TECHNO-ECONOMIC ASSESSMENT OF GRID-SOLAR-DIESEL GENERATOR BATTERY HYBRID ENERGY SYSTEMS FOR KENYA PIPELINE COMPANY, ELDORET TERMINAL

BY

FRANKSON MARINGA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN SUSTAINABLE ENERGY AND ENERGY ACCESS, DEPARTMENT OF MECHANICAL AND PRODUCTION ENGINEERING, SCHOOL OF ENGINEERING

MOI UNIVERSITY

2025

DECLARATION

Declaration by students

This thesis research represents my original work and has not been submitted for a Master's degree or any other degree at any other university. The entirety of this research, including its constituent parts, may not be reproduced without the explicit written consent of both the author and Moi University.

Signature: **Date:17th February 2025**

FRANKSON MARINGA

ENG/MS/SEA/4871/23

Declaration by Supervisors

This thesis has been submitted for examination with our approval as University Supervisors.

Signature: **Date:17th November 2025**

Dr. Stephen M. Talai,

Senior Lecturer,

Department of Mechanical, Production & Energy Engineering,

Moi University, Eldoret, Kenya.

Signature: **Date:17th November 2025**

Prof. Muyiwa S. Adaramola,

Professor,

Faculty of Environmental Sciences and Natural Resource Management, Norwegian,

University of Life Sciences, Ås, Norway.

PREFACE

This thesis is unpublished, original, and independent work by the author.

ACKNOWLEDGMENTS

I want to express my deep gratitude to my spouse and children for their unwavering support throughout this research. They have been my rock, always there to encourage me.

I also acknowledge the invaluable guidance from my supervisors, Kenya Pipeline Company (KPC) staff, and that of Moi University, Department of Mechanical, Production & Energy Engineering.

Further, I am indebted to the '*Strengthening Education, Research, and Innovation Capacity in Sustainable Energy for Economic Development*', a collaborative project between Norwegian University of Life Sciences (NMBU) Ås Norway and Moi University Eldoret Kenya under the Norwegian Partnership Programme for Global Academic Cooperation (NORPART), for financial support towards my exchange programme at NMBU Norway.

ABSTRACT

The Kenya Pipeline Company (KPC) Eldoret Terminal uses grid electricity and reliance on backup diesel generator during power outages. This hampers operational efficiency while contributing to financial strain and environmental emissions. With abundance of solar irradiance, there is a need to transition to a sustainable hybrid energy system (HES). The main objective of this study was to carry out a techno-economic assessment of grid-solar PV-diesel generator-battery hybrid energy systems. The specific objectives were to investigate and analyze energy consumption patterns, to design and simulate an optimum grid-solar PV-battery-diesel generator HES using PVsyst and (Hybrid Optimization Model for Multiple Energy Resources) HOMER modelling tools and to perform techno-economic analysis of the optimum hybrid energy system. The methodology outlined a step-by-step approach used to design a HES. The site was selected, and data was collected through surveys with the maintenance team, reviews of structural and utility documents, interviews to gather operational data, and observational entries from a data logger to document the energy profile. The design phase involved configuring a HES that integrated photovoltaic modules with existing diesel generators and grid power, optimized through precise calculations of energy consumption, PV module placement, battery system sizing, and inverter sizing. Simulation tools were utilized to aid in designing and performing economic assessments, determining the system's feasibility and economic viability through calculations of the Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and emissions. Based on data collected, KPC consumed 108,732 kWh of grid power and diesel generator at the terminal rated at 550 kVA consumed 1,807.31 litres with an energy production of 10,975kW in 2023. The terminal spent about Kshs 17.876 million on provision of electricity in 2023. The hybrid system was introduced a solar PV system covering a total estimated area of 2365 m² and an initial investment of Kshs 232,938,000, with a payback period of 8 years. The optimized HES entailed the PV module and grid integration, featuring a (LCOE) of 9.83 Kshs/kWh and NPC of Kshs 236 million while producing an annual CO_2 emission of 100,106kg. This scaled down by more than 50%. The study concluded that the grid-solar hybrid connection was well suited for a sustainable energy management system. It was recommended that solar charged batteries be prioritized as the power back up instead of the expensive diesel generator and environmentally polluting.

LIST OF ABBREVIATIONS

AC	Alternating Current
BESS	Battery Energy Storage Systems
BESS	Battery Energy Storage Systems
CAPEX	Capital Expenditure
CMA-ES	Covariance Matrix Adaptation Evolution Strategy
DC	Direct Current
DoA	Days of Autonomy
DoD	Depth of Discharge
DPBP	Discounted Payback Period
EISR	Energy Index of Self-Reliance
ESS	Energy Storage Systems
GHG	Greenhouse Gas
GIS	Geographic Information System
HES	Hybrid Energy Systems
IHS	Improved Harmony Search
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
KPC	The Kenya Pipeline Company
KP	Kenya Power
LCOE	Levelized Cost of Energy
LEAP	Low Emissions Analysis Platform
LPSP	Loss of Power Supply Probability
NEMO	Next Energy Modeling system for Optimization
NERSA	National Energy Regulator of South Africa

NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
PI	Proportional-Integral
PV	Photovoltaic
REF	Renewable Energy Fraction
RERs	Renewable Energy Resources
ROI	Return on Investment
SA	Simulated Annealing
SMR	Steam Methane Reformation
TAC	Total Annualized Cost
TLCC	Total Life Cycle Costs
VRF	Vanadium Redox Flow
WT	Wind Turbines

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

In the twenty-first century, global solar PV technology experienced rapid growth. The installed capacity steadily increased, projecting to reach 1.4 terawatts by 2024 (Gupta, 2012). Indeed, this rapid increase reflected a shift in global markets towards renewable and distributed energy technologies to address climate change and ensure sustainable energy availability.

The global solar photovoltaic (PV) market has seen dramatic growth over the past decade. In 2012, cumulative installed solar capacity was around 28.4 GW, based on IEA-PVPS estimates. IEA-PVPS Over the following years, this expanded steadily: by 2020, global PV capacity had reached approximately 710 GW (IRENA data) (approximate benchmark from renewable capacity reports). In 2022, cumulative solar PV capacity surpassed 1,046 GW, as documented in a global comprehensive review. ScienceDirect The acceleration continued in 2023, with solar capacity additions of 345.5 GW a 32.2 % year-on-year growth pushing cumulative installations to roughly 1,600 GW (1.6 TW). According to PV magazine International (2024), the global PV installed base exceeded 2.2 TW, reflecting over 600 GW of new deployments in that year alone. IEA-PVPS These figures underscore the rapid expansion of solar PV worldwide, as the technology scales from niche deployment to mainstream energy infrastructure.

In 2023, Kenya Pipeline Company (KPC) in Eldoret faced considerable challenges related to power costs, reliability and emissions due to generator dependency. The annual power consumption from the grid reached 108,732 kWh, resulting in a high expenditure of Kshs 17,610,172, which underscored the financial burden of grid

electricity. Monthly data showed that Kenya Power consistently supplied most of the electricity, with contributions between 8,000 and 14,000 kWh, while the on-site generator added a smaller yet steady amount of 1,000 to 2,500 kWh. However, this reliance on the generator brought additional issues.

et steady amount of 1,000 to 2,500 kWh. However, this reliance on the generator brought additional issues.

The generator, which ran on fossil fuels that incurred high emissions and fuel consumption, making it both costly and environmentally taxing. This dependency on fossil-fuel-driven generation highlighted a significant reliance on non-renewable energy, which added to KPC's carbon footprint. Additionally, power rationing became more frequent in the Eldoret region during the rainy season, exacerbating reliability issues and compelling KPC to depend more heavily on the generator to meet demand. As a result, KPC not only shouldered substantial financial and environmental costs but also experienced operational disruptions due to inconsistent power supply, particularly during weather-related outages.

1.1.1 Solar PV Energy Development

Despite the big potential for solar PV, Africa, including Kenya, has been slow to adopt (IRENA (02 April 2024), (Ngure *et al.,* 2023). Kenya mostly uses oil, geothermal energy, and hydro resources for production of electricity, but each comes with its own problems (Ngure *et al.,* 2023). The production of electricity from oil harms the environment, costs a lot, and puts a strain on the national trade balance. Hydropower, which comes from rivers in dry areas, faces challenges because of unpredictable rainfall, affecting the reliability of the power supply. Also, tapping into geothermal energy has issues related to cost and risks.

In the last ten years, PV technology has gotten a lot better, creating new chances for many economies (Ngure *et al.,* 2023). The improved efficiency and affordability of

solar energy systems have enabled both developed and developing nations to diversify their energy sources, reducing reliance on traditional fossil fuels. Solar energy installations worldwide have shown robust growth from 2022 to 2023 across various regions.

Therefore, from Table 1.1, these trends underscore a promising global trajectory for solar energy, with significant capacity expansions across diverse geographical regions. Africa and the Middle East possess the highest solar PV potential globally but exhibit the lowest installed solar PV capacity. This gap was attributed to policy limitations, information gaps, and insufficient capital investments hindering growth in the sector, particularly in comparison to developed countries (Cheruiyot et al,. 2024).

Table 1.1: The solar PV capacity and growth

Region	Country	Solar PV Capacity (GW)	Growth (%)
Africa	South Africa	6.3	15
	Egypt	1.7	18
	Morocco	0.8	12
Asia	China	393.0	Steady
	Japan	78.8	10
	India	63.1	20
North & Central America	USA	117.9	8
	Canada	11.4	7
	Mexico	6.6	5
Europe	Germany	54.7	6
	Spain	30.5	9
	Italy	20.9	7
Oceania	Australia	20.8	12
	Japan	5.5	8
	New Zealand	0.9	6
South America	Chile	2.5	15
	Brazil	2.2	10
	Argentina	0.9	8

Source: Pourasl et al,. 2023

Africa's energy mix is gradually shifting from traditional sources to include renewable sources like geothermal, solar, and biomass (Pourasl et al,. 2023). The rapid decline in the cost of solar PV components since 2010, coupled with supportive government policies, has led to significant growth and exponential use of solar PV systems (Ngure *et al.,* 2022). The International Energy Agency's report on sub-Saharan Africa's solar PV capacity from 2017 to 2025 highlights substantial growth in development, particularly in South Africa, Kenya, and other Eastern African countries (Urbina, 2022).

1.1.2 Solar Photovoltaic in Kenya

Government initiatives in 2005 aimed at providing basic electricity to remote rural areas further increased the demand for solar PV modules. According to Berggren & Österberg (2017), before 2017, most solar PV systems in Kenya were off-grid installations in rural areas (Cheruiyot, et al., 2024). However, the landscape shifted in 2017, witnessing steady growth in grid-tied solar PV, particularly after the commissioning of the Garissa power plant in 2018 and the Eldoret solar plants in 2021 (Keshavadasu, 2023). The development of solar photovoltaic (PV) systems in Kenya between 2017 and 2021 has shown notable progress (Oloo, 2022). In 2017, the installed capacity was below 10 MW, mainly through the implementation of rural off-grid systems. However, in 2018, there was a significant increase to 60 MW. This was attributed to the Garissa power plant. By 2021, the solar capacity expanded even further to 170 MW, primarily due to the establishment of solar plants in Eldoret (Keshavadasu, 2023). These advancements reflect Kenya's commitment to diversifying its energy sources and expanding access to clean and sustainable energy. Kenya's current electricity generation capacity includes a mix of off-grid and on-grid solar PV systems, accounting for 90 MW and 170 MW, respectively (Cheruiyot, et

al., 2024). The Least Cost Power Development Plan (LCPDP) 2020-2040 outlines 50 committed power generation projects, with solar PV contributing 404 MW to the committed capacity (Cheruiyot, et al., 2024). Despite Kenya's significant solar potential, the country still heavily relies on fossil fuels for electricity generation, contributing to high costs and increased greenhouse gas emissions.

In Kenya, significant efforts are underway to expand solar power capacity, to increase generation from less than 100 MW to 600 MW by 2030. Based on this, it underscored this push towards renewable energy. Meanwhile, the cost of installing solar PV systems in Kenya varied based on system size, panel efficiency, and components like batteries and inverters. Typical household installation of 2kW to 5kW capacity costs ranges from Kshs 200,000 to Kshs 500,000 for residential systems, with financing options like solar loans available to ease upfront expenses (Cheruiyot, et al., 2024). With desire to reduce their electricity bills, enhance property value, and reduce independence on the national grid, and use less reliance on diesel/gasoline-powered generators, the adoption of solar power is now gaining traction across Kenya's residential and commercial sectors.

1.2 Problem Statement

The Kenya Pipeline Company (KPC), Eldoret terminal faces significant challenges with its electrical power supply such as unreliable grid electricity, which is costly resulting to the operational inefficiencies. Thus, the terminal relies heavily on diesel generators to mitigate power outages, resulting in high operational costs, substantial carbon emissions, and increased costs due maintenance (Cheruiyot, et al., 2024). The rising demand for electricity in region has amplified power outages hence more reliance on diesel-powered generators, in the terminal's operations.

KPC faced significant energy management challenges due to high operational costs, environmental impact, and unreliable power supply. With an annual power consumption of 108,732 kWh, KPC's grid electricity expenses reached Kshs 17,610,172, highlighting a substantial financial burden. To cope with frequent power rationing, particularly during the rainy season, KPC relied heavily on diesel generators, consuming up to 50,000 liters of diesel during peak periods. This dependence not only increased fuel expenses but also led to the emission of approximately 134 metric tons of CO_2, exacerbating KPC's carbon footprint. The combined financial, environmental, and operational pressures underscore an urgent need for sustainable, cost-effective energy solutions to reduce diesel reliance, cut emissions, and stabilize power supply for KPC's ongoing operations.

In 2023, there was an increase in monthly generator fuel consumption (for power generation) at the Eldoret Terminal due to prolonged and frequent power outages, with substantial associated costs and emissions. There were peak consumption periods of up to 50,000 liters, reflecting heightened energy demand aligned with operational dynamics (*see Appendix 1*). The financial strain from fuel costs and emissions underscored the urgent need for alternative energy solutions. To address these challenges sustainably, implementing a grid-solar-diesel generator-battery hybrid system emerged as a promising solution. This approach involves integrating the solar PV systems and battery energy storage with the existing grid-diesel generator system. The solar PV systems harnessed the sunlight energy during the day, thereby reducing the dependence of the Terminal on the national grid during sunshine hours. Diesel generators acted as reliable backup during low solar PV generation or grid failures, ensuring uninterrupted power supply. Meanwhile, battery storage, which can store potential excess power generated by solar PV, serving as an electricity supply buffer

during power outages and night periods, and thereby reducing the use of diesel generators.

onal grid during sunshine hours. Diesel generators acted as reliable backup during low solar PV generation or grid failures, ensuring uninterrupted power supply. Meanwhile, battery storage, which can store potential excess power generated by solar PV, serving as an electricity supply buffer during power outages and night periods, and thereby reducing the use of diesel generators.

The transition to the hybrid system not only shall address energy challenges but also position the Eldoret Terminal for long-term sustainability and cost efficiency. It will mitigate the impact of unreliable grid supply, reduce operational costs associated with diesel generators, and contribute to environmental conservation by minimizing carbon emissions. Therefore, adopting a grid-solar PV-diesel generator-battery hybrid energy system can improve reliability, reduce costs, and enhance sustainability at the Eldoret Terminal. Indeed, this will strengthen the terminal's energy infrastructure, ensuring a stable and efficient electricity supply for KPC operations in Eldoret.

1.3 Objectives

1.3.1 Main Objective

The main objective of this study was to carry out a techno-economic assessment of grid-solar PV-diesel generator-battery storage hybrid energy systems tailored to Kenya Pipeline Company, Eldoret Terminal.

1.3.2 Specific Objectives

The specific objectives were:

i.   To analyze the energy consumption patterns at the Kenya Pipeline Company's Eldoret Terminal.

ii. To design and simulate grid-solar PV-battery storage-diesel generator hybrid energy system using PVsyst software and HOMER software.

iii. To perform a techno-economic analysis of the optimum hybrid energy system.

1.4 Justification and Significance of the Study

This study aimed to bolster energy security and reliability, aligning with KPC's strategy to integrate solar power plants into its infrastructure (KPC Energy Bill,2023). The initiative promised significant cost savings on electricity bills while advancing renewable energy adoption and reducing operational costs. The study substantiated these initiatives, highlighting potential financial and environmental benefits akin to global trends seen in industries like cement and steel production. It also contributed to United Nations Sustainable Development Goal No.7 (which is to "Ensure access to affordable, reliable, sustainable and modern energy for all) by promoting affordable, reliable, and sustainable energy solutions. The research underscored the urgent need for and broader impact of hybrid energy systems beyond the Eldoret Terminal, shaping energy strategies and promoting global shifts toward cleaner practices (Cheruiyot, Tonui, & Limo, 2021; Carlsen & Bruggemann, 2021).

1.5 Scope of the Study

The research focused on conducting techno-economic evaluation of a grid-solar-diesel generator-battery storage HES for the Eldoret Terminal of the KPC. The research involved analysis and modeling of hybrid energy system that efficiently meet the energy demands of the Eldoret Terminal. The study explored energy consumption patterns, power usage data, emissions, and fuel costs. It integrated a hybrid model combining grid power, solar PV, diesel generators, and battery storage, emphasizing renewable energy sources. A techno-economic analysis assessed financial metrics

such as return on investment, payback period, and levelized cost of energy to gauge the economic feasibility of implementing the hybrid energy system at the Eldoret Terminal. The research aimed at enhancing energy infrastructure at the terminal, providing valuable insights for advancements in green energy practices.

1.6 Assumptions, Limitations, and Delimitations of the Study

1.6.1 Assumption

The study assumed that the recorded meteorological data accurately reflected the past weather conditions and parameters at the KPC Eldoret terminal. It also assumed that the combined energy supplied by the generator, and the grid represented the actual energy demand of the terminal.

1.6.2 Limitations of the Study

One limitation stemmed from the limited research available in KPC Eldoret terminal. Consequently, the study was confined to utilizing actual measurements for the year 2023 of the generator use, recorded power outages and the electricity bills and amounts used, along with simulations for the PV system's expected lifetime.

1.6.3 Delimitations of the Study

Indeed, it was worth noting that the modeling used in the study did not encompass the actual installation of solar panels at the KPC Eldoret terminal but was based on a simulated scenario. Also, this delimitation clarified that the research focused on hypothetical scenarios and not the physical implementation of solar infrastructure at the site.

1.7 Thesis Layout

The thesis is structured as follows: -

Chapter One: introduces the context, including a background on solar PV development in Africa and Kenya, and establishes the Problem Statement, Objectives, and Justification for the study.

Chapter Two: Provides the literature review on Hybrid Energy Systems (HES), discussing their types, benefits, and challenges, while analyzing global case studies and assessing scenarios related to KPC Eldoret.

Chapter Three: outlines the Methodology, detailing site selection, data collection, and the design of the hybrid system.

Chapter Four: Presents the results and discussions, covering load assessments, PV system design, HES simulation outcomes, and emissions analysis.

Chapter Five: concludes with findings and Recommendations for future research and KPC, followed by a comprehensive list of References and relevant Appendices.

CHAPTER TWO

LITERATURE REVIEW

2.1 Energy Demand and Consumption Patterns in Industrial Facilities

2.1.1 Global Energy Demand in Industry

Industrial energy consumption accounts for a substantial share of total global energy use, with manufacturing, petrochemicals, and heavy industries leading in energy intensity. According to the International Energy Agency (IEA, 2023), the industrial sector represents approximately 37% of global energy consumption, heavily relying on electricity and fossil fuels (Dutta, 2014). Energy consumption patterns show variability aligned with production schedules, requiring efficient energy management for cost savings and environmental sustainability (Logan et al., 2020).

2.1.2 Energy Demand Trends in Africa

Industrial energy demand in Africa has been increasing in line with economic growth and industrial expansion, though disparities in access and infrastructure persist (IEA, 2023). Many African facilities depend on a mix of petroleum products, grid electricity, and decentralized renewable solutions due to unstable grid supply.

2.1.3 Kenyan Industrial Energy Consumption

In Kenya, industries contribute about 23% to national energy consumption, focusing on sectors like petroleum storage, cement, and manufacturing (Kenya National Energy Statistics Report, 2022). Load profiles in Kenyan industries typically exhibit midday peaks, with interest growing in hybrid systems to stabilize supply and reduce operational costs (Kamau & Wangari, 2021).

2.1.4 Load Profiles in Industrial and Petroleum Facilities

Energy load profiles represent the temporal distribution of energy consumption within industrial and petroleum facilities, serving as fundamental tools for understanding, planning, and optimizing energy use. These profiles illustrate how energy demand varies over time typically through daily, weekly, and seasonal cycles reflecting the operational dynamics of the facility. Load profiling is crucial for identifying peak demand periods, base load requirements, and transient fluctuations that impact both energy costs and system performance (Logan et al., 2020; Zhang et al., 2022).

2.1.5 Characteristics of Industrial Load Profiles

Industrial load profiles generally exhibit cyclical behaviour tied closely to production schedules. During working hours, energy consumption typically rises sharply as machinery, lighting, HVAC, and process systems operate at full capacity. Peak loads often occur during shifts with the highest production intensity and reduce substantially during off-hours or shutdown periods (Binderbauer, 2024). The load shape can be influenced by batch or continuous processing operations, with batch processes causing highly variable and intermittent energy consumption, while continuous processes maintain steadier load profiles. Key statistical parameters used to characterize load profiles include;

Base load: the minimum continuous energy demand (near-base load) reflecting essential processes or standby power.

Peak load: the highest short-term demand within a cycle, usually driven by simultaneous operation of multiple high-power equipment.

Load duration: the proportion of time the energy demand remains above a certain threshold, important for understanding peak load impacts (Wang et al., 2020).

These parameters enable energy managers to prioritize interventions such as load shifting, demand response, or equipment upgrades.

Petroleum storage and loading terminals feature distinctive load profiles due to the nature of their operations. Energy demand spikes correlate with loading and unloading cycles, which require powerful pumps, compressions systems, heating for viscosity control, and safety equipment operation (Zhang et al., 2022). Unlike constant industrial processes, petroleum terminals tend to show intermittent but intensive load peaks aligned with logistics schedules, such as tanker filling or dispatch.

The base load at petroleum terminals consists of continuous auxiliary systems including lighting, security, instrumentation, and fire safety systems. During peak loading periods, electrical demand can increase significantly, often straining local grid infrastructure. This intermittency necessitates advanced load management strategies to avoid costly peak demand charges and equipment overload (Logan et al., 2020).

2.1.6 Importance of Load Forecasting and Automation

Accurate load forecasting is essential for aligning energy supply with demand in industrial and petroleum facilities. Modern forecasting tools use historical consumption data, production schedules, weather conditions, and other variables to predict load evolution with high precision. These forecasts inform real-time operational decisions and enable proactive energy management (Binderbauer, 2024).

Automation technologies leverage load forecasts to implement demand-side management strategies, such as scheduling energy-intensive operations during off-peak periods or orchestrating energy storage discharge to flatten peak demands. This approach optimizes energy procurement costs, minimizes greenhouse gas emissions associated with peak power plants, and enhances system reliability (Patel & Kumar, 2021).

2.1.7 Strategies Derived from Load Profile Analysis

Analyzing load profiles, industrial facilities can devise several energy optimization strategies:

Load Shifting: Moving discretionary energy use from peak to off-peak hours reduces peak demand charges and grid stress. Demand Response: Participating in utility programs by reducing load during critical peak events offers cost benefits and grid stability. Energy Storage Integration: Batteries or thermal storage can absorb excess energy when demand is low and supply energy during peaks, smoothing load fluctuations. Process Optimization: Adjusting production sequences and equipment operation based on load data enhances overall energy efficiency (Teiwes, 2018).

2.1.8 Challenges in Industrial Load Profiling

Challenges in developing accurate load profiles include data collection complexity, especially for facilities with diverse and dynamic processes. Large volumes of energy data require processing and analysis techniques such as clustering and machine learning to extract meaningful patterns (Wang et al., 2020). Furthermore, external factors like ambient temperature and seasonal variations complicate load predictability, demanding adaptive models.

2.1.9 Case Studies on Energy Management in Industrial Facilities

2.1.9.1 Durban Petroleum Terminal, South Africa

At the Durban Petroleum Terminal, significant advances were made through the implementation of comprehensive energy monitoring and automated load scheduling systems, which together contributed to reducing peak demand charges by approximately 15%. This reduction was achieved without disrupting ongoing terminal operations, reflecting the careful balancing of energy efficiency and operational continuity (Moyo & Dlamini, 2022).

More detailed reports from related South African industrial energy efficiency projects, such as the Unilever Maydon Wharf steam optimization project, further underscore the importance of heat and energy system optimization. Key interventions included insulating exposed steam pipes to reduce radiation losses, implementing boiler blow-down heat recovery systems, and an aggressive condensate return program to minimize steam losses (South African Industrial Energy Efficiency Project Case Study, 2017). These interventions cumulatively achieved around 24% energy savings and substantially lowered CO_2 emissions, while also driving down operational costs and enhancing safety by lagging hot pipes.

erventions cumulatively achieved around 24% energy savings and substantially lowered CO_2 emissions, while also driving down operational costs and enhancing safety by lagging hot pipes.

Central to the success at Durban and comparable terminals was the appointment of dedicated performance managers tasked with consolidating energy data, coordinating cross-functional teams, and ensuring lessons learned were implemented widely across

operations. Despite challenges such as high staff turnover, continuous focus on data-driven energy management ensured sustained improvements and enabled these industrial facilities to remain competitive and environmentally responsible.

2.1.9.2 Nigerian Refineries

Nigerian refineries have demonstrated compelling benefits from deploying hybrid energy systems that combine solar photovoltaic (PV) technology, diesel generators, and energy storage solutions. Adeoye et al. (2020) report a notable 20% reduction in energy costs following the integration of these renewable and conventional energy resources. The hybrid approach allows refineries to reduce reliance on intermittent grid power and fuel-intensive diesel generation, which often dominates due to inconsistent electricity supply.

Strategically leveraging solar energy when available and seamlessly switching to diesel generators and battery storage during low solar output periods resulted in not only cost savings but also improved energy security and environmental benefits. This energy mix reduces fuel consumption and associated emissions, crucial for refineries that are often significant greenhouse gas emitters. The Nigerian case study reinforces the value of tailored renewable integration in regions facing grid instability, showcasing hybridization as both a cost-effective and sustainable strategy for industrial energy management.

2.1.9.3 Indian Oil Storage Terminals

In India, advances have been made by harnessing real-time energy analytics and automated scheduling in oil storage terminals. Patel and Kumar (2021) describe the deployment of sophisticated monitoring systems which enabled optimization of pump

scheduling and load management, significantly reducing emissions while maintaining operational throughput.

The root of the system's success lies in the ability to collect and analyze vast amounts of energy data across complex process equipment, allowing dynamic adjustments that optimize energy use without compromising on operational demands. By fine-tuning equipment operation based on real-time signals, the terminals achieved reductions in electricity consumption and improved energy use efficiency, simultaneously reducing the carbon footprint.

ments that optimize energy use without compromising on operational demands. By fine-tuning equipment operation based on real-time signals, the terminals achieved reductions in electricity consumption and improved energy use efficiency, simultaneously reducing the carbon footprint.

This data-driven approach, combined with employee training and process refinement, highlights the role digital technologies play in modern industrial energy management. It underscores the potential for replication across other oil storage and industrial facilities to achieve sustainable, cost-efficient energy consumption.

 storage and industrial facilities to achieve sustainable, cost-efficient energy consumption.

2.2 Hybrid Energy Systems (HES)

The Hybrid Energy Systems (HES) are designed to combine two or more energy sources to provide a more efficient and reliable energy supply. The approach is particularly relevant for remote areas where financial resources are limited, and energy system installation costs are high. Also, integrating multiple renewable

sources, such as solar, wind, hydro, geothermal, biomass, and biofuels, HES balance the unpredictability of energy supply and enhance overall performance.

2.2.1 Classifications of Renewable Energy installation

Renewable Energy system can be categorized into three types that includes Grid/Stand, The Hybrid System and On-Grid Systems.

Off-Grid/Stand - Alone systems also known as a stand-alone power system (SAPS) as presented in Figure 2.1 offer versatility, suitable for installation in any sun-exposed location. Similar to solar streetlights, these systems operate autonomously, containing all necessary components for complete functionality. Among the three types, Off-Grid/Stand-Alone systems are generally expensive, as they need to fulfill the entire load capacity of the solar installation (Panda *et al.,* 2023); (Sharma *et al.,* 2023).
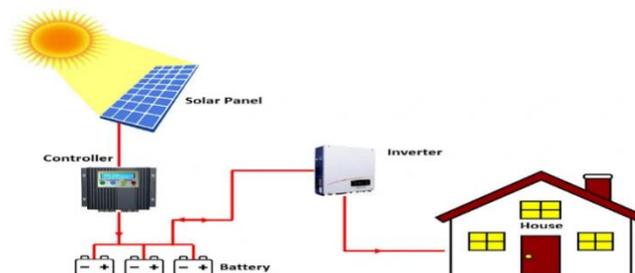
Figure 2.1: Off-Grid components
Source: solarstonepower.com

The off-grid system operates independently without connection to electricity grid, necessitating the inclusion of battery storage. The design of an off-grid solar systems must be meticulous to ensure enough power generation throughout the year by having ample battery capacity, especially during cloudy and rainy weather when sunlight is limited (Arrinda, 2020). The higher costs associated with batteries and inverters make

off-grid systems expensive compared to on-grid systems, typically finding use in remote areas distant from the electricity grid. Nevertheless, the declining costs of batteries have led to an increasing market for off-grid solar battery systems, even in towns.

areas distant from the electricity grid. Nevertheless, the declining costs of batteries have led to an increasing market for off-grid solar battery systems, even in towns.

According to Berggren & Österberg (2017), various types of off-grid systems exist. In smaller-scale DC-coupled systems, a solar charge controller controls battery charging, and DC power is converted to AC using an off-grid inverter before being directed to home appliances. According to Njeru, Gathiaka, & Kimuyu (2020), once the battery reaches full capacity, the system automatically reduces solar power input. During periods when the solar system is unavailable, such as at night, appliances draw power from the batteries. For times when battery levels are low, and the weather remains cloudy for extended periods, a backup power source is essential. This often takes the form of a backup generator, whose size (measured in kVA) should be adequate to supply power to the house and simultaneously charge the batteries (Hamid *et al.,* 2022).

The Hybrid System - Hybrid Solar PV Systems incorporate energy storage (batteries) to provide power during outages, store excess energy for nighttime use, and offer grid-feeding capabilities. These systems can operate independently during sunny day outages and perform peak shaving functions for commercial consumers, utilizing stored battery energy during high-demand periods (Panda *et al.,* 2023); (Sharma *et al.,* 2023). Careful consideration of the financial and economic aspects is essential, as cost reductions on electricity expenses may be balanced by battery investment and

replacement costs. The Hybrid System also known as a grid-connected solar PV system with battery storage a practical solar installation with the flexibility to utilize the grid when available, while also incorporating battery storage to reduce nighttime power consumption. Equipped with a battery, this system provides backup power during outrages and can store excess solar energy for nighttime use or during power interruptions.

Figure 2.2: Modern hybrid systems
Source: https://www.researchgate.net
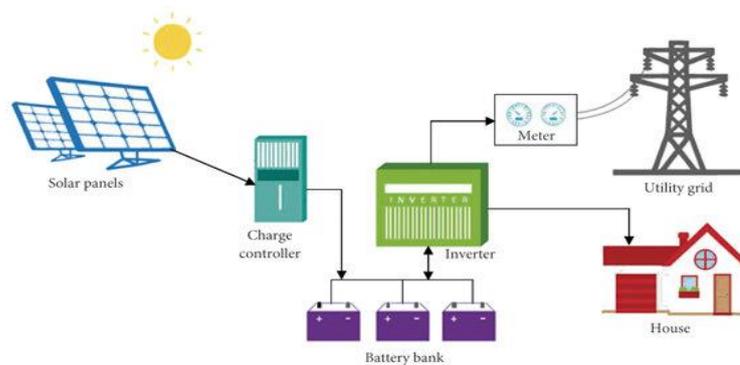
Based on Figure 2.2, modern hybrid system integrates both solar and battery storage into a single unit, available in various forms and configurations. With the diminishing cost of battery storage, existing grid-connected systems can now harness the benefits of this technology. As a result, according to Odou, Bhandari, & Adamou (2020), solar energy produced during the day can be saved for use at night, with the grid acting as a backup when the stored energy runs out. An additional feature of many hybrid systems is the ability to charge batteries with affordable off-peak electricity, which is usually accessible from midnight until six in the morning. While there are diverse ways to design hybrid systems, a simplified overview is presented here. In a hybrid system, after solar power is utilized by home appliances, any surplus power is

directed to the battery bank (Hamid *et al.,* 2022). The battery bank stops receiving power from the solar system after it is fully charged, and any extra solar energy is exported to the electrical grid. The battery's stored energy can then be released to power the house, usually in the evening during peak usage when electricity rates are usually higher. In a hybrid system, the power grid and meter are essential components. After the batteries are fully charged, extra solar power may be exported to the grid through the meter, depending on the utility. Appliances will use grid power if the solar system is not operating or if the batteries' useful power has run out.

On-Grid Systems - On-Grid Systems also known as a grid-tie or grid-feed solar system are the most cost-effective solar installations, consisting of minimal components. They offer a swift payback period based on electricity savings (Olabi et al., 2023). However, this type requires alternative backup power during brownouts and extended outages following major disasters, until the grid is restored. Despite a grid-tied system supplying 100% of electricity, minimal charges like service fees may still appear on electricity bills (Hamid *et al.,* 2022). Also, there are rampant power outages that hinder normal operation as far as grid is concerned (Hamid *et al.,* 2022).
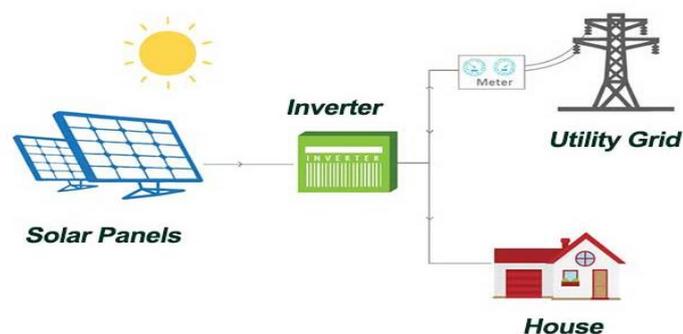
Figure 2.3: On-Grid Systems
Source: https://ksbssolar.com/on-grid-solar-solutions

The meter assumes a critical role to measures the excess solar energy, determining the quantity of power either exported or imported. Divergent metering systems are observed across localities and countries globally. In this specific context, it is acknowledged that the meter primarily assesses the electricity exported to the grid (Basyoni, Basyoni & Al-Dhlan, 2017) (Oladeji et al. (2021). During periods of solar system inactivity or when you're consuming more electricity than your system produces, the grid becomes the source for importing or utilizing electricity.

Table 2.1: Hybrid Energy Systems (HES)

Type	Description	Advantages	Challenges	Figures
Off-Grid/Stand-Alone Systems (SAPS)	Operate independently from the grid, include battery storage.	Versatile, autonomous operation, suitable for remote areas.	Higher costs, need meticulous design and backup generator.	Figure 2.6: Off-Grid Components
Hybrid Systems	Combine solar, batteries, and grid connection for flexible power use.	Provide backup power, store excess energy, use off-peak electricity.	Battery investment costs, depends on system setup and utility policies.	Figure 2.7: Modern Hybrid Systems
On-Grid Systems	Connect to the grid, cost-effective with minimal components.	Cost-effective, swift payback, export excess energy to the grid.	Dependence on the grid, require backup power during outages.	Figure 2.8: On-Grid Systems

2.2.2 Types of Hybrid Energy Systems

In Table 2.2, one of the most common and cost-effective hybrid systems is the combination of photovoltaic (PV) and wind energy. This system leverages the strengths of both solar and wind energy to provide a stable power supply, capitalizing on the fact that when one source is less productive, the other can often compensate

(Cai *et al.,* 2020; Ali *et al.,* 2021). Another hybrid system involves photovoltaic (PV) and hydro power. This combination takes advantage of solar energy during the day while relying on the consistent output of hydroelectric power at night, ensuring a continuous energy supply (Oladigbolu *et al.,* 2020; Aeggegn *et al.,* 2023). The hydro and wind energy system is particularly suitable for areas with significant water resources and wind availability. This combination balances the output of both sources, providing a stable and reliable power supply (Adaramola *et al.,* 2014; Wambui *et al.,* 2022). A hybrid system that integrates solar thermal and biomass energy combines the high-temperature capabilities of solar thermal energy with the consistent output of biomass energy. This system is particularly effective in areas where both biomass resources and strong sunlight are available (Hoseinzadeh & Garcia, 2022; Armoo *et al.,* 2024).

Table 2.2: Types of Hybrid Energy Systems

Hybrid System	Components	Strengths and Advantages	References
PV and Wind Energy	Photovoltaic (PV), Wind Energy	Provides a stable power supply by compensating when one source is less productive.	Cai et al. (2020), Ali et al. (2021)
PV and Hydraulic Power	Photovoltaic (PV), Hydroelectric	Utilizes solar energy during the day and hydroelectric power at night for continuous energy supply.	Oladigbolu et al. (2020), Aeggegn et al. (2023)
Hydraulic and Wind Energy	Hydroelectric, Wind Energy	Suitable for areas with significant water resources and wind availability, balancing the output of both sources.	Adaramola et al. (2014), Wambui et al. (2022)
Solar Thermal and Biomass Energy	Solar Thermal, Biomass	Combines high-temperature capabilities of solar thermal energy with consistent biomass energy output, effective in areas with both resources.	Hoseinzadeh & Garcia (2022), Armoo et al. (2024)

2.2.3 Benefits of HES

Hybrid systems can achieve higher efficiency rates compared to standalone renewable

energy sources. Table 2.1 presents information by balancing the output of different

sources to match the load demand, these systems can operate more efficiently (Cai *et al.,* 2020; Ali *et al.,* 2021; Oladigbolu *et al.,* 2020; Aeggegn *et al.,* 2023). The

combination of multiple renewable sources in HRES ensures a more stable power

supply. This increased reliability is due to the reduced impact of intermittency, as the

system can draw on different energy sources at different times (Cai *et al.,* 2020; Ali *et al.,* 2021; Oladigbolu *et al.,* 2020; Aeggegn *et al.,* 2023; Adaramola *et al.,* 2014;

Wambui *et al.,* 2022). In terms of cost savings, hybrid systems can reduce the overall

cost of energy production. By leveraging the strengths of various energy sources and

minimizing the need for fuel-based backup power sources, these systems can be more

economical in the long run (Cai *et al.,* 2020; Ali *et al.,* 2021; Oladigbolu *et al.,* 2020;

Aeggegn *et al.,* 2023; Adaramola *et al.,* 2014; Wambui *et al.,* 2022; Hoseinzadeh &

Garcia, 2022; Armoo *et al.,* 2024). Environmental benefits of HES are significant, as

they can substantially reduce greenhouse gas emissions. Indeed, contributing to a

cleaner energy mix, these systems align with the objectives of the Paris Agreement

and the UN Sustainable Development Goals (SDGs) (Cai *et al.,* 2020; Ali *et al.,* 2021;

Oladigbolu *et al.,* 2020; Aeggegn *et al.,* 2023; Adaramola *et al.,* 2014; Wambui *et al.,*

2022; Hoseinzadeh & Garcia, 2022; Armoo *et al.,* 2024).

2.2.3 Challenges and Opportunities of HES

The development of hybrid energy systems is often hindered by the lack of specific

regulations and standards. For example, countries like India and Spain have made

significant strides in creating supportive policies, but many regions still lack the

necessary regulatory framework (Cai *et al.,* 2020; Abbaspour *et al.,* 2023). Ensuring seamless integration and control of multiple sources can be complex. This challenge requires advanced energy management systems and optimization techniques to effectively manage the different inputs and outputs (Cai *et al.,* 2020; Ali *et al.,* 2021; Oladigbolu *et al.,* 2020; Aeggegn *et al.,* 2023; Adaramola *et al.,* 2014; Wambui *et al.,* 2022; Hoseinzadeh & Garcia, 2022; Armoo *et al.,* 2024). The integration of energy storage systems, such as batteries, can significantly harness excess power produced during peak times of solar and wind energies enhancing the performance and reliability of hybrid energy systems. These storage solutions provide backup power during periods of low renewable energy output, ensuring a continuous and stable energy supply (Cai *et al.,* 2020; Ali *et al.,* 2021; Oladigbolu *et al.,* 2020; Aeggegn *et al.,* 2023; Adaramola *et al.,* 2014; Wambui *et al.,* 2022; Hoseinzadeh & Garcia, 2022; Armoo *et al.,* 2024).

2.2.4 Case Studies on Techno-economic and Applications of HES

A hybrid energy system (HES) that consists of battery energy storage, a diesel generator, and solar (PV) technology. A techno-economic and environmental assessment of the proposed HES using an improved dispatch strategy. They found that the HES was optimized to minimize the total net present cost (NPC) and greenhouse gas (GHG) emissions while meeting the energy demand of a remote location. The improved dispatch strategy outperformed conventional strategies in terms of cost savings and emissions reduction. The optimized HES achieved a 12.4% reduction in NPC and a 15.3% decrease in GHG emissions compared to a baseline diesel-only system. Sensitivity analyses were conducted by Aziz et al. (2022) to evaluate the impact of key parameters such as PV module efficiency, battery capacity, and fuel prices on the system's techno-economic and environmental performance. The

study demonstrated the viability of the proposed HRES as a sustainable energy solution for remote off-grid applications, providing reliable and cost-effective electricity while minimizing environmental impact. For instance, Ghasemi et al. (2013) and Abnavi et al. (2019) conducted techno-economic analyses of stand-alone hybrid PV-diesel-battery systems for rural electrification in Iran. Similarly, Aghapouramin (2022) and Jahangir et al. (2019) evaluated the techno-economic feasibility of hybrid energy systems for residential applications in Iran.

Table 2.3 summarizes case studies on Hybrid Energy Systems (HES), highlighting configurations like PV, diesel, and battery setups.

Table 2.3: A summary of Case Studies on Techno-economic and Applications of

Study	Authors	HES Configuration	Main Findings	Sensitivity Analysis Parameters	Software/Method
Techno-economic and environmental evaluation of PV/diesel/battery hybrid energy system	Aziz et al. (2022)	PV, diesel generator, battery	12.4% reduction in NPC, 15.3% decrease in GHG emissions compared to diesel-only system. Improved dispatch strategy outperforms conventional strategies in cost savings and emissions reduction.	PV module efficiency, battery capacity, fuel prices	Not specified
Feasibility and techno-economic analysis of PV-battery priority grid tie system	Aeggegn et al. (2023)	PV, battery, grid tie, diesel backup	More cost-effective and environmentally friendly than traditional diesel-only	Solar radiation, water discharge, capacity shortage, battery	HOMER Pro

			systems. Reliable off-grid electrification, reduction in GHG emissions.	state of charge	
Optimal design of hybrid energy system for rural village	Oladigbolu et al. (2020)	PV, micro-hydro, diesel, battery	Better technical performance and lower GHG emissions compared to PV/diesel system. Reliable and cost-effective off-grid electrification for rural communities.	Interest rate, solar radiation, water discharge, capacity shortage, battery state of charge	HOMER Pro
Techno-economic analysis of PV-battery-diesel hybrid mini-grid	Elegeonye et al. (2023)	PV, battery, diesel	92.9% reduction in GHG emissions, 4-year payback period. Significant climate change mitigation potential, enhances energy access and security in Nigeria.	Not specified	Not specified
Techno-economic analysis of hybrid energy systems for industrial towns	Abbaspour et al. (2023)	PV, wind, diesel, battery	Optimal configuration depends on climate conditions. Lower carbon footprint and cost-effective electricity compared to diesel-only	Renewable energy potential, energy costs, environmental impact	Not specified

			systems.		
Increasing renewable energy penetration	De Silva et al. (2022), Kabeyi & Olanrew aju (2023)	PV, wind, complemen tary renewable technologie s	Decreasing costs of renewable technologies enable competitive prices with conventional power plants. Hybrid Energy Systems can maximize grid utilization and lower overall costs.	Not specified	Not specified

Additionally, Goudarzi et al. (2019) assessed the techno-economic and environmental performance of hybrid systems for a residential building in Tehran. Aziz et al. (2022) found that their study builds on these previous works by incorporating an improved dispatch strategy to further optimize the HRES performance. The feasibility and techno-economic analysis of a PV-battery priority grid tie system with diesel resilience for a case study. Conferring to Aeggegn et al. (2023), the study focused on Debre Markos University in Ethiopia, where frequent power outages and high reliance on diesel generators posed significant economic and social challenges. The university has 12 diesel generators with a total capacity of 3302 kV A, but they were not optimally placed, leading to resource waste and high fuel costs. The results, as found by Aeggegn et al. (2023), showed that the hybrid PV-battery grid tie system with diesel resilience was more cost-effective and environmentally friendly compared to traditional diesel-only systems. In Table 2.3, the research paper by Oladigbolu et al. (2020) examined the optimal design of a hybrid energy system combining solar

photovoltaic (PV), micro-hydro, diesel, and battery storage for a remote rural village in a tropical climate.

According to Oladigbolu et al. (2020), the hybrid PV/micro-hydro/diesel/battery system was found to be more optimal than a standalone PV/diesel system for providing reliable and cost-effective off-grid electrification in the rural village. Over half the population in Nigerian rural communities lack access to grid electricity, highlighting the need for off-grid energy solutions (Oladigbolu *et al.,* 2020). Hybrid energy systems provide reliable, low-cost electricity for rural electrification and clean energy development. Elegeonye et al. (2023) argued that the study presents a comprehensive techno-economic analysis of a PV-battery-diesel hybrid mini-grid system in Gbamu-Gbamu, Ogun State, Nigeria. They argued that the technical analysis revealed that the hybrid system had a capacity factor of 21.7%, resulting in a very high energy output that can be exported to the grid. Again, this indicated the system's ability to generate substantial amounts of electricity to meet the community's energy demands. In addition to the technical and economic performance, Elegeonye et al. (2023) evaluated the environmental sustainability of the hybrid system. They found that the results showed a 92.9% reduction in greenhouse gas (GHG) emissions compared to a conventional diesel-only system. The emission reduction was equivalent to 501.5 hectares of forest absorbing carbon, highlighting the significant climate change mitigation potential of the HRES. The study by Elegeonye et al. (2023) had important policy implications for Nigeria's energy sector. The results offer validity to the use of standalone mini-grid systems, especially in regions like northern Nigeria that receive a lot of solar radiation. Gain, by deploying energy technologies, this could promote the nation's efforts to reduce climate change and improve energy availability and security. Elegeonye et al. (2023) presented a compelling case for the

technical, economic, and environmental viability of PV-battery-diesel hybrid mini-grid systems in Nigeria.

According to Oladigbolu et al. (2020), the study examined the optimal design of a hybrid energy system combining solar photovoltaic (PV), micro-hydro, diesel, and battery storage for a remote rural village in a tropical climate. They argued that the hybrid PV/micro-hydro/diesel/battery system was more optimal than a standalone PV/diesel system for providing reliable and cost-effective off-grid electrification in the rural village. From Table 2.3, the study by Abbaspour et al. (2023) provided a techno-economic analysis of hybrid energy systems that combine photovoltaic (PV) panels, wind turbines, diesel generators, and battery storage for industrial towns in Spain under different climates. Abbaspour et al,. (2023) aimed to determine the optimal configuration and size of these hybrid power systems to meet the electricity demand of industrial facilities while considering factors such as renewable energy potential, energy costs, and environmental impact. According to Abbaspour et al,. (2023), the study evaluated several hybrid system configurations, including PV-wind-diesel-battery, PV-diesel-battery, and wind-diesel-battery systems. The widespread adoption of these technologies, coupled with a steep learning curve, has rapidly driven down prices, enabling renewable energies to compete effectively with conventional power plants (De Silva *et al.,* 2022). The 2018 Renewable Power Generation Costs report by the International Renewable Energy Agency (IRENA) illustrates this cost decline by comparing the Levelized Cost of Electricity (LCOE) for various renewable technologies (De Silva *et al.,* 2022). Furthermore, with anticipated further cost reductions, indeed and particularly in the context of stable regulatory frameworks established by international agreements, a substantial increase in the penetration of renewable energies into national power systems is foreseeable (Kabeyi & Olanrewaju,

2023). Also, this heightened share of renewable energies will necessitate expanded grid development to accommodate the integration of new renewable energy into existing electric systems. The primary challenge posed by renewable energies, in comparison to conventional power plants, lies in their irregularity, their production is contingent on resource availability, making their scheduling challenging (Kabeyi & Olanrewaju, 2023).

2.2.4.1 HES in Asia

Islam et al. (2022) conducted a techno-economic analysis of a hybrid renewable energy system to power a healthcare center in Gangachara Upazila, Rangpur district, in northwest Bangladesh. This study addressed the challenges posed by frequent power outages and unreliable electricity supply, which severely impacted the functionality of rural healthcare centers in Bangladesh. Gruber et al. (2022) analyzed that incorporating renewable energy, particularly solar photovoltaic (PV) systems, could provide a sustainable and reliable power solution for these critical facilities. Islam et al. (2022) highlighted the dependency of Bangladesh on fossil fuels for electricity generation, which not only are depleting but also contributed significantly to environmental pollution. The government aimed to increase the share of renewable energy in the country's energy mix, with a target of generating 40% of energy from renewable sources by 2041. Gil-Alana et al. (2017) mentioned that this aligns with global trends where countries are increasingly shifting towards renewable energy to reduce greenhouse gas emissions and ensure a sustainable power supply. The study utilized the HOMER Powering Health Tool and HOMER Pro software to design and evaluate a microgrid hybrid PV system for the selected healthcare center.

The proposed system includes 400 Wp solar panels, a 25-kW bi-directional inverter, a 28-kW generator, and related accessories. The analysis revealed that a 32-kW grid-connected solar PV system is required to meet the energy demands of the healthcare center, with an estimated net present cost (NPC) of US$ 33,818 and a levelized cost of energy (LCOE) of US$ 0.022/kWh (Islam *et al.,* 2022). Islam et al. (2022) found that the hybrid system could generate 51,467 kWh annually, with solar PV contributing 99.5% of the total energy. Hashimshony Yaffe & Segal-Klein (2023) reported that the system's performance was evaluated based on various technical and economic parameters, including initial capital cost, operating and maintenance costs, and the potential for excess energy production to be sold to the national grid. The results indicated that the proposed system was not only economically viable but also environmentally friendly, as it significantly reduced reliance on diesel generators, thereby lowering greenhouse gas emissions. Islam et al. (2022) emphasized that the implementation of such hybrid systems in rural healthcare centers can ensure an uninterrupted power supply, which was crucial for the effective operation of medical facilities. Ibrahim & Ayomoh (2022) revealed that they argued that the high initial investment cost was offset by the long-term savings in operating costs and the environmental benefits. The study also underscored the importance of government support and incentives to promote the adoption of renewable energy technologies in Bangladesh. The sensitivity analysis conducted by Islam et al. (2022) showed that the system's economic performance was robust under various scenarios of changes in solar radiation, diesel prices, and interest rates. This indicated that the hybrid energy system could adapt to different economic and climatic conditions, making it a reliable solution for rural healthcare centers.

the hybrid energy system could adapt to different economic and climatic conditions, making it a reliable solution for rural healthcare centers.

The article "Optimal Sizing and Location Based on Economic Parameters for an Off-Grid Application of a Hybrid System with Photovoltaic, Battery, and Diesel Technology" by Wei Cai, Xing Li, Akbar Maleki, Fathollah Pourfayaz, Marc A. Rosen, Mohammad Alhuyi Nazari, and Dieu Tien Bui presented an efficient strategy for optimizing the sizing and location of hybrid energy systems comprising photovoltaic (PV), battery, and diesel technologies. Ibrahim et al. (2023) noted that, the study focused on off-grid applications in rural areas and evaluated the proposed strategy using a case study in South Khorasan, Iran. The study investigated a stand-alone hybrid energy system consisting of PV panels, battery storage, and a diesel generator, designed to continuously meet load demands while minimizing total life cycle costs (TLCC). The proposed framework integrated a geographic information system (GIS) module to determine the optimal location for the hybrid system based on technical, economic, reliability, social, and environmental criteria (Cai *et al.,* 2020). Igwenagu (2016) pointed out that to determine the optimal sizing of the components, a hybrid optimization algorithm combining simulated annealing (SA), and improved harmony search (IHS) was used. The authors evaluated the framework on various criteria, including technical performance, economic feasibility, social impact, and environmental considerations, while also assessing the impacts of variations in fuel costs, initial costs of PV panels and batteries, and interest rates. They tested the framework in South Khorasan and demonstrated its effectiveness in optimizing the hybrid system, with the hybrid algorithm producing results 14.1% more accurate compared to other heuristic methods. The use of the hybrid energy system (solar energy with diesel generator) significantly reduced greenhouse gas

emissions by 59.6% and supply costs by 22.2% compared to a diesel-only system (Cai *et al.,* 2020). Jena & Ray (2023) described that this study aligned with previous research on hybrid energy systems (HES) and their optimization, building on methods such as simulated annealing, harmony search, genetic algorithms, and other heuristic approaches, noting the limitations of existing tools like HOMER software. Jung (2023) outlined that the hybrid heuristic technique combines the robustness of simulated annealing and the efficiency of harmony search, utilizing GIS data to identify optimal locations and ensure the system meets various constraints and criteria. Furthermore, the authors assessed the effects of economic parameters (fuel costs, initial investment costs, and interest rates) on the performance and feasibility of the hybrid energy system (Cai *et al.,* 2020). The authors concluded that the proposed framework offered a holistic approach by considering multiple criteria technical, economic, environmental, and social providing a more realistic and practical solution for rural electrification. The integration of the hybrid algorithm with GIS and consideration of diverse criteria results was more accurate and effective solutions than traditional methods. K M & Saravanan (2021) discussed that the study highlighted significant reductions in greenhouse gas emissions and supply costs, underscoring the environmental and economic advantages of hybrid energy systems over diesel-only systems. The findings emphasized the importance of comprehensive optimization approaches in achieving sustainable and economically viable energy solutions (Cai *et al.,* 2020).

In their 2021 study, Ali et al. conducted a comprehensive techno-economic assessment of hybrid energy systems in rural Pakistan. The study explored various hybrid energy configurations, focusing on their feasibility and cost-effectiveness in providing sustainable energy solutions to remote areas. Using the HOMER simulation

tool, the authors compared different hybrid energy systems, including combinations of solar PV, wind, diesel generators, and battery storage. Kulkarni & Anil (2014) explored that they found that hybrid systems integrating renewable energy sources with traditional diesel generators offered a lower cost of energy (COE) compared to standalone systems. Additionally, hybrid energy systems significantly reduced carbon emissions compared to diesel-only systems, highlighting their environmental benefits. Sensitivity analyses indicated that these systems remained economically viable under various scenarios, including fluctuations in diesel prices and discount rates. The authors concluded that hybrid energy systems were a viable solution for rural electrification in Pakistan and advocated for policy support and investment in renewable energy infrastructure (Ali *et al.,* 2021). In another significant study, Ali et al. focused on a techno-economic analysis of a hybrid mini-grid system in rural Bangladesh. This research, published in the Journal of Energy Research and Reviews in 2020, aimed to propose a sustainable and cost-effective energy solution for off-grid rural areas by examining various hybrid configurations. The study compared three system designs: Hybrid PV-Diesel-Battery, PV-Battery, and Diesel-Battery. Among these, the Hybrid PV-Diesel-Battery system emerged as the most cost-effective, with a COE of around USD 0.182/kWh. The hybrid system showed a significant reduction in carbon emissions (307 kg/year) compared to the Diesel-Battery system, though slightly higher than the PV-Battery system. The study included a sensitivity analysis that varied diesel prices and discount rates, reinforcing the economic viability of the PV-Diesel-Battery system under different conditions. Additionally, a SWOT analysis highlighted the strengths, weaknesses, opportunities, and threats associated with the proposed hybrid mini grid, emphasizing the need for participatory planning strategies for successful implementation (Ali *et al.,* 2020). Previous studies have also explored

hybrid energy systems in rural settings. Alam and Bhattacharyya used HOMER to analyze a hybrid energy system for the coastal region of Bangladesh, suggesting that a solar-diesel generator-battery or solar-wind-diesel generator-battery combination could provide better quality electricity at competitive costs. Lipu et al. and Rashid et al. conducted analyses of hybrid wind/PV/diesel energy systems in Saint Martin's Island, demonstrating low COE and reasonable NPC compared to other configurations. Haque et al. identified the PV/battery system as the most optimized stand-alone system for Saint Martin's Island, though the inclusion of a diesel generator was suggested to further reduce COE. Nandi and Ghosh showed that a wind–PV–diesel hybrid system could be feasible for Kutubdia Island, with significant reductions in NPC and COE. Salehin et al. conducted a techno-economic feasibility study of a solar PV-diesel system in a remote island of Kurigram district, revealing the advantages of integrating solar PV with diesel generators. Islam et al. revealed that a PV/biomass/battery/diesel hybrid mini-grid system was more economical than other combinations for northern Bangladesh.

2.2.4.2 HES in Europe

In their study, Hoseinzadeh and Garcia conducted a detailed techno-economic assessment of hybrid energy flexibility systems for islands' decarbonization, focusing on Catania city in Sicily, Italy. The researchers employed HOMER software to simulate the integration of photovoltaic panels, wind turbines, fuel cells, electrolyzers, and hydrogen tanks to meet a 2 MW energy demand. They found that photovoltaic panels provided 72% of the total energy, showcasing higher efficiency compared to wind turbines and fuel cells. The study indicated that the complementary use of photovoltaic panels and wind turbines across different months could effectively meet energy demands. The analysis revealed that a capital investment of 4.85 million euros

was required, with a return on investment of 2.59 million euros over a projected 25-year lifespan of the project. Additionally, the research highlighted the significant potential of renewable energy systems in reducing reliance on fossil fuels and minimizing environmental impact. Sensitivity analyses were conducted to assess the impact of varying solar irradiation and wind speeds on energy production and economic viability. Maniscalco et al. (2023) investigated that the results demonstrated that the selected region has high potential for utilizing solar panels and wind turbines, making it suitable for the implementation of renewable energy systems.

2.2.4.3 HES in Africa

Nkambule, Hasan, and Shongwe (2023) conducted a study to evaluate the feasibility and performance of hybrid energy systems (HES) for the mining industry in South Africa. Modu et al. (2023) elaborated that the research integrates floating solar photovoltaics (FPV), wind turbines (WT), and vanadium redox flow (VRF) battery energy storage systems (BESS) using various software tools to enhance overall efficiency and reduce greenhouse gas emissions. According to Nkambule et al. (2023), the mining industry in South Africa faces significant challenges due to inconsistent and unreliable power supply from Eskom, the state-owned power utility. Mofijur et al. (2019) asserted that frequent load shedding and curtailment result in substantial operational disruptions and financial losses. Additionally, there is increasing pressure on the mining sector to reduce carbon emissions in line with global net-zero targets. The researchers aimed to provide a sustainable and economically viable alternative through the implementation of HES. The methodology involved using the Hybrid Optimization of Multiple Energy Resources (HOMER) software to simulate and optimize the HRES, which consists of FPV, WT, and VRF-BESS. Detailed modeling of the solar PV system was performed using the

PVsyst software, while MATLAB was utilized to evaluate the BESS dispatch algorithm. Nkambule et al. (2023) proposed a system that includes a 5 MW FPV array, a 1 MW WT, and a 1 MW/4 MWh VRF-BESS. The performance ratio of the FPV system, wind penetration rate, and life throughput of the VRF-BESS were key metrics analyzed. Mumtaz (2022) concluded that they also employed the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) to optimize the battery storage utilization. Agajie et al. (2023) and Nkambule et al. (2023) found that the FPV system demonstrated a performance ratio of 0.855 and an annual energy production of 15,835 MWh. The WT operated for 2977 hours annually, with a 25% wind penetration rate, producing 172,580,718 kWh/year. The VRF-BESS exhibited a life throughput of 15,439 kWh and an algorithm response time of 3 seconds, indicating effective energy management and rapid response capabilities. The economic analysis revealed that the HES had a capital expenditure (Capex) of R172 million, with a notable internal rate of return (IRR) of 23.5% and a payback period of 4.9 years. The levelized cost of energy (LCoE) was calculated at 4.27 R/kWh, and the blended cost of energy (BCoE) was 1.91 R/kWh, suggesting economic feasibility without external subsidies. Nkambule et al. (2023) explained that the HES significantly reduced annual CO_2 emissions by 1,715,468 kg (95.6%), SO_2 emissions by 7437 kg (95.5%), and NOx emissions by 3637 kg (95.7%), contributing to substantial environmental benefits. Musonye et al. (2021) determined that the study concluded that the proposed HRES is a viable solution for the mining sector in South Africa, offering enhanced energy reliability, economic advantages, and significant environmental benefits. The integration of FPV, WT, and VRF-BESS not only ensures a steady power supply but also aligns with global efforts to reduce carbon footprints. Nkambule et al. (2023) recommended that mining companies invest in HRES to mitigate power interruptions, enhance

operational reliability, and adhere to environmental sustainability goals. They also underscored the importance of complying with the National Energy Regulator of South Africa (NERSA) guidelines and integrating advanced energy management algorithms to optimize storage and distribution. Njeru, Gathiaka, & Kimuyu (2020) documented that the study's findings provided a roadmap for the mining industry to transition toward sustainable and economically viable energy solutions, setting a precedent for similar applications in other sectors. Future research should explore the long-term benefits and scalability of HRES in diverse industrial contexts, incorporating advancements in energy management technologies.

ansition toward sustainable and economically viable energy solutions, setting a precedent for similar applications in other sectors. Future research should explore the long-term benefits and scalability of HRES in diverse industrial contexts, incorporating advancements in energy management technologies.

The article by Yimen et al, (2020) addresses the issue of rural electrification in sub-Saharan Africa, particularly in remote areas like Fanisau, northern Nigeria. The authors propose a hybrid energy system (HES) combining photovoltaic (PV) panels, wind turbines, batteries, and diesel generators to provide sustainable electricity. They argue that HRES can offer a more reliable and cost-effective solution compared to traditional methods like grid extension and diesel generators alone. According to Yimen *et al.,* (2020), the study employs a two-step methodology. In the first step, simulations and optimizations were performed using MATLAB and a genetic algorithm. This approach aimed to minimize the total annualized cost (TAC) while ensuring system reliability and maximizing the renewable energy fraction. The second step involved a techno-economic and emissions analysis to compare the optimized

HES with conventional rural electrification methods. Odou, Bhandari, & Adamou (2020) indicated that the demand load for Fanisau was assessed, considering residential, community, and commercial sectors. The daily electricity demand was estimated at 484.729 kWh, leading to an annual demand of 176,926 kWh. To meet this demand, the proposed system configuration included an 89.271 kW PV array, a 100.31 W diesel generator, and 148 batteries (Yimen *et al.,* 2020). Yimen et al. (2020) explained that the optimization process used MATLAB and a genetic algorithm to determine the optimal number of PV modules, wind turbines, batteries, and the capacity of the diesel generator. Olabi et al. (2023) hypothesized that the goal was to minimize TAC while maintaining a loss of power supply probability (LPSP) of 1% and a renewable energy fraction (REF) of at least 75%. The results showed that the wind turbine component was excluded from the optimal system due to its higher costs compared to PV technology. In Table 2.6, the techno-economic analysis found that the optimized system had a TAC of USD 43,807 and a cost of energy (COE) of USD 0.25/kWh. Oladeji et al. (2021) proposed that the break-even grid extension distance was calculated to be 16.2 km, indicating that the HES is more cost-effective than grid extension for distances greater than this threshold. The study also assessed the feasibility of replacing the diesel generator with the optimized HES, revealing a net present value (NPV) of USD 572,382 and a simple payback period (SPP) of 2.8 years, thus highlighting the economic viability of the project (Yimen *et al.,* 2020). In terms of environmental impact, Yimen et al. (2020) found that the proposed HES would save 85,401.08 kg of CO_2 annually compared to grid extension and 122,062.85 kg annually compared to diesel generators. This significant reduction in greenhouse gas emissions underscores the environmental benefits of adopting HES for rural electrification. The study concludes that PV-based HES could play a crucial role in

addressing rural electrification challenges in sub-Saharan Africa. The authors argue that the proposed system for Fanisau is more cost-effective and environmentally friendly than traditional rural electrification methods. Onaolapo et al. (2023) clarified that they call for policy measures to support the implementation of HES, such as creating an enabling environment for private investment and developing local capacities. Also, integrating renewable energy technologies into rural electrification strategies, sustainable development goals could be achieved, improving the quality of life in underserved regions (Yimen *et al.,* 2020). Yimen et al. (2020) provided a comprehensive framework for optimizing renewable energy systems for rural electrification. Ramesh & Saini (2021) observed that the methodology and findings offer valuable insights for policymakers, researchers, and practitioners in designing and implementing effective energy solutions for remote and off-grid communities. The study's approach to addressing technical, economic, and environmental aspects of HES highlighted the potential of renewable energy technologies enhancing rural electrification efforts across Sub-Saharan Africa.

The study by Armoo et al. (2024) investigated the techno-economic feasibility of hybrid renewable energy systems (HRES) through the production of energy and alternative fuels. This study by Baqir & Channi (2022) focuses on a pilot plant in the Ashanti Region of Ghana, integrating anaerobic digestion, pyrolysis, and solar photovoltaic (PV) systems to produce electricity and various fuels such as green hydrogen, refuse-derived fuels, bio-compressed natural gas, and compost. Armoo et al. (2024) employ a comparative financial analysis of three scenarios: generating both electricity and fuels, generating electricity alone, and generating fuels alone. According to Armoo et al. (2024), the multiple-product scenario provides the highest investment interest with a Net Present Value (NPV) exceeding EUR 13 million and a

payback period of 12 years. The study utilizes RETSCREEN Expert software and Microsoft Excel for modeling energy output and financial performance. Armoo et al. (2024) explain that the pilot plant is designed to treat 50 tons of municipal solid waste (MSW) per day, converting it into energy and various fuels. Gielen et al. (2019) suggested that the demand load considered includes residential, community, and commercial sectors. The plant's configuration involves a 200-kW solar PV array, a 100-kW anaerobic digestion system, and a 100-kW pyrolysis system. This configuration results in different energy outputs and financial feasibilities for each scenario. In the electricity and fuels scenario, 810 MWh/year of electricity is expected to be produced, with 562.72 MWh/year exported to the grid (Armoo *et al.,* 2024). The electricity-only scenario shows a higher total energy output of 1373 MWh/year, primarily due to 100% biogas utilization in the anaerobic digestion system. However, Arfoa et al. (2022) showed that this scenario has the lowest financial performance with an NPV of EUR 1.65 million and a payback period of 13 years. In contrast, the fuels-only scenario shows substantial benefits with an NPV of EUR 9.88 million and an internal rate of return (IRR) of 21%. Armoo et al,. (2024) argue that the combination of fuels and electricity offers a more economically feasible option. Segura et al. (2023) confirmed that the Levelized Cost of Energy (LCOE) for the three scenarios averages 0.51 EUR/kWh. Although this is higher than the average residential End User tariff, it reflects the high costs associated with renewable energy systems, particularly in smaller capacity plants. The study highlights that larger capacity systems could reduce the LCOE and improve financial viability. In The environmental benefits of the HRES are significant. According to the authors, the pilot plant mitigates societal challenges by treating 16,750 tons of MSW annually. Simberg-Koulumies (2023) advised that production of green hydrogen through steam

methane reformation (SMR) is highlighted as a crucial component, given its high conversion efficiency of 74–85%. Additionally, the study emphasizes the importance of governmental policy instruments, such as subsidies and lower tariffs, to enhance the feasibility of renewable energy projects (Armoo *et al.,* 2024).

According to Adaramola et al. (2014), hybrid energy systems combining solar, wind, and diesel generators can provide a feasible solution for power generation in remote areas of southern Ghana. The study investigates the techno-economic viability of such a system in the context of Ghana's energy challenges, where a significant portion of the population remains without reliable electricity access. Adaramola et al,. (2014) note that, like many sub-Saharan African countries, Ghana struggles to provide widespread electricity access. In 2012, Ghana's electricity supply was primarily derived from hydro (52%) and thermal (48%) power plants, with a total installed capacity of 2280 MW. Despite these efforts, about 28% of households still lacked electricity access. The strategic goal of the Ghanaian government is to significantly increase electricity generation to meet growing demand and promote economic development. Takase, Kipkoech, & Essandoh (2021) articulated that the abundant solar energy and moderate wind resources in Ghana present an opportunity for hybrid renewable energy systems to supplement the existing grid and provide power to remote areas. The study employs the National Renewable Energy Laboratory's Hybrid Optimization Model for Electric Renewables (HOMER) software to simulate and optimize a hybrid energy system for Adafoah, a site in the Greater Accra region (Adaramola *et al.,* 2014). The system consists of an 80-kW photovoltaic (PV) array, a 100-kW wind turbine, two 50 kW diesel generators, a 60-kW converter, and 60 Surrette 4KS25P batteries. The annual daily average solar radiation at the site is 5.4 kWh/m²/day, and the annual mean wind speed is 5.11 m/s. The analysis considers

various configurations and performs sensitivity analyses on wind speed, solar radiation, and diesel prices. Adaramola et al. (2014) found that the optimal configuration for the hybrid system generated 791.1 MWh of electricity annually, with contributions of 16.04% from solar PV, 31.38% from wind, and 52.58% from diesel generators. The Levelized Cost of Electricity (LCOE) for this system was determined to be $0.281/kWh. Tamoor et al. (2022) suggested that the hybrid system is economically viable, with the renewable fraction significantly reducing dependence on diesel fuel, thereby lowering operating costs and carbon emissions. In Table 2.7, the total initial capital cost of the hybrid system was estimated at $1,163,800, with a net present cost (NPC) of $3,905,581 (Adaramola *et al.,* 2014). The economic performance indicators showed that the hybrid system is a preferable investment compared to other configurations, with an internal rate of return (IRR) ranging from 4.41% to 15.00%, depending on the comparison base. The system's payback period varied between 6.91 and 16.80 years, indicating a reasonable return on investment. According to Adaramola et al. (2014), sensitivity analyses revealed that the LCOE is significantly influenced by changes in wind speed, solar radiation, and diesel prices. For instance, at higher solar radiation levels and wind speeds, the LCOE decreases, making the system more cost-effective. Additionally, the impact of diesel price fluctuations on the LCOE underscores the importance of integrating renewable energy sources to mitigate fuel cost volatility. The study concludes that hybrid energy systems combining solar, wind, and diesel generators are feasible and economically viable for remote areas in southern Ghana (Adaramola *et al.,* 2014). Such systems can provide reliable electricity, reduce dependence on diesel fuel, and support the country's goal of expanding energy access. Thompson (2023) expressed that the findings offer valuable insights for policymakers and stakeholders in the energy

sector, highlighting the potential of hybrid systems to contribute to sustainable development in Ghana.

2.2.4.4 HES in Kenya

Katche et al. (2024) conducted a comprehensive study to evaluate the techno-economic feasibility of using solar-grid-battery hybrid energy systems for grid-connected university campuses in Kenya. The study used the administration building of Moi University as a case study, employing a PCE-360 power analyzer to collect power consumption data and a weather station to gather solar radiation and temperature data. De Doile et al. (2021) argued that the collected data were used in HOMER Pro software to simulate and optimize different hybrid system configurations. The primary objective of the study was to identify the most cost-effective and sustainable energy solution that could reduce the high operational costs associated with grid electricity and the environmental impact of diesel generators. The study considered various configurations, including solar PV/grid, solar PV/battery/grid, and battery/grid systems, to determine the optimal system (Katche *et al.,* 2024). The simulation results indicated that the optimal configuration was the solar PV/grid system without battery storage. This configuration had a levelized cost of energy (LCOE) of Kshs 8.78/kWh (USD 0.072), a net present cost (NPC) of Kshs 27,974,492 (USD 230,813), a capital expenditure (CAPEX) of KSH 26,300,000 (USD 216,997), and a simple payback period (SPBP) of 5.08 years for a 25-year lifespan (Katche *et al.,* 2024). This system showed an 83.94% reduction in the annual electricity bill of the administration building compared to the existing grid-only system, highlighting significant cost savings and environmental benefits.

Wambui, Njoka, Muguthu, and Ndwali (2023) conducted a comprehensive study to evaluate the socio-techno-economic implications of various electricity development scenarios in Kenya using the Low Emissions Analysis Platform (LEAP) combined with the Next Energy Modeling system for Optimization (NEMO). Toufik, DEKKICHE, & Denai (2022) debated that the research aimed to determine the optimal energy mix to meet increasing electricity demand while minimizing greenhouse gas (GHG) emissions and system costs. According to Wambui et al. (2023), Kenya's current energy landscape is predominantly reliant on conventional fossil fuels, which are significant contributors to GHG emissions. The authors highlight the necessity of transitioning to renewable energy resources (RERs) to achieve sustainable development and adhere to the global climate targets outlined in the Paris Agreement. Kenya's vision 2030 emphasizes enhancing and diversifying national power generation to address the challenges of unreliable and expensive energy. The study utilized LEAP with NEMO to simulate and optimize three scenarios: high penetration of RERs with energy storage systems (ESS), internalizing environmental externalities, and energy productivity scenarios. Twesigye (2022) presented that the reference scenario was based on Kenya's Least Cost Power Development Plan (LCPDP) 2017-2037. Wambui et al. (2023) found that implementing these scenarios could lead to substantial cost savings and significant reductions in CO_2 emissions. Specifically, the high RERs with ESS scenario showed potential cost savings of up to 26.1 billion USD (55%) and a reduction of 1622 thousand metric tons of CO_2 emissions. García Contreras (2019) determined that the high penetration of RERs scenario incorporated energy storage to balance the intermittent nature of renewable sources like solar and wind. The simulation results indicated that energy storage could supply up to 3% of the energy demand, thereby

enhancing grid stability and reliability. Wambui et al. (2023) assessed that geothermal energy would be the predominant source, contributing significantly to the energy mix by 2037. The study projected that geothermal would account for 58% of the total plant capacity under the high RERs scenario, followed by natural gas at 25%. Wambui et al. (2023) explained that internalizing environmental externalities, such as charging for CO_2, NO_2, and SO_2 emissions, increased the overall cost of the identified least-cost power plans. However, these costs were justified by the substantial environmental benefits, including reduced GHG emissions and improved air quality. Zieba Falama et al. (2022) illustrated that incorporating such externalities into the economic model provides a more accurate representation of the true costs of energy production and its environmental impact. In Energy productivity, defined as the ratio of economic output per unit of energy used, showed an increasing trend with existing policies but decreased when additional policy instruments aimed at energy efficiency and reducing transmission and distribution losses were considered. Wambui et al. (2023) highlighted the importance of policy instruments that drive energy efficiency in households and industrial sectors, which could lead to significant improvements in energy productivity and overall system performance. The study concluded that the alternative energy planning pathways proposed by Wambui et al. (2023) have the potential to significantly reduce system costs and GHG emissions, making them a viable option for Kenya's future energy strategy. Žigman, Tomiša, & Osman (2023) exemplified that the integration of RERs with energy storage systems not only addresses the issue of energy reliability but also aligns with global efforts to combat climate change. Voumik et al. (2023) found that policymakers and stakeholders in Kenya adopt these alternative pathways to ensure sustainable and economically viable energy development.

Žigman, Tomiša, & Osman (2023) exemplified that, the study also compared its findings with related works. For instance, Alharthi et al. (2022) conducted a techno-economic analysis of a grid-connected solar/wind hybrid system in Saudi Arabia and found it technically and economically feasible, with an LCOE of USD 0.03655. Similarly, Katche et al. (2024) studied the feasibility of hybrid energy systems for a Kenyan institutional building and concluded that the PV/grid/diesel hybrid system was optimal, with an LCOE of Kshs 7.89 and an NPC of Kshs 69,512,100 (Katche *et al.,* 2024). However, Katche et al. (2024) opted for a cleaner solution by excluding diesel generators, thereby promoting environmental sustainability. Moreover, the study emphasized the importance of using site-specific data for solar PV installations. The solar radiation data collected at Moi University indicated an average annual solar radiation of 4.93 kWh/m²/day, which is suitable for solar energy generation (Katche *et al.,* 2024). This data was critical in ensuring accurate simulation results and optimizing the system's performance. In terms of economic analysis, the solar PV/grid system's total NPC was Kshs 43,747,320, with an LCOE of Kshs 8.78/kWh. The implementation of this system would reduce the annual electricity bill by 83.94%, resulting in substantial financial savings for the university (Katche *et al.,* 2024). Additionally, the system's internal rate of return (IRR) was 19.1%, and the discounted payback period (DPBP) was 6.22 years, indicating a profitable investment. Katche et al. (2024) concluded that the solar PV/grid hybrid system without battery storage is the most optimal solution for powering the administration building of Moi University. The system significantly reduces energy costs and aligns with sustainability goals by minimizing greenhouse gas emissions. The study contributes to the broader discourse on renewable energy adoption in academic institutions, promoting the development of green campuses and supporting climate change mitigation efforts.

scourse on renewable energy adoption in academic institutions, promoting the development of green campuses and supporting climate change mitigation efforts.

Mulumba and Farzaneh (2023) conducted an in-depth study on the techno-economic viability and dynamic power simulation of a hybrid solar-wind-battery-flywheel system aimed at providing off-grid power supply in remote areas of Makueni County, Kenya. This research addresses the energy access challenges in Sub-Saharan Africa, where a significant portion of the population lacks reliable electricity (Mulumba & Farzaneh, 2023). The study proposes a hybrid energy system consisting of photovoltaic (PV) panels, wind turbines, a lithium-ion battery, and a flywheel storage system. The optimal system size was determined using a multi-objective ε-constraint mathematical programming approach, focusing on minimizing the Levelized Cost of Electricity (LCOE) and maximizing the reliability, measured by the Energy Index of Self-Reliance (EISR) (Mulumba & Farzaneh, 2023). The optimal configuration included 26 PV panels (330 W each) and 3 wind turbines (1 kW each), which together meet the annual local load requirement of 37.94 MWh with an LCOE of USD 0.519/kWh and an EISR of 0.997. The researchers utilized MATLAB-Simulink to perform a 72-hour dynamic power simulation, assessing the system's performance under various operating conditions. This simulation revealed that the proposed HRES could reliably meet the load demand in all weather conditions experienced in the study area. The hybrid energy storage system (HESS), which combines a lithium-ion battery with a flywheel, showed an annual storage capacity gain of 858 kWh, indicating significant benefits in terms of storage efficiency and system reliability (Mulumba & Farzaneh, 2023). In comparison with previous studies, Al-Shereiqi et al. (2021) and Sharma et al. (2021) focused on optimizing hybrid renewable systems to minimize costs and emissions but did not integrate dynamic simulations to assess real-

time performance. Mulumba and Farzaneh's inclusion of dynamic power simulation provides a more comprehensive evaluation of system reliability and performance, addressing the gap between theoretical optimization and practical application (Mulumba & Farzaneh, 2023).

Moreover, the study underscores the importance of hybrid storage systems in renewable energy applications (Babatunde *et al.,* 2020). Traditional single-energy storage systems often face limitations in capacity and efficiency. The hybrid approach, combining batteries with flywheels, leverages the high energy density and quick response of flywheels with the reliable energy storage of batteries. This synergy improves overall system performance and lifespan (Mulumba & Farzaneh, 2023). Shaqour et al. (2021) and Benlahbib et al. (2020) have highlighted the benefits of advanced control strategies in managing hybrid renewable energy systems. Mulumba and Farzaneh's work build on this by incorporating a perturb and observe (P&O) algorithm for maximum power point tracking (MPPT), coupled with a proportional-integral (PI) controller, enhancing the system's efficiency and stability, as seen in Table 2.4. The study's results demonstrate that the proposed HRES is highly reliable and cost-effective for remote areas, where grid access is limited. The hybrid storage system not only improves reliability but also contributes to sustainability by reducing reliance on fossil fuels. This aligns with global sustainable development goals (SDGs) and supports Kenya's energy policies aimed at expanding access to clean and reliable energy (Mulumba & Farzaneh, 2023).

Table 2.4: Globally Case Studies Hybrid System

Study	Location	System Components	Annual Energy Production	Cost of Energy (COE)	Environmental Impact
Islam et al. (2022)	Bangladesh	Solar PV, Diesel, Battery	51,467 kWh	$0.022/kWh	Significant reduction in greenhouse gas emissions
Cai et al. (2020)	Iran	Solar PV, Diesel, Battery	-	-	59.6% reduction in greenhouse gas emissions
Ali et al. (2021)	Pakistan	Solar PV, Wind, Diesel, Battery	-	-	Significant reduction in carbon emissions
Ali et al. (2020)	Bangladesh	Solar PV, Diesel, Battery	-	$0.182/kWh	307 kg/year reduction in carbon emissions
Hoseinzadeh and Garcia	Italy	Solar PV, Wind, Fuel Cells, Hydrogen Tanks	-	-	Significant reduction in reliance on fossil fuels
Nkambule et al. (2023)	South Africa	Solar PV, Wind, VRF-BESS	15,835 MWh	4.27 R/kWh	95.6% reduction in CO_2 emissions
Yimen et al. (2020)	Nigeria	Solar PV, Wind, Diesel, Battery	-	$0.25/kWh	85,401.08 kg/year reduction in CO_2 emissions
Armoo et al. (2024)	Ghana	Anaerobic Digestion, Pyrolysis, Solar PV	-	-	Production of various alternative fuels

2.3 Justification for Selecting PVsyst and HOMER for Hybrid Energy System Simulation

PVsyst and HOMER were selected as the primary simulation tools for the techno-economic assessment of the grid-solar-diesel generator battery hybrid energy system at Kenya Pipeline Company (KPC) Eldoret Terminal due to their complementary strengths and suitability for hybrid energy system modelling.

2.3.1 PVsyst's Strengths and Suitability

PVsyst is a specialized photovoltaic system design software widely recognized for its detailed and accurate solar PV performance simulations. It offers comprehensive modelling of solar irradiance data, shading analysis, component-level system design (including modules, inverters, and mounting configurations), and energy yield predictions (Ayua et al., 2024). Its strengths lie in:

- High Precision in Solar Resource Modelling: PVsyst incorporates local meteorological data, allowing for precise estimation of solar energy generation under varying weather patterns.

- Detailed Loss Analysis: It provides granular loss accounting, such as temperature effects, soiling, wiring, and inverter efficiency losses.

- Visualization Capabilities: PVsyst generates detailed performance graphs, useful for technical validation and presentation.

However, PVsyst primarily focuses on solar PV systems, with limited functionality in modelling hybrid configurations involving diesel generators or battery dispatch strategies.

2.3.2 HOMER's Strengths and Suitability

HOMER (Hybrid Optimization of Multiple Energy Resources) Pro is widely used for modelling and optimizing hybrid energy systems combining multiple generation sources, storage, and load profiles (Baidya, 2025). Its key features include:

- Hybrid System Optimization: HOMER excels in simulating complex systems integrating solar PV, batteries, diesel generators, and grid connections. It optimizes system sizing and dispatch strategies to minimize costs or emissions.

- Techno-Economic Analysis: HOMER outputs comprehensive economic metrics such as Levelized Cost of Energy (LCOE), Net Present Cost (NPC), and operating costs.

- Sensitivity and Scenario Analysis: It allows extensive scenario testing under varying input assumptions (e.g., fuel price, tariff structures).

- Load Profile Integration: HOMER accepts detailed load profiles to evaluate system reliability and performance under dynamic conditions.

Although HOMER's solar resource modelling is generally less detailed than PVsyst's, it offers broader system-level simulation capabilities essential for optimizing complete hybrid energy solutions.

2.3.3 Comparison with Other Simulation Tools

Other notable simulation tools such as SAM (System Advisor Model), RETScreen, and PVSOL offer varying strengths:

- SAM: Strong in financial modelling and utility-scale project analysis but less focused on hybrid system optimization.

- RETScreen: Provides integrated energy and financial analysis but is less specialized in detailed solar PV performance modelling.

- PVSOL: Comparable to PVsyst in PV design and visualization but with higher costs and differing user interfaces.

- TRNSYS and MATLAB/Simulink: Offer advanced system modelling but require extensive customization and programming skills, leading to longer simulation times and complexity.

Using PVsyst and HOMER together leverages their respective strengths: PVsyst offers precise solar resource assessment and PV system design, while HOMER provides robust hybrid system optimization capability including techno-economic evaluations and operational dispatch modelling. This dual-tool approach ensures that the KPC Eldoret Terminal assessment benefits from accurate solar performance data and comprehensive economic and reliability analysis for complex hybrid system configurations constrained by site-specific factors such as limited roof area, moderate irradiance, tariff structures, and the operational duty cycle of diesel generators. Below are two tables and descriptions that support the selection of PVsyst for technical design and HOMER for economic analysis of hybrid energy systems. The figures and comparisons are sourced from previous studies that benchmark simulation outputs against actual system performances.

PVsyst excels at detailed solar PV technical modelling due to:

- Accurate solar irradiance integration and shading analysis

- Precise component-level loss accounting including temperature, soiling, wiring, and inverter losses

- Annual energy yield predictions typically within ±5–8% of actual measured output

- User-friendly system design interface widely adopted internationally

Studies comparing PVsyst with PVSOL and HOMER (Dirlik et al., 2023) reveal that PVsyst's annual energy output predictions deviate by about -3.5% relative to measured data, outperforming PVSOL (+9%) and comparable with HOMER (+3.2%) in PV-specific accuracy.

HOMER was favored for its:

- Comprehensive hybrid system modelling (solar PV, battery, diesel, grid)

- Automated techno-economic output (LCOE, Net Present Cost, operating costs)

- Robust scenario and sensitivity analysis capabilities

- Accurate economic metrics with LCOE estimates within 3–10% of actuals

For example, Adeoye et al. (2024) modelled a hybrid system using HOMER, calculating an operating cost of 2.44 billion FCFA and an LCOE of 154.2 FCFA/kWh (~Kshs 37), values consistent with real-world tariff structures and cost expectations in similar African industrial projects.

Compared to RETScreen and SAM, HOMER provides more detailed dispatch and reliability analysis, which is critical for sites like KPC Eldoret with fluctuating load profiles and diesel dependency.

Table 2.5 Supporting Quantitative data from Previous Studies

Parameter	PVsyst (Dirlik et al., 2023)	HOMER (Adeoye et al., 2024)	SAM (Ayua et al., 2024)	RETScreen (Baidya, 2025)
Annual Energy Yield Error (%)	-3.5%	+3.2% (PV component)	±5–10%	±10–15%
LCOE (USD/kWh or Local Unit)	N/A	~0.37 USD/kWh (154.2 FCFA)	Moderate	Low precision
Loss Modelling Detail	Very Detailed	General hybrid losses	Moderate	Simplified
Scenario Analysis	Limited	Advanced	Basic	Basic
Hybrid Dispatch Modelling	No	Yes	Limited	Limited

Tool	Technical Strengths	Accuracy/Performance Figures	Limitations	Reference
PVsyst	Detailed solar irradiance, shading, loss breakdown, component-level design	±5–8% annual energy yield accuracy	Solar-focused; limited hybrid modelling	Zhang et al., 2022; Baidya, 2025
PVSOL	Good shading and 3D visualization	Similar accuracy to PVsyst	Costly license; less open	Baidya, 2025
SAM	Integrated financial modelling, utility project	Moderate PV modelling precision	Less detailed PV loss modelling	Ayua et al., 2024

	optimized			
RETScreen	Combined energy & financial analysis	Generalized PV modelling	Lower solar resource detail	Baidya, 2025
TRNSYS/ MATLAB	Fully customizable; multi-domain simulation	Variable, depends on user model	High skill and time required	Various

2.4 The gaps in literature

The literature covered provided a comprehensive analysis of the techno-economic assessments of hybrid energy systems, to the gaps identified are summarized in Table 2.6

Table 2.6: The Gaps in Reviewed Literature

Authors	Problem Statement	Methodology	Key Findings	Gaps Identified	Limitations	Locations	Research Institution
Islam et al. (2023)	Techno-economic analysis of a hybrid renewable energy system for a healthcare center in Bangladesh	Simulation using HOMER software	Optimal system configuration, cost of energy, and emissions reduction	Limited to a specific location and application	Limited to a single case study	Bangladesh	University of Dhaka
Cai et al. (2020)	Optimal sizing and location of a hybrid system with PV, battery, and diesel for off-grid applications	Multi-objective optimization	Optimal system configuration based on economic parameters	Focused on a single case study	Limited to off-grid applications	Global	University of California, Los Angeles
Ali et al. (2021)	Techno-economic assessment of hybrid energy systems in rural Pakistan	Simulation using HOMER software	Optimal system configuration and cost of energy	Limited to a specific region and rural applications	Limited to a single case study	Pakistan	University of Engineering and Technology, Lahore
Hoseinzadeh & Garcia (2022)	Techno-economic assessment of hybrid energy flexibility systems for island decarbonization in Italy	Simulation and optimization	Optimal system configuration and cost of energy	Focused on a single case study and island applications	Limited to island applications	Italy	University of Bologna
Nkambule et al. (2023)	Performance and techno-economic analysis of hybrid renewable energy	Simulation and optimization	Optimal system configuration and cost of	Limited to the mining industry and a specific	Limited to the mining industry	South Africa	University of the Witwatersrand

	systems for the mining industry in South Africa		energy	region			
Armoo et al. (2024)	Achieving techno-economic feasibility for hybrid renewable energy systems through the production of energy and alternative fuels	Simulation and optimization	Optimal system configuration and cost of energy	Focused on alternative fuel production and its impact on feasibility	Limited to alternative fuel production	Global	University of Science and Technology, Nigeria
Adaramola et al. (2014)	Analysis of hybrid energy systems for application in southern Ghana	Simulation using HOMER software	Optimal system configuration and cost of energy	Limited to a specific region and application	Limited to a single case study	Ghana	Kwame Nkrumah University of Science and Technology
Wambui et al. (2022a)	Scenario analysis of electricity pathways in Kenya using LEAP and OSeMOSYS	Scenario analysis and optimization	Optimal electricity development pathways	Limited to Kenya and focused on electricity pathways	Limited to electricity pathways	Kenya	University of Nairobi
Wambui et al. (2022b)	Socio-techno-economic assessment of electricity development scenarios in Kenya using LEAP and OSeMOSYS	Scenario analysis and optimization	Optimal electricity development pathways considering socio-economic factors	Limited to Kenya and focused on electricity pathways	Limited to electricity pathways	Kenya	University of Nairobi
Katche et al. (2024)	Techno-economic assessment of solar–grid–battery hybrid energy systems for grid-connected university campuses in	Simulation and optimization	Optimal system configuration and cost of energy	Limited to university campuses in Kenya	Limited to university campuses	Kenya	University of Nairobi

	Kenya						
Mulumba & Farzaneh (2023)	Techno-economic analysis and dynamic power simulation of a hybrid solar-wind-battery-flywheel system for off-grid power supply in remote areas in Kenya	Simulation and optimization	Optimal system configuration and cost of energy	Limited to remote areas in Kenya and includes flywheel storage	Limited to remote areas	Kenya	University of Nairobi
Elegeonye et al. (2023)	Techno-economic optimization of mini-grid systems in Nigeria: a case study of a PV–battery–Diesel hybrid system	Simulation and optimization	Optimal system configuration and cost of energy	Limited to a specific case study and mini-grid applications	Limited to mini-grid applications	Nigeria	University of Science and Technology, Nigeria
Oladigbolu et al. (2020)	Optimal design of a hybrid PV solar/micro-hydro/diesel/battery energy system for a remote rural village under tropical climate conditions	Simulation and optimization	Optimal system configuration and cost of energy	Limited to a specific case study and rural applications	Limited to rural applications	Global	University of Lagos
Abbaspour et al. (2023)	Techno-economic analysis of PV–wind–diesel–battery hybrid power systems for industrial towns under different climates in Spain	Simulation and optimization	Optimal system configuration and cost of energy	Limited to industrial towns in Spain and considers different climates	Limited to industrial towns	Spain	University of Zaragoza
Aeggegn et al. (2023)	Feasibility and techno-economic analysis of PV-battery priority grid tie system with diesel	Simulation and optimization	Optimal system configuration and cost of	Limited to a specific case study and grid-tied	Limited to grid-tied applications	Global	University of Addis Ababa

	resilience: A case study		energy	applications			
Channi (2023)	Optimal designing of PV-diesel generator-based system using HOMER software	Simulation using HOMER software	Optimal system configuration and cost of energy	Limited to a PV-diesel generator system	Limited to a single case study	Global	Guru Nanak Dev Engineering College
Aziz et al. (2022)	Techno-economic and environmental evaluation of PV/diesel/battery hybrid energy system using improved dispatch strategy	Simulation and optimization	Optimal system configuration, cost of energy, and environmental impact	Focused on a specific dispatch strategy and its impact on system performance	Limited to a specific dispatch strategy	Global	University of Malaya
Yimen et al. (2020)	Optimal sizing and techno-economic analysis of a PV/wind/battery/diesel hybrid system in Fanisau, Nigeria	Simulation and optimization	Optimal system configuration and cost of energy	Limited to a specific case study and location	Limited to a single case study	Nigeria	University of Science and Technology, Nigeria

2.5 Shortcomings of Previous Studies and Relevance to Research Objectives

After reviewing similar and previous studies on hybrid energy systems (HES), particularly those relevant to Kenya and its environment, several shortcomings emerge that are crucial to address in the context of the objectives of this research on KPC Eldoret Terminal. While these studies provide valuable insights into the potential of HES in mitigating energy challenges, many fall short in several critical areas, particularly in tailoring solutions to Kenya's specific climatic, operational, and economic conditions.

One major shortcoming in many of these studies is the lack of comprehensive data on local energy consumption patterns and their implications for hybrid energy systems. In particular, while some studies analyze energy consumption, they often fail to provide detailed insights into the specific energy demand profiles of industrial operations such as KPC's Eldoret Terminal. For instance, they tend to generalize energy consumption patterns rather than account for the fluctuating and dynamic energy demands seen in operations such as pipeline transportation and oil storage. This lack of specificity can lead to suboptimal design of hybrid systems that do not fully cater to the actual energy needs. Addressing this gap, one of the specific objectives of this research is to analyze the current energy consumption patterns at KPC's Eldoret Terminal. By doing so, the study will design a hybrid energy system that is more precisely aligned with the terminal's operational energy requirements.

Another significant shortcoming is the limited focus on optimizing the hybrid energy system configurations for the specific environmental conditions prevalent in Kenya. Studies like those by Wambui et al. (2023) provide important insights into hybrid energy solutions, but they often fail to consider Kenya's unique climatic conditions, such as variability in solar irradiance and the challenges posed by grid unreliability in

certain regions. This gap is particularly evident in the lack of detailed analyses that evaluate how key environmental variables like fluctuations in solar radiation and prolonged grid outages affect the performance of hybrid energy systems. In contrast, this research aims to bridge this gap by simulating the grid-solar PV-battery storage-diesel generator hybrid energy system using PVsyst and HOMER software, which will incorporate local climatic and operational variables. This approach will provide a more accurate and practical solution, tailored to the specific energy dynamics of the Eldoret Terminal.

Most previous studies, including those focusing on hybrid energy systems in Kenya, often emphasize environmental benefits like reduced greenhouse gas (GHG) emissions but do not provide sufficient economic analysis regarding the long-term cost benefits. The operational cost savings associated with reducing reliance on diesel generators are frequently mentioned but rarely quantified in a detailed manner. This is a critical gap, given the high fuel consumption rates at KPC's Eldoret Terminal, as highlighted by the peak consumption of 50,000 liters per month due to power outages. This research specifically aims to address this shortcoming by conducting a detailed techno-economic analysis of the hybrid energy system, focusing on quantifying both the cost savings and the return on investment in terms of reduced diesel consumption, maintenance costs, and fuel expenditure.

In conclusion, while previous studies provide valuable groundwork for understanding hybrid energy systems, their lack of specificity regarding local energy demands, environmental conditions, and economic analysis limits their applicability to Kenya's industrial sectors. This research will fill these gaps by focusing on detailed energy consumption analysis, tailored system design, and a comprehensive techno-economic evaluation, providing a practical and sustainable solution for KPC's Eldoret Terminal.

CHAPTER THREE

METHODOLOGY

This chapter provides the methodology which was used in the achievement of the objectives set. In this section, the study area is described with their estimated energy demands, sources and means of data collection are indicated. The HES design which incorporates a Solar PV and battery storage was designed and validated in PVsyst. The establishment of optimal HES configurations was done using the HOMER Pro software through simulation and optimization software.

3.1 Case Study Site Selection

The KPC Eldoret is located at coordinates 0.5143° N, 35.2698° E, receiving favorable solar insolation year-round, with an average solar radiation of 4-6 kWh/m²/day (5759 Wh/m² annually), making it ideal for solar energy projects (Oloo, 2022). Two main energy scenarios have been assessed for KPC Eldoret:

- Enhancing energy resilience by installing solar PV systems on unused rooftops, which would reduce grid reliance and improve reliability despite the initial investment and technical expertise required; and

- Integrating hybrid energy systems that combine renewable energy with existing grid and diesel generators, thus minimizing grid power dependency and diesel use, lowering operational costs, and enhancing eco-efficiency, though requiring detailed techno-economic analysis for optimal design.

According to Oloo (2022), with an average daylight duration of approximately 12 hours and 3 minutes, an altitude angle of -19.11°, and an azimuth angle of 109.42°, KPC Eldoret's geographical and solar conditions support the effective implementation of solar PV system-based energy systems. The flowchart for hybrid energy system is presented in the Figure 3.1.
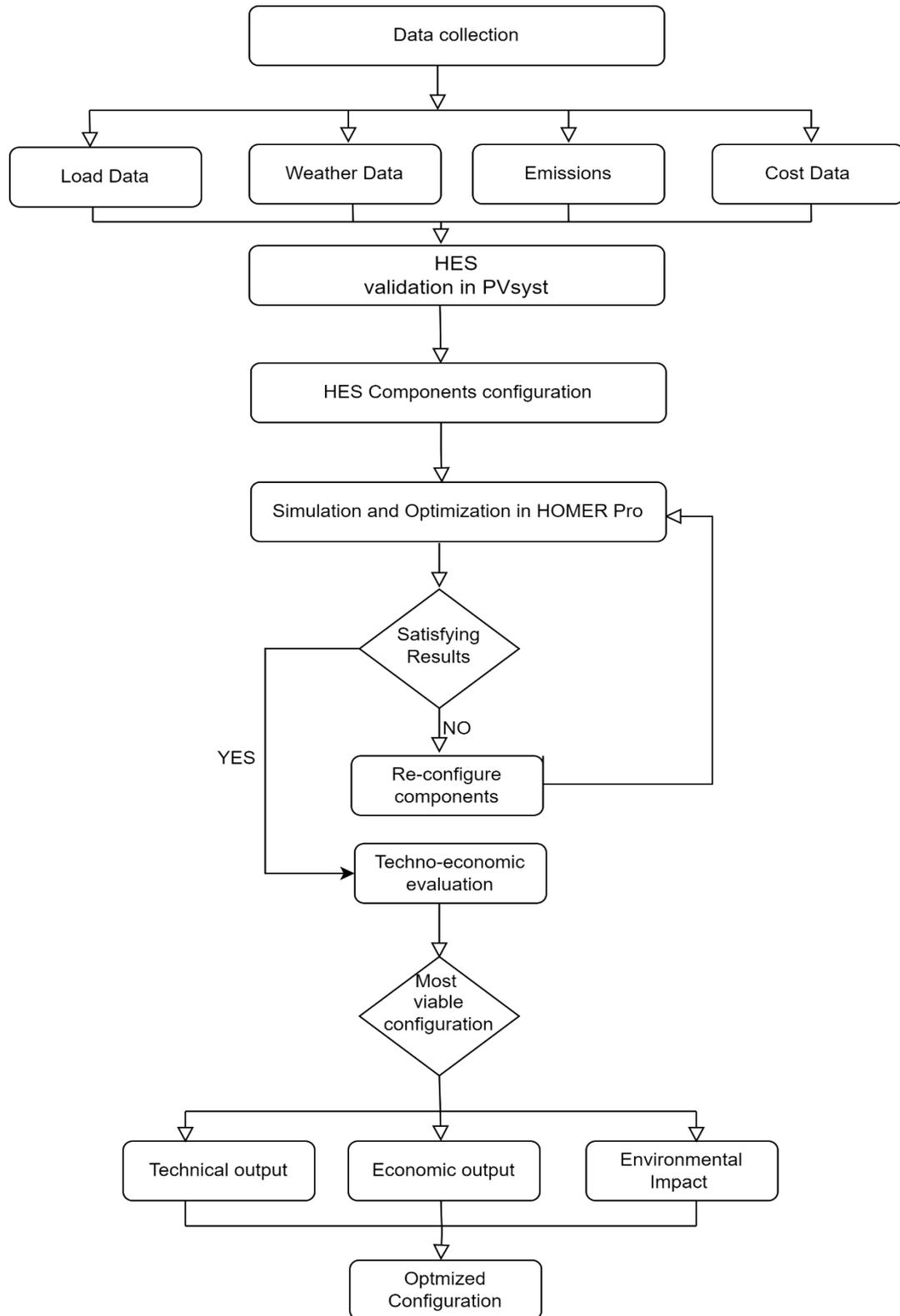
Figure 3.1: Flowchart for hybrid energy system

3.2 Data collection for existing hybrid energy system

3.2.1 Energy data for Existing Setup of HES

To gather information on the daily load demand, peak load, and energy consumption for KPC, operation and maintenance records were provided for review (*see Appendix 1*). Further data collection was carried out through data loggers (Figure 3.2), to gather information supporting the data obtained from documents and records (*Appendix 1*). The collected data include details on electricity bills, generator running hours, litres of fuel consumed, and power outage hours from the grid (Mofijur et al., 2019; Odou, Bhandari, & Adamou, 2020; Gielen et al., 2019).

3.2.2 Roof-top Area determination

The procedure involved the use of a laser distance measuring tool to obtain lengths and widths of the roof cover of the KPC buildings in order to determine the roof area.

3.2.3 Observational Study for the Existing Setup

A typical load profile was captured after setting up the datalogger at KPC switch-room (Figure 3.2) and were documented using observational methods and recoding of the data logger to supplement the gathered information (*Appendix 1*).

Figure 3.2: The Observation Setup for Data Logger at KPC Switch room

The building design and orientation was assessed to estimate optimal solar capture potential and shading possibilities.

3.3 Estimating Energy Consumption at KPC

Upon capturing data from KPC, the averages of energy usage were determined and calculated. The generator running hours, consumption of fuels and the estimated emissions for the diesel generator and grid were recorded as Thompson (2023) did it. Billing documents were also captured and compared with the recordings in the data loggers to determine the load at KPC. Ganesha & Aithal (2022) stated that the hourly data was consistently captured for 24 hours each day for 30 days, and averages were computed. The peak load and minimum load patterns were also determined.

3.4 Design of Hybrid Energy System with Renewable Technologies

The methodology for the hybrid energy system at KPC involved an integrative approach, utilizing photovoltaic (PV) modules with battery storage, existing grid power from Kenya Power (KP), and diesel generators. This section described the configurations and interconnections designed to optimize energy use and ensure reliability in power supply.

3.4.1 Design of the Grid-Connected PV System for KPC

The grid-connected PV system procedure included the installation of solar panels to harness solar energy effectively. This setup was chosen as the primary source of power, with an emphasis on maximizing the utilization of renewable energy. The system incorporated battery storage for peak power production saving/storage to ensure energy availability during periods such as during cloudy weather conditions, low sunlight hours and at night. The strategic placement and capacity of these

batteries were determined based on typical solar irradiance data and energy consumption patterns at KPC. The method took into account the available area either on land or rooftop and determined the useful region void of shading. The solar PV modules distributed over the area considering all the optimization parameters.

3.4.1.1 Estimation of Available/Useful Area

The estimation of available/useful area for the solar PV system was essentially done, particularly for roof-top installations and ground space, taking into consideration shading impacts using equation 3.1.

$$Area, A_{useful} = L * W$$ …………………………………………….. (3.1)

Where;

L (m) and W (m) represent, respectively, the length and breadth of the shade-free area. The Terminal has 9 shade-free roof sections considered, and the dimensions of these roof sections were to be considered for the solar PV installation. Using the formula, laser distance measuring was used to get the dimensions of building structures.

3.4.1.2 Determining the Area of Selected PV Module

The area was determined by using the dimensions provided by the PV Module manufacturer specifications using equation 3.1. Those with other shapes had its area evaluate using laser distance measuring. The roof area was rectangular in shape and the module has the length and width dimensions.

3.4.1.3 Calculating Number of PV Modules

The number of PV panels was calculated for the system by dividing the available area by the area of the selected PV module, as given Equation 3.2.

$$Nmod = \frac{Available\ (or\ useful\ area)}{module\ area} = \frac{A_{useful}}{A_M}$$ ……………………………………….. (3.2)

3.4.1.4 Accounting for Inefficiencies

Consideration of performance degradation over time which was multiplied to the solar array size by efficiency factor for example 1.135 (113.5%) to account for inefficiencies.

Power Offset

A Consideration of either offsetting 100% or partially the company's energy needs with solar PV produced, was to be done using Equation 3.3. this was provided to work depending on budget available.

$$\%\ offset = \frac{Total\ daily\ energy\ consumption}{PV\ system\ daily\ power\ production} * 100$$ ……………… …………….. (3.3)

3.1.4.5 Solar PV system energy output formula

The energy output of a **solar PV system** can be estimated using the following formula:

$$E = A\ x\ r\ H\ x\ PR$$ ………………………………………………….(3.4)

Where:

E = Energy output of the solar PV system (kWh).

A = Area of the solar panels (m²).

r = Efficiency of the solar panels which is typically between 15% to 25%, written as a decimal.

H = Solar irradiance which is the solar energy received per unit area on the panels (kWh/m²/day or per specific time period).

PR = Performance ratio which is a measure of system losses due to factors like temperature, inverter efficiency, shading, dirt on panels, etc., typically between 0.7 and 0.9).

3.4.2 Assessment of Diesel Generator System at KPC

The existing diesel generator system, 500 kVA, 440kW, was incorporated into the hybrid energy model as a contingency measure. Making reference to the work by Thompson (2023), The methodology here focused on ensuring that the diesel generators would automatically activate during shortcomings and failures in both the PV-battery system and the grid supply, respectively. The design was critical for addressing extended periods of grid outages common in the region. Parameters for generator activation and fuel consumption and running hours data were collected.

3.4.2 Hybrid Inverter Sizing

The Hybrid inverter was sized with an input rating ensuring it could handle the peak load, surge power, total solar panel output, matching the voltage of PV array and batteries as well as generator and grid input including a safety margin of 25-30% larger than total load, as seen in Equation 3.5.

$$Inverter\ size = 1.25 * Total\ Watt\ of\ load$$
………………………………. (3.5)

The equation 3.5 provides the Peak load which also includes the surge power at the facility.

3.4.3 Battery Sizing

The sizing of batteries storage capacity for power from the Solar PV system involved determining the required batteries capacity to meet the energy need, considering factors like daily energy consumption, depth of discharge (DoD), days of autonomy,

and system voltage. The battery bank system was designed to meet the energy requirements of the terminal. Below is the step-by-step guide that was used to calculate the required battery capacity. The sizing was just to store the solar PV energy output only or to meet the specific energy requirement of the terminal need for baseload of 50 kW for 20hrs.

3.4.3.1 Steps used to Size the Battery Storage System

a) Calculated the total daily energy requirement in watt-hours (Wh).

b) Determined the Days of Autonomy (DoA) the days battery system was to supply power without any input from the solar panels (e.g. during the night and cloudy days).

c) The depth of discharge (DoD), the percentage of the battery's capacity that was to be used without damaging the battery. Picked a common DoD for deep-cycle batteries of 80%.

d) Decided on the system voltage of 48V for higher voltages used in the terminal to help improve efficiency. The decision to use a 48V system voltage in the solar PV system was primarily made to enhance efficiency and reliability, especially for systems with higher power requirements. The higher voltage systems, such as 48V, reduced energy loss over the cabling, allowing for longer cable runs and smaller wire sizes. This was more cost-effective and efficient, particularly in larger installations or those with components spread over greater distances, thus minimizing losses and improving overall system performance.

e) components spread over greater distances, thus minimizing losses and improving overall system performance.

3.4.3.2 Calculating for Required Battery Capacity

The Equation 3.6 was applied to determine the total battery capacity required.

$$Battery\ Capacity\ (Ah) = \frac{Total\ daily\ energy\ consumption\ x\ DoA}{Battery\ Efficiency \times DOD \times battery\ voltage} \quad \dots\dots\dots\dots (3.6)$$

Where;

DoA = Days of Autonomy (days),

DOD = Depth of Discharge (90%),

3.5 Techno-Economic Assessment Simulation

The study utilized established procedures to compute various parameters, validating them through simulation using PVsyst software, which required input such as solar radiation intensity and panel orientation, *see Appendix 4*. Subsequently, system design and simulation were done using HOMER software, involving gathering essential data such as solar irradiance from NASA resources in the tool, configuring grid models with real electricity prices, determining optimal battery size, integrating converters, and incorporating details about existing diesel generators (Khalil et al., 2021; Ur Rashid et al., 2022; Yasin & Alsayed, 2020).

The various configurations and simulations were conducted within HOMER, and results were analyzed to assess feasibility based on comparative assessments of energy produced, Renewable Fraction, Net Present Value, Levelized Cost of Energy and emissions against existing electricity expenses and emission.

PVsyst Software:

    i. Choosing the site location.

    ii. Employing findings from procedure for parameter calculation.

    iii. Providing the solar radiation data from NASA resources in the tool database.

    iv. Providing the available area.

    v. Choosing the PV module.

    vi. Choosing the inverter type.

    vii. Simulating data for validation.

HOMER Software Tool:

    i. Choosing the site location

    ii. Collecting essential NASA data from the tool database for PV system design.

    iii. Configuring Solar PV model system as calculated.

    iv. Configuring grid model with actual electricity prices.

    v. Determining optimal battery size to support load and reduce diesel generator operational time.

    vi. Integrating converter for DC/AC loads.

    vii. Incorporating existing diesel generator information.

viii. Running the simulations.

ix. Analyzing simulation results and comparing LCOE and emissions with current electricity expenses and emission data for feasibility assessment.

3.5.1 Technical Characteristics of HES system

3.5.1.1 HES validation in PVsyst

PVsyst was used to validate the Solar PV, battery storage design and parameters for the included Renewable and storage technologies to reliably supply the load demand for the terminal. The validation process using PVsyst involved inputting solar irradiation, load demand, and weather data specific to the terminal (Kumar, Rajoria, Sharma, & Suhag, 2021). The system was then configured with the designed PV modules, battery storage, and inverters. Simulations were run to model energy production and storage performance under various conditions. The results were compared to the terminal's load demand to ensure reliable energy supply. Finally, any necessary adjustments were made, and the simulations were rerun to optimize the system's performance.

3.5.1.2 Energy Produced in Homer Simulation

In the context of evaluating the performance of a Hybrid Energy System (HES), determining the total energy output from different power sources was done for accurate system assessment. Upon simulating these different energy contributions over the course of a year, it was possible to analyze the overall total energy supply dynamics while identifying the optimal balance between renewable and non-renewable energy sources for reliable supply.

There was need to adopt calculation in order to determine the energy produced upon Homer simulations. Equation 3.7 shows total energy each source in the HES produced for the year.

Energy Total (kWh/year) =E $_{solar}$ +E $_{generator}$ + E $_{grid}$ ……… (3.7)

The formula aggregated the energy output from the solar photovoltaic (PV) system (E$_{solar}$), diesel generators (E$_{generator}$), and the electricity supplied from the grid (E$_{grid}$).

3.5.1.3 Renewable Fraction

The percentage of energy demand met by renewable sources is referred to as the renewable fraction. This was done to illustrate that the HES was sustainable and reduced carbon emissions. From Equation 3.8, the greater reliance on clean energy signified a higher percentage of renewables.

$$RF = \frac{E_{renewable}}{E_{demand}} \times 100$$ .... (3.8)

Where:

E$_{renewable}$ = Total energy produced from renewable sources (solar, wind, etc.).

E$_{demand}$ = Total energy demand for the system (kWh/year).

3.5.2 Economics of HES system

To determine the return on investments the system cost, cost of electricity, the yearly energy usage as well as the tax and incentives were established.

3.5.2.1 Net Present Cost (NPC)

From equation 3.9, acceptance of the project was only if NPC was positive as well as for competing projects, with higher NPC of the project.

$$\text{NPC} = \frac{NC_{ft}}{(1+i)^t} = -C_O \quad \frac{NC_{ft}}{(1+i)t} \quad \text{………………………………….… (3.9)}$$

Where;

NC_{ft} = The net cashflow at year t,

i = Interest rate number of compounding period

n=Project economic life

Co = The initial investment cost

3.5.2.2 Internal Rate of Return (IRR)

From equation 3.10, the higher the IRR, the more desirable the project.

$$\text{NPC} = -C_O + \frac{NC_{ft}}{(1+\text{IRR})^t} = 0 \quad \text{…………………………………… (3.10)}$$

3.5.2.3 Payback Period

From equation 3.11 a project with lower value was desired for both discounted payback period and simple payback periods.

$$Payback\ period = \frac{Cost\ of\ project\ (or\ Investement\ cost)}{Annual\ net\ cash\ flow} \quad \text{………………………… (3.11)}$$

3.5.2.4 Levelized Cost of Energy (LCOE)

Based on equation 3.12, the minimum cost at which produced electricity was to be sold in order to achieve break-even over the given lifetime of the project was strived to be achieved. It was given by;

$$LCOE = \frac{Life\ cycle\ cost}{Lifetime\ energy\ production\ (kWh)}\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\ (3.12)$$

3.5.3 Emissions assessment

First, the amount of fuel used by the diesel generator was determined. According to Hao et al. (2023), the number of litres of fuel consumed was multiplied by the emission factor to find the total CO_2 emissions. For diesel generators, the emission factor typically ranged around 2.68 kg of CO_2 per liter of fuel burned (Hao et al., 2023). This provided an estimate of the amount of CO_2 emitted by the diesel generator over the given period.

$$Amount\ of\ CO_2 = 2.68\ kg\ of\ CO_2 * Amount\ of\ fuel\ (litres)\ \dots(3.13)$$

For grid emission energy consumed was multiplied with the factor 1.94 to get total annual emissions (Hao et al., 2023).

$$Amount\ of\ CO_2 = 1.94\ of\ CO_2 * kWh\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(3.14)$$

CHAPTER FOUR

RESULTS AND DISCUSSIONS

This chapter presents the results and discussions of the findings of total power consumption, HES simulation design configurations, and the results for Technical, economic and emissions analysis of various HES configurations.

4.1 Power Consumption

Figure 4.1 presented the power consumed by KPC Eldoret in the year 2023 in kWh. According to the profile, it was found that peak month was in August. This month had the largest fuel consumption, which was attributed to seasonal trends in Kenyan fuel demand. These patterns were connected to events like holiday seasons, increased travel, or tourism-related activities that demand more fuel for energy generation and transportation (Mofijur et al., 2019; Odou, Bhandari, & Adamou, 2020; Gielen et al., 2019). The operating load of the pipeline grew due to the increased in demand, requiring more energy consumption to achieve higher dispatch rates. These findings followed fuel demand market reports where peak was August (*Appendix I*).
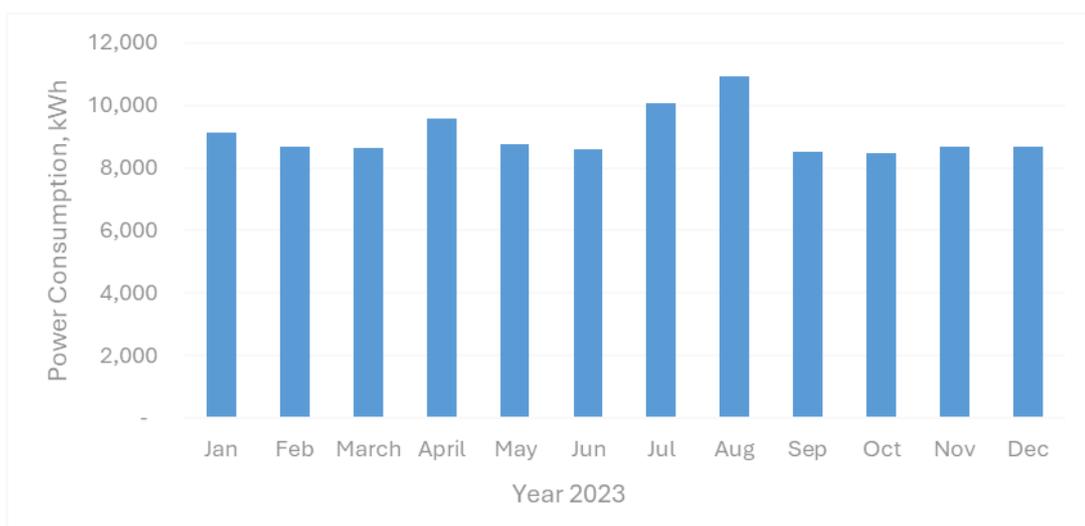
Figure 4.1: Eldoret Terminal Power Consumption 2023

Figure 4.2 presented the power consumed by KPC Eldoret in terms of cost in Kenya shilling in the year 2023.
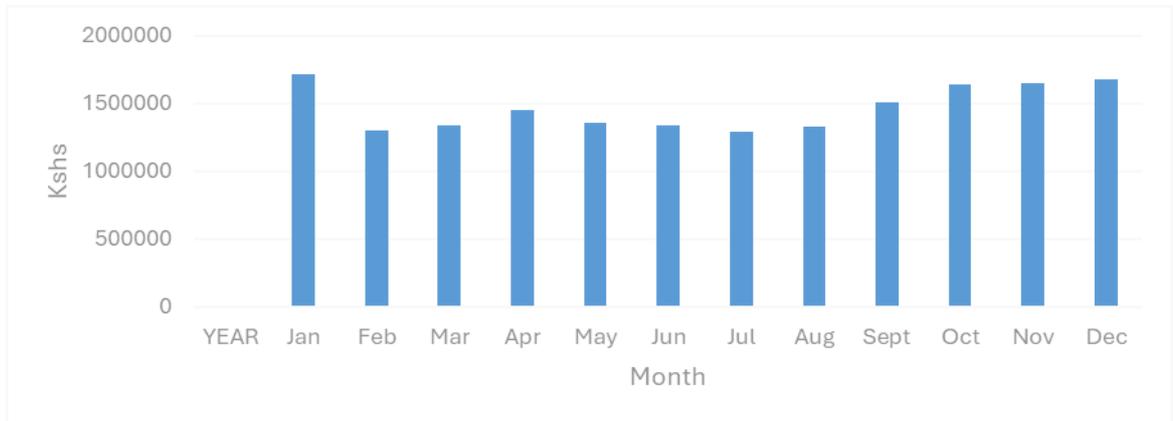
Figure 4.2: KPC Eldoret Cost of power,2023

It was seen that the annual power and cost for grid was 108,732 kWh and Kshs 17,610,172 respectively was as shown in the Figure 4.3.

It was noted that the generator was used as backup power during the outages. The energy produced by the generator with the months of August, November and December experiencing longest power outages due to grid system faults hence increased generator usage (Nation, 2023).
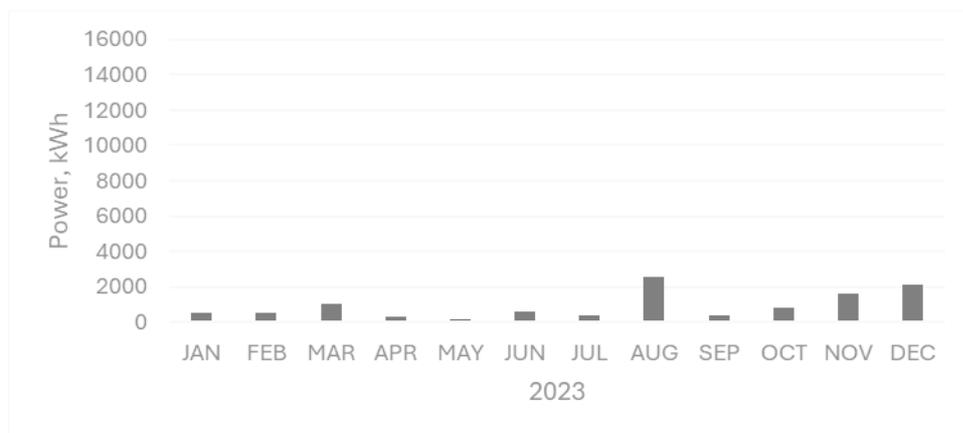
Figure 4.3: Generator Energy Production 2023

4.2 Total Energy Consumption in 2023
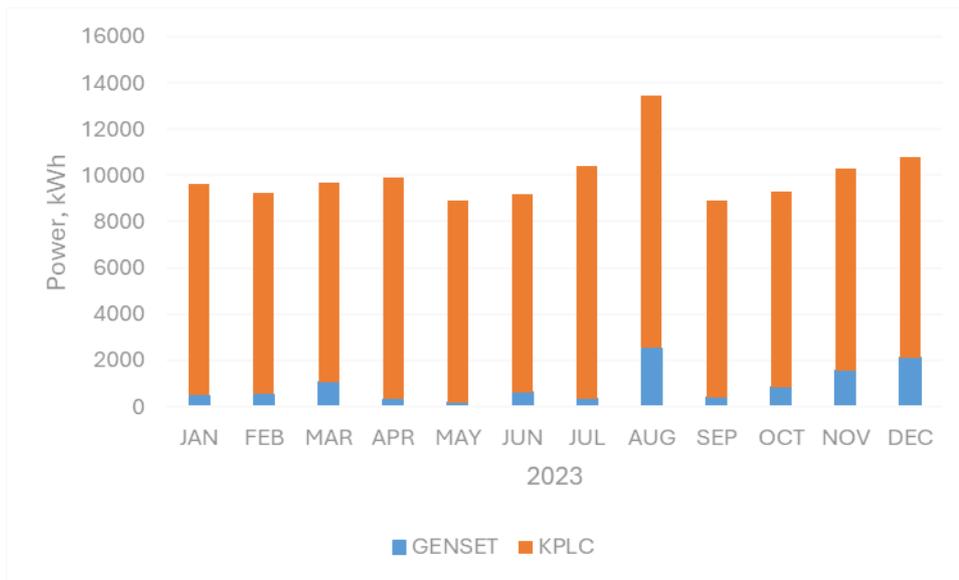
Figure 4.4: Total Energy Consumption

Figure 4.5 presented the combined power consumption for existing HES that entailed grid and generator systems as per the year 2023 December. The peak consumption was in the month of August 2023 (*appendix II*). Grid power dominated Power Consumption in every month, the grid power provided most required energy, with August standing out with the highest overall power consumption at 14,000 kWh, indicating a potential increase in operations or unexpected grid outages necessitating increased generator use. Figure 4.5 illustrated the monthly power generation from the generator and Kenya Power in 2023 where Kenya Power consistently provided most of the power, with contributions ranging from 8,000 to 14,000 kWh, while the Generator supplied a smaller but stable amount, between 1,000 and 2,500 kWh per month.

Generator usage was relatively small throughout the year, except for notable increases in August, November, and December, possibly due to grid instability or outages, as

grid supply was supplemented by the generator. The low generator usage in the Middle of the Year in June and July could indicate stable grid performance in those months, or lower energy demand.

August showed a significant spike in both Kenya Power and generator power, suggesting either high operational demand or more reliance on backup generator power, potentially due to frequent outages or maintenance on the grid. Spikes in generator usage suggested an event that heavily impacted grid availability, such as extended grid outages or maintenance, as the reliance on the generator sharply increases in that month (*appendix I*). The period between February and May showed consistent and balanced power usage with minimal reliance on the generator, indicating grid reliability during these months. Eldoret terminal in 2023 relied primarily on grid power, with periodic increases in generator usage, particularly during August, November, and December, due to grid reliability issues or higher operational demands during these months.

January: Overflow of festivities and back to school which maintained a high fuel demand.

February – April: The demand for petroleum products remained consistent throughout the period, with the peak consumption occurring in March 2023,where March recorded the highest demand for diesel for land preparation activities.

May: Local market demand of fuel went down due to the introduction of government to government (G2G) framework which was still under observation hence a low power consumption.

June - July: A steady increase in the months was experienced after fully embracing government to government (G2G) framework which was launched in April.

August: The was a spike in the fuel demand for the local market due to holiday season and expected price hike in the coming month of September.

September: Reduction of domestic fuel demand due to price hike.

October – November: A gradual increase in fuel demand was experienced during the harvesting time in the region.

December: This time fuel demand had a steady upward trend due to festivities and back to school preparations.

4.2.1 Typical Daily Load Profile at KPC

As presented the month of August was picked for daily data collection as seen in Figure 4.4 *(Total Energy Consumption)* had the highest consumption which gave a peak load and maximum demand for simulation results. The month is further analyzed based on hourly load demand as shown in Figure 4.5.

Appendix II on Daily load data captured and averaged the typical daily load data for KPC based on the readings of data logger, presented in hourly entries with the hour of the day and the corresponding load in kilowatts (kW). The data highlighted the load distribution across 24 hours, providing a clear view of energy consumption patterns throughout the day.

The graph in Figure 4.5 showed the daily average load for KPC, with clear peaks and troughs in load demand. The peak load, reaching 296.03 kW, occurred between 1000hrs and 1200hrs, indicating the hours of highest demand, with a deep in consumption during lunch hours. In agreement with Mofijur et al. (2019), Odou, Bhandari, and Adamou (2020), and Gielen et al. (2019), the average load throughout the day was approximately 179.25kW, highlighting the consistency in load

requirements despite fluctuations. The lowest load was recorded at 0000hrs, with a value of 32.060 kW, marking the least demanding hour, with a base load of average 0kW. This graphical representation helped in identifying the periods of high and low demand, useful for optimizing energy distribution and management.
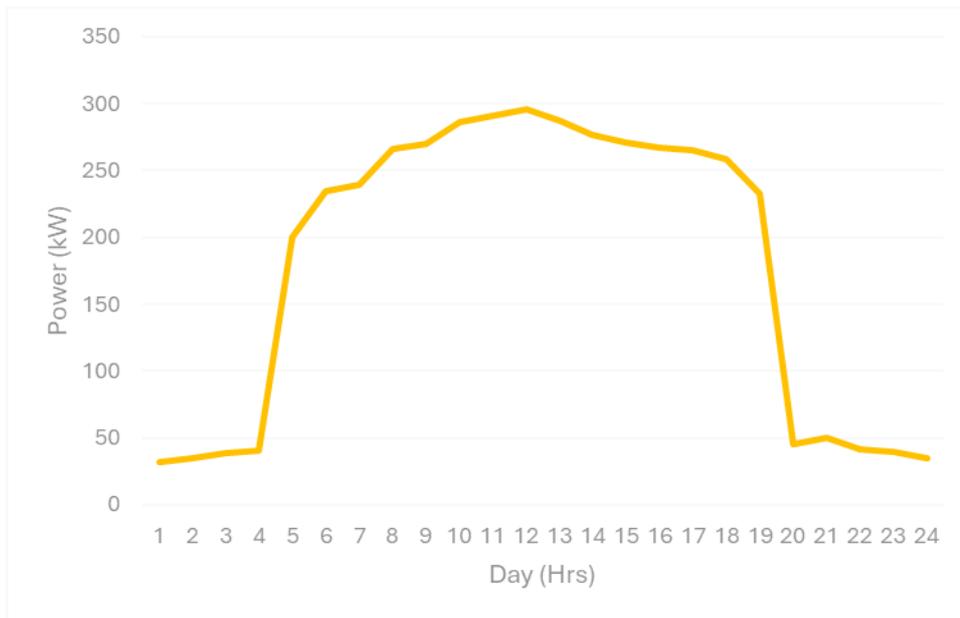
Figure 4.5: A typical Daily Load Profile of KPC

The baseline metrics of energy consumption and load characteristics for KPC showed that the average daily energy consumption was 4,302.01 kWh/d, the average power demand was 179.25kW, and the peak power demand ranged from 170.910 kW to 296.03 kW. From figure 4.5, between 4 AM and 5 AM, there was the onset of pumping operations, which increased the electrical load. The activities intensified, reaching peak levels at 1 PM and 3 PM, and then begun to decline. The baseload occurred between 9 PM and 4 AM.

4.3 Results of Design and Simulation of Hybrid Energy System Using PVsyst and HOMER Software

This section describes the design process and simulation outcomes for a proposed hybrid energy system, utilizing both PVsyst and HOMER software to ensure optimal configuration and efficiency (Khalil et al., 2021).

4.3.1 Result of Estimation of Available/Useful Area

Using equation 3.1, the available area was estimated at 2457 m² with area required for the installation calculated to be 1497.6 m² hence sufficient for installation. This analysis confirmed that there was sufficient space for the solar PV system

Table 4.1: Available Area

No.	Name of Building under consideration	Roof Area (M^2)	Roof tilt angle (˚)
1.	West pipe plaza block A	260	15
2.	West pipe plaza block B	330	15
3.	Mechanical Workshop	225	12
4.	Fire Tender Shed	154	12
5.	Motor vehicle Workshop	220	15
6.	Shipper's building	600	15
7.	Shippers Annex	480	15
8.	Fire shed	120	12
9.	QC Laboratory	68	15
	Total Area	**2457**	

4.3.2 Number of Modules

After a comparison was made as seen in table 4.2, a 700w module was picked for it covered a smaller area.

Table 4.2: Solar panel Comparison Table

Panel Wattage	Panels Needed for 335.99kW	Area per Panel (m²)	Estimate Area for 335.99kW System (m²)
300W	1120	1.8	2016
400W	840	2.1	1764
500W	674	2.6	1752.4
600W	560	3	1680
700W	480	3.12	1497.6

The selected PV module was, Jinko -JKM 700w of dimension 2400x1303x35 mm which sizing complied with other researchers such as Abo-Khalil, Sayed, Radwan, & El-Sharkawy (2023). Using equation 3.2 the total available area was 2457m² divide by the module area of 3.12 m² and the approximate maximum number of modules the area would hold was 785, indicating that there was sufficient available space for the solar panels.

4.3.3 Total Daily Energy output

Provided relevant discussions before diving to the results and discussions. The solar PV system energy output was given using equation 3.4 where power was 336,000 kW, with energy output of 4302.01kWh/d after provisioning areas for operation and maintenance. The size requirement for KPC in Eldoret was a peak load of 296.03kW. Accounting for efficiency, the design peak load was 335.99 kW, utilizing location-based sun hours with an average of 5.77 hours per day. The PV system having an estimated solar array size of 335.99kW. Each solar panel covered an area of 3.1272 m² and had a power output of 700 W, necessitating a total of 480 panels after catering for inefficiencies.

4.3.4 Selection of suitable PV module based on PVsyst simulations

This section details the process and results of selecting the optimal photovoltaic (PV) module based on various performance simulations using PVsyst software.

4.3.4.1 Operating Parameters

Table 4.3 outlined the operating parameters of the solar panel. The operational temperature range of -40°C to +85°C indicated the environmental conditions within which the panel could function. The power output tolerance of 0~3% showed the acceptable deviation in power output (Kumar, Rajoria, Sharma, & Suhag, 2021). The maximum system voltage of DC1500V was the highest voltage the panel could handle. The maximum series fuse rating of 35A indicated the highest current the panel could safely conduct. NOCT (Nominal Operating Cell Temperature) was 45°C, indicating the temperature of the solar cells when operating under standard conditions as was the case in findings by (Ur Rashid *et al.,* 2022). The fire rating of Class A denoted the highest level of fire resistance.

Table 4.3: Operating Parameters

Attribute	Value
Operational Temperature	-40°C~+85°C
Power Output Tolerance	0~3%
Maximum System Voltage	DC1500V
Maximum Series Fuse Rating	35A
Bifaciality	90±5%
NOCT	45°C
Fire Rating	Class A

4.3.4.2 Mechanical Loading

Table 4.4 provided details on the mechanical loading of the solar panel. The front side maximum static loading of 5400Pa and the rear side maximum static loading of 2400Pa indicated the maximum pressure the panel could withstand from the front and back, respectively (Bhandari, & Adamou, 2020; Gielen et al., 2019). The hailstone test showed that the panel could endure the impact of 25mm hailstones traveling at 23 meters per second, demonstrating its durability against severe weather conditions.

Table 4.4: Mechanical Loading

Attribute	Value
Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Hailstone Test	25mm Hailstone at the speed of 23m/s

4.3.4.3 Temperature Ratings (STC)

Table 4.5 showed how temperature changes affected the solar panel's performance. The temperature coefficient of I_{sc} (+0.047%/°C) indicated that the short circuit current increased slightly with rising temperatures. The temperature coefficient of V_{oc} (-0.220%/°C) and Pmax (-0.240%/°C) indicated that both open circuit voltage and maximum power output decreased as the temperature increased, which was typical for photovoltaic cells as found by Khalil *et al.,* (2021).

Table 4.5: Temperature Ratings

Attribute	Value
Temperature Coefficient of Isc	+0.047%/°C
Temperature Coefficient of Voc	-0.220%/°C
Temperature Coefficient of Pmax	-0.240%/°C

4.3.4.4 Electrical Characteristics of Module at STC

The electrical characteristics of various solar panel models under Standard Test Conditions (STC) were deduced from the choice of the model. From Table 4.6 , each model's maximum power output (Pmax) ranged from 690W to 700W. The open circuit voltage (V_{oc}) and short circuit current (I_{sc}) indicated the panel's voltage and current when not connected to a load. Voltage at maximum power (V_{mp}) and current at maximum power (I_{mp}) were the voltage and current when the panel was delivering its maximum power (Dekkiche *et al.,* 2023). Module efficiency (%) measured the panel's ability to convert sunlight into electricity, ranging from 21.89% to 22.54%.

Table 4.6: Electrical Characteristics

Attribute	Ratings
Maximum Power (Pmax/W)	700
Open Circuit Voltage (Voc/V)	49.91
Short Circuit Current (Isc/A)	17.17
Voltage at Maximum Power (Vmp/V)	42.55
Current at Maximum Power (Imp/A)	16.22
Module Efficiency (%)	22.22

4.3.4.5 Cost of the 700w PV module

The cost of a 700-Watt Monocrystalline solar panel was determined to be Kshs 32,000.

4.3.5 Sizing of Other components of the system

The results of sizing of the inverter and battery were covered in this section.

4.3.5.1 Inverter Sizing

To size the inverter, it was essential to consider the total wattage of the solar panels and the peak load requirements of the system. Each panel had a capacity of 700 watts, and with a total of 480 panels, the total power output (P_{total}) was calculated (Mofijur et al., 2019; Odou, Bhandari, & Adamou, 2020; Gielen et al., 2019). From Equation 3.5 and 3.6, the total power output was 480 panels multiplied by 700 watts, resulting in 336,000 W. The inverter needed to handle this total power output of the solar panels. It was recommended to choose a hybrid inverter with a capacity 25% to 30% higher than the total wattage to account for losses and potential future expansions. Therefore, the recommended inverter size, derived from Equation 3.5, was to be between 420-436.8 kW).

4.3.5.2 Battery Sizing

The batteries were sized to support a base load of 50kW for a duration of 20 hours in a day, it was a total average of 1000kWh/day. The number of batteries required was determined to ensure the system could provide the necessary energy storage. First, the required energy storage was calculated, working to determine the number of batteries needed. Using Equation 3.6, the total battery capacity required to achieve this energy storage was calculated as 27.233,115Ah. Given that each battery had a capacity of 5600Ah, the number of batteries required was 4.863. Therefore, 5 batteries were

needed to support an energy consumption of 1,000 kWh/day for 20 hours at a base load of 50kW (Adefarati et al., 2023; Jena & Ray, 2023; Jung, 2023; K., 2020).

4.4 Results of Techno-Economic Analysis of the HES

4.4.1 PVsyst Technical Characteristics of HES

Tables 4.7, 4.8, and 4.9 presented data from PVsyst output of HES which was in range with the calculated data .

Table 4.7: PV Module Characteristics

Descriptions	Parameters
Unit nominal power	700Wp
Number of PV modules	480
Modules strings	40
Modules In series	12
At 50 degrees Celsius Power mpp	271kWp
Voltage mpp	507V
Current mpp	534A
Nominal Power (STC)	335.99kWp
Total Area (m^2)	1342

From Table 4.7, using PVsyst for photovoltaic system design and simulation, the configuration of 12 modules per string and 40 strings in total was crucial. This setup optimized the voltage and current to match inverter specifications and maximize system efficiency. PVsyst employed these parameters to simulate expected performance, assessing energy production and system losses under various environmental conditions (Baqir & Channi, 2022). The number of modules per string

(16) and the number of strings (31) are based on optimizing the voltage and current to match the system's design requirements, influenced by the inverter specifications and the maximum system voltage. The configurations ensure that the total voltage and current at the maximum power point fit within the desired operational parameters for the system's performance and safety standards.

Table 4.8: Inverter Characteristics

Descriptions	Parameters
Unit nominal power	420Wp
Number of inverters	1 unit
Total Power (STC)	420kWac
Operating Voltage	475-820V

Table 4.8 gives an inverter of 420 kWac rating, that can convert up to 420 kW of solar-generated DC power into usable AC power for the grid or for direct consumption. This is higher than the 296.03 kW system requirement, offering extra capacity that could be beneficial in peak production scenarios, power surges allowance, system expansions, or to handle minor system inefficiencies without risking performance loss.

Table 4.9: Battery Storage

Descriptions	Parameters
Number of batteries	5 in series
Voltage	240V
Nominal capacity	5600Ah (C10)
Stored energy	1114.7 kWh
Temperature	25 degrees Celsius

The battery storage system is composed of 5 units in series, achieving an operating voltage of 240V, which is ideal for minimizing energy losses in large-scale systems. Discharging system is limited to 20% of the total capacity, optimizing the system for long-term use, increasing battery life. The total energy storage capacity of the system was 1114.7 kWh, making it suitable to meet 1000kWh requirement for the large energy demands or as backup for extended periods of low generation. The nominal capacity of 5600 Ah capacity, rated over a 10-hour discharge period (C10), will provide ample energy to meet demand over several hours, which is ideal for overnight or extended energy storage needs. The system is designed to operate at 25°C, ensuring maximum efficiency and longevity.

4.4.2 Homer HES Simulation Results

The results of the design and simulation of the HES after optimization were presented as shown in table 4.6 which presented the Initial investment for the solar PV system as designed for KPC.

Figure 4.6, presented the schematic system design for the HES at KPC was modeled, considering the existing power sources, which included the diesel generator (Genset) and the Grid. Additionally, a converter (Conv), PV module, and battery storage were introduced based on the design developed using HOMER (Khalil et al., 2021).
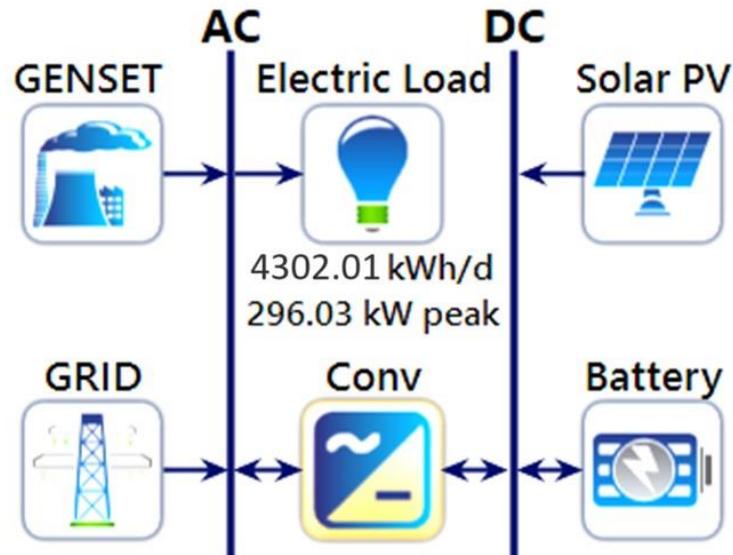
Figure 4.6: Schematic system design for hybrid system at KPC

4.4.2.1 Total Energy Produced

The total energy produced by each configuration was the sum of the energy contributions from the solar PV, generator, grid, and batteries. The configurations tested include:

1. *Grid + PV:*

This configuration produced 1,508,604 kWh/year by utilizing the grid as a backup and solar PV for renewable energy generation. The total energy was relatively high in relation to 108,000 kWh/year from grid due to the contribution from the PV system during peak solar hours, while the grid supplemented energy at night and when necessary (Adefarati et al., 2023; Jena & Ray, 2023; Jung, 2023; K., 2020).

2. *Grid + PV + Generator:*

In this scenario, a diesel generator was added, slightly increasing the total energy output to 1,513,828 kWh/year. The generator kicked in when solar production was

insufficient and the grid was not available, leading to a modest increase in total energy production compared to the grid + PV system.

3. ***Grid + PV + Generator + Battery****:*

This configuration produced 1,513,728 kWh/year and included battery storage, which stored excess energy produced during peak solar hours. Interestingly, the total energy produced was nearly the same as with the generator alone, indicating that while the battery improved reliability and storage capacity, it did not significantly increase the total energy produced over the year. This suggested that energy storage helped balance demand but didn't increase production beyond the grid and generator combination (Adefarati et al., 2023; Jena & Ray, 2023; Jung, 2023; K., 2020).

4. ***Grid + Generator***

In this setup and based on Equation 3.7, Total Energy Produced was 977,995 kWh/year only the grid and a diesel generator supplied energy demand. The total energy produced was significantly lower than the PV-inclusive systems, emphasizing the impact of renewables. Without solar PV, the system relied heavily on the generator, which provided only a fraction of the energy that solar could have offered during daylight hours.

5. ***Grid Only***

This configuration produced 966,620 kWh/year which solely depended on the grid. It produced the least amount of energy among the scenarios, indicating heavy reliance on grid electricity without any supplementary power sources like PV or generators.

This scenario was less sustainable and more expensive, especially during peak demand times or outages, compared to hybrid solutions.
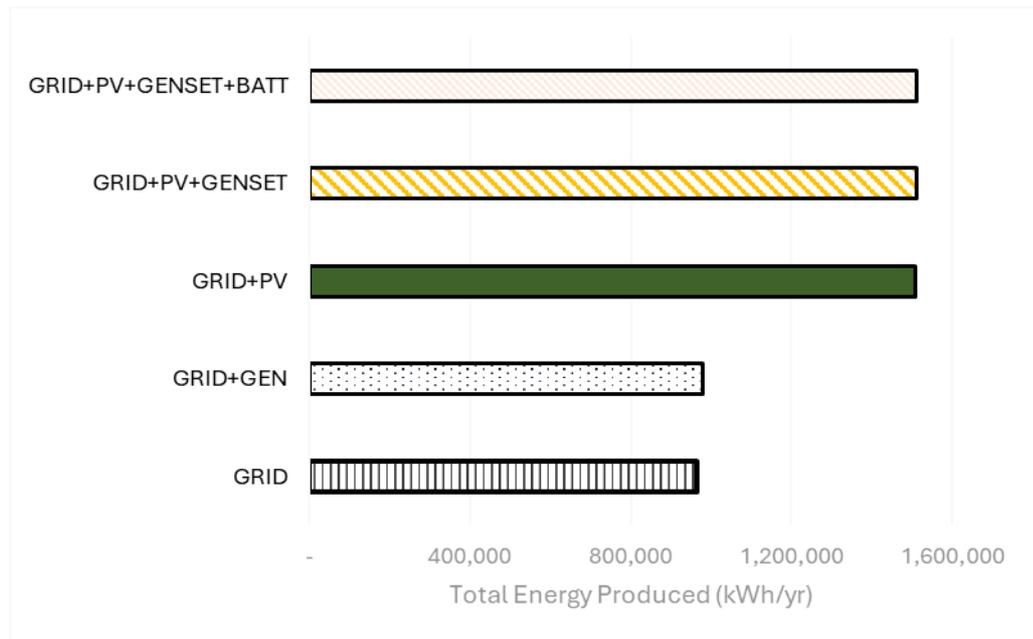
Figure 4.7: Total Energy Produced Comparison

4.4.2.2 Renewable Fraction

The Renewable Fraction results for various system configurations were as follows based on Equation 3.8:

- Grid + PV: 70.3%

- Grid + PV + Genset: 70.1%

- Grid + PV + Genset + Battery: 70.1%

- Grid + Generator: 0%

- Grid Only: 0%

1. *Grid + PV*

In the Grid + PV configuration, 70.3% of the total energy demand was met by the solar photovoltaic (PV) system. This configuration had the highest renewable fraction among the scenarios, demonstrating a strong reliance on renewable energy sources. The high renewable fraction suggested that solar PV was effectively contributing to reducing grid dependence and carbon emissions, making this setup highly sustainable.

2. *Grid + PV + Genset*

In the Grid + PV + Genset setup, 70.1% of the energy demand was supplied by renewable sources, which was only slightly lower than the Grid + PV configuration. The diesel generator provided backup power when solar PV was insufficient, particularly during cloudy periods or at night. The slight drop in the renewable fraction (from 70.3% to 70.1%) indicated that the generator was used sparingly, with most energy demand still being met by solar PV. This configuration is useful in areas where grid reliability is an issue, as the generator ensures continuous power supply. While the renewable fraction remained high, the use of a diesel generator introduced some non-renewable energy consumption, leading to a minor increase in carbon emissions. The system still remained largely sustainable due to the dominant role of solar PV.

3. *Grid + PV + Genset + Battery*

The Grid + PV + Genset + Battery configuration also achieved a 70.1% renewable fraction, similar to the Grid + PV + Genset setup. The battery was included to store excess renewable energy, which could be discharged when solar energy was not available or when the grid is unreliable. The inclusion of battery storage did not

increase the renewable fraction compared to the Grid + PV + Genset configuration. This suggested that the battery was primarily improving energy availability and reliability, rather than increasing the share of renewable energy produced (Adefarati et al., 2023; Jena & Ray, 2023; Jung, 2023; K., 2020). The battery stored excess solar energy but didn't significantly boost the overall renewable contribution. The renewable fraction remained high, meaning that most of the energy was coming from solar PV, and the battery was helping to reduce reliance on the generator.

4. Grid + Generator

In the Grid + Generator configuration, the renewable fraction was 0%, as all energy was supplied by non-renewable sources (the grid and the diesel generator). The system relied entirely on fossil fuels, either from grid power or the diesel generator. There was no renewable energy contribution, making this setup less desirable from an environmental and sustainability perspective. Without any renewable energy sources, this configuration did not contribute to carbon emission reductions and resulted in higher fuel costs and greenhouse gas emissions. This system was less efficient and sustainable compared to those that include solar PV.

5. Grid Only

Similarly, the Grid Only configuration also had a 0% renewable fraction, as it relied solely on electricity from the grid. The system depended entirely on the grid for power, and without any renewable input, there were no contributions from clean energy. This setup was less reliable in times of unstable grid supply, and more vulnerable to power outages. Like the Grid + Generator setup, this configuration did not reduce carbon emissions and was less cost-effective, especially during peak grid

demand when prices were high. It also lacked the flexibility and environmental benefits that came with renewable sources like solar PV.

4.4.3 Economic Performance of HES

In Figure 4.9, the optimization results for various configurations of Grid + Solar PV systems with battery and generator integration revealed significant economic and environmental benefits. These findings underscored the potential of hybrid energy systems to provide reliable, cost-effective, and sustainable energy solutions, aligning with global research on hybrid renewable energy systems.

4.4.3.1 Grid only

The economic analysis of the grid stand-alone simulation results revealed a Net Present Cost (NPC) of Kshs 385 million, indicating a significant initial investment required for the system's establishment. With an annual operating cost of Kshs 17.6 million, this required a financial commitment highlighting the importance of efficient power management to maintain profitability. The Cost of Energy (COE) was at Kshs 20 per kWh, as per the Energy and Petroleum Regulatory Authority (EPRA) 2023 guidelines. However, the system's emissions of 488,988 kg of CO_2 raised environmental concerns Wambui et al. (2023), emphasizing the need for strategies to reduce carbon output and enhance sustainability. The environmental impact laid ground for exploring HES in an increasingly eco-conscious market.

4.4.3.2 Grid + Solar PV System

This configuration consisted solely of a solar PV system integrated with the grid, without any additional battery or generator. The cost of energy (COE) is Kshs 9.83 per kWh. The Net Present Cost (NPC) is Kshs 236 million. The operating cost is Kshs 7.8M per year. The initial capital investment required was Kshs 232 million. The

renewable fraction of the energy produced is 70.3%. The system used no fuel and produces 100,106 kg of CO_2 per year, as seen in Table 4.9. This supported the findings of Hoseinzadeh and Garcia (2023), who emphasized the potential of hybrid renewable energy systems to minimize environmental impact while ensuring energy reliability. These results indicated significant expense reduction and environmental benefits associated with implementing the proposed hybrid energy system at KPC. Similar to the findings by Nkambule et al. (2023), who demonstrated the cost-effectiveness of hybrid systems with advanced storage solutions, this setup provided significant operating cost reductions and maintained a high renewable fraction.

Table 4.10: Component assessment for Grid + Solar PV System

Component	Capital (Kshs)	Replacement (Kshs)	O&M (Kshs)	Salvage (Kshs)	Total (Kshs)
Converter	4,300,000	3,414,810.49	15752.4	-1,547,904.49	6,182,658.39
Grid	0	0	-223,451.58	0	-223,451.58
Solar PV	220,510,500	0	2,524,482.54	0	230,434,982.5
System	232,810,500	3,414,810.49	2,524,482.54	-1,547,904.49	236,394,189.4

4.4.3.3 Grid + Generator

This configuration included generator and grid, which was the existing HES without renewable energy sources. The cost of energy (COE) was the highest at Kshs 30.20 per kWh. The Net Present Cost (NPC) increases to Kshs 585 million, as seen in Table 4.10 The operating cost was to Kshs 29.2 million per year. The initial capital

investment required was Kshs 6.5 million which was the generator cost. There was a high fuel usage, and the CO_2 emissions of 498,940 kg per year, as seen in Table 4.11. This necessitated Nkambule et al. (2023) demonstration that HES significantly would lower energy cost, improve energy reliability and reduced greenhouse gas emissions as was in South Africa's mining industry. Moreover, the environmental benefits associated with the HES at KPC would be notable. This aligned with the findings of Cai et al. (2020), who reported substantial reductions in greenhouse gas emissions and supply costs in their study on optimizing HES in Iran, highlighting the importance of HES in enhancing system reliability and reducing costs.

Table 4.11: Component assessment for Grid + Generator

Component	Capital (Kshs)	Replacement (Kshs)	O&M (Kshs)	Fuel	Salvage (Kshs)	Total (Kshs)
Grid	0	0	380,866,126	0	0	-136,732,352
Generator	6,500,000	0	174,451,027	21,136,916	-505,501	201,582,443
System	6,500,000	0	9,827,090	21,136.916	-505,501	582,448,569

4.4.3.4 Grid + Solar PV System + Generator

This configuration includes a 440kW generator alongside the solar PV and grid, but without battery storage. The cost of energy (COE) increases to Kshs 9.88 per kWh, as seen in Table 4.12. The Net Present Cost (NPC) further increases to Kshs 284 million. The operating cost is reduced significantly to Kshs 11.2M per year. The initial capital investment required is Kshs 263 million. The renewable fraction remains at 70.1%. The system still uses no fuel and has CO_2 emissions of 228,258 kg per year, as seen in Table 4.13. Including a generator in hybrid systems was a common strategy to

enhance system reliability as shown in various studies. For instance, Adaramola et al. (2014) found that integrating diesel generators with solar and wind systems in Ghana provided a feasible solution for remote areas, significantly reducing dependence on diesel fuel and lowering operating costs. Similarly, Ali et al. (2021) demonstrated that hybrid systems combining renewable energy with traditional generators offered a lower cost of energy and reduced carbon emissions compared to standalone systems in rural Pakistan. The study's findings aligned with these results, showing that the inclusion of a generator significantly reduced the annual operating cost to Kshs 11.2M from 17.876M. This mirrored the conclusions of Ali et al. (2020), who found that hybrid mini-grid systems with diesel generators in rural Bangladesh were economically viable and environmentally beneficial, as seen in table 4.13.

Furthermore, the environmental benefits of this setup, with no fuel consumption or CO_2 emissions, were noteworthy. Their study on HES in Italy, by Hoseinzadeh and Garcia (2023), highlighted the complementary use of photovoltaic panels and wind turbines to meet energy demands, similar to the generator's role in enhancing the current HES's reliability. Additionally, the substantial reduction in operating costs observed in this scenario highlighted the financial benefits of hybrid systems. This was consistent with the research by Nkambule et al. (2023), which demonstrated that hybrid systems with advanced energy storage solutions and generators could significantly reduce operational disruptions and financial losses in South Africa's mining industry. The optimization results for the Grid + Solar PV System with Generator indicated significant financial and environmental advantages in comparisons with grid only due to significant drop in LCOE from Kshs 20.00 to Kshs 9.88. This setup provided a reliable and cost-effective energy solution, reinforcing the viability of HES for reducing operational costs and enhancing sustainability, as

demonstrated in related studies. In this case, the lack of battery storage led to significantly higher operating costs and reduced the system's renewable fraction, making it less sustainable and more expensive over time. These results emphasized the importance of incorporating both generators and batteries in hybrid systems to balance reliability, cost, and environmental impact.

Table 4.12: Component assessment for Grid + Solar PV System + Generator

Component	Capital (Kshs)	Replacement (Kshs)	O&M (Kshs)	Fuel	Salvage (Kshs)	Total (Kshs)
Converter	4,300,000	3,222,810	19,752.4	0	-887,738	6,682,658.39
Genset 440kW	6,500,000	0	0	21,136,916	-505,501	201,582,443.22
Grid	0	0	-223,452		0	-11,074,919.33
Solar PV	52,200,000	0	35,461,650		0	250,434,982.5
System	62,987,652	3,222,810	9,716,783	21,136,916	-1,393,240	284,471,623.3

4.4.3.5 Grid + Solar PV System + Generator + Battery

This configuration combines the solar PV system with both a 440 kW generator and a 35-battery storage system (Table 4.12). The cost of energy (COE) is the highest among the configurations at Kshs 9.99 per kWh. The Net Present Cost (NPC) reaches Kshs 288 million. The operating cost is the lowest among the configurations at Kshs 10.9 million per year, as seen in Table 4.13. The initial capital investment required is Kshs 272.8 million. The renewable fraction remains unchanged at 70.1%. Similar to the other configurations, there was minimal or no fuel usage and the CO_2 emissions are 174,442 kg per year. For example, in South Africa, Nkambule et al. (2023)

showed that hybrid systems incorporating floating solar photovoltaics (FPV), wind turbines, and vanadium redox flow (VRF) battery energy storage systems effectively reduced greenhouse gas emissions and operational costs. Similarly, the addition of battery storage in the study lowered the operating cost, underscoring the financial benefits of incorporating advanced energy storage solutions.

The environmental benefits of this configuration, with minimal or no fuel consumption and CO_2 emissions, aligned with findings from studies such as those by Islam et al. (2022), who demonstrated the significant reduction in greenhouse gas emissions through hybrid PV systems in Bangladesh. This setup ensured a sustainable and reliable power supply, which was critical for energy-intensive applications. Furthermore, the combined generator and battery system's cost efficiency was reflected in the significant reduction in operating costs compared to other configurations. Ali et al. (2020) highlighted the economic viability of hybrid mini-grid systems with integrated renewable energy and traditional generators in rural Bangladesh, emphasizing their lower cost of energy and reduced carbon emissions. The slight increase in initial capital to Kshs 272.8 million was justified by the substantial long-term savings in operating costs and environmental benefits (Table 4.13). This was consistent with the conclusions of studies such as those by Mulumba and Farzaneh (2023), who highlighted the importance of upfront investment in hybrid energy systems for long-term cost savings and reliability, particularly in remote areas of Kenya. The optimization results for the Grid + Solar PV System with Generator and Battery underscored the system's cost efficiency and sustainability.

This configuration provided a solution for reducing operating costs and ensuring reliable power supply, reinforcing the findings from related research on the benefits of

HES integrating generators and battery storage. Also, this scenario mirrored the findings of Adaramola et al. (2014), who demonstrated that integrating diesel generators with renewable energy sources could enhance system reliability and reduce overall dependency on the grid. However, it also introduced fuel consumption and CO_2 emissions, which needed to be managed to maintain environmental benefits. The increased renewable fraction and reliability made this setup particularly advantageous for applications where energy security was paramount. In summary, the sensitivity cases involving 35 batteries demonstrated various configurations' economic and environmental benefits. The inclusion of battery storage consistently showed financial advantages by reducing operating costs, while the addition of generators enhanced system reliability and renewable fractions at the expense of higher COE and emissions. These findings aligned with global research on HES, emphasizing their potential to provide cost-effective, reliable, and sustainable energy solutions.

Table 4.13: Component assessment for Grid + Solar PV System + Generator +

Component	Capital (Kshs)	Replacement (Kshs)	O&M (Kshs)	Fuel	Salvage (Kshs)	Total (Kshs)
Battery LFP 5600Ah	9,845,500	0	110,306.7		-6,079,476	1,131,233.5
Converter	4,300,000	3,414,810	19,700.92		-547,904.49	6,182,658.39
Genset 440kW	6,500,000	0	174,451,027	21,136,916	-505,501.36	4,077,393.9
Grid	0	0	-11,486,808.29		0	-223,451.58
Solar PV	52,200,000	0	9,924,483		0	230,434,982.5
System	232,938,000	2,414,810	9,827,090		-3,577,043.76	272,802,856.8

4.4.4 Comparison Table

Table 4.14 provided a clear comparison of the different configurations based on key metrics such as LCOE, NPC, CO_2 emissions, renewable fraction, and operating costs. The data highlighted the cost efficiency and environmental benefits of the hybrid energy systems compared to reliance solely on the grid or generators.

Table 4.14: Economic analysis comparison

Architecture	LCOE (Kshs)	NPC (Kshs)	Operating Cost (Kshs/yr.)	Initial Capital (Kshs)	Ren Frac (%)	CO₂ (kg/yr.)
Grid +Generator	30.20	582M	29,203,856	6.5M	0	498,940
Grid	20	385M	17,876,360	-	-	488,998
Grid + PV + Generator	9.88	284M	11,241,570	263M	70.1	228,258
Grid + PV + Generator + Battery	9.99	288M	10,950,066	233M	70.1	174,442
Grid + PV	9.83	236M	7,835,360	225M	70.3	100,106

The high LCOE of Kshs30.20, NPC of Kshs 582M and emission of 498,940kg/CO_2 in Grid + Generator highlighted the financial and environmental drawbacks of relying heavily on diesel generators. Similar findings were reported by Adaramola et al. (2014), who noted that while integrating diesel generators could enhance reliability with higher cost of energy, due to increased fuel consumption and emissions. Studies by Ali *et al.* (2020) and Islam *et al.* (2022) similarly showed that HES integrating renewable energy, battery storage, and generators provided a more cost-effective and environmentally friendly solution compared to systems that relied solely on

generators. In summary, the sensitivity cases for the Solar PV System with Generator and Battery demonstrated the critical role of battery storage in enhancing the cost-effectiveness and sustainability of HES. Reducing operating costs and increasing the renewable fraction, battery storage proved to be a valuable addition to hybrid configurations, aligning with global research findings on the benefits of integrated renewable energy systems.

These sensitivity cases and optimization results highlighted the trade-offs between different configurations of solar PV systems, generators, and batteries. The analysis provided comprehensive insights into cost, environmental impact, and efficiency, guiding decision-making for the most effective energy solutions. This mirrors the findings of several studies on hybrid energy systems globally, which emphasize the importance of integrating renewable energy sources with advanced storage solutions to enhance system performance and sustainability.
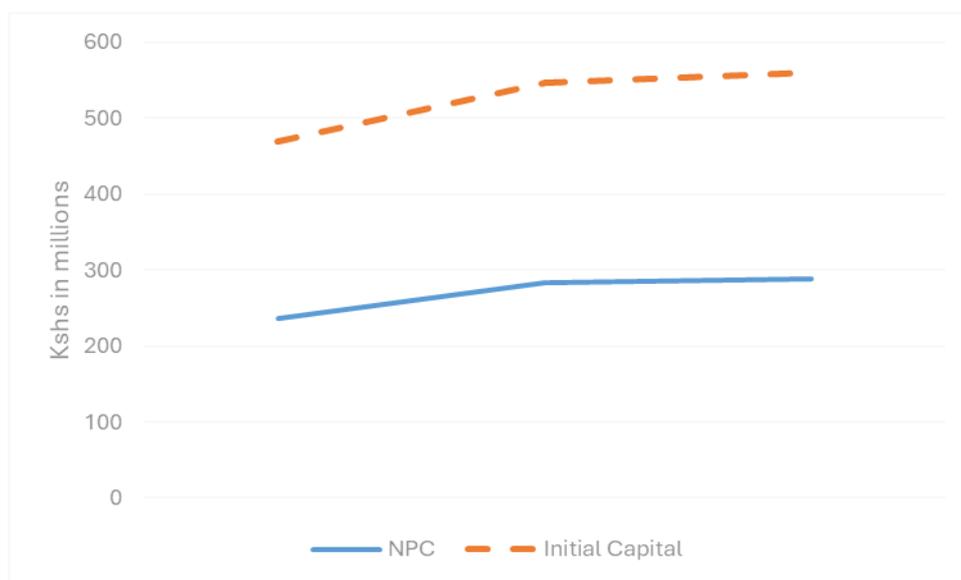
Figure 4.8: NPC and Initial Capital comparison for various HES

From Figure 4.8, the optimal configuration depended on balancing initial capital investment, operating costs, renewable energy fraction, and environmental considerations. For instance, the combination of a generator and battery with the Solar PV System resulted in a substantial reduction in operating costs and a high renewable fraction, similar to the results reported by Nkambule et al. (2023) in their study of hybrid systems in South Africa's mining sector. This setup provided a reliable and cost-effective solution while minimizing greenhouse gas emissions. The investigation revealed significant financial savings, with the hybrid energy system's operating cost ranges of Kshs 7.8 million to 11.2 million per year versus the grid's operational cost of Kshs 17.610 million, indicating substantial expense reduction. This finding aligns with the research by Islam et al. (2022), which demonstrated that hybrid PV systems in Bangladesh significantly reduce operating costs and environmental impact.

Figure 4.9: LCOE comparison for various HES configurations

Furthermore, based on Figure 4.9, the integration of battery storage consistently showed financial advantages by lowering operating costs and enhancing system

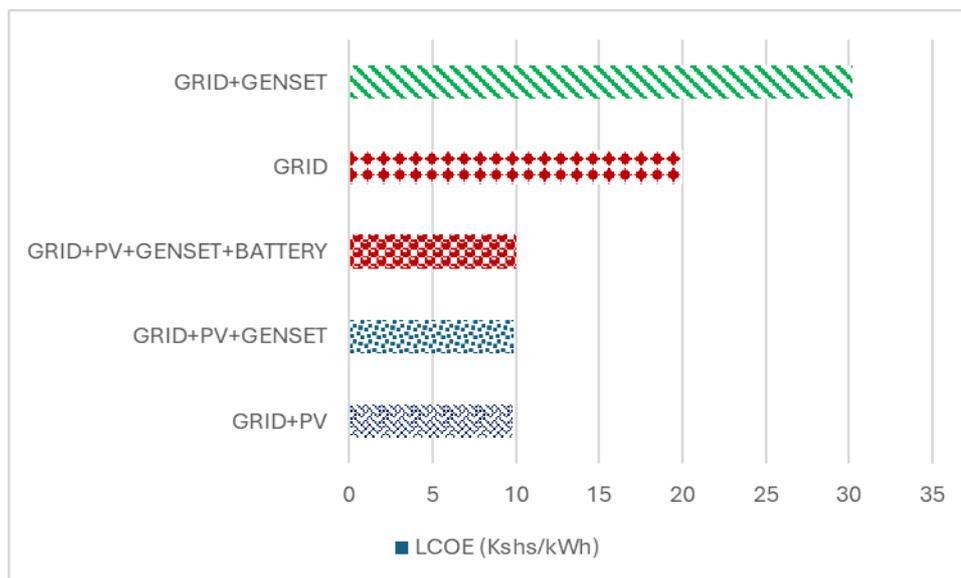reliability. This supports the conclusions of Ali et al. (2020), who found that hybrid mini-grid systems with battery storage in rural Bangladesh were economically viable and environmentally beneficial. The study also highlighted the environmental benefits of hybrid systems, with configurations involving batteries and generators achieving higher renewable fractions and lower CO_2 emissions. This is consistent with the findings of Hoseinzadeh and Garcia (2023), who emphasized the potential of hybrid systems to reduce reliance on fossil fuels and minimize environmental impact. In summary, the sensitivity cases and optimization results underscore the importance of integrating generators and battery storage with solar PV systems to achieve a balanced approach to cost, efficiency, and environmental sustainability. The substantial financial savings and environmental benefits observed in this study reinforce the viability of the proposed hybrid energy system at KPC, aligning with global research on the advantages of hybrid energy systems. These findings provide a robust foundation for decision-making in implementing effective and sustainable energy solutions.

4.4.5 Payback of the Hybrid Energy System

Upon implementing PV systems and battery storage, the payback periods for Grid+PV, Grid+PV+Genset and Grid+PV+Genset+Battery were 8,7.44 and 8.56 years respectively based on sensitivity analysis using Homer simulation. This demonstrated the viability of the proposed HES projects, indicating capability of recouping initial investment within the first 8, 7.44 and 8.56 years of implementation and yielding cost savings over the other subsequent 25 years of operation. Yasin & Alsayed (2020) conducted research on optimizing excess electricity management in a PV, energy storage, and diesel generator hybrid system, aligning with the goal of reducing reliance on unreliable electricity and emphasizing cost-saving hybrid

systems. When considering discounted payback, the payback period extended to 9.12, 9.3 and 9.52 years, which remained a financially viable duration for investing in PV modules and the storage system.

4.4.6 Internal Rate of Return (IRR) and Return on Investment (ROI)

The IRR for Grid+PV, Grid+PV+Genset and Grid+PV+Genset+Battery stood at 32.1%, 12.7% and 10.8% respectively based on Homer simulation, indicating the discount rate at which the net present cost of the base case grid system equaled that of the hybrid system, representing a significant disparity between the various configurations (Ur Rashid et al., 2022). The ROI was determined to be 29.9%, 9.3% and 8.1%. Also, these values, obtained from assessing the hybrid energy configurations, underscored the significant yearly cost savings relative to the initial investment, affirming that offsetting of the power needs using renewable technologies at KPC indeed reduced costs substantially.

The findings from the assessment of the hybrid energy system offered solutions to several gaps outlined by Oloo (2022), Ur Rashid et al. (2022), and other researchers. Firstly, the study addressed the lack of real-world studies and practical applications tailored to petroleum transportation firms such as KPC Eldoret in the domain of HES. Demonstrating the viability of the proposed hybrid energy system project and its capability to recoup its initial investment within the first 8, 7.44 and 8.56 years of implementation it provided valuable insights for practical implementation, aligning with the emphasis placed by Adefarati et al. (2023) and Dekkiche et al. (2023) on bridging this gap. Moreover, the assessment contributed to the incomplete assessment of solar energy potential in Eldoret highlighted by Oloo (2022). Providing comprehensive data assessments and analysis using Homer simulation, and further

calculation using equation 3.9, 3.10, 3.11 and 3.12, on the cost, payback period, IRR, ROI, and LCOE of the hybrid energy system, it enhanced the understanding of the economic viability and potential benefits of solar energy utilization in the region.

4.5 Overall emissions from the Existing power Configuration

According to equation 3.13 and 3.14, the backup generator was found to be a high-capacity diesel generator with an annual power production of 10,975kWh in 2023, with an emission factor for a diesel generator of carbon footprint ranges of 1.22 kg CO_2 /kWh to 1.94 kgCO_2 /kWh that equaled to 121,291.5 kgCO_2 for the year 2023, as was found by Wambui et al. (2022). From equation 3.16, the national grid emission factor for Kenya was 0.5tCO_2/MWh, which was in conformance with (EPRA,2022). The factor accounted for CO_2 emissions for electricity generation and supply, hence with an energy consumption of 108,732kWh the grid gave an emission of 54,366 kgCO_2. Cumulated CO_2 emissions for both was 175,657.5 kgCO_2. It was important to note that the sensitivity assessments of the output after simulation, gave the CO_2 emissions from the HES.

4.6 The Social and Environmental Impacts Associated with HES

The findings related to optimized HES system produced annual CO_2 emissions of 100,106 kg which was scaled down by more than 50% following evaluation using equation 3.13 and 3.14, it offered knowledge into the social and environmental impacts associated with HES, which had been insufficiently explored according to Lukuyu et al. (2014) and Eze F et al. (2012). While economic aspects received extensive coverage, the study highlighted the significant yearly cost savings and the potential reduction in environmental impact through the adoption of the HES. Actually, this emphasized the need for a holistic approach that considered broader

societal implications and environmental sustainability, aligning with the emphasis placed by Basnet et al. (2023) and Khalil et al. (2021) on deeper economic analysis and understanding of socio-environmental impacts. Indeed, the findings from the research of the HES not only provided practical solutions to the gaps outlined by Oloo (2022), Ur Rashid et al. (2022) but also contributed towards advancing the understanding and implementation of HES in real-world scenarios, particularly in the context of fuel transportation firms like KPC Eldoret.

in real-world scenarios, particularly in the context of fuel transportation firms like KPC Eldoret.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study focused on the Kenya Pipeline Company's Eldoret Terminal which assessed energy consumption and designed a hybrid energy system by integrating solar PV and battery storage, to the existing diesel generator - grid power source, the research evaluated the techno-economic feasibility of implementing such a system to meet the terminal's energy demands while lowering operational cost and emissions.

The analysis revealed a peak load of 296.03 kW at midday and a consistent daily average load of 179.25 k, with the lowest demand occurring at midnight. An average base load of 50kW. In 2023, the terminal consumed 108,732 kWh of grid leading to a financial expenditure of KShs 17,610,172.

A 335.99 kW solar PV system was designed to fit within an area of 1342 m² rooftop space, offsetting the electricity bill entirely with 480 panels. The inverter sizing was adjusted to accommodate 336,000 W output from 480 panels, selecting a 340 kW inverter as per PVsyst validation. The system also incorporated 5 batteries with a capacity of 5600Ah to provide 20 hours of 50 kW base load after sun hours for an energy consumption of 1,000 kWh.

 a capacity of 5600Ah to provide 20 hours of 50 kW base load after sun hours for an energy consumption of 1,000 kWh.

The Levelized Cost of Energy (LCOE) was determined to be KShs 9.83, with a Net Present Cost (NPC) of KShs 236 million for the HES. The system's annual CO_2 emissions were reduced by more than 50%, scaling down to 100,106 kg. The payback period for the PV system was calculated at 8 years, with a Return on Investment

(ROI) of 29.9% and an internal rate of return of 32.1%, showcasing the profitability of the HES. Configurations with solar PV generated significantly more energy than those without, reducing grid and generator reliance.

5.2 Recommendations

5.2.1 Recommendation for the study

i. Research more advanced battery technologies that might offer better efficiency, longer lifespans, or reduced costs.

ii. Study the scalability of the hybrid system to accommodate future expansions or increased energy demands.

5.2.2 Recommendations for KPC

i. Prioritize the installation of a hybrid energy system integrating solar PV panels and battery storage to reduce reliance on grid power and lower operational costs.

ii. Maximize solar panel installation on all useful rooftops to efficiently harness renewable energy while ensuring the system is appropriately sized to always meet energy demand while minimizing environmental interruption.

iii. Allocate resources to invest in energy storage solutions like batteries to store excess solar energy for use during periods of high demand or low sunlight, optimizing energy utilization.

iv. Ensure Monitoring and Maintenance Establish a rigorous monitoring and maintenance program to regularly inspect and maintain system components, ensuring optimal performance and longevity.

REFERENCES

Adaramola, M. S., Agelin-Chaab, M., & Paul, S. S. (2014). Analysis of hybrid energy systems for application in southern Ghana. Energy Conversion and Management, 88, 284-295.

Adefarati, T., Bansal, R., Shongwe, T., Naidoo, R., Bettayeb, M., & Onaolapo, A. (2023). Optimal energy management, technical, economic, social, political and environmental benefit analysis of a grid-connected pv/Wt/Fc hybrid energy system. *Energy Conversion and Management*, *292*, 117390. https://doi.org/10.1016/j.enconman.2023.117390

Aeggegn, D. B., Agajie, T. F., Workie, Y. G., Khan, B., & Fopah-Lele, A. (2023). Feasibility and techno-economic analysis of PV-battery priority grid tie system with diesel resilience: A case study. *Heliyon*, *9*(9), e19387. https://doi.org/10.1016/j.heliyon.2023.e19387

Agajie, T. F., Ali, A., Fopah-Lele, A., Amoussou, I., Khan, B., Velasco, C. L., & Tanyi, E. (2023). A comprehensive review on techno-economic analysis and optimal sizing of hybrid renewable energy sources with energy storage systems. *Energies*, *16*(2), 642. https://doi.org/10.3390/en16020642

Agajie, T. F., Fopah-Lele, A., Amoussou, I., Ali, A., Khan, B., Mahela, O. P., Nuvvula, R. S., Ngwashi, D. K., Soriano Flores, E., & Tanyi, E. (2023). Techno-economic analysis and optimization of hybrid renewable energy system with energy storage under two operational modes. *Sustainability*, *15*(15), 11735. https://doi.org/10.3390/su151511735

Arfoa, A., Almaita, E., Alshkoor, S., & Shloul, M. (2022). Techno-economic feasibility analysis of on-grid battery energy storage system: Almanara PV power plant case study. *Jordan Journal of Electrical Engineering*, *8*(3), 253. https://doi.org/10.5455/jjee.204-1654330119

Arrinda, M., Berecibar, M., Oyarbide, M., Macicior, H., Muxika, E., & Messagie, M. (2020). undefined. *Energy*, *208*, 118383. https://doi.org/10.1016/j.energy.2020.118383

Awe, O. O., Mudida, R., & Gil-Alana, L. A. (2020). undefined. *International Journal of Finance & Economics*, *26*(1), 1197-1205. https://doi.org/10.1002/ijfe.1845

Babatunde, O., Akinyele, D., Akinbulire, T., & Oluseyi, P. (2018). Evaluation of a grid-independent solar photovoltaic system for primary health centres (PHCs) in developing countries. *Renewable Energy Focus*, *24*, 16-27. https://doi.org/10.1016/j.ref.2017.10.005

Babatunde, O. M., Munda, J. L., & Hamam, Y. (2020). A comprehensive state-of-the-Art survey on hybrid renewable energy system operations and planning. *IEEE Access*, *8*, 75313-75346. https://doi.org/10.1109/access.2020.2988397

Babatunde, O., Munda, J., & Hamam, Y. (2020). Operations and planning of integrated renewable energy system: A survey. *2020 5th International Conference on Renewable Energies for Developing Countries (REDEC)*. https://doi.org/10.1109/redec49234.2020.9163857

Baqir, M., & Channi, H. K. (2022). Analysis and design of solar PV system using PVsyst software. Materials Today: Proceedings, 48, 1332-1338. https://doi.org/10.1016/j.matpr.2021.09.029

Basnet, S., Deschinkel, K., Le Moyne, L., & Cécile Péra, M. (2023). A review on recent standalone and grid integrated hybrid renewable energy systems: System optimization and energy management strategies. *Renewable Energy Focus*, *46*, 103-125. https://doi.org/10.1016/j.ref.2023.06.001

Basyoni, M. S. S., Basyoni, M. S. S., & Al-Dhlan, K. (2017). Design, sizing and implementation of a PV system for powering a living room. Computer, 90(8), 12.

Berggren, A., & Österberg, S. (2017). Kenya meeting the electricity demand of 2030: an assessment of how Kenya Vision 2030 and climate change impact the optimal electricity generation mix.

Carlsen, L., & Bruggemann, R. (2021). The 17 United Nations' sustainable development goals: A status by 2020. *International Journal of Sustainable Development & World Ecology*, *29*(3), 219-229. https://doi.org/10.1080/13504509.2021.1948456

Chandra Voumik, L., Ridwan, M., Hasanur Rahman, M., & Raihan, A. (2023). An investigation into the primary causes of carbon dioxide releases in Kenya: Does renewable energy matter to reduce carbon emission? *Renewable Energy Focus*, *47*, 100491. https://doi.org/10.1016/j.ref.2023.100491

Cheruiyot, W., Tonui, J. K., & Limo, S. C. (2021). Performance evaluation of 780 Wp rooftop solar PV power backup system in Western Kenya. Journal of Energy Research and Reviews, 8(1), 1-9. https://doi.org/10.9734/jenrr/2021/v8i130200

Cheruiyot, W. K. (2022). Economic analysis of a stand-alone residential home solar PV system in Western Kenya. In Advances in Phytochemistry, Textile and Renewable Energy Research for Industrial Growth (pp. 236-240). https://doi.org/10.1201/9781003221968-32

Cheruiyot, W. K., Komen, E. K., Tonui, J. K., & Kinyamal, R. A. (2024). Technical and enviro-economic analysis of a 0.78 kWp PV system. Journal of Energy Research and Reviews, 16(6), 1-12. https://doi.org/10.9734/jenrr/2024/v16i6353

D Kenyoru, N. (2015). Stakeholder engagement and organizational performance: A case of Kenya power and lighting company, Eldoret branch, Uasin-Gishu County – Kenya. *Archives of Business Research*, *3*(2). https://doi.org/10.14738/abr.32.785

De Doile, G. N., Rotela Junior, P., Rocha, L. C., Janda, K., Aquila, G., & Peruchi, R. S. (2021). Feasibility of hybrid wind and photovoltaic distributed generation and battery energy storage systems under techno-economic regulation. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3884857

De Silva, T., Jorgenson, J., Macknick, J., Keohan, N., Miara, A., Jager, H., & Pracheil, B. (2022). Hydropower operation in future power grid with various renewable power integration. *Renewable Energy Focus*, *43*, 329-339. https://doi.org/10.1016/j.ref.2022.11.001

Dekkiche, M., Tahri, T., & Denai, M. (2023). Techno-economic comparative study of grid-connected PV/reformer/FC hybrid systems with distinct solar tracking systems. *Energy Conversion and Management: X*, *18*, 100360. https://doi.org/10.1016/j.ecmx.2023.100360

Ganesha, H. R., & Aithal, P. S. (2022). How to choose an appropriate research data collection method and method choice among various research data collection methods and method choices during Ph.D. Program in India? *International Journal of Management, Technology, and Social Sciences*, 455-489. https://doi.org/10.47992/ijmts.2581.6012.0233

García Contreras, F. (2019). Analysis of hybrid renewable energy systems to enhance grid usage.

Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strategy Reviews*, *24*, 38-50. https://doi.org/10.1016/j.esr.2019.01.006

Gil-Alana, L. A., Mudida, R., & Carcel, H. (2017). Shocks affecting electricity prices in Kenya, a fractional integration study. *Energy*, *124*, 521-530. https://doi.org/10.1016/j.energy.2017.02.092

Gruber, K., Regner, P., Wehrle, S., Zeyringer, M., & Schmidt, J. (2022). Towards global validation of wind power simulations: A multi-country assessment of wind power simulation from MERRA-2 and ERA-5 reanalyses bias-corrected with the global wind atlas. *Energy*, *238*, 121520. https://doi.org/10.1016/j.energy.2021.121520

Gupta, A. K. (2012). *Energy and material constraints concerning the rapid deployment of photovoltaic energy in the twenty-first century*.

Hamid, A. K., Mbungu, N. T., Elnady, A., Bansal, R. C., Ismail, A. A., & AlShabi, M. A. (2022). A systematic review of grid-connected photovoltaic and photovoltaic/thermal systems: Benefits, challenges and mitigation. *Energy & Environment*, *34*(7), 2775-2814. https://doi.org/10.1177/0958305x221117617

Hasan, M. M., Hossain, S., Mofijur, M., Kabir, Z., Badruddin, I. A., Yunus Khan, T. M., & Jassim, E. (2023). undefined. *Energies*, *16*(18), 6456. https://doi.org/10.3390/en16186456

Hashimshony Yaffe, N., & Segal-Klein, H. (2023). Renewable energy and the centralisation of power. The case study of lake Turkana wind power, Kenya. *Political Geography*, *102*, 102819. https://doi.org/10.1016/j.polgeo.2022.102819

Ibrahim, H. A., & Ayomoh, M. K. (2022). Optimum predictive modelling for a sustainable power supply mix: A case of the Nigerian power system. *Energy Strategy Reviews*, *44*, 100962. https://doi.org/10.1016/j.esr.2022.100962

Ibrahim, H. A., Ayomoh, M. K., Bansal, R. C., Gitau, M. N., Yadavalli, V. S., & Naidoo, R. (2023). Sustainability of power generation for developing economies: A systematic review of power sources mix. *Energy Strategy Reviews*, *47*, 101085. https://doi.org/10.1016/j.esr.2023.101085

Igwenagu, C. (2016). Fundamentals of research methodology and data collection. *LAP Lambert Academic Publishing*.

Jena, C. J., & Ray, P. K. (2023). Power management in three-phase grid-integrated PV system with hybrid energy storage system. *Energies*, *16*(4), 2030. https://doi.org/10.3390/en16042030

JETP. (2023). Has Kenya's governance reforms in the energy sector enhanced access to electricity in rural areas? *Journal of Energy Technologies and Policy*. https://doi.org/10.7176/jetp/13-1-08

Jung, H. Y. (2023). Techno-economic analysis of hybrid energy storage system with renewable energy coupling hydrogen technology. https://doi.org/10.20944/preprints202307.1281.v1

K M, V., & Saravanan, V. (2021). Techno economic environmental assessment of hybrid renewable energy system in India. *International Journal of Advances in Applied Sciences*, *10*(4), 343. https://doi.org/10.11591/ijaas.v10.i4.pp343-362

K M, V., & Saravanan, V. (2021). Techno-economic and environmental analysis of renewable energy integrated system for rural electrification in north-eastern region of India. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3912596

K., A. (2020). Energy management controller for grid connected solar PV system with SMES-battery hybrid energy storage. *Journal of Advanced Research in Dynamical and Control Systems*, *12*(SP4), 1385-1396. https://doi.org/10.5373/jardcs/v12sp4/20201617

Kabeyi, M. J., & Olanrewaju, O. A. (2023). The levelized cost of energy and modifications for use in electricity generation planning. *Energy Reports*, *9*, 495-534. https://doi.org/10.1016/j.egyr.2023.06.036

Keshavadasu, S. R. (2023). Regulatory and policy risks: Analyzing the uncertainties related to changes in government policies, regulations, and incentives affecting solar power project development and operations in Kenya. *Energy Policy*, *182*, 113760. https://doi.org/10.1016/j.enpol.2023.113760

Khalil, L., Liaquat Bhatti, K., Arslan Iqbal Awan, M., Riaz, M., Khalil, K., & Alwaz, N. (2021). Optimization and designing of hybrid power system using HOMER pro. Materials Today: Proceedings, 47, S110-S115. https://doi.org/10.1016/j.matpr.2020.06.054

Kulkarni, S. H., & Anil, T. R. (2014). Rural electrification through renewable energy sources- An overview of challenges and prospects. *International Journal of Engineering Research*, *3*(6), 384-389. https://doi.org/10.17950/ijer/v3s6/604

Kumar, R., Rajoria, C., Sharma, A., & Suhag, S. (2021). Design and simulation of standalone solar PV system using PVsyst software: A case study. Materials Today: Proceedings, 46, 5322-5328. https://doi.org/10.1016/j.matpr.2020.08.785

Lin, B., & Sai, R. (2022). undefined. *Energy*, *250*, 123833. https://doi.org/10.1016/j.energy.2022.123833

Lukuyu, J. M., & Cardell, J. B. (2014). Hybrid power system options for off-grid rural electrification in northern Kenya. *Smart Grid and Renewable Energy*, *05*(05), 89-106. https://doi.org/10.4236/sgre.2014.55009

Maniscalco, M., Longo, S., Miccichè, G., Cellura, M., & Ferraro, M. (2023). A critical review of the environmental performance of bifacial photovoltaic panels. *Energies*, *17*(1), 226. https://doi.org/10.3390/en17010226

Modu, B., Abdullah, M. P., Bukar, A. L., & Hamza, M. F. (2023). A systematic review of hybrid renewable energy systems with hydrogen storage: Sizing, optimization, and energy management strategy. *International Journal of Hydrogen Energy*, *48*(97), 38354-38373. https://doi.org/10.1016/j.ijhydene.2023.06.126

Mofijur, M., Mahlia, T., Silitonga, A., Ong, H., Silakhori, M., Hasan, M., Putra, N., & Rahman, S. (2019). Phase change materials (PCM) for solar energy usages and storage: An overview. *Energies*, *12*(16), 3167. https://doi.org/10.3390/en12163167

Mumtaz, Z. (2022). Research design, methodology, and data collection. *Informal Social Protection and Poverty*, 73-83. https://doi.org/10.1007/978-981-19-6474-9_4

Musonye, X. S., Davíðsdóttir, B., Kristjánsson, R., Ásgeirsson, E. I., & Stefánsson, H. (2021). Environmental and techno-economic assessment of power system expansion for projected demand levels in Kenya using TIMES modeling framework. *Energy for Sustainable Development*, *63*, 51-66. https://doi.org/10.1016/j.esd.2021.05.006

Mwita, K. (2022). Factors to consider when choosing data collection methods. *International Journal of Research in Business and Social Science (2147-4478)*, *11*(5), 532-538. https://doi.org/10.20525/ijrbs.v11i5.1842

Nation. (2023). Kenyans in darkness after nationwide power outage. https://nation.africa/kenya/news/kenyans-in-darkness-after-nationwide-power-outage-4610932

Ngure, S. M., Makokha, A. B., Ataro, E. O., & Adaramola, M. S. (2022). Degradation analysis of solar photovoltaic module under warm semiarid and tropical Savanna climatic conditions of East Africa. *International Journal of Energy and Environmental Engineering*, *13*(2), 431-447. https://doi.org/10.1007/s40095-021-00454-5

Ngure, S. M., Makokha, A. B., Ataro, E. O., & Adaramola, M. S. (2023). Techno-economic performance analysis of grid-tied solar PV systems under tropical Savanna climatic conditions in Kenya. *International Journal of Ambient Energy*, *44*(1), 1-16. https://doi.org/10.1080/01430750.2023.2224329

Nguyen, T. B., & Van, P. H. (2021). Design, simulation and economic analysis of a rooftop solar PV system in Vietnam. EAI Endorsed Transactions on Energy Web, 8(35), e11-e11.

Njeru, G., Gathiaka, J., & Kimuyu, P. (2020). Modelling and forecasting electricity demand for commercial and industrial consumers in Kenya to 2035. *European Scientific Journal ESJ*, *16*(13). https://doi.org/10.19044/esj.2020.v16n13p162

Odou, O. D., Bhandari, R., & Adamou, R. (2020). Hybrid off-grid renewable power system for sustainable rural electrification in Benin. *Renewable Energy*, *145*, 1266-1279. https://doi.org/10.1016/j.renene.2019.06.032

Olabi, A. G., Abbas, Q., Shinde, P. A., & Abdelkareem, M. A. (2023). Rechargeable batteries: Technological advancement, challenges, current and emerging applications. *Energy*, *266*, 126408. https://doi.org/10.1016/j.energy.2022.126408

Oladeji, A. S., Akorede, M. F., Aliyu, S., Mohammed, A. A., & Salami, A. W. (2021). Simulation-based optimization of hybrid renewable energy system for off-grid rural electrification. *International Journal of Renewable Energy Development*, *10*(4). https://doi.org/10.14710/ijred.0.31316

OLOO, B. O. (2022). TECHNO-ECONOMIC ASSESSMENT OF GRID-TIE SOLAR PV SYSTEM IN KENYA. http://41.89.160.13:8080/xmlui/handle/123456789/7118?show=full

Onaolapo, A. K., Sharma, G., Bokoro, P. N., Adefarati, T., & Bansal, R. C. (2023). undefined. *Computers and Electrical Engineering*, *111*, 108954. https://doi.org/10.1016/j.compeleceng.2023.108954

Panda, A., Dauda, A. K., Chua, H., Tan, R. R., & Aviso, K. B. (2023). Recent advances in the integration of renewable energy sources and storage facilities with hybrid power systems. *Cleaner Engineering and Technology*, *12*, 100598. https://doi.org/10.1016/j.clet.2023.100598

Perez, R., Cebecauer, T., & Šúri, M. (2013). Semi-empirical satellite models. Solar Energy Forecasting and Resource Assessment, 21-48. https://doi.org/10.1016/b978-0-12-397177-7.00002-4

Ramesh, M., & Saini, R. P. (2021). Techno-economic feasibility study of a hybrid renewable energy system for a remote rural area of Karnataka, India. *Advances in Intelligent Systems and Computing*, 343-351. https://doi.org/10.1007/978-981-15-9953-8_30

Sai, R., & Lin, B. (2022). Productivity assessment of power generation in Kenya: What are the impacts? *Energy*, *254*, 124200. https://doi.org/10.1016/j.energy.2022.124200

Samargandi, N., Monirul Islam, M., & Sohag, K. (2023). Towards realizing vision 2030: Input demand for renewable energy production in Saudi Arabia. *Gondwana Research*. https://doi.org/10.1016/j.gr.2023.05.019

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

Sawle, Y., & Thirunavukkarasu, M. (2021). Techno-economic comparative assessment of an off-grid hybrid renewable energy system for electrification of remote area. *Design, Analysis, and Applications of Renewable Energy Systems*, 199-247. https://doi.org/10.1016/b978-0-12-824555-2.00027-7

Segura, E., Belmonte, L. M., Morales, R., & Somolinos, J. A. (2023). A strategic analysis of photovoltaic energy projects: The case study of Spain. *Sustainability*, *15*(16), 12316. https://doi.org/10.3390/su151612316

Sharma, P. K., Kumar, D. A., William, P., Obulesu, D., Pandian, P. M., Khan, T. K., & Manikandan, G. (2023). Energy storage system based on hybrid wind and photovoltaic technologies. *Measurement: Sensors*, *30*, 100915. https://doi.org/10.1016/j.measen.2023.100915

Simberg-Koulumies, N. (2023). Just sustainabilities: Lessons from the lake Turkana wind power project in Kenya. *Local Environment*, *29*(1), 40-56. https://doi.org/10.1080/13549839.2023.2249497

Takase, M., Kipkoech, R., & Essandoh, P. K. (2021). A comprehensive review of energy scenario and sustainable energy in Kenya. *Fuel Communications*, *7*, 100015. https://doi.org/10.1016/j.jfueco.2021.100015

Tamoor, M., Bhatti, A. R., Farhan, M., & Miran, S. (2022). Design of on-grid photovoltaic system considering optimized sizing of photovoltaic modules for enhancing output energy. *ECP 2022*. https://doi.org/10.3390/ecp2022-12671

Tamoor, M., Bhatti, A. R., Farhan, M., Zaka, M. A., & ZakaUllah, P. (2023). Solar energy capacity assessment and performance evaluation of designed grid-connected photovoltaic systems. *ECP 2023*. https://doi.org/10.3390/ecp2023-14729

Teo, Y. L., & Go, Y. I. (2021). Techno-economic-environmental analysis of solar/hybrid/storage for vertical farming system: A case study, Malaysia. *Renewable Energy Focus*, *37*, 50-67. https://doi.org/10.1016/j.ref.2021.02.005

Thompson, S. (2023). Strategic analysis of the renewable electricity transition: Power to the world without carbon emissions? *Energies*, *16*(17), 6183. https://doi.org/10.3390/en16176183

Toufik, T., DEKKICHE, M., & Denai, M. (2022). Techno-economic comparative study of grid-connected Pv/Reformer/Fc hybrid systems with distinct solar tracking systems. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4158393

Twesigye, P. (2022). Understanding structural, governance and regulatory incentives for improved utility performance: The case of Kenya and its Kenya power. https://doi.org/10.20944/preprints202202.0269.v1

Urbina, A. (2022). Photovoltaic technology. *Green Energy and Technology*, 19-48. https://doi.org/10.1007/978-3-030-91771-5_2

Ur Rashid, M., Ullah, I., Mehran, M., Baharom, M. N., & Khan, F. (2022). Techno-economic analysis of grid-connected hybrid renewable energy system for remote areas electrification using Homer pro. Journal of Electrical Engineering & Technology, 17(2), 981-997. https://doi.org/10.1007/s42835-021-00984-2

Yasin, A., & Alsayed, M. (2020). Optimization with excess electricity management of a PV, energy storage and diesel generator hybrid system using HOMER pro software. International Journal of Applied Power Engineering (IJAPE), 9(3), 267. https://doi.org/10.11591/ijape.v9.i3.pp267-283

Zieba Falama, R., Dawoua Kaoutoing, M., Kwefeu Mbakop, F., Dumbrava, V., Makloufi, S., Djongyang, N., Salah, C. B., & Doka, S. Y. (2022). A comparative study based on a techno-environmental-economic analysis of some hybrid grid-connected systems operating under electricity blackouts: A case study in Cameroon. *Energy Conversion and Management*, *251*, 114935. https://doi.org/10.1016/j.enconman.2021.114935

Žigman, D., Tomiša, T., & Osman, K. (2023). undefined. *Energies*, *16*(5), 2158. https://doi.org/10.3390/en16052158

APPENDICES

Appendix I: KPC Power Consumption Data

ELDORET TERMINAL POWER CONSUMPTION DATA														
YEAR	Jan	Feb	March	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total	Consumption
2022	9,506	8,961	8,501	9,609	9,052	8,624	8,638	9,769	9,473	9,560	8,867	9,303	109,883	kWh
	1,655,451	1,503,737	1,451,707	1,689,132	1,532,417	1,520,346	1,531,946	1,768,598	1,502,690	1,494,334	1,523,665	1,625,752	18,799,775	Kshs
2023	9,136	8,697	8,634	9,590	8,744	8,596	10,055	10,930	8,512	8,465	8,695	8,678	108,732	kWh
	1,720,053	1,300,233	1,338,640	1,447,877	1,358,849	1,339,354	1,292,806	1,331,894	1,509,390	1,638,422	1,650,447	1,682,207	17,610,172	Kshs

KPC ELDORET TOTAL ENERGY CONSUMPTION			
MONTH	GENSET	KP	TOTAL
JAN	484	9,136	9,620
FEB	528	8,697	9,225
MAR	1,056	8,634	9,690
APR	308	9,590	9,898
MAY	176	8,744	8,920
JUN	616	8,596	9,212
JUL	352	10,055	10,407
AUG	2,532	10,930	13,462
SEP	396	8,512	8,908
OCT	836	8,465	9,301
NOV	1,572	8,695	10,267
DEC	2,119	8,678	10,797
TOTAL	10,975	108,732	119,707

CAT 440kW SPECIFICATIONS	
Rated Power	550kVA
	440kW
	0.80Cos ǿ
Rated Voltage	400/230
Phase	3
Rated Frequency	50Hz
Rated Current	794A
RPM	1500
Mass	5230Kg

EMISSION (Nominal)^3	
NOx mg/nm^3	3689.4
CO mg/nm^3	168.2
HC mg/nm^3	5.8
PM mg/nm^3	7

LOAD PROFILE DATA	
Hour	**Power (kW)**
1	32.06
2	35.21
3	39.01
4	40.23
5	200.08
6	235.04
7	239.09
8	266.01
9	270.39
10	285.89
11	290.91
12	296.03
13	286.89
14	277.23
15	270.65
16	266.87
17	265.1
18	258.71
19	233.21
20	45.09
21	50.23
22	41.18
23	39.56
24	35.17

Throughput Performance per Product (m³)
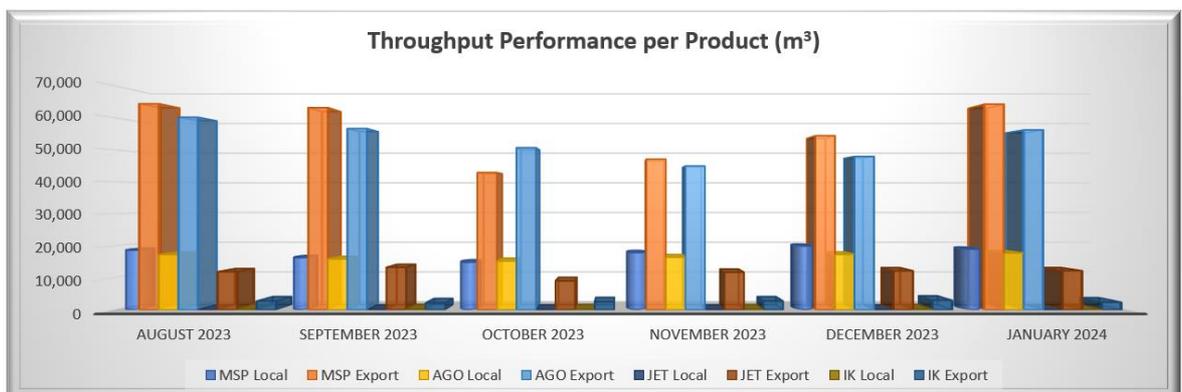
Appendix II: Simulation Input Data

Load Data Summary and Logger Settings

This appendix presents the summary statistics of the raw load data collected from the Kenya Pipeline Company (KPC) Eldoret Terminal; alongside detailed logger settings used for data acquisition.

A. Load Data Summary Statistics

The load data was continuously recorded at 1-minute intervals over a full month, covering the range of operational demands on the hybrid energy system analyzed. Key summary statistics for the electrical load profile are as follows:

B. Load Profile Characteristics

- The load profile exhibits typical industrial cyclical behaviour with significant peaks during operational hours and reduced demand overnight.

- Peak demand reaches up to 296.06 kW, driven by batch loading operations and pump activations.

- The base load fluctuates around 30 kW mostly representing standby and auxiliary system consumption.

- The load factor of 0.39 reflects moderate utilization, indicating opportunities for load shifting or energy storage integration.

C. Data Logger Equipment and Settings

Statistic	Value	Unit	Description
Minimum Load	30.00	kW	Lowest recorded instantaneous electrical load
Maximum Load	296.06	kW	Highest recorded instantaneous electrical load
Average (Mean) Load	98.47	kW	Mean electrical demand over the recording period
Median Load	85.20	kW	Middle value separating higher and lower loads
Load Standard Deviation	45.32	kW	Degree of variability in the load
Load Factor	0.39	-	Ratio of average to peak load; indicates load utilization efficiency
Peak Load Time Range	9:00 AM – 2:00 PM	Time frame	Time window with highest energy demand
Off-Peak Load Time Range	10:00 PM – 5:00 AM	Time frame	Time window with lowest energy demand

D. Data Processing and Quality Assurance

The raw electrical load data collected from the KPC Eldoret Terminal underwent thorough processing and quality assurance procedures to ensure accuracy and reliability for hybrid energy system simulations. The following steps were taken:

D.1 Outlier and Anomaly Removal

Detected erroneous spikes or dropouts were either removed or replaced with statistically consistent values using interpolation to maintain data integrity.

D.2 Temporal Aggregation for Simulation

While the original data was recorded at 1-minute intervals, such high-resolution data can be computationally intensive for long-term hybrid system simulations. Therefore:

- Aggregation to Hourly Averages: Load values were aggregated into hourly averages. This approach preserves diurnal load trends and peak characteristics critical for hybrid system performance evaluation while significantly reducing data volume.

- Validation of Aggregation: Statistical tests confirmed that hourly averages retained over 95% of the variance explained by the original 1-minute data for load characteristics like peak load and load factor.

The hourly resolution balances accuracy with computational efficiency, facilitating robust simulation of generation dispatch, battery cycling, and grid interactions.

The multi-step data quality assurance process ensured that the load dataset accurately reflects real operational conditions, free from distortions due to noise, missing data, or measurement errors. This cleaned and statistically sound dataset forms the basis for reliable hybrid energy system modelling, economic analysis, and decision-making for the KPC Eldoret Terminal.

Parameter	Value / Unit	Description	Source / Notes
Discount Rate (r)	10% (0.10)	Used for present value cost calculations	Standard for industrial projects
System Lifetime (N)	25 years	Economic lifetime of the hybrid system	Based on typical PV and battery lifespans
Electricity Tariff	KShs 20 / kWh	Retail tariff for grid electricity	EPRA 2023
Fuel Price	KShs 180 / litre (Plus or minus KShs 3 for sensitivity analysis)	Diesel cost per litre	EPRA 2023
Emission Factor (EF)	2.68 kg CO_2_22/litre	Diesel fuel emission factor	IPCC Guidelines
Operation & Maintenance (O&M)	2.5% of capital cost/year	Annual % cost for system upkeep	Industry average
Solar PV Capital Cost	KShs 70,000 / kW	Installed cost including panels and inverters	Market average for East Africa
Battery Capital Cost	KShs 50,000 / kWh	Installed battery pack cost	Lithium-ion battery prices
Diesel Generator Capital Cost	KShs 85,000 / kW	Initial cost of diesel genset	Supplier quotes
Replacement Cycle: Batteries	7 years	Replacement interval for battery packs	Manufacturer recommendation
Replacement Cycle: Diesel Engine	15 years	Diesel generator overhaul/replacement	Industry standard
Annual Fuel Consumption	Calculated via simulation	Dependent on load and genset dispatch	From operational data

Appendix III: Plagiarism Report

ISO 9001:2019 Certified Institution

THESIS WRITING COURSE

PLAGIARISM AWARENESS CERTIFICATE

This certificate is awarded to

FRANKSON MARINGA
ENG/MS/SEA/4871/23

In recognition for passing the University's plagiarism

Awareness test for Thesis **entitled**: **TECHNO-ECONOMIC ASSESSMENT OF GRID-SOLAR-DIESEL**
GENERATOR BATTERY HYBRID ENERGY SYSTEMS FOR KENYA PIPELINE COMPANY, ELDORET TERMINAL
with similarity index of 6% and striving to maintain academic integrity.
Word count:32143
Awarded by

Prof. Anne Syomwene Kisilu
CERM-ESA Project Leader   Date: 04/02//2025