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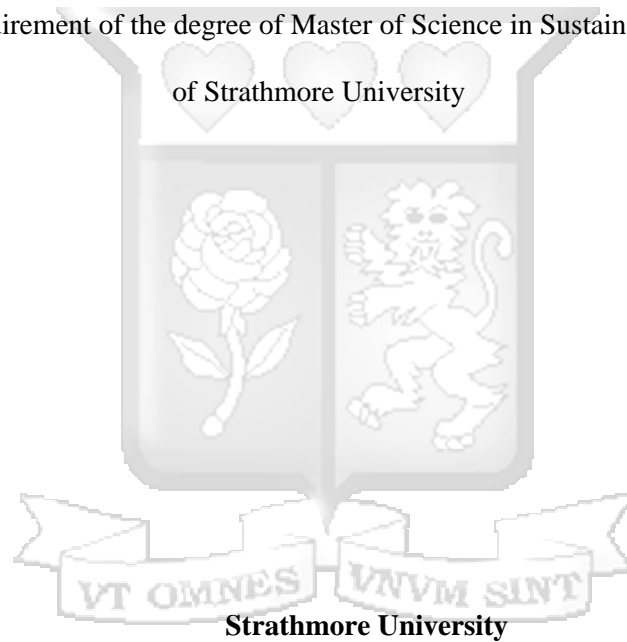
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Adoption of Behind-the-Meter Battery Storage Systems for Residences in Kenya

By

Anne Wacera Wambugu

A Thesis submitted to the School of Computing and Engineering Sciences in Partial
fulfilment for the Requirement of the degree of Master of Science in Sustainable Energy Transitions



March 2024

Declaration

I declare that this work has not been previously submitted and approved for the award of a degree by this or any other University. To the best of my knowledge and belief, the dissertation contains no material previously published or written by another person except where due reference is made in the proposal itself.

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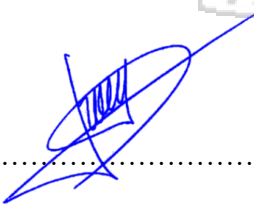

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Approval

This Thesis of Anne Wacera Wambugu has been submitted to the School of Computing and Engineering Sciences with my approval as the university supervisor.

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Dedication

To my dad who was so confident that I'd become an electrical engineer, that I became one. To my husband for the years of unwavering support that got me this far. To my colleagues, who have been ever present for brainstorming sessions.



Abstract

This research investigates the adoption of Behind-the-Meter Battery Energy Storage Systems (BTM BESS) in Kenyan urban households, focusing on mitigating the challenges posed by unreliable electricity supply, particularly for households engaged in work-from-home (WFH) activities. Electricity reliability challenges in Kenya's densely populated urban areas presents a significant challenge to the growing WFH workforce. While BTM BESS offer a potential solution for reliability, their affordability with grid-charging remains uncertain. The study develops a modified Levelized Cost of Storage (LCOS) model that integrates the WFH Reliability Metric and the WFH Income Value of Lost Load, offering a nuanced understanding of BTM BESS affordability tailored to the needs and economic realities of WFH individuals. Analysis reveals that BTM BESS becomes increasingly affordable as a reliability solution for WFH individuals, particularly those facing frequent outages or whose income is highly dependent on constant electricity access. This research contributes to the discourse on sustainable energy transitions by highlighting the economic and reliability advantages of BTM BESS for urban households in Kenya, proposing policy recommendations to enhance BTM BESS adoption and support the provision of reliable electricity as per Sustainable Development Goal 7 (SDG7).



Acknowledgements



Abbreviations and Acronyms

Ah	Ampere Hour
BESS	Battery Energy Storage System
BLCOS	Baseline Levelized Cost of Storage
BTM	Behind the Meter
BTM BESS	Behind-the-Meter Battery Energy Storage Systems
CAIFI	Customer Average Interruption Frequency Index
CAPEX	Capital Expenditure
CBK	Central Bank of Kenya
CEA	Collective Energy Africa
HDI	Human Development Index
IRENA	International Renewable Energy Agency
KNBS	Kenya National Bureau of Statistics
KPLC	Kenya Power and Lighting Company
kWh	Kilowatt hour(s)
LCC	Life cycle cost
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
LCPDP	Least Cost Power Development Plan
Li-ion	Lithium ion
MAIFI	Momentary Average Interruption Frequency Index
MLCOS	Modified Levelized Cost of Storage
NACOSTI	National Commission for Science, Technology and Innovation
NaS	Sodium Sulphur
Ni-Cd	Nickel–cadmium
PV	Photovoltaic
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SDG	Sustainable Development Goal
SGIP	Self-Generation Incentive Program
SU-IERC	Strathmore University Institutional Scientific and Ethics Review Committee
VOLL	Value of Lost Load
WFH	Work From Home

Definition of Key Terms

Term	Definition
Baseline LCOS	The standard formula for calculating the lifetime cost of BTM BESS per unit of usable energy delivered for that lifetime.
Behind-the-Meter Battery Energy Storage Systems	Refers to energy systems located on the customer's side of the utility meter. This means they are installed within homes, businesses, or other buildings rather than being part of the larger power grid.
Blackout or Outage	A period of time during which electrical power is unavailable from the central grid.
Energy	The capacity of a battery to deliver electrical power over a period of time, typically measured in kilowatt-hours (kWh).
Energy density	The amount of energy a battery can store relative to its size or weight.
Levelized cost of storage	A metric used to assess the lifetime cost of an energy storage system, typically BESS, per unit of usable energy delivered.
Life cycle cost	The cost of a battery system over its full life, including costs for research and development, testing, production, facilities, operations, maintenance, personnel, environmental compliance, and disposal.
Modified LCOS	A modification of the baseline LCOS that is adapted for assessing BTM BESS affordability for WFH individuals.
Reliability	The ability of a power system to deliver electricity consistently and with minimal interruptions

Term	Definition
The Grid	A complex network of power system components and distribution lines that deliver electricity from where it's generated to homes
Work From Home	A flexible work arrangement where employees perform their job duties from a location outside the traditional office, typically their own home.
WFH Income VOLL	A metric that quantifies the potential income lost by a WFH individual due to a single power outage. It factors in hourly income, the outage's duration, and its timing relative to peak working hours.
WFH Reliability Metric	A metric designed to assess the cumulative impact of power outages on the income-generating capacity of WFH individuals over a defined period. It considers outage duration, frequency, and timing (relative to work hours).

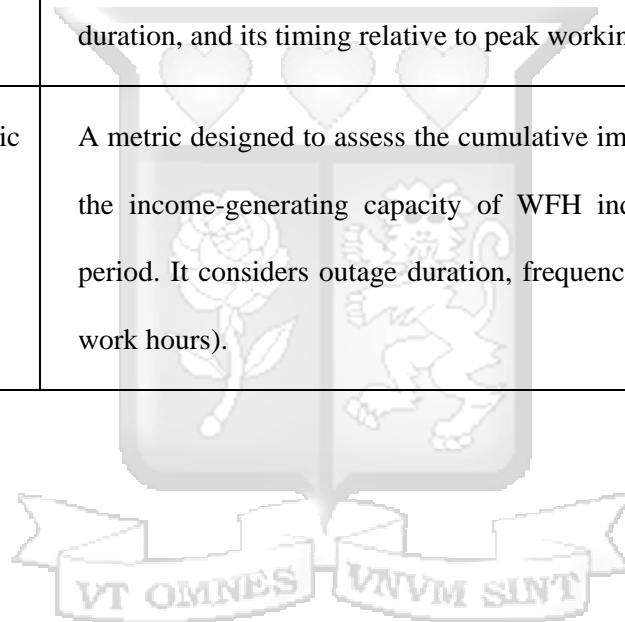


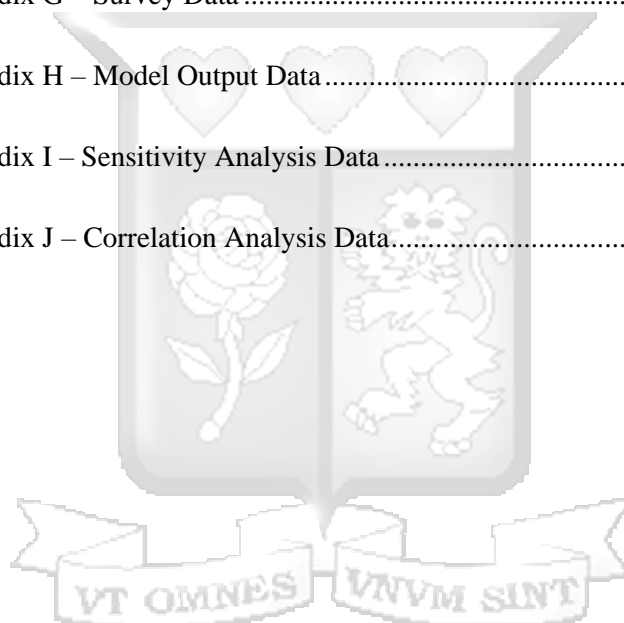
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CHAPTER ONE

1. Introduction

1.1 Research Background

The 2019 Kenyan census which surveyed 12 million households revealed that 50.4% of households utilize grid electricity for lighting, 19.3% rely on solar energy, and 30.3% remain without electricity access. Grid electricity connection rate in urban areas stands at 88.4% compared to 26% in rural settings, with 69.8% of all households enduring unreliable electricity supply (KNBS, 2019a). This disparity underscores a critical distinction between electricity access and reliability, with the latter being indispensable for catalysing economic development (Eric Hsu & Mitchell VanVuren, 2023).

The multi-tier framework posited by (Bhatia & Angelou, 2015), advocates for a holistic consideration of access that includes reliability, thus reframing the narrative around electricity access. This approach is particularly relevant in the urban areas in Kenya, where the combination of a growing population and inadequate grid infrastructure leads to frequent low voltage events and outages. The primary electricity provider, Kenya Power & Lighting Company (KPLC), faces financial constraints which restrict its ability to fix these reliability issues, and efforts to attract private sector investment in the sector have been unsuccessful (Newell & Phillips, 2016). Given the critical role that urban centers play in economic advancement, the reliability issue in urban areas should be resolved despite constrained electrification resources (Gertler et al., 2017).

The evolution of job markets towards digital domains further amplifies the need for reliable electricity in urban settings since digital infrastructure inherently relies on electricity (Melia, 2020). The proliferation of remote work, with the home office increasingly substituting the traditional work office further necessitates reliable electricity. Therefore, while the digital transition presents Kenyan workers with opportunities to access digital employment both domestically and internationally, the absence of reliable electricity renders these prospects unattainable (Guma, 2021) (Carl et al., 2016).

The emergence of behind-the-meter battery energy storage systems (BTM BESS) offers a decentralized solution for households to mitigate against reliability issues. Technological advancements and cost reductions in battery storage have facilitated the entry of BTM BESS into the consumer market, with lithium-ion technology emerging dominant due to its high energy density (Comello & Reichelstein, 2019) (IRENA, 2019). While characterized by high initial investment, BTM BESS have minimal operational and maintenance requirements. They also contrast with conventional generators in their environmental advantages such as noise levels (Wehner & Daim, 2019).

Like many urban centers across the globe, Kenya's urban landscape is increasingly characterized by vertical growth, with more residents moving into apartments rather than standalone homes. For urban dwellers living in apartments, BTM BESS presents an optimal reliability solution without the spatial demands associated with alternatives such as generators. The use of solar photovoltaic systems to charge BTM BESS in such scenarios is also limited by spatial constraints thus grid-charging emerges as the only viable alternative. For this reason, households should carefully consider the advantages of enhanced reliability against increased electricity costs, given the high cost of charging with grid electricity (Doroudchi et al., 2015) (Issa et al., 2019).

This study introduces a method for assessing the affordability of BTM BESS for households who work-from-home (WFH) and live in space constrained environments such as apartments. This is achieved by modifying the Levelized Cost of Storage (LCOS) for the households to incorporate considerations of electricity reliability into the computation.

1.2 Problem Statement

In Kenya, urban households face challenges due to unreliable electricity supply as it impacts productivity, particularly under the increasing prevalence of work-from-home (WFH) arrangements. Behind-the-Meter Battery Energy Storage Systems (BTM BESS) offer a promising solution to enhance electricity reliability but face adoption barriers such as cost concerns and uncertain economic benefits. This research aims to evaluate the affordability of BTM BESS given reliability issues, in contexts where household income is dependent on reliable electricity. It does this by calculating the Levelized Cost of Storage (LCOS) for the households then incorporating considerations of electricity reliability into the computation. The goal of the research is to provide information to urban households on the affordability of a BTM BESS tailored to their energy needs, wants and economic realities. The study also seeks to identify regulatory adjustments or changes that can improve the affordability of BTM BESS.

1.3 Research Objectives

1.3.1 General Objectives

This research aims to evaluate the affordability of BTM BESS by incorporating electricity reliability into LCOS in scenarios where household income is dependent on reliable electricity.

1.3.2 Specific Objectives.

This research seeks:

- To develop the WFH reliability metric.
- To develop a modified LCOS based on the WFH reliability metric.
- To recommend policies that can enhance the affordability of BTM BESS.

1.4 Research Hypothesis

The research hypothesis is - For households whose income is reliant on the reliability of electricity supply at home, such as WFH arrangements, BTM BESS is a cost-effective solution to improve reliability in spite of grid charging costs.

1.5 Justification

A lack of electricity reliability at a household level in urban environments is a challenge to individual productivity, thus a liability for the Kenyan economy. In line with Sustainable Development Goal 7, which emphasizes reliable and affordable energy, this research proposes the use of BTM BESS as a solution to reliability in urban settings. This strategy will have an added advantage of reducing the need for extensive investment by the financially constrained grid provider. The research achieves this by calculating an LCOS that accounts for electricity reliability.

1.6 Scope

This study concentrates on examining the adoption of BTM BESS by urban households residing in apartments within Nairobi County. The research specifically explores the financial feasibility, technical considerations, and regulatory environment influencing the adoption of BTM BESS. It aims to the use of BTM BESS to address electricity reliability issues faced by the study demography, considering their unique living conditions and energy needs.

1.7 Ethics in Research

The research permit application process was successfully completed. Necessary documents were submitted to and reviewed by the Strathmore University Institutional Scientific and Ethics Review Committee (SU-IERC), which granted Ethical Approval based on the project's ethical and scientific merits as shown in the document in Appendix A. This Ethical Approval facilitated the acquisition of a research license from the National Commission for Science, Technology, and Innovation (NACOSTI), ensuring the research adheres to the standards protecting participants' rights, safety, and dignity. As per the research license in Appendix B, the study is authorized to happen in specified regions, including Nairobi, underlining the project's compliance with regulatory requirements and ethical standards.

CHAPTER TWO

2. Literature Review

2.1 Introduction

This chapter explores the history of BTM BESS, the policy landscape for the technology in Kenya, and the economic viability for WFH consumers. The chapter also examines the challenges of unreliable electricity in Nairobi, contrasting BTM BESS with existing backup solutions. It then identifies gaps in existing literature regarding LCOS and reliability metrics to serve specific needs of WFH individuals in the face of unreliable electricity.

2.2 Empirical Review

2.2.1 *The History of BTM BESS*

BTM BESS has evolved significantly over the past few decades, driven by advancements in battery technology and a growing focus on renewable energy sources. Initially, energy storage was limited due to high costs and technological constraints but with the advent of electrochemical storage solutions, especially lithium-ion batteries, the landscape began to change. These batteries, characterized by high energy density and efficiency, became increasingly affordable, driving wider adoption for residential and commercial applications. In recent years, the implementation of BTM BESS has been further propelled by the decreasing costs of solar photovoltaic (PV) systems, allowing for the integration of solar energy with storage solutions. (Wehner & Daim, 2019)

Regulatory trends and incentives have played a crucial role in promoting BTM BESS adoption. A notable example is a US utility's innovative approach of distributing batteries to customers to prevent outages, showcasing the transition towards utilizing BTM BESS for grid stability and reliability (Penn, 2023). Another initiative, California's Self-Generation Incentive Program (SGIP), is providing financial incentives for energy storage installation thus lowering the barrier to entry for consumers (Wehner & Daim, 2019). Moreover, countries like Australia and Germany have conducted studies on home battery energy storage, which have illustrated the potential

of BTM BESS to increase self-sufficiency and reduce reliance on traditional energy sources (Baumgarte et al., 2020).

2.2.2 State of Policy Related to BTM BESS in Kenya

Existing Kenyan policies, as demonstrated by the supply-side focus of the Least Cost Power Development Plan (LCPDP) (Ministry of Energy, 2021), do not comprehensively address, or support the use of BTM BESS. This outlook emphasizes grid-scale batteries, neglecting the potential of widespread BTM BESS adoption. For instance, findings from Indonesia indicate that BTM BESS can offer substantial supply-side benefits like enhancing renewable energy integration (Feisal et al., 2020), improving grid stability (Knap et al., 2014), and mitigating peak demand (Leadbetter & Swan, 2012). These benefits highlight the missed opportunities in the current Kenyan policy outlook.

Despite this, the global trend of decreasing costs and improved accessibility of BTM BESS (Wehner & Daim, 2019), coupled with rising household incomes in Kenya (KNBS, 2019b), suggests a growing potential for BTM BESS uptake in Kenya. It is imperative that national policies evolve to incentivize BTM BESS adoption, harnessing both supply-side benefits such as reducing the need for investment in peaking plants (Gertler et al., 2017) and demand-side advantages such as improved reliability and productivity for Kenyans. This economic outlook is reliant on proper policy interventions such as subsidies to reach its full potential (Shuai & Raufer, 2021).

2.2.3 The Economic Viability of BTM BESS

The economic viability and usage of BTM BESS by consumers is determined by different factors. Key factors include the reduction in electricity bills through peak shaving where peak pricing exists, the potential for arbitrage by storing energy when prices are low and using it when prices are high, and incentives such as subsidies or feed-in tariffs for renewable energy generation. In Germany, the attractiveness of BTM BESS stems from a significant gap between retail rates and feed-in tariffs, making BTM BESS a financially sound choice for energy storage (Comello & Reichelstein, 2019). Similarly, in California and China, the economic feasibility of these systems is bolstered by state and national subsidy programs, respectively. (Wehner & Daim, 2019)(Shuai & Raufer, 2021)

In markets where grid reliability issues are prevalent, BTM BESS provides reliability, which enhances their economic attractiveness. In South Africa, load shedding has increased the demand for energy storage solutions (ESI Africa, 2022) and battery systems colloquially known as “inverters” are a common solution to blackouts in Nepal (Hoffmann, 2020). This points to BTM BESS being a critical element of urban energy frameworks, especially within densely populated cities that grapple with the challenge of reliably meeting energy demand. In such environments plagued by poor electricity reliability, the economic viability of BTM BESS can be expected to increase.

Electricity access studies in Sub-Saharan Africa understandably prioritize urban poor and other low-income populations, aiming to address the complex balance of sustainability, security, and affordability. However, higher income households also warrant attention in electricity research, as they too may face electricity access challenges such as reliability issues. In the case of BTM BESS, given the high system costs, higher-income households might be more inclined to adopt BTM BESS compared to low-income urban populations (Wehner & Daim, 2019). This information is crucial for policymakers as they develop strategies to promote BTM BESS adoption. It can help them facilitate adoption by incentivizing business models that support its uptake by the most relevant demographic (NREL, 2021).

2.2.4 Electricity Reliability in Nairobi

In Nairobi, urban households frequently encounter electricity outages, predominantly between 9 am and 7 pm, due to peak load demands leading to system overloading (Taneja, 2017). In response to these outages, electricity consumers resort to diesel generators as a backup power source, despite their high operational and maintenance costs, rapid depreciation, and significant space requirements (Issa et al., 2019). Solar systems, which offer substantially higher reliability than the local grid's performance, are increasingly becoming a go-to alternative (Ferrall et al., 2022).

In countries like Nigeria, where diesel generators are still prevalent, the adoption of solar PV combined with storage systems presents an economic option, advocating for a shift towards renewable solutions (Babajide & Brito, 2021). Moreover, (Borujeni et al., 2022) identified that the cost associated with solar and battery storage systems is 25% less than that of utilizing diesel generators. A

notable challenge with both diesel generators and solar photovoltaics remains their considerable space requirements, a significant issue for urban households, especially for those residing in apartments (Menkiti & Agunwamba, 2015); (Rao & Sastri, 1987). To address reliability concerns within these spatial constraints, BTM BESS supplemented by grid charging, emerges as a feasible solution for enhancing power reliability.

2.2.5 *Comparative Analysis*

2.2.5.1 *Lithium-Ion vs Generators*

Lithium-ion offers cleaner, quieter, and maintenance-free operation than generators. This makes it ideal for indoor use, such as in apartment buildings. They also exhibit efficient energy storage and release capabilities and support renewable integration thus enhancing sustainability. Conversely, generators often run on fossil fuels, providing extensive runtime but incurring environmental and noise costs. (Babajide & Brito, 2021; Collath et al., 2022)

2.2.5.2 *Lithium-Ion vs Super Capacitors*

Lithium-ion batteries excel in energy density, typically offering 10 times greater storage capacity compared to supercapacitors. This makes them ideal for applications requiring sustained power over longer periods, such as providing backup energy for electronics during extended power outages i.e. BTM BESS applications (Collath et al., 2022; Moradi et al., 2022). Supercapacitors, on the other hand, boast superior power density, allowing for rapid charge and discharge cycles. This makes them well-suited for scenarios requiring high bursts of energy for short durations. Their longevity and short-term energy release capabilities are advantageous in applications such as providing short-term backup power for critical systems or powering power tools. (Argyrou et al., 2021; Shah et al., 2023)






2.2.5.3 *Lithium-Ion vs Lead Acid*

Lithium-ion batteries offer several advantages over lead-acid batteries. They offer significantly higher energy density (up to twice the capacity), leading to a smaller footprint for equivalent storage. Additionally, lithium-ion batteries demonstrate a longer lifespan and provide greater efficiency during charging and discharging cycles, translating to less energy wasted. While the

upfront cost of lithium-ion batteries is generally higher, their superior durability and performance contribute to a lower total cost of ownership over time due to reduced maintenance requirements and replacement frequency. Lead-acid batteries, while initially cheaper, have a lower energy density which necessitates more space for equivalent storage capacity, which can be a significant disadvantage in space-constrained environments like urban households. (Makola et al., 2023; Yudhistira et al., 2022)

2.2.5.4 Lithium-Ion for BTM BESS in Kenya

Lithium-ion batteries dominate the BTM BESS landscape globally (Wehner & Daim, 2019) driven by key advantages discussed above. This is evidenced by the significant lead they hold in energy density over other options illustrated in Figure 2-1 (Asian Development Bank, 2018), thus they offer a compelling solution for BTM BESS applications.

	Energy density (kW/kg)	Round Trip Efficiency (%)	Life Span (years)	Eco-friendliness
 Li-ion	1st 150-250	1st 95	1st 10-15	1st Yes
 NaS	2nd 125-150	2nd 75-85	2nd 10-15	2nd No
 Flow	3rd 60-80	3rd 70-75	4th 5-10	4th No
 Ni-Cd	4th 40-60	4th 60-80	3rd 10-15	3rd No
 Lead Acid	5th 30-50	5th 60-70	5th 3-6	5th No

Li-ion = lithium-ion, Na-S = sodium-sulfur, Ni-Cd = nickel-cadmium.

Figure 2-1: Characteristics of different battery technologies.

(Source: Asian Development Bank, 2018)

BTM BESS packs are made and sold in standard sizes which are determined by the manufacturers (Wehner & Daim, 2019). To gain an outlook into the Kenyan ecosystem, product comparisons presented in Table 2-1 were made by scrapping data from major energy solutions retailers including [Center for Alternative Technologies\(CAT\)](#), [Davis and Shirtliff](#), [GoSolar](#), [Generators Kenya](#). The batteries chosen were rated at 5kWh based on the total daily average Kenyan household needs according to (Osiolo et al., 2017).

Table 2-1: Backup solutions available for apartment dwellers in Kenya

Battery Type	Cost	Availability	Efficiency	Durability	Scalability	Noise Levels	Space Requirements
Lithium-ion	High	High	High (90-95%)	Moderate (5-10 years)	High	Low	Low
Lead acid	Low	High	High (80-85%)	Low (3-7 years)	Moderate	Low	Large

The sizes available from a vendor named GT Powertank and their respective costs are as shown in Table 7-1 in Appendix C. The sizes available for sale in Kenya from a vendor named Collective Energy Africa and Ecoflow their respective costs are as shown in Table 2-2 (Collective Energy Africa, 2022):

Table 2-2: Sizes and costs of Li-ion batteries sold by two vendors.

Vendor Name	Capacity in kWh	Battery Cost
Ecoflow	0.256	KES 45000
	0.512	KES 70000
	0.768	KES 85000
	1.024	KES 148000
	1.612	KES 233500
	2.016	KES 279500
	3.6	KES 310000
Collective Energy Africa	5	1,950 USD
	10.24	7,700 USD
	15.4	8,800 USD

2.3 Theoretical Framework

2.3.1 Levelized Cost of Storage

A crucial step in implementing BTM BESS is the selection of the optimal battery capacity or size. The reviewed literature reveals a variety of methods for battery capacity optimization, including probabilistic approaches (Carpinelli et al., 2019), analytical methods (Tounsi Fokui et al., 2021), direct-search based methods (Hannan et al., 2021), nature inspired methods (Zhang et al., 2022), simulation tools like MATLAB and HOMER Grid (Richard et al., 2020); (Tsai et al., 2020) and hybrid methods that combine techniques (Elkazaz et al., 2020). While these techniques are valuable for determining the required capacity of BTM BESS, ensuring the affordability of BTM BESS requires the assessment of economic viability.

Levelized Cost of Energy (LCOE), which is referred to as the Levelized Cost of Storage (LCOS) for battery energy storage systems (Comello & Reichelstein, 2019; Xu et al., 2022), is a valuable metric for assessing the economic viability of energy systems (Aldersey-Williams & Rubert, 2019) thus is used for energy storage systems like BTM BESS (Hoffmann, 2020; Richard et al., 2020; Tsai et al., 2020; Yang et al., 2018). Yang et al., 2018 and Tsai et al., 2020 utilize LCOE across different BESS configurations, from residential to grid-scale BESS, demonstrating the metric's adaptability to different capacity requirements. Comello & Reichelstein, 2019 take a more storage centric approach which focuses on the minimum price per kWh needed for the storage system to be economically viable.

The literature revealed a distinction between optimizing battery capacity (focusing on storage potential) vs optimizing financial indicators (prioritizing investment returns) and highlighted the complex interplay between technical and financial optimizations (Hannan et al., 2021; Yang et al., 2018). The reviewed studies that engaged in both types of optimizations typically utilized the same software or tool for both battery capacity optimization and financial optimization tasks, suggesting that it is common practice to employ a single tool or software to address both dimensions. This approach points to the importance of integrating tools in optimizing both the capacity and economic viability of BTM BESS.

2.3.1.1 LCOS Equation

As per the literature, the LCOS can be represented as follows:

$$LCOS = \frac{CAPEX + \sum_{n=1}^N \frac{OPEX_n}{(1+r)^n} + \sum_{n=1}^N \frac{Tax_n}{(1+r)^n} + \sum_{n=1}^N \frac{Chg_n}{(1+r)^n} + C_{rep} + C_{res}}{\sum_{n=1}^N \frac{DChg_n}{(1+r)^n}} \quad (\text{Xu et al., 2022}) \quad \text{Equation 2-1}$$

Where:

- CAPEX is the capital expenditure on the battery system.
- $OPEX_n$ is the annual value of the operation and maintenance costs.
- Tax_n is the annual tax amount paid on the battery.
- Chg_n is the annual value of the charging costs.
- $DChg_n$ is the annual discharge value of the battery.
- C_{rep} is the discounted value of the replacement cost of batteries.
- C_{res} is the discounted residual value of the batteries.

This LCOS equation accounts for taxes which is a relevant modification that will be used in this research.

2.3.2 *Measuring Reliability*

2.3.2.1 *Reliability Indices*

In the face of unreliable grids, decentralized backup systems such as BTM BESS, offer a lifeline for maintaining electricity during blackouts, ensuring the continued operation of businesses and essential services like hospitals (Hoffmann, 2020). For centralized grids, utilities use metrics such as the System Average Interruption Duration Index (SAIDI), measuring outage duration, and the System Average Interruption Frequency Index (SAIFI), measuring outage frequency, to guide infrastructure investments (Ferrall et al., 2022). Ferrall et al., 2022 highlight key limitations of SAIDI and SAIFI metrics as follows:

1. SAIDI and SAIFI are system-wide averages hence obscure the varying experiences of individual households. Customers with reliable power and those facing frequent outages can fall under the same SAIDI score, blurring individual needs.
2. SAIFI fails to distinguish between brief disruptions and extended power cuts. This is especially problematic in WFH scenarios, where short, frequent outages can be more disruptive than a single, longer outage.

Ayaburi et al., 2020 corroborate this by examining the limitations of traditional reliability metrics in accurately reflecting the consumer experience, especially in areas with high access rates but poor quality of service. The authors acknowledge the complexity of reliability beyond mere access, emphasizing the need for metrics that better align with the realities of electricity usage in different contexts. Precedence for battery capacity optimization based on system reliability exists (Sakulsuteebut & Audomvingseree, 2018), thus a consumer facing metric will be developed in this research using the details found in traditional metrics, as shown in Table 2-3.

Table 2-3: Summary of reliability indices

Metric	What it Measures	Summary of Measurement
SAIDI	Average total outage duration experienced by a customer per year	Focuses on the cumulative burden of outages
SAIFI	Average frequency of interruptions a customer experiences per year	Indicates how often power goes out, regardless of duration
MAIFI	Average frequency of momentary interruptions (under 5 mins) a customer experiences per year	Captures the frequency of very brief disruptions
CAIFI	Average frequency of sustained interruptions (over a threshold) a customer experiences per year	Counts only longer, more disruptive outages

2.3.2.2 Value of Lost Load

Understanding the financial benefits of improving grid reliability requires quantifying the Value of Lost Load (VOLL), which represents the cost consumers are willing to pay to avoid power disruptions. VOLL plays a vital role in determining the economic feasibility of investments aimed at boosting power system reliability. Beyond its use in infrastructure planning, VOLL functions as a gauge of society's overall valuation of energy security. Quantifying VOLL enables the shaping of energy policy decisions and informs investments that ensure a stable and reliable energy supply (Gorman, 2022).

Gorman, 2022, acknowledges the importance of considering factors such as the electricity consumption context, geographic location, outage timing and duration when estimating VOLL. Despite that, VOLL typically focuses on the cost that a utility incurs as a result of an outage, such as lost revenue, and repair costs thus does not capture an individual consumer's experience. Despite that, VOLL as a concept provides a framework for developing more nuanced metrics (Bouman et al., 2018).

A common assumption in VOLL calculation is that it is difficult to quantify. However, where lost income is directly tied to power disruptions i.e. a lost hour of work has an associated cost in the form of lost earnings. Therefore, WFH presents an opportunity to refine VOLL calculations to represent the economic consequences of power outages for the growing WFH workforce. Importantly,

there is precedent for adjusting and refining VOLL calculations using outage duration, time of day, notification period, and consumer type (Marchisio et al., 2022).

2.4 Gaps in the Literature

2.4.1 *Levelized Cost of Storage*

The traditional LCOS model provides a framework for the financial viability assessment of BTM BESS. However, a review of literature yielded limited results addressing the economic impact of unreliable power for WFH individuals. To address this gap, this research develops the WFH reliability metric which is then incorporated into the WFH income VOLL which quantifies the potential income loss WFH individuals face due to outages. WFH income VOLL is then incorporated into the traditional (or baseline) LCOS model, creating a modified LCOS, which is an LCOS that integrates income lost during outages in WFH situations. This modified LCOS allows for a more nuanced evaluation of BESS affordability tailored to the needs of WFH users.

2.4.2 *Measuring Reliability*

Traditional reliability metrics, like those presented in Table 2-3, focus primarily on outage duration and frequency. Metrics such as SAIDI and SAIFI can be calculated for specific time periods thus indirectly provide the impact of outage timing but do not capture the experiences of individual households thus WFH individuals who face potential income loss during outages. Existing VOLL metrics are designed to assess outage-related income loss factor in outage duration, time of day, and compensation for outages but are also calculated from a utility's perspective. Therefore, there's a gap in current metrics when it comes to capturing the WFH experience and the associated income loss from outages in this context. To address this shortcoming, the modified LCOS incorporates functions that consider outage duration, frequency and income lost in WFH situations. By including these elements, the modified LCOS provides a more nuanced assessment of the affordability of BTM BESS for WFH populations.

2.4.3 Summary of Gaps

Table 2-4: Summary of gaps in literature

Area of Focus	Question	Gap in Existing Knowledge	Addressing the Gap
Methodology for Assessing Affordability	Does the standard LCOS formula sufficiently capture the economic benefits of enhanced reliability for households who WFH, thus depend on electricity for income?	Current LCOS calculations do not fully reflect the income-generation benefits of reliability in work-from-home settings.	This thesis proposes a modified LCOS model that accounts for the benefits of enhanced reliability for households who WFH, thus depend on electricity for income
Consumer-Centric Reliability	How can one represent unreliable electricity in households who WFH, thus depend on electricity for income?	Current reliability indices are system-level metrics such as SAIDI, SAIFI and VOLL. This is despite the difference between system level reliability and individual level reliability calculation.	This thesis develops simple formulae for individual level reliability calculation and incorporate that into LCOS.
Policy and Regulatory Environment	What policy adjustments could accelerate BTM BESS adoption and improve affordability, specifically urban apartment dwellers?	Existing research does not focus on the unique challenges of this group in the Kenyan context e.g., grid-charging necessity and space constraints.	This thesis offers policy recommendations that address barriers and incentives, tailored to this demographic's needs.

2.5 Conceptual Framework

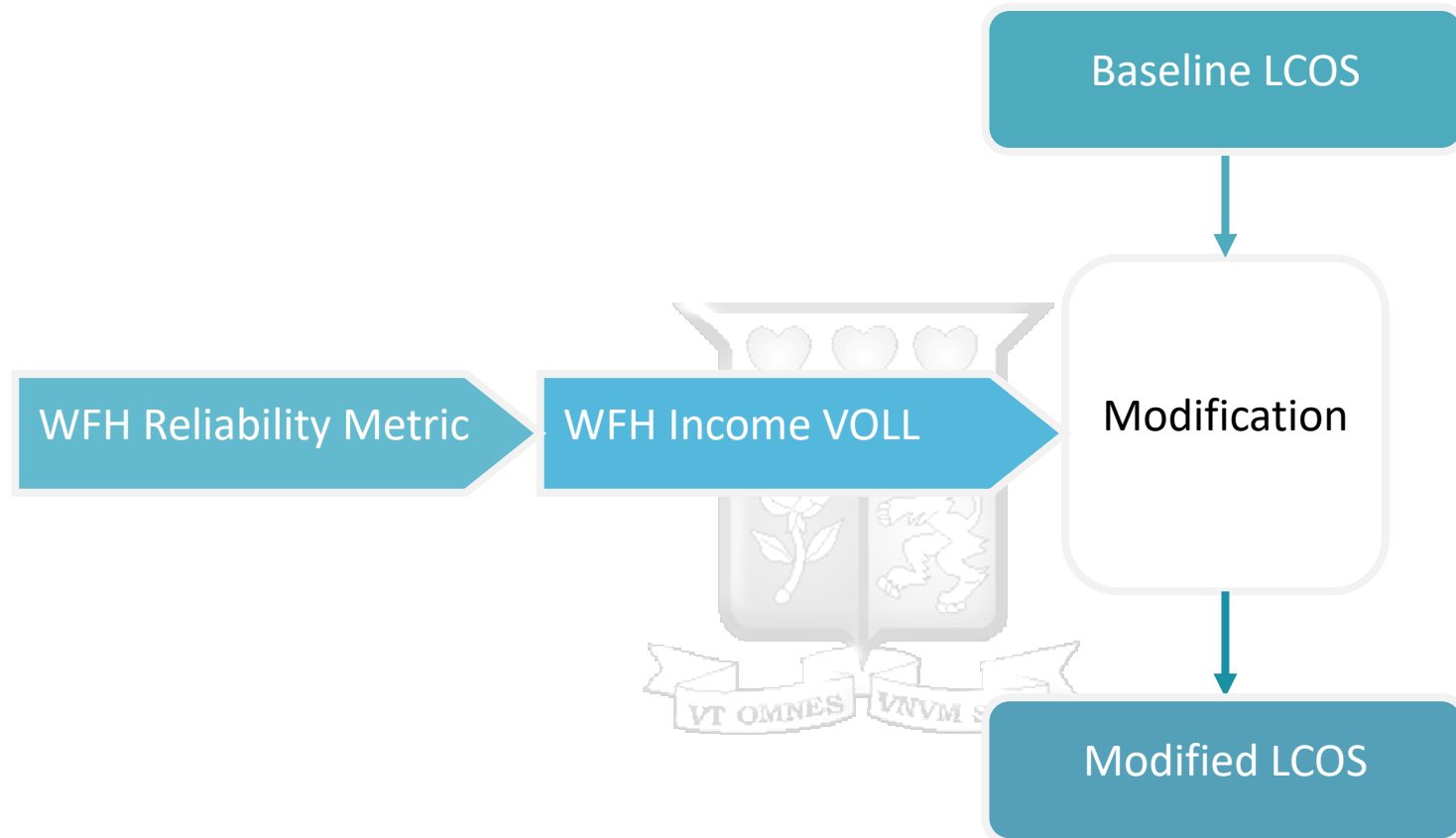


Figure 2-2: Conceptual framework.

CHAPTER THREE

3. Research Methodology

3.1 Introduction

This chapter introduces the research methodology that will be used to address the study objectives. A mixed-methods design guided the research, incorporating both quantitative and qualitative data to create a robust and contextually relevant tool. This methodology was supported by the philosophies of pragmatism and critical realism, emphasizing problem-solving and situating the tool within the socioeconomic realities of WFH households. Data collection, analysis methods, tool development, and validation strategies are also detailed.

3.2 Research Philosophy

This research employed a combined approach of pragmatism and critical realism, which acted as an influence on the choice of methodologies employed within the research. Pragmatism's emphasis on problem-solving was seen to be essential for the tool development, to address the challenges faced by WFH households in Nairobi. Thus, quantitative data informed the core of the tool's calculations, in line with a pragmatic focus on measurable results.

The tool isn't entirely engineering as it is built on a technoeconomic foundation, the LCOS equation, with socioeconomic modifications, WFH VOLL. Therefore, critical realism was adopted to situate the tool within socioeconomic contexts. Qualitative methods were used to understand the subjective experiences of WFH households when it comes to reliability, in line with critical realism.

3.3 Research Design

3.3.1 Data Collection

This research adopted a mixed-methods approach, collecting both quantitative and qualitative data. This approach aligns with the pragmatic philosophy, focusing on the development of a practical affordability assessment tool grounded in real-world scenarios. Data collection involved both primary and secondary sources. Primary data was collected using the survey in Appendix F which was

administered online, and secondary data was collected through desk research (e.g., BTM BESS prices). The following information was sought during data collection:

- Reliability issues experienced by households.
- Income from WFH activities.
- BTM BESS ownership

The collected data was then used to inform the development of the tool, as described in Section 3.4.

3.3.2 *Target Population and Sample*

This research focused on middle-income households residing in apartments within Nairobi County, Kenya. Specifically, the study targeted individuals and families who rely on work-from-home (WFH) arrangements as a significant source of income. Income levels were defined according to the classifications established by the Kenya National Bureau of Statistics (KNBS). According to the KNBS, Nairobi housed roughly 1.5 million households in 2019, with approximately 70.89% categorized as low-income. This study targeted the remaining 20.21%, constituting an estimated 300,000 middle-income households (KNBS, 2019a).

While the target population was estimated at 300,000 households, financial constraints necessitated a smaller sample size. The Yamane formula was used to calculate an appropriate sample:

$$n_y = \frac{N}{1 + Ne^2} \quad (\text{Yamane, 1967}) \quad \text{Equation 3-1}$$

Where:

- n_y is the Yamane sample size.
- N is the total population size (300,000).
- e is the margin of error (0.05 for a 95% confidence level).

Using this formula, a sample size of 399 households was determined.

To further accommodate the financial constraints, the study employed a combination of convenience and snowball sampling techniques. Participants were recruited through various channels, including online communities catering to middle-income Nairobi, apartment dwellers, and work-from-home professionals. Additionally, participants were encouraged to refer others within their networks who met the study's criteria. Efforts were made to diversify the sample as much as possible within these sampling approaches. In the survey, a screening page was utilized to ensure participants met the target population criteria.

3.3.3 Data Analysis

Raw survey responses were collected anonymized, cleaned and analysed using Microsoft Excel. The resulting data can be found in Appendix G. Data cleaning involved identifying and correcting inconsistencies, missing values, and outliers to improve data quality. Statistical functions within Excel were employed to calculate descriptive statistics such as averages and percentages. Additionally, Excel's charting and graphing capabilities were utilized to visualize data patterns and trends, helping to identify any significant correlations or relationships among variables relevant to BTM BESS affordability and household reliability needs.

3.4 Tool Development and Validation

The modified LCOS tool builds upon the baseline (or traditional) LCOS model, enhancing its ability to assess BTM BESS financial viability for WFH individuals. This enhancement is achieved by integrating two novel metrics: the WFH Reliability Metric and the WFH Income VOLL. These metrics quantify the financial impact of power outages on WFH income generation. The specific equations underpinning the developed tool are detailed in this section, along with a visual representation in Figure 3-1.

3.4.1 Equations

3.4.1.1 Battery Capacity

Energy consumption scenarios in Appendix D were considered for the baseline and modified LCOS.

3.4.1.2 Baseline LCOS Equation

The LCOS equation, Equation 2-1, was modified for use as follows:

$$LCOS = \frac{CAPEX + \sum_{n=1}^N \frac{Chg}{(1+r)^n} + C_{res}}{\sum_{n=1}^N \frac{Dchg}{(1+r)^n}} \quad \text{Equation 3-2}$$

Where:

- CAPEX is the Capital expenditure on the battery system.
- Chg is the annual value of charging costs.
- C_{res} is the discounted residual value of the battery.
- $Dchg$ is the annual discharged energy.
- r is the discount rate.
- n is the lifetime of the battery.

3.4.1.3 Modified LCOS Equation

The LCOS equation, Equation 2-1, was modified for use as follows:

$$LCOS = \frac{CAPEX + \sum_{n=1}^N \frac{Chg}{(1+r)^n} + \sum_{n=1}^N \frac{VOLL}{(1+r)^n} + C_{res}}{\sum_{n=1}^N \frac{Dchg}{(1+r)^n}} \quad \text{Equation 3-3}$$

Where:

- CAPEX is the Capital expenditure on the battery system.
- Chg is the annual value of charging costs.
- $VOLL$ is the annual WFH Income VOLL
- C_{res} is the discounted residual value of the battery.
- $Dchg$ is the annual discharged energy.
- r is the discount rate.
- n is the lifetime of the battery.

3.4.1.4 WFH Reliability Metric

To quantify the impact of frequent power outages on income generation for WFH individuals, a metric called the WFH Reliability Metric was developed. The metric considers three factors in the measurement of reliability: outage timing, outage duration and outage frequency. Its calculation is as follows:

$$R_w = \frac{O_{dy} * O_{hr}}{H_w} \leq 1 \quad \text{Equation 3-4}$$

Where:

- **R_w** is the weekly WFH Reliability Metric.
- **O_{dy}** is the frequency in outage days per week.
- **O_{hr}** is the duration in outage hours per day.
- **H_w** is the weekly WFH hours.

3.4.1.5 WFH Income VOLL

Assessing the true economic cost of unreliable power for WFH individuals requires a metric that integrates both income loss potential and reliability. To achieve this, the weekly income and WFH reliability metric were combined to form the WFH income VOLL as follows:

$$VOLL = R_w * I_w \quad \text{Equation 3-5}$$

Where:

- **$VOLL$** is the WFH income VOLL.
- **R_w** is the weekly WFH reliability metric.
- **I_w** is the weekly income.

Below is a mind map of the modified LCOS tool that includes its relationship to baseline LCOS. A detailed map of WFH income VOLL can be found in Appendix E

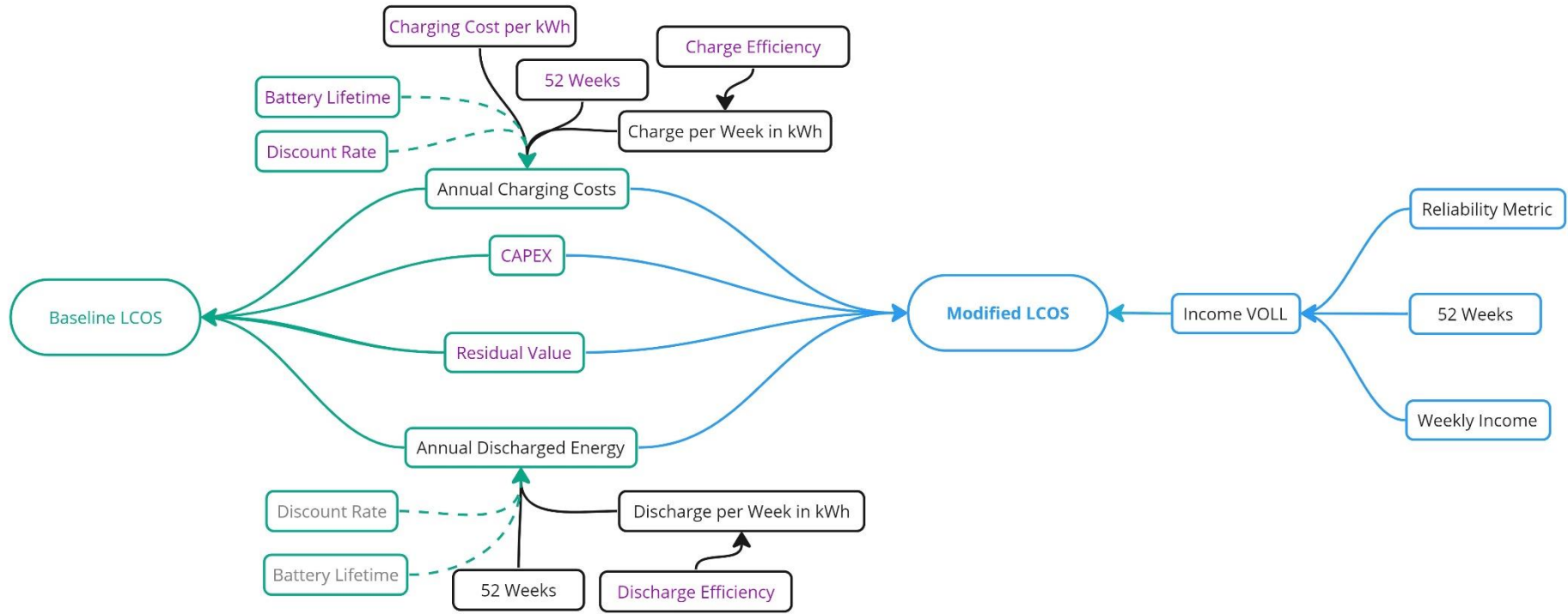


Figure 3-1: Mind map of the modified LCOS tool.

3.4.2 Tool Development

The affordability assessment tool was developed in Python using Jupyter Lab, NumPy, and Pandas libraries. It accepts cleaned survey data in Excel/CSV format as input and generates an output file in Excel/CSV format. The output contains calculated metrics, including baseline LCOS and modified LCOS for each respondent as well as appliances use scenarios provided in Appendix D. These scenarios represent different combinations of appliances, aligning with potential BTM BESS needs identified in the survey. The tool automatically matches outage durations with appliance scenarios to recommend suitable battery systems selected from the list in section 2.2.4.4.

The python script's algorithm is as follows:

1. Data Import - Survey data was read from an Excel file.
2. Respondent Iteration - For each respondent in the dataset:
 - Appliance scenario selection: Appliance use scenarios discussed in section 3.4.1 were used.
 - Battery sizing: The tool determined the optimal battery size based on the total power consumption as per the appliance scenarios and the outage variables.
 - Income VOLL calculation: The potential income loss due to outages was calculated based on weekly WFH income.
 - CAPEX and residual value: The tool estimates the initial BTM BESS investment (CAPEX) and its potential value at the end of its useful life (residual value).
 - LCOS calculation: The baseline LCOS and modified LCOS were calculated according to the established formulas in 3.4.2 and 3.4.3 respectively.
 - Output: Results for each scenario were written to a separate worksheet within an Excel file as shown in Appendix H.

3.4.3 *Tool Testing and Validation*

To test and validate the affordability assessment tool, a sensitivity analysis was performed, focusing on key variables impacting WFH reliability needs: outage days per week, outage hours per day, and weekly WFH income. Variations in these parameters were systematically applied to both the baseline LCOS (BLCOS) and the modified LCOS (MLCOS) models, observing their impact on calculated costs. Additionally, survey results from WFH individuals provided insights into real-world experiences, including the frequency, duration, and financial impact of power outages. Correlation analysis was performed to examine the relationships between outage patterns, income losses, and model outputs, further assessing the model's alignment with the economic realities of WFH households.



CHAPTER FOUR

4. Results and Discussion

4.1 Introduction

This section presents the results of the modified LCOS model assessing BTM BESS affordability for WFH households. It also provides insights from a survey on the impact of unreliable electricity, which was incorporated into the modified LCOS model. Key findings reveal a strong negative correlation between weekly WFH income and the modified LCOS, indicating that BTM BESS offer greater affordability benefits to WFH individuals.

4.2 Data Overview

Data used to perform sensitivity analysis can be found in Appendix I

4.2.1 Sensitivity Analysis

This analysis focused on three key variables that directly reflect the experiences of WFH individuals: outage days per week, outage hours per day: The length of each outage, weekly WFH income i.e. the total income from WFH activities. These variables were selected as they are the key inputs under analysis, directly influencing both the baseline LCOS (BLCOS) and modified LCOS (MLCOS).

4.2.1.1 Outage days per week

Outage days per week was varied from 0 to 7 with other values kept constant. This analysis was repeated with outage hours per day of 8, 4 and 1, as well as weekly WFH incomes of KES 50,000 and KES 20,000.

Increasing the number of outage days per week led to a decrease in the BLCOS. This trend remained consistent across the tested scenarios. Notably, scenarios with very few outage days resulted in significantly higher BLCOS values. This result suggests that more outages decrease the cost of owning a BESS for an electricity consumer on a per kWh basis.

Increasing outage days per week reduced MLCOS values. MLCOS was negative in the scenarios tested, suggesting that a BTM BESS could effectively pay for itself by preventing income loss during outages.

4.2.1.2 *Outage hours per day*

Outage hours per day was varied from 1 to 8 with other values kept constant. This analysis was repeated with outage days per week of 7, 4 and 1, as well as weekly work from home incomes of KES 50,000 and KES 20,000.

Increasing outage duration per day also reduced the BLCOS, though the impact was less pronounced compared to the effect of outage days per week. This trend also remained consistent across the tested scenarios. This result suggests that more outages decrease the cost of owning a BESS for an electricity consumer on a per kWh basis. However, the effect is less pronounced because longer outage durations in a single day necessitate larger battery sizes, increasing the CAPEX thus the total cost of the battery.

The impact of increasing outage duration on the MLCOS was minimal, generally leading to a slight reduction. Similar to the effect on BLCOS, this indicates that the cost benefits of utilizing a BESS for longer hours are mostly negated by the necessity to purchase a higher capacity battery.

4.2.1.3 *Weekly WFH income*

Weekly WFH income was varied with the following values: KES 5,000, KES 10,000, KES 20,000, KES 30,000, KES 50,000, and KES 100,000. This analysis was repeated with outage hours per day of 8, 4 and 1 as well as outage days per week of 7, 4 and 1.

Increasing weekly WFH income significantly reduced the MLCOS, suggesting that BTM BESS offer greater financial benefits for higher-earning WFH individuals. A majority of MLCOS values were negative. Positive MLCOS values occurred in scenarios with low outages or high appliance power draws, but the values were still lower than the BLCOS. This indicates an overall benefit of BTM BESS for WFH users, especially when income loss due to outages is considered.

4.2.2 *Survey Results*

Survey results analysed in this section can be found in Appendix G

4.2.2.1 *Response Rate*

A total of 52 responses were received from the initial survey distribution. 4 responses were excluded because participants did not experience blackouts or work from home, leaving 48 potentially relevant responses. A further 7 responses were excluded due to very low reported outage frequency, resulting in a final sample size of 41 participants used for analysis.

4.2.2.2 *Demographics*

The survey captured responses from a demographically diverse group of individuals who work from home and experience blackouts. The majority are aged 30-39 (over 60%), with a balanced gender representation (around 59% male, 41% female), and mostly located in Nairobi (57%). Employment types range from full-time (46%) to freelance (20%) and entrepreneurial, showcasing the varied work arrangements within the remote working model.

4.2.2.3 *Work Schedule*

Work schedules were flexible, with most respondents working from home multiple days per week (over 60% at least 3 days). Start and end times varied, as did weekend work (59% reported working weekends). These findings highlight the adaptable nature of remote work but also the potential for disruption if power outages occur during core working hours.

4.2.2.4 *Blackout Impact*

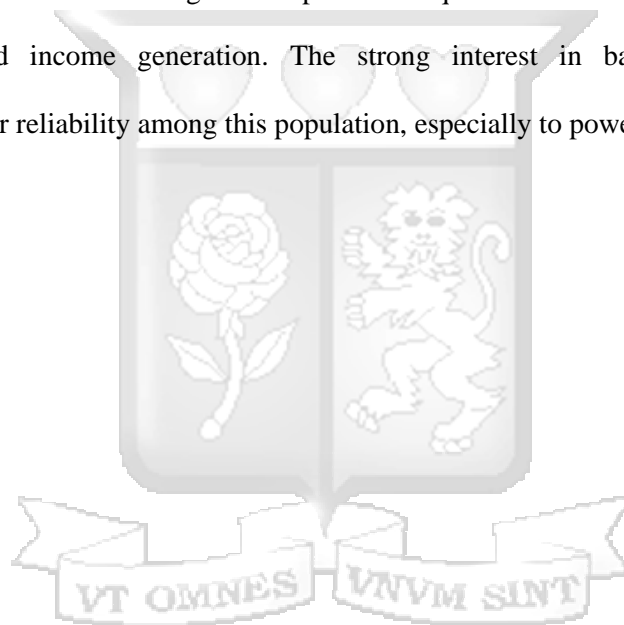
Blackouts were reported as frequent and disruptive. Over a third of respondents experienced outages 1-2 days per week, with durations lasting hours or even the whole day (33%). Mornings were identified as the most disruptive time for outages (55%), affecting productivity and work quality. Blackouts impacted deadlines, focus, and important communications for a majority of respondents (56%).

4.2.2.5 *Battery Backup*

Only 17.8% own a battery backup system, suggesting a significant potential market. Respondents cited a primary desire to power laptops (33% of current owners), but also mentioned appliances like refrigerators and TVs, indicating the wish to mitigate disruption to both work and comfort. The most preferred payment method is a one-off purchase (42%), though a sizeable portion expressed interest in loans (26%), payment plans, or service-integrated billing (20%), demonstrating a need for flexible financing options.

4.2.2.6 *Implications for Battery Affordability*

These results showcase the negative impact of frequent and disruptive power outages on WFH productivity and income generation. The strong interest in battery backup solutions demonstrates a desire for reliability among this population, especially to power work-related devices.



4.3 Model Results: BLCOS and MLCOS

4.3.1 Correlation Analysis

The correlation coefficients for this section are in Appendix H

Table 4-1: Correlation between BLCOS and MLCOS vs important variables

BLCOS vs:	MLCOS vs:
<p>Discharged Energy: Longer and more frequent outages (resulting in higher discharged energy) correlate with lower BLCOS values. This aligns with the BLCOS formula's which prioritizes energy consumption in the initial years of a storage investment.</p>	<p>Discharged Energy: The weaker correlation here reveals a more complex relationship. While discharged energy certainly influences MLCOS, other factors also play significant roles in determining affordability for WFH users.</p>
<p>Weekly WFH Income: Low correlation coefficients reveal a weak relationship between income and BLCOS. The mix of positive and negative coefficients means the direction of the relationship isn't even consistent across scenarios.</p>	<p>Weekly WFH Income: The strong negative correlations indicate a clear, inverse relationship. This means that as income increases, the MLCOS decreases i.e. high-earning WFH users experience greater affordability benefits from a BTM BESS system.</p>
<p>Income VOLL: The correlation suggests that as income losses due to outages (Income VOLL) increases, BLCOS decreases. Since BLCOS does not directly factor in income, this appears to be a "ghost" effect primarily driven by the outage variables, which are included in BLCOS.</p>	<p>Income VOLL: The correlation between Income VOLL and MLCOS is notably stronger than with BLCOS. This shows the importance of the MLCOS in affordability assessments, as it directly captures the relationship between income preservation and BTM BESS value for WFH users.</p>

4.3.2 Baseline LCOS

The baseline LCOS values were plotted using the data in Appendix H. The result, Figure 4-1, shows the baseline LCOS decreasing with an increase in appliances powered in kW.

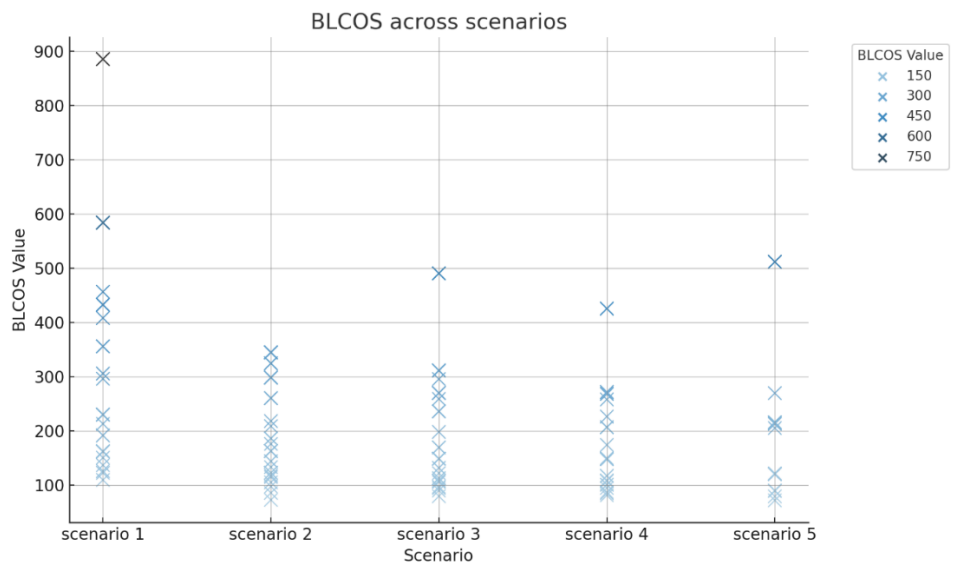


Figure 4-1: Baseline LCOS across appliance scenarios.

4.3.3 Modified LCOS

The modified LCOS values were plotted using the data in Appendix H. The result, Figure 4-2, shows the modified LCOS increasing with an increase in appliances powered in kW.

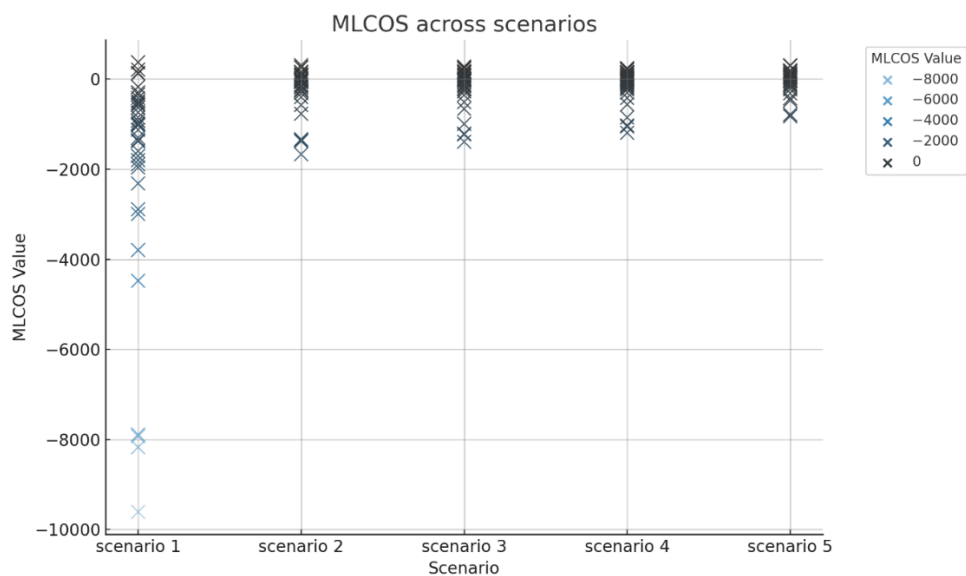


Figure 4-2: Modified LCOS across appliance scenarios.

4.4 Discussion

4.4.1 Outages and BTM BESS Costs

Strong positive correlations were revealed as per data in Appendix H. Correlation between outage hours per day, outage days per week and key factors impacting the cost of a BTM BESS for WFH users was as follows:

CAPEX: Longer and more frequent outages necessitate larger, more expensive battery systems to ensure power throughout the desired backup period. This highlights a key challenge for affordability where those most impacted by outages also face the highest upfront investment costs.

Lifetime charging costs: More outages directly translate to more frequent battery recharging, leading to higher lifetime electricity costs. This recurring expense further influences the long-term affordability of BESS for WFH individuals.

Lifetime discharged energy: Longer or more frequent outages increase the total energy the battery discharges over its lifetime. This has implications for potential battery wear-and-tear, impacting maintenance or replacement costs.

Income VOLL: The positive correlation between outage hours, outage days and income VOLL reinforces the negative economic impact of unreliable electricity on WFH incomes. This strengthens the argument for considering income protection as a core metric when assessing BTM BESS affordability for this group.

4.4.2 Baseline and Modified LCOS

The baseline LCOS metric is designed to measure the cost-effectiveness of energy storage systems over their entire lifespan. Based on the data, it has several key limitations when it comes to evaluating the affordability of batteries as a backup solution for WFH individuals:

- **Unrealistic usage assumption:** BLCOS prioritizes energy discharge in the initial years of a battery's life. This assumes consistent usage, which is not how WFH batteries would typically be used. WFH users may experience long inactive periods punctuated by blackouts, making the BLCOS calculation less relevant.

- Masking upfront costs: Since higher energy consumption spreads upfront investment over more units of energy, the BLCOS calculation can make larger batteries seem more affordable. This masks the reality that larger batteries, needed to cover longer or more frequent outages, represent a significant affordability barrier for WFH individuals.

The MLCOS addresses the shortcomings of BLCOS by specifically considering the unique needs and financial realities of WFH individuals who rely on reliable power for income generation as follows:

- Prioritizing the present: Unlike the BLCOS, the MLCOS prioritizes immediate income preservation over the lifespan of the battery. This more accurately reflects how WFH users must assess financial risk, as unreliable electricity poses a direct and immediate threat to their income generation.
- Income centric: By directly incorporating WFH income VOLL, the MLCOS provides a metric tailored to the financial decision-making process of WFH users depending on power reliability for income.
- Payback emphasis: The negative MLCOS values communicate the potential for the BTM BESS used by WFH individuals to "pay for itself" through income preservation during outages. This tangible metric simplifies the affordability analysis for WFH individuals.
- Realistic battery sizing: The MLCOS reveals that smaller battery systems, capable of powering essential work devices during outages, are often the most financially viable option. This aligns with the reality that WFH users may prioritize income preservation for short periods rather than powering their entire home consistently.

4.4.3 Limitations of the study

The primary metric used to quantify income loss due to power outages was designed to capture direct lost earnings (e.g., missed billable hours for freelancers).

This approach has limitations when applied to WFH individuals with salaried or contract-based employment. In these cases, wages are typically unaffected by short-term outages. For this reason, while the survey aimed to capture a diverse range of WFH individuals, the income loss metric introduced a bias in data analysis towards respondents for whom the direct link between outages and lost income was strongest such as freelancers.

The true financial impact of unreliable power for employed WFH individuals likely includes costs that are more difficult to quantify directly, such as decreased productivity, the stress of meeting deadlines under disruptive conditions, or potential long-term impacts on performance evaluations. However, while income loss may not be immediate, prioritizing a backup solution's impact on current cash flow, as captured by the MLCOS, is more relevant than BLCOS for this group.

Constraints, including budget, time, and the decentralized nature of WFH populations, limited the sample size achieved. This impacts the representativeness of the findings as it may not fully reflect the wide spectrum of work arrangements, housing situations, and technological reliance experienced by WFH individuals across the city. This limitation underscores the need for larger-scale or collaborative research efforts to build a more comprehensive dataset.

Lastly, the relatively small sample size (52 respondents) limits the generalizability of the findings to the broader WFH population within Nairobi. Further research with larger and more diverse samples is needed to confirm the trends identified in this study and gain a more comprehensive understanding of the affordability challenges faced by WFH individuals across various income levels and work arrangements.

CHAPTER FIVE

5. Conclusion and Recommendations

5.1 Conclusion

Baseline LCOS is a standard metric often used in the context of grid-tied solar systems, where consistent energy discharge throughout the day is prioritized to maximize output. It focuses on short to medium-term returns, thus it decreases as total appliance power draw increases. This aligns with the assumption that higher energy consumption spreads upfront investment over more units of energy. However, this metric might be less suitable for assessing the needs of WFH individuals, particularly when immediate reliability is critical, and the pattern of energy discharge might be intermittent. These usage patterns can result in less total energy discharged in the battery's early life compared to consistent usage, potentially making BLCOS calculations misleading for WFH use cases.

Modified LCOS has an income preservation focus, thus increasing as total appliance power draw increases. This aligns with the intuition that larger batteries needed for higher wattage appliances are generally more expensive. While a desire for high autarky (independence from the grid) might exist, for many WFH users, the importance of income preservation should take priority. Prioritizing smaller systems that ensure core work devices remain functional during outages could deliver a stronger return on investment compared to investing in batteries capable of powering multiple appliances throughout the home. Therefore, MLCOS provides a more accurate picture of affordability for WFH users by prioritizing the immediate need for income preservation over complete energy independence.

5.2 Recommendations

1. Prioritize needs-based sizing.

This study highlights the importance of adopting a targeted approach to BTM BESS sizing for WFH households, prioritizing income preservation over whole-home backup as guided by the MLCOS metric. Analysis of individual usage patterns should be used to identify essential productivity devices during outages, and battery systems should be sized accordingly. This low-autarky strategy can optimize cost-effectiveness, ensuring reliable power for critical income-generating activities.

2. Integrate BTM BESS into energy planning.

County energy plans for urban counties should seek to address the unique needs and potential contributions of the WFH population. With remote work on the rise, considering WFH reliability has the potential to increase county revenues. Incorporating incentives or guidelines for household BTM BESS into can lay policy ground that will enable the promotion of grid resilience while enhancing economic stability for WFH individuals, particularly in areas prone to disruptions. A stable and reliable WFH workforce contributes to overall community economic robustness.

3. Develop WFH specific financing models.

To facilitate widespread BTM BESS adoption among WFH individuals, innovative financing models tailored to this demographic are urgently needed. Government subsidies could be a powerful tool used to boost BTM BESS demand, potentially driving down costs and improving grid stability for the broader community.

4. Situational use of LCOS.

There's a need for more nuanced affordability assessments given the limitations of the traditional LCOS metric, as shown in this research. Rather than relying on a blanket application of LCOS, the metric should be adapted to prioritize specific metrics most relevant to different user groups and use cases. The modified LCOS model developed in this thesis provides a potential framework for such tailored evaluations.

6. References

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7. Appendices

7.1 Appendix A – SU-IERC Ethical Approval



27th October 2023

Ms Wambugu Anne Wacera
anne.wacera@strathmore.edu

Dear Ms Wambugu,

RE: Adoption of Behind-the-Meter Battery Storage Systems for Residences in Kenya

This is to inform you that SU-ISERC has reviewed and **approved** your above SU-masters research proposal. Your application reference number is SU-ISERC1866/23. The approval period is from 27th October 2023 to 26th October 2024.

This approval is subject to compliance with the following requirements:

- i. Only approved documents including (informed consents, study instruments, MTA) will be used.
- ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by SU-ISERC.
- iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to SU-ISERC within 72 hours of notification.
- iv. Any changes anticipated or otherwise that may increase the risks or affected safety or welfare of study participants and others or affect the integrity of the research must be reported to SU-ISERC within 72 hours.
- v. Clearance for the export of biological specimens must be obtained from relevant institutions.
- vi. Submission of a request for renewal of approval at least 60 days prior to the expiry of the approval period. Attach a comprehensive progress report to support the renewal.
- vii. Submission of an executive summary report within 90 days of completion of the study to SU-ISERC.

Before commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology, and Innovation (NACOSTI) <https://research-portal.nacosti.go.ke/> and obtain other clearances needed.

Yours sincerely,

Mr Ambrose Rachier,
Chairperson; SU-ISERC



7.3 Appendix C – List of Li-ion batteries sold by GT Powertank

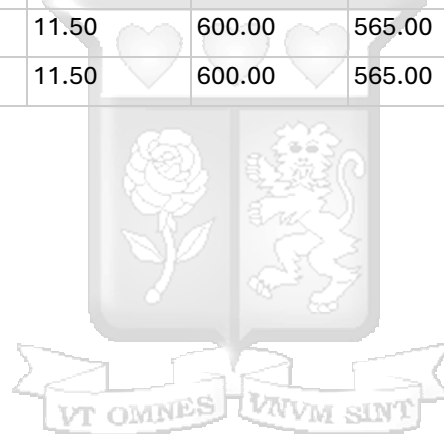
Table 7-1: List of Li-ion batteries sold by GT Powertank

Product Series	Product Model	Specification	Product Picture	Dimension (W x H x D) mm	FOB Price	Landed Price	Warranty in Years	Availability	Application
All-in-one ESS (on/off-grid type)	GE0605H (2nd Gen)	6KW inverter + 5.12KWH LFPbattery		650×1160×214 mm	US\$2,257.26	Ksh 358,001.44	5	ON ORDER	Residential & Small commercial
All-in-one ESS (on/off-grid type)	GE0610H (2nd Gen)	6KW inverter + 10.24KWH LFPbattery		650×1620×214 mm	US\$3,522.06	Ksh 726,178.33	5	ON ORDER	Residential& Small commercial
All-in-one ESS (off-grid type)	GE0610	6KW inverter + 10.24KWH LFPbattery		650×1620×214 mm	US\$3,790.32	Ksh 624,265.70	5	ON ORDER	Residential& Small commercial
All-in-one	GE0810	8KW inverter + 10.24KWH LFPbattery		650×1620×214 mm	US\$3,919.86	Ksh 645,600.94	5	Locally Available	Residential& Small commercial

7.4 Appendix D – Energy Consumption Scenarios

Table 7-2: Energy consumption scenarios

Appliance Type	LED Bulbs	Incandescent Bulbs	Laptop	Wi-Fi Router	Desktop PC	Refrigerator	Printer	TV	Home Theatre	Total in W	Total in kW
Appliance Wattage	10.00	70.00	90.00	11.50	600.00	565.00	167.50	260.00	550.00		
Scenario 1	20.00	140.00	90.00	11.50						261.50	0.26
Scenario 2	20.00	140.00	90.00	11.50	600.00	565.00				1426.50	1.43
Scenario 3	20.00	140.00	90.00	11.50	600.00	565.00	167.50			1594.00	1.59
Scenario 4	20.00	140.00	90.00	11.50	600.00	565.00	167.50	260.00		1854.00	1.85
Scenario 5	20.00	140.00	90.00	11.50	600.00	565.00	167.50	260.00	550.00	2404.00	2.40



7.5 Appendix E – Detailed Map of WFH Income VOLL

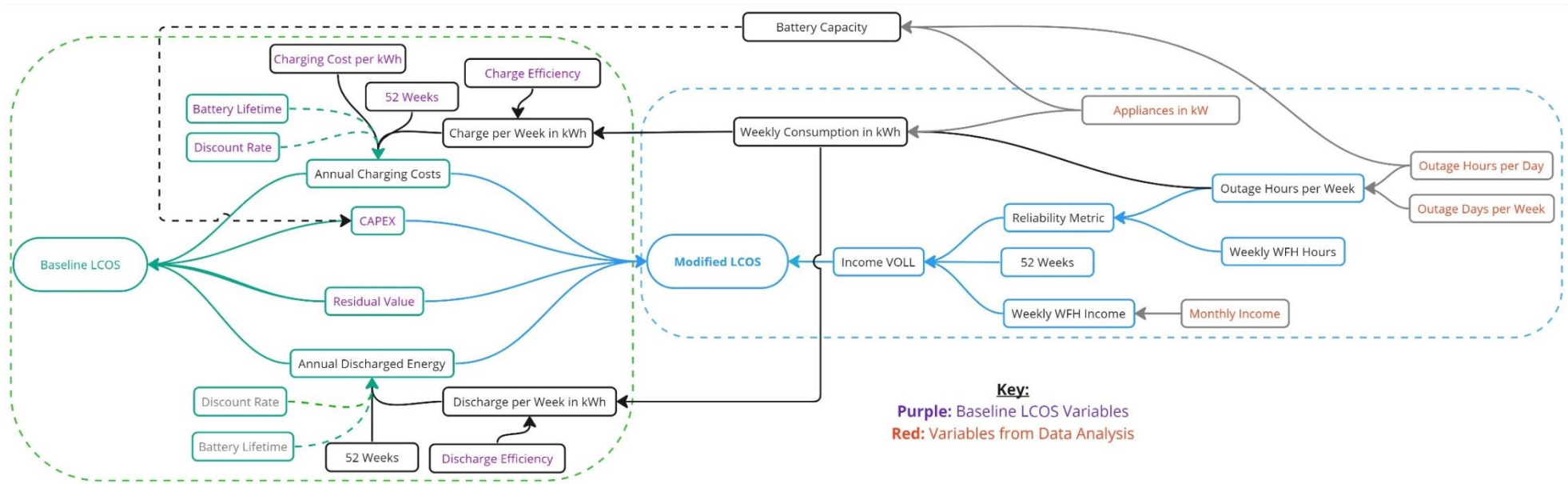
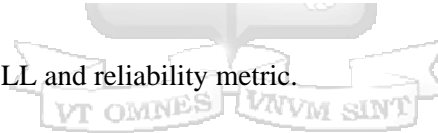


Figure 7-1: Detailed mind map of WFH income VOLL and reliability metric.



7.6 Appendix F – Household Survey

Introduction

Hello. My name is Anne Wambugu, an electrical engineer and master's student at Strathmore University studying Master of Science in Sustainable Energy Transitions. I'm studying the affordability of batteries as a tool to counter blackouts (for people who work from home) for my thesis. The study is licensed by NACOSTI under research license: NACOSTI/P/23/31094.

Before you start:

1. To ensure the survey is focused, please note it's specifically designed for those who:
 - Work from home frequently.
 - Experience blackouts at home.
2. The phone number and email address collected by the survey is meant to:
 - Enable verification that the respondents are human beings rather than bots.
 - Enable the identification of duplicate responses.
 - Ensure that the respondents live in Kenya.
3. The survey will be up until 22nd March 2024.
 - Feel free to share it so someone else can fill it.

If this is of interest, enter your Kenyan phone number to proceed to the consent page.

- Enter phone number.
 - Entry
- Enter email address:
 - Entry

Consent Page

Before proceeding, note the following:

- Participation in this research study and survey is voluntary.
- You will not be paid to participate in this study and there is no direct benefit to you anticipated from participating in this study.
- You have the right to decline to participate or to withdraw at any point during this survey without penalty or loss of benefits to which you are otherwise entitled.
- If you decide to withdraw from this study, the research group will not call your household in the future to collect any information.
- You are not required to answer a question if you do not want to, and you may choose to end the survey at any time if you like.
- At any time, you may ask for access to the information you provide and request the destruction of that information if you wish.
- I, the researcher, will take steps to keep your information as confidential as possible as follows:

- Personally identifiable information will be removed during data processing and any publication or presentation will not contain any identifiable information.
- After the removal of personally identifiable information, data will be kept for potential future research by me, without needing further consent from you.

If you agree to participate in this study with the above knowledge, consent below:

- I understand the procedures described above and agree to participate in this survey:
 - Yes/No

Prerequisites

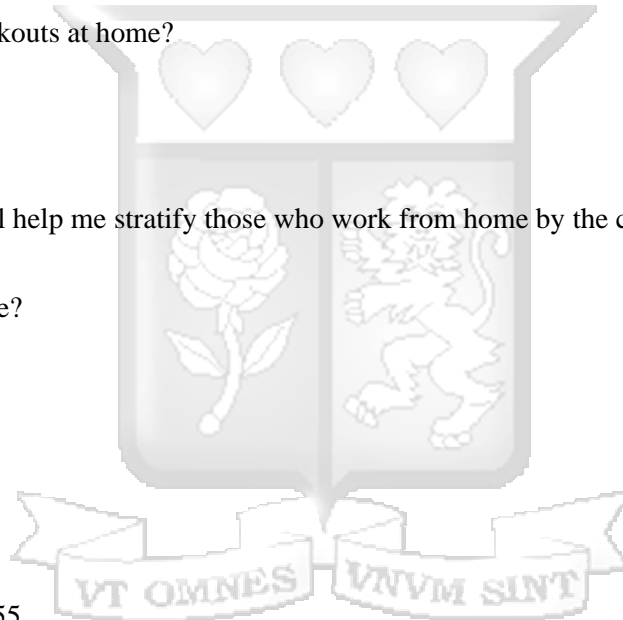
This section ensures that a core premise of the thesis is met by the respondents.

1. Do you work from home frequently?
 - Yes/No
2. Do you get blackouts at home?
 - Yes/No

Demography

This section will help me stratify those who work from home by the collected identifiers.

1. What is your age?
 - 20-25
 - 26-29
 - 30-35
 - 36-39
 - 40-45
 - 46-49
 - 50-55
 - Above 55
2. What is your gender?
 - Male
 - Female
 - Prefer not to say
3. What is your employment situation?
 - Employed (Full-Time)
 - Employed (Part-Time)
 - Freelancer
 - Entrepreneur
 - Other
4. Do you live in an apartment?
 - Yes/No
5. Where do you live?
 - List of major towns in Kenya
6. If you're in Nairobi, what's your neighbourhood?
 - List of Nairobi neighbourhoods



Work hours.

This section helps me understand when you need reliable electricity for work.

1. How many days per week do you work from home?
 - Once a week
 - 2
 - 3
 - 4
 - 5
 - 6
 - All the days
2. What time do you usually start working?
 - Select time.
3. What time do you usually stop working?
 - Select time.
4. Do you work on weekends?
 - Yes/No

Disruption by blackouts

This section helps me understand how disruptive blackouts are to you.

1. Do you experience blackouts that disrupt your work?
 - Yes/No
2. How long does a blackout have to last to be disruptive for you?
 - Less than 1 hour
 - 1 - 3 hours
 - 3 - 5 hours
 - The whole day
3. What is the worst time that a blackout can occur?
 - Morning
 - Afternoon
 - Evening
4. Which of these statements best represents how blackouts disrupt your work?
 - Blackouts lower work quality and cause missed deadlines.
 - I face difficulty regaining focus or flow of work when there's a blackout.
 - Important conversations are cut short or don't happen due to blackouts.
 - All of the above
 - Blackouts do not impact my work in any way.
5. Which of these statements best represents what you do in a blackout scenario
 - I leave the house and go to a café.
 - I have an office I can go to depending on the situation.
 - I check which of my friends has electricity and go to them.
 - All of the above
 - I have a backup system that helps me work.

Blackouts Experienced: Last Week

This section helps me understand how many blackouts you got last week.

1. Last week - How many days did you experience a disruptive blackout?
 - Only one day
 - 2 days
 - 3 days
 - 4 days
 - 5 days
 - 6 days
 - All the days
 - I didn't experience a blackout last week.
2. What was the longest blackout you experienced last week?

Clarification: If electricity came back for a few minutes then disappeared, ignore those few minutes they came back.

 - Less than 1 hour
 - 1 - 3 hours
 - 3 - 5 hours
 - The whole day
 - I didn't experience a blackout last week.
3. How many blackouts did you experience on the worst day? (Use last week)

Clarification: This means electricity would keep going on and off, with large durations in between coming back and going off.

 - One blackout
 - 2-5 times that day
 - More than 5 times that day
 - I didn't experience a blackout last week.
4. Is last week a normal occurrence?
 - Yes, it is.
 - It tends to be worse.
 - It tends to be better.

Blackouts Experienced: Most Disruptive Week

This section helps me understand the worst week you have ever experienced.

1. Think back to the most disruptive week this year. Approximately what month did it happen?
 - January 2024
 - February 2024
 - March 2024
2. How many days did you experience a blackout that week? (Most disruptive week)
 - Only one day
 - 2 days

- 3 days
 - 4 days
 - 5 days
 - 6 days
 - All the days
3. What was the longest blackout you experienced that week? (Most disruptive week)
Clarification: If electricity came back for a few minutes then disappeared, ignore those few minutes it came back.
- Less than 1 hour
 - 1 - 3 hours
 - 3 - 5 hours
 - The whole day
4. How many of blackouts did you experience on the most disruptive day? (Use the most disruptive week)
Clarification: This means electricity would keep going on and off, with large durations e.g. 1 hour in between coming back and going off.
- One the whole day
 - 2-5 times a day
 - More than 5 times a day
5. Is the most disruptive week a normal occurrence?
- Yes, it is.
 - It tends to be worse.
 - It tends to be better.
6. How many disruptive blackouts have you experienced in 2024?
- None
 - A few
 - Many
 - Very many

Battery affordability

This section helps me determine the affordability of batteries for households

1. Do you have a battery backup?
 - Yes/No
2. How much did your battery backup cost?
 - Amount
3. What does your battery backup power?
 - List of appliances
4. Would you want to get a battery backup?
 - Yes/No
5. What would you want it to power?
Consider that the more appliances you select, the more expensive and that you have to pay for the battery.

- List of appliances
6. How would you want to pay for the battery backup?
- One off payment.
 - Loan that I pay back slowly as I use the battery.
 - Hire purchase: Pay slowly then once done I pick it.
 - I pay slowly inside a service bill.
7. What is your monthly income? (Preferably your work from home income)
- If you have two work-from-home incomes, combine them then put "the income is*

from two people both who work from home" in the text box (question 8)

- Up to KES 50,000/=
 - Up to KES 100,000/=
 - Up to KES 200,000/=
 - Up to KES 400,000/=
 - Up to KES 600,000/=
 - Up to KES 1,000,000/=
 - More than KES 1,000,000/=
8. What is the maximum % of your income that you'd be willing to spend on a battery?
- None
 - 1-5%
 - 6-10%
 - 11-15%
 - 16-20%
 - 20-25%
 - More than 26%
9. Is there anything else you'd like to share about your experience with blackouts and work-from-home?
- Text box

End of survey

Thank you so much for making it to the end of the survey.

- If you have any other details you'd like to provide me, or if you'd like to be updated on the results of this research, send an email to anne.wacera@strathmore.edu. Else, check electricityaccess.com in January 2025 – I'll put the update there.

Once again - your participation in this survey is deeply appreciated. Thank you!

7.7 Appendix G – Survey Data

Link to Drive: https://drive.google.com/file/d/1CKtI22GA10vO_U-MA_FwkhhCepMS538V/view?usp=sharing

Note that it is set to “anyone in Strathmore University with link can view”.

7.8 Appendix H – Model Output Data

Link to Drive: https://drive.google.com/file/d/1FU7OM8j0ATBUg5P5GkKNAX3Dci_bSSUw/view?usp=sharing

Note that it is set to “anyone in Strathmore University with link can view”.

7.9 Appendix I – Sensitivity Analysis Data

Link to Drive 1: <https://drive.google.com/file/d/1GBmAk0s1X2vtu9SxCaRY0UyK2JuAod58/view?usp=sharing>

Link to Drive 2: <https://drive.google.com/file/d/1mMkDjsdaf6he6Vo6iU6CasYqV8TokNWn/view?usp=sharing>

Link to Drive 3: <https://drive.google.com/file/d/1NfDzH9WOOxPJkzq2IrQu2WF6Tc5vhogd/view?usp=sharing>

Note that it is set to “anyone in Strathmore University with link can view”.



7.10 Appendix J – Correlation Analysis Data

BLCOS vs	Discharged Energy	P-Value	Weekly WFH Income	P-Value	Income VOLL	P-Value		
scenario_1.0	-0.653938687	3.54E-06	0.123701065	0.440976878	-0.370415318	0.017127546		
scenario_2.0	-0.703736707	2.86E-07	-0.065931002	0.682132446	-0.437579442	0.004222564		
scenario_3.0	-0.660790719	2.58E-06	0.106179501	0.508787583	-0.381610977	0.013820295		
scenario_4.0	-0.701893889	4.50E-07	0.072483121	0.656701106	-0.412316439	0.008198264		
scenario_5.0	-0.514681383	0.004280976	0.297166021	0.117465926	-0.365643232	0.05110691		
MLCOS vs	Discharged Energy	P-Value	Weekly WFH Income	P-Value	Income VOLL	P-Value		
scenario_1.0	-0.020305839	0.899721836	-0.887685454	1.04E-14	-0.511079748	0.000638599		
scenario_2.0	-0.102129368	0.525175211	-0.867230257	2.24E-13	-0.540421943	0.000264897		
scenario_3.0	-0.144243456	0.368245913	-0.85043452	1.95E-12	-0.57266115	9.13E-05		
scenario_4.0	-0.200111481	0.215696752	-0.850649757	3.67E-12	-0.577477131	9.56E-05		
scenario_5.0	-0.216604303	0.259065014	-0.753832117	2.34E-06	-0.506919944	0.005009542		
Outage Hours per Day vs	CAPEX	P-Value	Charge Costs	P-Value	Discharged Energy	P-Value	Income VOLL	P-Value
scenario_1.0	0.936032157	3.26E-17	0.853663158	1.90E-11	0.853663158	1.90E-11	0.394276337	0.02355618
scenario_2.0	0.966810339	8.90E-23	0.853663158	1.90E-11	0.853663158	1.90E-11	0.394276337	0.02355618
scenario_3.0	0.964162115	3.09E-22	0.853663158	1.90E-11	0.853663158	1.90E-11	0.394276337	0.02355618
scenario_4.0	0.968771803	3.30E-23	0.853663158	1.60E-10	0.853663158	1.60E-10	0.394276337	0.019048264
scenario_5.0	0.991198822	1.77E-23	0.853663158	3.86E-07	0.853663158	3.86E-07	0.394276337	0.012926176
Outage Days per Week vs	CAPEX	P-Value	Charge Costs	P-Value	Discharged Energy	P-Value	Income VOLL	P-Value
scenario_1.0	0.432940806	0.233767596	0.716128459	1.37E-06	0.716128459	1.37E-06	0.525318781	0.00031643
scenario_2.0	0.45875611	0.209159298	0.716128459	1.37E-06	0.716128459	1.37E-06	0.525318781	0.00031643
scenario_3.0	0.490195871	0.132390784	0.716128459	1.37E-06	0.716128459	1.37E-06	0.525318781	0.00031643
scenario_4.0	0.486138027	0.186973136	0.716128459	5.06E-06	0.716128459	5.06E-06	0.525318781	0.000239024
scenario_5.0	0.561490107	0.160230013	0.716128459	3.08E-06	0.716128459	3.08E-06	0.525318781	6.18E-06