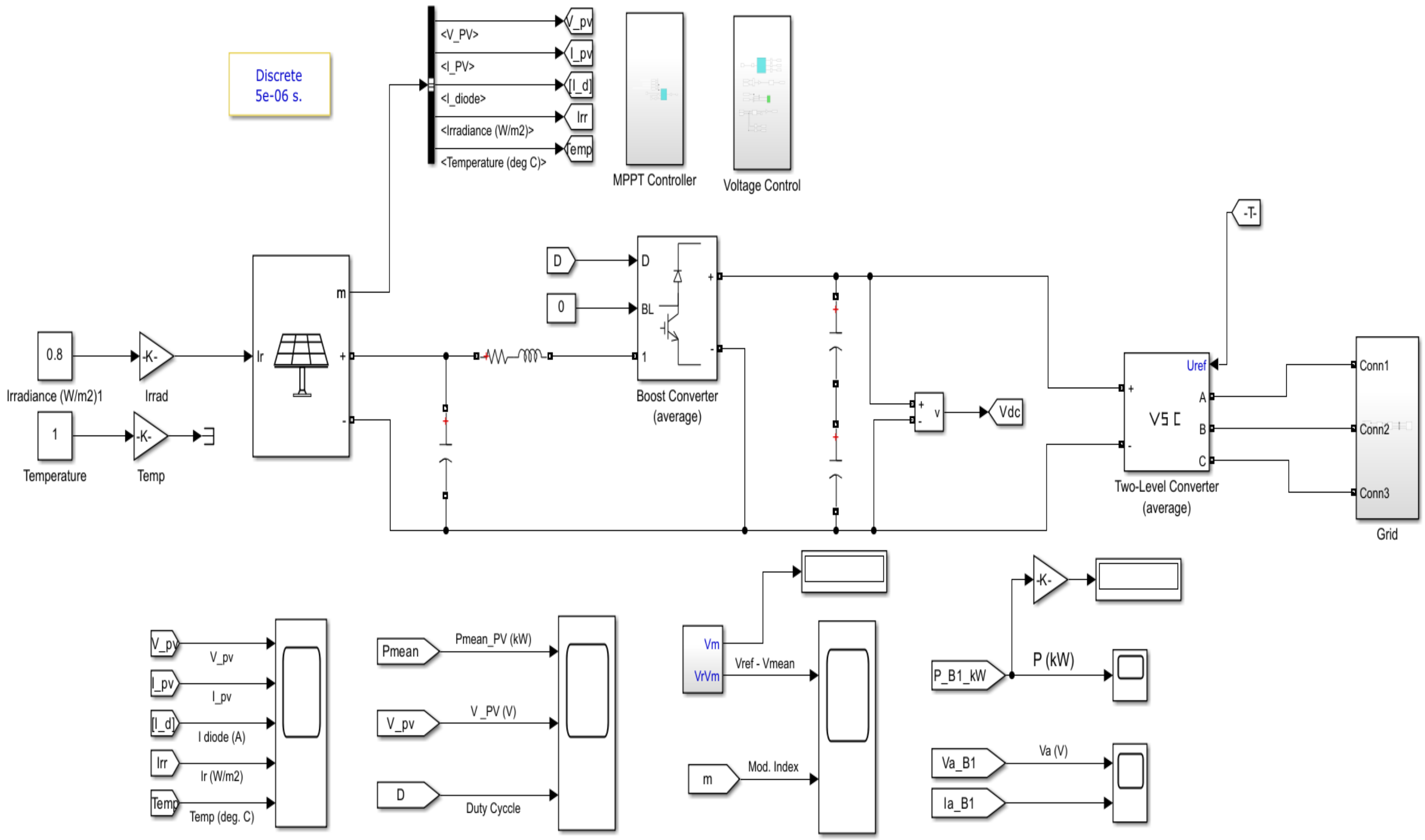


Figure 4.11: A 35 kW Solar Power System Grid Connected.

The solar power array comprised 66 parallel strings, each with 5 modules connected in series per string. The chosen module was the SunPower SPR-305E-WHT-D, selected for its parameter characteristics. The solar power array was connected to a boost converter as shown in Figure 4.11 to operate the MPPT controller. The output of the boost converter was then converted to a three-phase AC signal using a three-phase inverter. The solar power system was then coupled to a distribution network via a 50-kVA transformer.

4.5.2 Dynamic Performance and Stability of Solar Power System

Figure 4.12 illustrates the dynamic behavior of solar power power, solar power voltage, and solar power current under a constant temperature of 25°C.

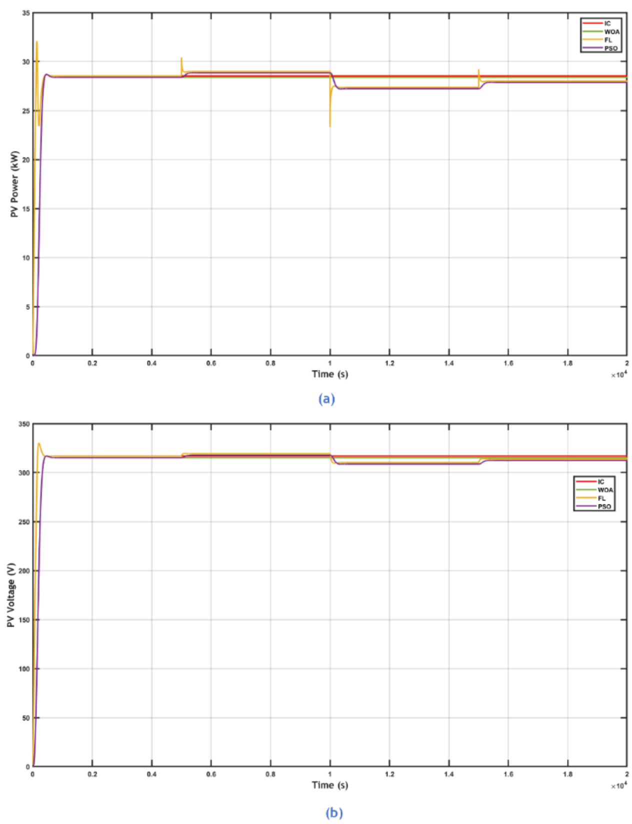


Figure 4.12: The dynamic performance for 35 kW grid-connected solar power system under PSC, (a) Solar Power and (b) Solar Power Voltage

Additionally, the time response analysis is given in Table 4.22.

Table 4.22: The dynamic performance and time response analysis

Parameters	IC	FL	PSO	WOA
Overshoot (%)	1.5726	0.1042	0.0304	0.0021
Peak power (kW)	20.4387	21.7032	24.7455	26.7519
Extracted power (Kw)	18.5704	20.7826	24.0853	26.6891
Rise time (s)	0.0781	0.0625	0.0492	0.0436
Settling time at 5% (s)	0.1776	0.0802	0.0621	0.0549
Steady error (%)	5.8951	2.1679	0.1733	0.044
GMPPT efficiency (%)	98.9920	99.5971	99.7776	99.9872

From Table 4.22 and Figure 4.11, the IC technique presented the worst performance in terms of time response analysis and dynamic behavior.

Although the PSO method successfully tracked the GMPP, its dynamic performance and time response parameters were inferior to those of the WOA-based MPPT. Additionally, the extracted solar power under the WOA-based MPPTe was 26.689 kW with an efficiency of 99.95% (based on an optimal solar power of 26.702 kW) and a steady state error of 0.04%. Therefore, these simulation results show that WOA-based MPPT was superior to other MPPT techniques regarding tracking efficiency and stability.

4.5.3 Dynamic Performance and Stability of Solar Power Systems

With PSC corresponding to duration 1 s to 1.5 s and 1.5 s to 2 s. Therefore, the G step-down is achieved at $t = 1\,s$ and $t = 1.5\,s$. As depicted in Figure 4.13, all the implemented GMPP techniques followed the step-down to reach the GMPP. However, it was observed that the IC‘s response was undesirable. Nevertheless, WOA-based MPPT outperformed the PSO and FL techniques regarding dynamic response and stability.

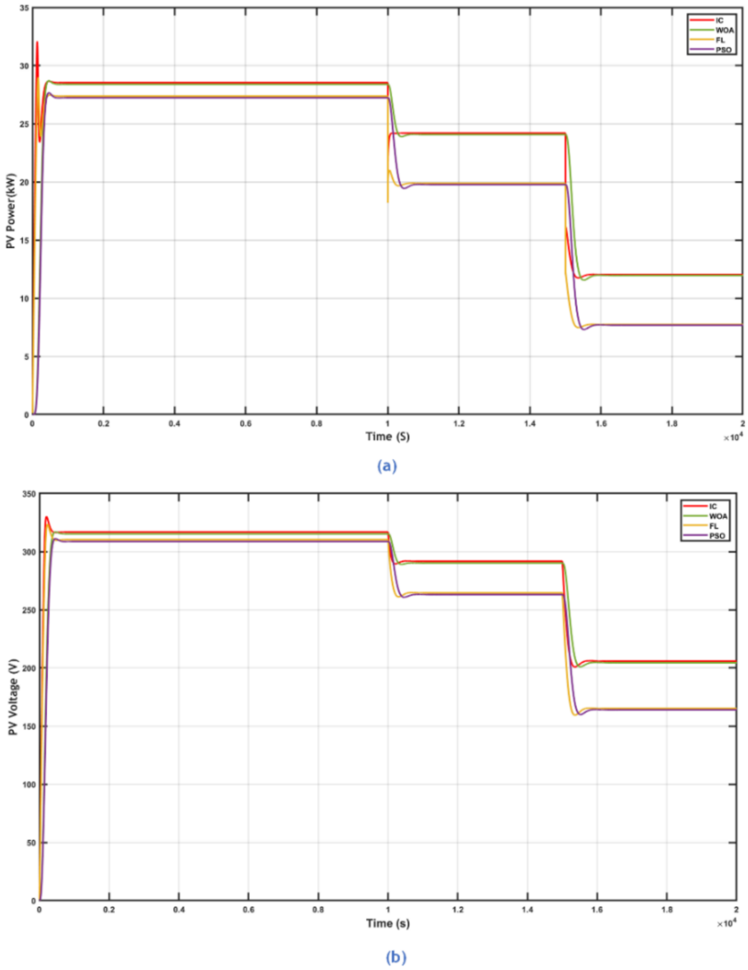


Figure 4.13: The dynamic performance in the step-down case for a 35-kW grid-connected Solar Power system

4.6 Conclusions

First, the rapid uptake of solar power in Kenya indicates a strong foundation for renewable energy development. The analysis of Sectoral Innovation Systems (SIS) revealed important dynamics between technology diffusion, policy frameworks, institutional arrangements, and stakeholder collaboration. These elements are essential to scaling up solar electrification in a coordinated and sustainable manner.

Second, the study found that a phased and strategic approach to achieving full renewable energy integration—anchored in the expansion of solar infrastructure—is both technically feasible and economically viable. This transition must be supported by a conducive environment for innovation, targeted investment, and sustained capacity development across key sectors.

Third, the deployment of robust MPPT algorithms, such as the WOA-based approach, is crucial in optimizing solar power system output. The developed algorithm demonstrated superior performance in maximizing energy harvesting, reducing power losses, and adapting efficiently to variable environmental conditions—making it well-suited for real-world applications in Kenya's diverse climatic zones.

Overall, the study underscores the pivotal role of accelerated solar electrification in Kenya's energy transformation. By harnessing cross-sectoral synergies, advancing renewable energy technologies, and adopting a systemic and inclusive policy approach, Kenya can position itself as a leader in sustainable energy in sub-Saharan Africa.

However, achieving this vision will require overcoming several challenges. These include policy and regulatory barriers, limited access to financing, and shortages in technical expertise. Addressing these issues is imperative to unlocking the full potential of solar electrification and ensuring that the energy transition is equitable, resilient, and aligned with national development goals.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This chapter provides a comprehensive summary of the key findings from this thesis, followed by actionable recommendations based on the research outcomes. Additionally, it outlines suggestions for future work to further advance the understanding and implementation of solar electrification within Kenya's energy sector.

5.1 Conclusions

This thesis set out to explore the role of solar power in Kenya's transition to a sustainable, reliable, and low-carbon energy future, focusing specifically on solar integration, sectoral innovation dynamics, scalability of solar infrastructure, and the performance of WOA-based Maximum Power Point Tracking (MPPT) algorithms. The research findings comprehensively address the four primary objectives and provide critical insights into the technical, economic, and systemic potential of solar power within the Kenyan context.

The first objective aimed to assess the progress and impact of accelerated solar power integration in Kenya. The results demonstrate that the deployment of solar power systems has generated substantial benefits. These include enhanced cost-effectiveness, significant reductions in carbon dioxide (CO_2) emissions, improved energy reliability, and strengthened national energy security. Such outcomes affirm the strategic importance of solar energy in addressing Kenya's growing electricity demand, while simultaneously contributing to climate change mitigation efforts. The continual decline in the cost of solar modules and associated system components, coupled with increasing engagement from both public and private sectors, has made the expansion of solar power systems increasingly feasible. Furthermore, distributed solar power systems have played a crucial role in enhancing electricity access in off-grid and underserved areas, thereby underscoring solar energy's dual potential to promote sustainability and energy equity.

The second objective examined the sectoral innovation systems (SIS) that underpin the adoption of solar power technology in Kenya. The analysis revealed that the growth of solar power uptake has been significantly influenced by global trends, particularly the rapid decline in solar technology costs over the past decade. This reduction in cost has been driven by technological innovation, economies of scale, and the international standardization of large-scale solar power system designs. These standardized designs require minimal modifications to adapt to local conditions, thereby facilitating faster and more efficient deployment. The SIS framework further emphasized the critical roles of institutional and policy support, local capacity building, and knowledge diffusion in driving clean energy adoption. Collaboration among diverse stakeholders—including government agencies, private investors, research institutions, and civil society—has been pivotal in creating an enabling environment for solar energy development.

The third objective investigated the scalability and feasibility of substantially increasing Kenya's solar power capacity. The findings confirm that it is both technically and economically viable to expand solar generation to approximately 4,601 megawatts (MW), representing about 31.96% of the country's total electricity production. This expansion would make a significant contribution towards Kenya's renewable energy targets. The feasibility analysis accounted for critical factors such as solar irradiance availability, land resources, infrastructure readiness, and system deployment and grid integration costs. Notably, Kenya's abundant solar resource potential supports the feasibility of both centralized and decentralized solar installations. Economic viability is further reinforced by decreasing capital costs and favorable return on investment metrics, making large-scale solar power projects attractive to utilities and investors.

The fourth and final objective focused on evaluating the performance of an advanced MPPT algorithm based on the Whale Optimization Algorithm (WOA). This algorithm was developed and rigorously tested to optimize energy extraction from solar power systems under varying environmental conditions. The results demonstrate that the WOA-based MPPT algorithm achieves an efficiency of 99.95%, with a steady-state error of only 0.04%. This represents a significant improvement over the commonly used Particle Swarm Optimization (PSO) algorithm, which attained 99.7% efficiency and a 0.2% steady-state error. In addition to superior energy harvesting efficiency, the WOA-based approach offers enhanced stability and faster convergence to the maximum power point, particularly under fluctuating irradiance and temperature conditions, thus proving well suited for practical application in dynamic real-world environments.

In conclusion, this thesis highlights the transformative potential of solar energy within Kenya's evolving energy landscape. Accelerated solar power integration, underpinned by robust innovation systems, scalable infrastructure development, and advanced control algorithms, can substantially contribute to Kenya's energy access, environmental sustainability, and economic development objectives. However, fully realizing this potential will require continued and focused policy support, targeted financial investments, and sustained efforts to enhance local technical and institutional capacities. Addressing persistent challenges such as financing constraints, grid integration complexities, and regulatory uncertainties will be crucial to effectively scaling up solar energy solutions.

Ultimately, the findings offer a robust foundation for policymakers, energy planners, and stakeholders to formulate and implement informed strategies that position solar power as a cornerstone of Kenya's clean energy transition. Furthermore, the insights generated provide valuable lessons for other developing countries aiming to leverage solar technology in pursuit of sustainable and inclusive energy futures.

5.2 Recommendations and Future Work

Based on the comprehensive findings of this thesis, several critical recommendations are proposed to enhance the adoption, scalability, and sustainability of solar electrification in Kenya. These recommendations target policy frameworks, capacity building, public engagement, and financing, all of which are pivotal for realizing the full potential of solar energy in Kenya's transition to a clean energy future.

5.2.1 Strengthen Policy Support

A foundational step toward accelerating solar electrification involves the development and enforcement of robust and supportive policies. The government and regulatory bodies should prioritize establishing clear, consistent, and transparent policy frameworks that incentivize investment and innovation in solar technologies. This includes streamlining permitting and licensing processes to reduce administrative delays, introducing fiscal incentives such as tax exemptions, subsidies, or feed-in tariffs, and ensuring regulatory stability to build investor confidence. Additionally, policies should encourage integration of solar energy within the broader national energy planning and infrastructure development, fostering an enabling environment that balances growth with sustainability.

5.2.2 Enhance Capacity Building and Promote Research & Development

The technical complexity and evolving nature of solar technologies necessitate ongoing capacity-building efforts. Investment in training programs is essential to equip local technicians, engineers, policymakers, and entrepreneurs with the knowledge and skills required to deploy, operate, and maintain solar systems effectively. Strengthening educational institutions and vocational training centers can create a skilled workforce that supports the sector's growth and innovation. Simultaneously, fostering research and development tailored to Kenya's specific climatic, geographic, and socio-economic contexts will catalyze the development of adaptable and cost-effective solar solutions. Encouraging partnerships between academia, industry, and government can accelerate innovation and technology transfer.

5.2.3 Increase Public Awareness and Engagement

Public acceptance and demand are critical drivers of solar power adoption. Targeted awareness campaigns should be conducted to educate the public about the benefits of solar electrification, including its role in reducing energy costs, lowering carbon emissions, and enhancing energy access in underserved areas. These campaigns should utilize diverse communication channels, such as community outreach, social media, and educational programs, to reach different demographic groups effectively.

Increasing awareness will foster community ownership, reduce misconceptions, and motivate households and businesses to invest in solar technologies.

5.2.4 Innovate Financing Mechanisms

Financial barriers remain one of the most significant constraints to widespread solar electrification, especially among low-income populations. To address this, diverse and innovative financing models must be expanded and tailored to local needs. Microfinance schemes can provide small, manageable loans to households and small enterprises, enabling incremental adoption of solar technologies. Community-based investment models, such as cooperatives or crowdfunding, can mobilize local resources and share risks. Moreover, public-private partnerships can leverage government support and private sector efficiency to scale large projects. Establishing credit guarantee schemes and risk mitigation instruments can also enhance lender confidence and reduce borrowing costs.

5.3 Further Research on Energy Storage Solutions

The intermittent nature of solar energy highlights the critical need for efficient and cost-effective energy storage systems, particularly in contexts where existing hydro storage may be insufficient. Future research should prioritize the development and localization of battery storage technologies and other innovative storage solutions that are well-suited to Kenya's climatic conditions, economic realities, and grid infrastructure. Enhancing storage capacity is essential to improving the reliability and stability of solar energy systems, ensuring a continuous electricity supply during periods of low solar irradiance and peak demand. In addition, research should explore hybrid energy systems that integrate solar with other renewable sources, alongside advanced grid management technologies. Such integrated approaches can optimize overall energy system performance, support grid resilience, and accelerate the transition to a sustainable energy future in Kenya.

Implementing these recommendations will be essential to overcoming current challenges and unlocking the transformative potential of solar electrification in Kenya. Together, they provide a strategic roadmap for policymakers, investors, practitioners, and communities to collaboratively drive Kenya’s clean energy transition toward a sustainable, inclusive, and resilient future.

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APPENDICES

Appendix I: Interview Guide for Key Informant Interviews for IREK Project

1. *Before starting the interview:*

Interviewers introduce themselves and introduce the IREK project, current activities/stage of research project and aims of this interview

The Innovation and Renewable Electrification in Kenya (IREK) project is a five-year research project funded by the Danish Ministry of Foreign Affairs. It is a collaboration between Aalborg University in Denmark, the African Centre for Technological Studies and Moi University in Kenya. The research is taking place in Denmark, Kenya, China and Germany between 2015-2019.

The project aims to bring together the fields of research from development studies and innovation studies, to address the problem of access to sustainable energy. Specifically, we are examining the implementation of two renewable electrification technologies – wind and solar.

The project research questions are broadly grouped under two main headings, each with a set of sub-questions or hypotheses:

1. *The role of global technology collaboration*
    a. Where will the most relevant technologies for wind and solar driven electrification in Kenya come from?
    b. Is South-South technology collaboration more relevant in this respect, compared to North-South collaboration?
    c. How important is the 'software' element of this technology cooperation (business models and capabilities) compared to the 'hardware' element?
2. *The role of local policies and institutions (or the national system of innovation)*
    a. How to design policies to ensure that the process of renewable electrification in Kenya leads to local job creation and income generation?
    b. What incentives will be necessary to make the adoption of these technologies more attractive?
    c. What types of technological and soft capacity building are most urgently needed?

We are at the phase of starting our qualitative data collection. We have already conducted a stakeholder analysis which aimed to assess policy makers and stakeholders' understanding of wind and solar mini-grids and the innovation landscape in Kenya – this will be followed up by another survey to gauge any potential changes at the end of the project's life. The interviews we are currently conducting are 'key informant interviews' with experts within the energy and renewable energy field.

Our question guide for this interview is structured as follows:

1. First, we would like to start with a general introduction and background to each of our respondents and the organisations they work for.

2. Secondly, we will focus on international technology collaboration in the renewable energy sector and differences between actors from Europe (DK and Germany) and from China.
3. Thereafter, we have a section on the national policy environment and elements of a 'national innovation system' within the renewable energy sector.
4. Finally, we would like to zoom in on the solar/wind sector specifically and explore some of the differences in the drivers and demands for big vs small scale energy projects, before wrapping up the interview.

2. *Ask for permission to record the interview*

We would like to record our interviews strictly for internal purposes as there is a larger team of researchers involved and we will be sharing all of our interview findings within the group. Based on the interview we will prepare a short summary that we would be happy to share with our respondents so that they can provide any further comments or follow up thoughts to issues and to correct any potential factual errors.

Question guide

Section 1: General introduction and background (*this section is intended to get the interview and respondent started off to a good start where they with the knowledge of our aims can introduce themselves and their background*)

1.0 To start with we would like to hear more about your background, role and responsibilities and the organisation you work for.
I am a renewable energy consultant and have practiced in the sector for over 5 years, working primarily on projects aimed at increasing access to modern energy services.
I am also affiliated with the Kenya Renewable Energy Association; whose main objective is to improve the business environment for renewable energy

2.0 What is the focus of your work? What are your current priorities?
KEREA's focus is representing the private sector, and engaging with them (and other stakeholders including NGOs, academia, government, development partners, and counterpart RE associations) with the overall goal of supporting uptake of renewable energy technologies. KEREA undertakes a wide range of activities towards this end – encompassing technical, policy, regulatory, capacity building, and consumer engagement aspects amongst others.
As a consultant I support project design and implementation in energy access projects (mostly in the area of rural electrification), and this includes – field research, engagement with stakeholders, documentation, amongst others.

Section 2: International technology collaboration in the Kenyan energy sector

1 A number of technologies needs in the energy sector have been identified nationally (from geothermal to wind and solar) - where are actors in the energy sector looking to obtain these technologies and skills from?

Based on the current trend, technologies may be acquired from Europe, US, China and India. Available skills (local expertise) are increasingly improving and new ones becoming available through capacity building activities such as training and regulatory interventions such as licencing, these skills may be acquired locally (though perhaps not exhaustively) and therefore international as well. In some instances, international providers of technology may provide skills transfer to local counterparts (generally limited to the technology).

2 What is in your view the role of international technology collaboration for the development of the Kenyan renewable energy sector? Which international actors are most present and/or powerful in this regard?

Kenya may be a good sink for technologies as there is limited capacity to develop them locally (except the assembly of solar modules, solar water heaters, and batteries which is currently undertaken) and this – importation - is a trend that may continue. There have also been limited attempts to develop wind technologies.

Technology collaboration has an important role in terms of the potential to "design for end users", where technology companies could consider/collect information available from local counterparts and innovate their designs. A lot of this has been done in the Pay As You Go Area (pico solar, micro and mini grids) – in terms of billing, monitoring, etc.

Some collaboration is already visible in terms of demonstration and testing of technologies developed elsewhere – to determine performance under Kenyan conditions and understand end user interaction with technologies. Overall, these are ultimately related to technology importation, which is a matter of preference by individual private sector actors and they may be the best source of this information (if more detail is sought). I expect China and Germany may be the top 2, in terms of importation, with European countries leading in terms of demonstration/testing.

3 Which energy sources are gaining traction among international actors and with whom? Who are the key players in this sector and what is driving them?

Solar may have the most interest due to documentation that costs are reducing significantly, and the ability to deploy across various sizes/capacity. This is highly private sector driven (a lot of private investment with some minimal input from financial instruments (few companies have benefited from RE funding). There is increasing interest now in industrial and commercial scale solar but this has not yet translated to completed project installations/capacity. Private sector developments are driven by – demand, - availability of finance (which may also be a limitation), and enabling regimes.

Wind gained some interest in the recent past due to possibility of hybridization with solar. However, installations have been limited to Kenya Power Utility Scale installations. The progress in the area of small wind has been limited with a number of companies offering hybridization shifting more towards solar.

Medium and large scale wind has much more interest, driven by international private sector in collaboration with government, development partners, and international investors. There may be limited ability of local private sector to enter into that space and there may be a number of challenges faced to date by developers which may limit local and international interest in doing so.

4 To what extent are Chinese technologies more suitable than e.g. European ones for the local context? Do you agree or disagree with such a hypothesis? Why?
They may be perceived to be more suitable for the Kenyan context based on – being more easily available (it is easier for Kenyan businesses to develop relationships with Chinese companies as they are many in number and perhaps there may be few exclusivity arrangements, it is easy to visit China and companies that develop/manufacture the technologies, and get into arrangements to "manufacture to order". They may be more affordable (short term/immediate cost being the most important factor for consumers and therefore by extension the private sector). The auxiliary aspects offered by the Chinese technologies' providers may be easily available in terms of models employed to avail the products e.g. delivery to Kenya, payment arrangements such as payment for consignment after sales, etc.

Suitability in terms of quality may vary providers – could be of lesser, comparable/equal or better quality – when looking at Chinese versus European products and there may be a wide range of products in each category, but the perception may be that the former is always cheaper and "acceptable" quality may be available.

5 What are the main opportunities as well as challenges that the sector faces, from generation to transmission and distribution? Where do international actors fill a gap?
Cost – driven by limited access to services (infrastructure such as roads, as well as instruments such as finance and microfinance) – limits ease of development of projects, increases cost of transmission and distribution, and the ability of end users to uptake electricity. The latter is addressed to some extent by government projects and the national tariff structure, but even then, uptake is not exhaustive where electricity is available. It is not addressed in private sector projects (but may be mitigated in some depending on funding instruments used e.g. offsetting capital costs and therefore making the project financially viable at a lower tariff.

Opportunities may lie in - incentivising private sector to enter unsaturated markets which have the above characteristics, and – reducing the costs of doing so. International actors may – innovate to drive down cost of technologies, continue to avail technologies, collaborate better in consideration of limitations e.g. adopt some financial models, shift to "design and manufacture to order", - those availing finance such as equity investors participating more and with consideration of the country context, - engage in local skills development, etc.

All aspects that international actors may engage in may require input of local content to be effective. The bigger question may be "in which areas, and how, would international actors engage/collaborate with national actors to increase access to sustainable energy?"

Section 3: **The national and sectoral innovation system** (*mention that we are specifically looking at wind and solar but comments on RE sector in general are relevant*)

1 How do the national plans and policies in your view manage the tensions or potentially conflicting objectives of providing both increased energy access and clean energy? Are some aspects coming to the forefront while others lose out? (e.g. balancing energy access, security, inclusiveness/affordability, and modern/clean energy objectives)

National plans and policies may be considered to be focused on increasing generation, increasing demand/access, and managing/reducing costs in the long run. Kenya in 2016 had over 80% RE generation, and overall there isn't a conflict between increasing generation and access, and clean energy development. The foreseeable future may see more solar, wind and geothermal coming online, and maintaining the status quo. Increasing energy access and clean energy development may be aligned.

However, the extent to which this generation and connection is impacting now and, in the future, currently unconnected people/households (using kerosene and firewood) may not be obvious. It may be that most of the new generation is taken up by commercial and industrial sector and not by households (based on high costs of connection, which is comparatively high against income/socio-economic status of households) and grid extension.

"Balancing energy access" and "inclusiveness" may be a question of ensuring all categories of energy consumers access it (by addressing initial cost – extending from the current "last mile connectivity project" which has reduced costs while extending the grid/mini grids into "unattractive" geographical areas.
"Inclusiveness" may in addition be addressed by development and implementation of related policies (perhaps outside of energy sector but augmented, e.g. agriculture) which drive improvement of socio-economic conditions.

"Affordability" would be addressed by the above 2, and consumer awareness. Documentation may suggest that users of kerosene and firewood incur high costs at the moment which may be equal to or lower than the cost of modern energy service. To the extent that this is true, the barrier to be addressed would be the level of understanding of energy cost and the ability to model interventions per consumer behaviour (this is the foundation of the success of PAYG in Kenya, and matching with financial instruments that allow PAYG to be offered). While this is mostly discussed in relation to pico solar, it may have greater potential in relation to grid when cost per kWh is considered. It may also be a matter of technology innovation – and transfer from private sector to grid. For instance, universal use of pre paid meters may address this partially by reducing cost risk.

There may be perceived tension by providers of small scale solar and wind that national policies and plans do not adequately address their role in "last mile" connectivity. This may tension related to time – in that solar may be ideal in the immediate and short term, but may not be ideal in the long term, and therefore difficult to incorporate into policy and plans which are long term in their nature. The greater tension here is the possible certainty of reduction in cost of solar, but possible uncertainty of the minimum cost. It may be better to err on the side of developing policies and plans that incorporate in greater detail solar and wind technologies (within the confines of best fit at the time of deployment). In this context, current solar and wind may be enabled NOW to benefit from interventions aimed at the grid (such as subsidized connection costs, installation of transmission lines, last mile connectivity funding, and cross subsidization of electricity tariffs such as in diesel run mini grids). Further the may be enabled NOW to benefit from interventions such as net metering and a more attractive FiT, with consideration of the tension in "term".

2 To what extent is the institutional framework supporting the national renewable energy industry and building innovation capabilities in Kenya?

As above, RE industry may grow with the above considerations, and the institutional framework may therefore be considered limited in its support in light of the outlined tensions.

There may be tension in terms of "availability" and "suitability" of current frameworks, where the RE industry may not be limited directly but may not be adequately supported (and therefore limited in relation to the other actors/aspects being supported).

An ideal institutional framework may be one that enhances the role of RE in energy access and supports this role in the immediate term by availing equal/similar or more opportunities within the broader sector. This will drive innovation to improve technologies and further drive down costs overall (RE and energy industry) in a more enabled, open and competitive market.

3 Where are the key bottlenecks of the (renewable) energy system in terms of both backward and/or forward linkages from energy generation (from generation to transmission and distribution as well as research and policy support frameworks)?
Adequately/suitably enabling policies and plans, and approach to implementation (RE providers treated as grid providers, at least)
Incentives (financial and structural)
Mainstreaming of technologies and models (PAYG, smart metering, etc. currently proven in demonstration projects by individual companies)
Research documenting the effect of interventions outlined in 6 may be useful (building cases/scenarios)

4 To what extent do government policies seek to address the gaps in the institutional framework to build a domestic/national renewable energy industry? Can you provide any examples of initiatives (or the lack of them) that aim to support the Kenyan renewable energy industry?

a. In terms of capability building/educating skills labour (*is there a lack of capabilities and in which parts of the value chain?*)
Building capacity is in the early stages and is currently limited to solar PV, **solar water heating, energy auditing, and energy management. There may be room for development of capabilities in the entire industry – specially to reach critical mass in availability of human resources.**
Government regulations (ERC) are increasingly being developed to define capabilities required, but inadequate intervention in ensuring avenues for building capabilities.

b. In terms of absorption of foreign technologies e.g. by standard setting and import duties (*is there a supportive regulatory framework for the industry?*)
The limitation may be in terms of ease of entry into the market and (fair)competitiveness.
Solar PV **is exempt, but the current problem may be in implementation of the exemption, with relevant departments/institutions inadequately applying this exemption. Foreign technologies may not be disadvantaged other than in this way, as the industry is dependent on them and it is counter intuitive that their absorption would be intentionally limited.**
Standards are available, but the current problem may be in loopholes in implementation of testing of products, with sub standard products making their way into the market.

c. In terms of building local content and manufacturing to supply the industry e.g. are there any local content requirement or policies related to this (e.g. *is the Kenyan manufacturing sector a missing link?*)
Local content regulations provide an opportunity for manufacturing – but the opportunity may not be attractive/taken up until barriers to uptake of RE in the sector are addressed.

Policies as discussed in point 6 may be directly related to the need and viability of local manufacturing.
In the immediate term building local content in terms of human resources, and focusing on mainstreaming innovative technologies already in the industry, may be steps towards local manufacturing (with adequately enabling policies and plans)

Section 4: **Specific questions on wind/solar and large vs small** (*optional depending on informant*)

1 To what extent is the policy framework enabling for this particular sector? In which specific ways and why or why not?
2 How would you assess the technological expertise and capacity available for the development of this sector (in terms of equipment manufacturing, project development, construction and installation, operations and maintenance)?
   a. What are the main challenges/opportunities in this regard?
   b. Where are the capabilities and expertise located?
   c. Which kinds of knowledge and skills are needed for the further development of this sector in Kenya?
   d. Are there any particular kinds of niches or innovations emerging from within this sector?
3 Who/what is in your opinion contributing to setting the agenda of this sub-sector (at national, regional or local level)?

1. How would you compare the need for large-scale vs small-scale renewable projects in this sector? Please justify, explain your thoughts on this.
2. Where do you see the biggest potential for building innovative capacities (small or big) within this subsector? In which kinds of projects and why?
3. To what extent do you think that there are efforts towards supporting more inclusive innovation in this sector?

Section 5: **Wrap-up**

1. Is there anything else you would like to share with us? Did something come to your mind that we didn't ask/speak about? **No**
2. Do you have any recommendations for other relevant contacts that we should speak with? **If you would like to speak with members of the association, we would be happy to assist**

Appendix II: Developed WOA-Based MPPT code for MATLAB

```
% Whale Optimization Algorithm (WOA) for MPPT in PV system
% Developed and refined for MATLAB
% Author: Dominic Samoita
% Date: 22/07/2025

clear; clc;

%% PV System Parameters (example)
Isc = 5.0;     % Short-circuit current (A)
Voc = 21.0;    % Open-circuit voltage (V)
Pmax = 80.0;   % Maximum power (W)

Vpv = 0:0.1:Voc;
Ipv = Isc * (1 - exp(1.2*(Vpv - Voc))); % Example IV curve
Ppv = Vpv .* Ipv;

% Define objective function
objective = @(V) -interp1(Vpv, Ppv, V, 'linear', 'extrap');

%% WOA Parameters
SearchAgents = 30;        % Number of whales
MaxIter = 100;            % Maximum number of iterations
dim = 1;                  % Dimension (Voltage)
lb = 0;                   % Lower bound (min voltage)
ub = Voc;                 % Upper bound (max voltage)

% Initialize whales
positions = lb + (ub - lb) * rand(SearchAgents, dim);
best_pos = positions(1, :);
best_score = objective(best_pos);

% Main WOA loop
for t = 1:MaxIter
    a = 2 - t * (2 / MaxIter);  % Decreasing 'a' from 2 to 0

    for i = 1:SearchAgents
        r1 = rand();
        r2 = rand();
        A = 2 * a * r1 - a;
        C = 2 * r2;

        p = rand();
        l = -1 + 2 * rand();
        D = abs(C * best_pos - positions(i, :));

        if p < 0.5
            if abs(A) < 1
```

```
                positions(i, :) = best_pos - A * D;
            else
                rand_whale = positions(randi([1, SearchAgents]), :);
                D = abs(C * rand_whale - positions(i, :));
                positions(i, :) = rand_whale - A * D;
            end
        else
            b = 1;  % Spiral shape parameter
            positions(i, :) = D * exp(b * l) * cos(2 * pi * l) + best_pos;
        end

        % Boundary check
        positions(i, :) = max(min(positions(i, :), ub), lb);

        % Evaluate new solution
        score = objective(positions(i, :));
        if score < best_score
            best_score = score;
            best_pos = positions(i, :);
        end
    end
end

%% Result
MPPT_voltage = best_pos;
MPPT_power = -best_score;
fprintf('Optimal Voltage: %.2f V\n', MPPT_voltage);
fprintf('Maximum Power: %.2f W\n', MPPT_power);

% Plot result
figure;
plot(Vpv, Ppv, 'b-', 'LineWidth', 2); hold on;
plot(MPPT_voltage, MPPT_power, 'ro', 'MarkerSize', 10, 'LineWidth', 2);
xlabel('Voltage (V)');
ylabel('Power (W)');
title('WOA-based MPPT');
grid on;
```

Appendix III: List of Publications

1. Samoita, D., Charles, P., Prof, N., Alberg, P., & Remmen, P. A. (2024). *Towards 100 % Renewable Energy : Incrementing Solar Electrification in Kenya*. *Journal of Energy Technologies and Policy 14*(3), 30–52. https://doi.org/10.7176/JETP/14-3-03

2. Samoita, D., Nzila, C., & Okinda, C. (2024). Potential of Accelerated Integration of Solar Electrification in Kenya's Energy System. *Renewable Energy Research and Applications*, *5*(2), 159–170.

3. Samoita, D., Nzila, C., Østergaard, P. A. P. A., & Remmen, A. (2020). Barriers and solutions for increasing the integration of solar power in Kenya's electricity mix. *Energies*, *13*(20), 5502. https://doi.org/10.3390/en13205502

4. Hansen, U. E., Gregersen, C., Lema, R., Samoita, D., & Wandera, F. (2018). Technological shape and size: A disaggregated perspective on sectoral innovation systems in renewable electrification pathways. *Energy Research and Social Science*, *42*, 13–22. https://doi.org/10.1016/j.erss.2018.02.012

Appendix IV: Plagiarism Awareness Certificate

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