A Framework for Sizing Solar PV Systems Adaptable to Off Grid Areas

By

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Declaration

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

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Approval

This dissertation of Nyangoka Isaac Kerina has been submitted at the School of Computing and Engineering Sciences with my approval as the university supervisor.

Signature………………………….. Date…13th April 2024………

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Abstract

Solar PV sizing is the process of determining the quantity and capacity of solar PV system components to meet a given energy demand. This process is needed to ensure that the components are not undersized resulting in insufficient energy or oversized increasing the system cost. There are several solar PV sizing frameworks currently in use in the market such as intuitive, numerical, and analytical frameworks. However, these frameworks have neglected some key adaptability factors unique to off-grid areas such as the ability of the household to pay and the type of roofing structure. This neglect has seen development of solar PV systems that are beyond the budget of most households in off-grid areas and with specifications that technically inhibit their effective use in the setup. Therefore, for enhanced adaptability, there is need to develop a new solar PV sizing framework that considers the unique adaptability factors of off grid areas. This study identified these unique adaptability factors and investigated how they influence the size of a solar PV system. Through the modification of the exiting numerical sizing framework, these adaptability factors were integrated in the sizing process within the context of this study. It was established that by integrating these factors, the resultant PV systems were more adaptable to off-grid areas in terms of cost, mobility, durability and reliability.

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Abbreviations and Symbols

AC	Alternating Current
DC	Direct Current
EE	Energy Efficiency
MTF	Multitier Framework
PAYGO	Pay As You Go
PV	Photovoltaic
PPP	Public Private Partnership
RE	Renewable Energy
SHS	Solar Home System
KNBS	Kenya National Bureau of Statistics

Definition of Terms

Off grid Areas	Areas located far from major towns and economic hubs isolated from the national electric grid and characterized by low income and dispersed population (Jamal et al., 2020).
PV Module	Photovoltaic panel used to harness light energy from the sun (Ali et al., 2018)
Solar Home System	A small-scale standalone PV system, autonomous source of power supply for both rural and urban households, businesses or offices that are of-grid or have unreliable access to power supply (Ali et al., 2018).
Solar PV Sizing	The process of determining the quantity and capacity of solar PV system components to meet a given energy demand (Hartvigsson et al., 2021).
Household	A group of people residing in the same compound or homestead, which could include one or multiple dwelling units, and they have a common household head with a common cooking and lighting arrangement (*KNBS VOLUME IV 2019*.)**.**

1. Chapter 1: Introduction to the Study

1.1 Introduction

The challenge of sizing solar PV systems adaptable to off-grid areas revolve around developing solar systems that are capable of functioning reliably in these areas at a cost that is affordable to majority of the households. This adaptation calls for an understanding of the unique adaptability factors that are typical of these areas. This understanding is important if universal access to clean energy is to be achieved in rural off-grid areas which account for 60% of the population without electricity connectivity in Africa (Mugisha et al., 2021).

Off-grid areas can be defined as areas which are physically remote from towns and service centers of economic or political functions (Jamal et al., 2020). These areas are usually inhabited by communities with low income and literacy levels with poor road networks and isolation from a centralized electricity grid. These factors cumulatively make these areas unattractive for energy investment despite the great electrification potential they possess.

1.2 Background of the Study

Statistics from World Bank indicate that up to 625million people in Sub-Saharan Africa still rely on fossil-based sources of energy. Most of this population live in off-grid areas which can be supplied with solar energy as an alternative to the environmentally harmful fossil fuels such as kerosene and charcoal. It is therefore important to study the unique adaptability factors that hinder adoption of solar energy solutions in these areas and possibly address them at the sizing stage. Some of these unique adaptability factors include, low income, roofing structures, and nomadic culture all of which influence the effective deployment, uptake, and use of solar energy solutions (Guta, 2018).

In Kenya for instance, electricity connectivity is placed at 85% which imply that 15% of households, mostly located in rural off-grid areas, still face accessibility challenges. Similar statistics can be observed in Ethiopia which has 41% connectivity and Rwanda at 51% (Mugisha et al., 2021). This connectivity gap can be covered by solar energy solutions which are easier to deploy in remote areas as compared to the national grid. However, despite this huge market potential for solar energy, these areas still remain underserved because of some unique adaptability factors that need to be addressed at the sizing stage.

Solar PV system sizing is the process of determining the capacity and number of various solar PV system components that can be deployed to meet the energy demand at a given time (Hartvigsson et al., 2021).These components include solar PV modules, charge controllers, solar batteries and inverters. Other components include electrical cables and switch gear apparatus such as fuses and circuit breakers. Based on an appropriate configuration chosen, these components put together comprise the solar PV system (Ali et al., 2018).

This sizing of solar PV components is important as it ensures the system being designed is capable of meeting the energy demand requirement while avoiding oversizing which lead to increased capital cost (de Almeida et al., 2020). As such, the overall objective of sizing is to increase the reliability of the solar system while minimizing the capital cost. This is important especially in off-grid areas which are characterized by low income and present access difficulties for maintenance (J. Lee & Shepley, 2020).

There are several frameworks currently used to size solar PV systems. These include intuitive, numerical, analytical, hybrid, software, and AI based frameworks. These frameworks have found wide application in the market and are designed to make the sizing process faster and more accurate (Kumar, 2017). However, some of these frameworks are commercial products which need licenses to install and use and are therefore out of reach for mid and small sized energy service providers operating in rural off-grid areas. Further, preliminary investigations indicate that these frameworks have neglected some unique aspects of off-grid communities resulting in solar PV systems that cannot be effectively acquired, deployed and used in off-grid areas.

Neglecting key off-grid adaptability factors has seen a higher demand for solar solutions within high- and medium-income communities while the low-income communities remain without access. These low income communities as a result end up purchasing substandard solar solutions that fail within the first few years of acquisition (Gebreslassie, 2020). Therefore, for enhanced adaptability, there is need for a new solar PV sizing framework that takes into account the unique socio-cultural and economic characteristics of off grid areas to design solar systems.

1.3 Problem definition

Solar PV sizing frameworks are meant to make the sizing process easier by converting various input parameters such as energy demand into workable solar solutions (Kumar, 2017). While these frameworks have taken consideration to include critical technical parameters, they seem to be neglect various adaptability factors unique to off-grid areas (Guta, 2018; Mugisha et al., 2021). Some of these unique adaptability factors are the ability to pay, the ability to be relocated to different areas, and the nature of the roofing where the PV modules are to be mounted. It is suspected that this neglect is part of the reason why there is low uptake of solar solutions in off-grid areas since the systems developed by the current frameworks are by design socially, culturally and economically unfavorable to communities living in off-grid areas. As O'Shaughnessy et al., (2018) observes, it is necessary while sizing solar PV systems to consider these unique characteristics of off-grid areas for enhanced adaptability.

Therefore, this study sought to investigate the influence of economic, mobility, location, and technological factors on the sizing of solar PV systems and to propose a new sizing framework to integrate these factors.

1.4 Research Objective

1.4.1 General Objective

The general objective of this study was to develop a solar PV sizing framework that factors in unique characteristics of off-grid areas that influence solar PV sizing to enable better adaptability of developed solar PV systems.

1.4.2 Specific Objectives

The specific objectives of this study were as follows:

1. To investigate the effect of integrating adaptability factors in sizing solar PV systems.
2. To analyze how adaptability factors have been integrated in existing solar PV sizing frameworks.
3. To develop a solar PV sizing framework for sizing solar PV systems adaptable to off-grid areas.
4. To validate the performance of the developed framework in different adaptability contexts.

1.5 Research Questions

The research questions for this study are as follows:

1. What are the solar PV adaptability factors unique to off-grid areas and how do they influence solar PV system design?
2. What are some of the existing solar PV sizing frameworks in the market and how have they addressed these adaptability factors? What are the challenges of non-integration?
3. How can we develop a sizing framework to overcome these adaptability challenges?
4. How can we validate the performance of the developed framework in overcoming the adaptability challenges?

1.6 Scope of the study

This study will be limited to addressing the adaptability of standalone solar photovoltaic systems in off-grid areas and the development of a solar PV sizing framework. Larger solar PV systems such as mini-grid are outside the boundaries of this scope. The practical market testing of the developed tool will be left to other researchers in the same field.

1.7 Justification

This research draws its relevance from the energy tri-lemma which summarizes the global energy challenges as relating to the necessity to solve the problem of energy poverty, reliability, and sustainability (Grigoryev & Medzhidova, 2020). These three problems can be summarized into the three pillars of the energy trilemma as discussed by Šprajc et al., (2019).

Energy security is the first pillar of the energy trilemma which addresses energy problems relating to the availability and reliability of energy. This pillar not only intends to explore feasible technologies of exploiting energy resources but also ensures that these technologies will work as designed to reduce interruptions. This is done in view of the available energy resources and the energy demand at any given time.

The second pillar of the energy trilemma is energy sustainability which works to ensure the technology adopted to exploit available energy resources will not result in environmental harm. Since most energy resources are derived from nature, the objective of this pillar is to ensure that energy resources will be exploited in a manner that will not compromise the ecological balance. This pillar is further concerned with ensuring that this exploitation is done in a manner that will ensure energy resources are available for future generations.

Energy equity is the last pillar of energy trilemma which intends to ensure sustainable and reliable energy resources are available to all at an affordable cost. Since energy is harnessed from communally owned resources such as land, water, or wind; this pillar has the objective of ensuring that the burden of generating energy is equitably borne by all members of the community and the benefits enjoyed by all as well.

Linking this description of energy trilemma to the objectives of this study, it is important that the study be carried out because of various reasons. The research promotes the adoption of solar energy as a renewable source of energy in the place of fossil-based sources of energy such as kerosene and firewood which contribute to environmental pollution and deforestations especially in off-grid areas. The research further endeavors to develop a solar PV sizing framework that will be used to develop reliable solar systems that are easy to deploy, use and move in off-grid areas. This will ensure energy security for off-grid communities.

The core of this research is to ensure energy justice for these communities whose needs are presumed unprofitable for energy investment. These intentions are in line with the Sustainable Development Goal number 7 on universal access to affordable and renewable sources of energy. This SDG aims to alleviate energy poverty, promote industrialization, facilitate gender equity and reduce the vulnerability of planet earth to climate change (Chirambo, 2018). This study will enhance energy equity by addressing the unique adaptability characteristics that limit the deployment, use and movement of solar PV systems within off-grid communities. The developed framework will allow investors and developers to make entry in a market segment that is otherwise neglected due to economic, geographical, cultural, and social constraints.

Therefore, the outcome of this study should concern investors in the energy industry who are seeking to open up new markets and institutions which are working to alleviate the living conditions of off-grid communities. These communities will directly benefit as they will have access to reliable solar PV systems currently seen be out of reach due to cost and design limitations.

2. Chapter Two: Literature Review

2.1 Introduction

This chapter explores technical, economic, location, mobility and constraint factors (collectively referred to as adaptability factors) that are unique to off-grid areas and how they influence the sizing of solar PV systems. The chapter further investigates whether these adaptability factors have been integrated in the current solar PV sizing frameworks to understand their successes and challenges in sizing solar PV system for off-grid areas. Possible solutions are discussed on how the challenges can be overcome in the development of a new sizing framework. The chapter concludes by exploring means through which the new framework can be evaluated to validate its effectiveness over existing frameworks.

2.2 Solar PV System Adaptability Factors

There are several factors that are considered when sizing a solar PV system. These factors include technical, environmental, economic, and socio-cultural factors. However, as far as the deployment, use and movement of solar PV systems in off-grid areas is concerned, these factors can be categorized broadly into technical, economic, location, and mobility factors as illustrated in Khatib et al., (2016a). These factors directly influence the solar PV sizing process and when ignored, the designed system will not be functional in an off-grid set up. **Figure 2-1** illustrates adaptability factors categorization.

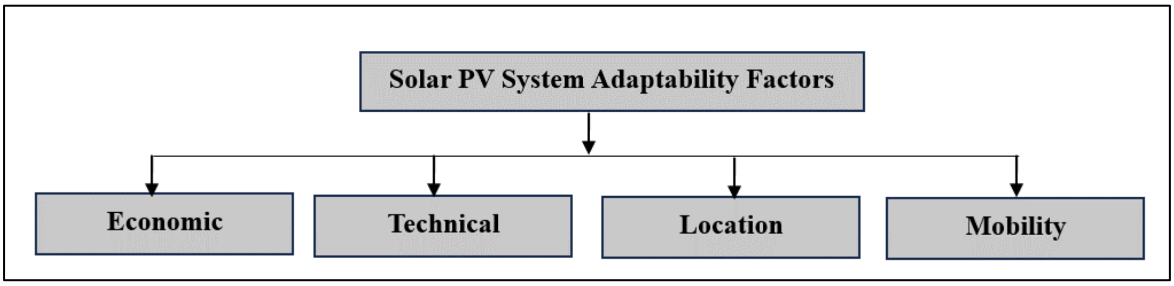


Figure 2-1 *: Categories of adaptability factors.*

These factors assist planners to design suitable systems that can find practical application in a given set up.

a) **Economic factors**

These are factors relating to the cost of developing the solar system and the rate of recovery of these cost from the benefits accrued from utilization of the energy generated. The objective in this case is to deliver a reliable solar system at the least cost possible without compromising on the quality of the system. Economic factors affecting adaptability of solar PV systems in off-grid areas include the household income and the cost of solar PV systems.

b) **Technical factors**

These are factors that relate to the load demand and the choice of specific equipment such as the type of PV modules and battery technology which have a direct impact on the reliability of the PV system. Technical factors that affect the adaptability of a PV system in off-grid areas include change in energy demand and the system quality.

c) **Location factors**

The performance of a solar system is dependent on location specific parameters such as the level of solar irradiation at the site, temperature of the location, humidity and dust. It is important to consider these factors at the sizing stage since they influence the output energy that can be harnessed from the PV array. In this study, temperature and irradiation will be examined for their effect on solar PV sizes.

d) **Mobility factors**

The ability of a solar PV system to be moved conveniently from one location to another is directly related to its size and design. This is important in off-grid nomadic communities where frequent movement is a cultural practice. Factors that will affect mobility include the type of the system and the mounting technique.

2.3 Integration of Adaptability Factors in Sizing Solar PV Systems

Off grid areas possess great potential for adoption of solar energy because of their remote location usually far from the national electric grid. However, the adoption of solar energy solutions in these areas is still low due to unique adaptability factors which may be technical, economic, location, mobile or constraining in nature. Therefore, it is important to consider these factors when sizing solar PV systems in order to harness the potential in off-grid areas (Mugisha et al., 2021).

The physical location of off-grid areas further curtails electrification efforts due to their distance from towns and service centers. This economically affects development in these areas and makes the prospects of grid connection unprofitable. A dispersed population together with unfavorable topography further isolates off-grid areas from investment projects in energy. As such, standalone off-grid solar PV systems present a viable solution for energy access in these areas if they are sized with these unique adaptability factors in mind rather than a cost benefit approach (Jamal et al., 2020).

Tentative findings reveal that existing sizing frameworks seem to put emphasis on technological factors while paying little attention to the other adaptability factors that may determine the level of adoption of PV systems. This neglect has led to development of solar PV systems that are not well suited to operate in off-grid areas in terms of reliability and affordability. Therefore, this section explores these adaptability factors that are unique to off-grid areas and how they manifest in solar PV sizing.

2.3.1 Economic factors in sizing solar PV systems

This study has established that there are two economic factors that directly influence the solar PV sizing process. These include availability of electrical equipment and household income. While other factors which are not economic in nature end up having an economic implication on the sizing process, these two are the main factors that directly arise as a result of the economic situation of the community.

Household Income and System cost

This factor relates to the ability of the community to purchase electrical equipment and pay for a solar PV system. Off-grid areas especially in Africa have poor access to basic amenities such as roads, healthcare, communication infrastructure and education which contribute to their low economic growth and subsequently low income per household. Lack of these amenities as argued by A. Sharma et al., (2020) further contribute to low energy demand and the need to migrate in search of these amenities.

Low-income discourage investors and entrepreneurs in the energy industry from venturing in these areas as there is no guarantee that they will recoup their investment within reasonable time. Further, this has made communities lose interest in solar solutions as they are more concerned with fending for immediate needs such as food, education, clothing, and shelter. As such, some households may not even be aware of the available solar solutions and financing programs to purchase them. For instance, in Rwanda, there are savings and credit societies offering facilities to enable households to subscribe to local mini-grid but the community has no confidence and awareness to engage in these programs (Mugisha et al., 2021).

Therefore, the solar market in these regions is not well developed to attract investments subject to the market forces of demand and supply. This can be alleviated at the sizing stage by incorporating the household income as an input parameter to the sizing process.

Another aspect of cost that affect investment in solar PV systems in off-grid areas is existing market regulations. Where investors opt to set up of mini-grids in off-grid areas they encounter costly procedures related to license acquisition which slows down initiation of these projects as observed by Cross & Murray, (2018). Where the investor succeeds to set up the project, this cost is transferred to the community which is already burdened with low income. Therefore, it is important to size solar systems that avoid set up hurdles such as license and land acquisition which increase the unit cost of energy being charged to the community. This can be achieved by sizing smaller systems that do not exceed the limits that require license acquisition.

While there are attempts by existing sizing frameworks to accommodate economic considerations such as time value of money and payback period, there is no direct consideration of the ability of the household to pay. The economic focus of these frameworks is on the supplier side while the factors pertinent to the economic condition of the end user remain neglected. This may explain why solar PV systems developed by these frameworks fail to gain market prominence in off-grid areas.

2.3.2 Technical factors in sizing solar PV systems

This study has identified several technical factors that are key to the sizing of solar PV systems. These include rating of electrical equipment and their usage, available PV technology, expected reliability index, PV and inverter parameters among others.

However, the study has revealed that the technical factors which uniquely affect the adaptability of the solar PV system in off-grid areas are energy utilization and equipment depreciation as discussed below.

Energy demand and utilization

Economic prosperity brings about increased energy demand in off-grid areas by enabling communities to have access to information through mobile telephony, radios, and television. A research by Bamundekere, (2019) revealed that a majority of the households purchased radio and television devices for the first time when the solar capacity was increased to 8.5 megawatts. This imply that access to electricity in off-grid areas rapidly stimulate economic growth. This prosperity results in acquisition of more electronic loads and longer hours of use which leads to increased energy demand.

Therefore, it is important to forecast the energy utilization patterns and expected increase in energy demand at the sizing stage of solar PV systems. This will ensure the developed system is able to meet the growing energy demand which rises as the community readily appreciates the convenience that comes with supply of electricity. This pressure in energy demand is further increased by the growing population which has been the trend in off-grid communities worldwide (De Almeida et al., 2020).

While households have the potential to increase energy usage by acquiring more electrical equipment upon electrification**,** some households in off-grid areas may not have electrical equipment in their possessions to warrant the need for a solar system in the first place. This is because communities in these areas commonly use charcoal for cooking and kerosene for lighting as discussed by Guta, (2018) and Mugisha et al., (2021) . Even in cases where electrical loads exist, households do not use energy intensive equipment such as fridges and television sets limiting the prospects of the solar energy market in these regions.

This makes the approach of sizing solar systems by taking data on the rating and hourly usage of electrical equipment ineffective. However, there is need to transition communities in these areas from over reliance on fossil-based energy sources to renewable energy sources and the absence of electrical loads should not be a reason for neglect.

The general assumption by existing sizing frameworks that off-grid households already have electrical equipment awaiting connectivity to electricity presents the challenge of lack of key input data since these households still rely on fossil sources of energy with limited awareness of available renewable energy solutions (Lian et al., 2019). Therefore, continued use of these frameworks will see development of solar solutions with no practical mechanisms of penetrating off-grid markets. This study proposes the use of household income as a key input parameter to the sizing process instead of the energy demand being used by current sizing frameworks.

The requirement to have load data as an input parameter in existing sizing frameworks presents a challenge of rigidity in solar energy utilization as systems are sized at the present moment with a small margin for future growth. The objective of this study is to developed a sizing framework that will accommodate a changing energy utilization pattern.

System Quality and Runtime

Off-grid areas are characterized by rugged usage of equipment which speed up the rate of degradation that eventually affect the overall performance of the system overtime. This rate is further increased by the irregular maintenance since these areas are remote and not easily accessible by technicians (George et al., 2019; Hubble & Ustun, 2018).

Therefore, it is important to foresee the effect of degradation on the system performance at the sizing stage to ensure the developed system is able to meet the energy demand throughout its useful life without compromising on the expected runtime.

In some cases, during sizing of solar PV system, designers get to select the system quality based on the budget at hand. This is done by compromising on the system reliability which is defined by the quality and size of the battery. In this case, then the designers are imposing limitations on the sizing process.

These limitations informed by the low ability to pay for high quality systems have resulted in the flooding of the market with substandard solar systems. These systems usually packaged as ready-made products end up failing after few years of use which further dampens the faith of communities in the ability of solar energy to meet their needs.

In Rwanda, for instance, it was reported that solar lanterns which do not meet global certification standards have increased by over 15% in 2017 alone. A similar situation was also observed in Kenya by Cross & Murray, (2018) where families have been left in the dark after investing in substandard solar solutions which fail within the first year of use. This problem of substandard solar products finding a ready market in off-grid areas has also led to counterfeiting of major solar brand in the market which discourages investors.

Therefore, it can be concluded that the solution to increasing adoption of solar energy solutions in off-grid areas is not designing low-cost solar systems that these communities can afford but designing quality systems and providing mechanisms through which these communities can economically pay within reasonable time.

2.3.3 Location factors in sizing solar PV systems

These factors relate to the impact of movement from one area to another on the solar PV sizing process. Since some off-grid communities are nomadic in nature, designers of solar PV systems need to take this into account when considering location specific parameters of temperature and irradiation in the sizing process.

Temperature and Irradiation in solar PV sizing

Some off-grid communities such as pastoralists are accustomed to occasional relocation which allows them to adapt to unique circumstances in their environment such as drought, flooding, and insecurity. Their frequent migration from one area to another has eventually become part of their culture to the point that it continues even with provision of modern solutions to some of the problems that prompted the migration.

Frequent movements imply that development of permanent solar PV installations may not be ideal within nomadic communities. This calls for a rethink in the sizing approach of solar systems targeting these areas where mobile systems maybe designed to allow for relocation and ease of set up in new locations.

Nasrin et al., (2018) observed that due to heightened decrease in voltage, the power generated by PV modules decreases as temperature rises. The results of the study indicated that while PV power rises with solar intensity, efficiency typically drops due to increased cell temperature.

Therefore, the sizing approach should allow development of solar systems that can reliably function in diverse weather conditions rather than systems designed with meteorological data of a single location.

2.3.4 Mobility Factors

These factors relate to the ability of a PV system to be moved from one area to another conveniently and the ease of set up in a new area. This study has revealed that the main factor influencing the mobility of a solar PV system in an off-grid set up is its mounting technique together with the system type as discussed below.

Solar PV system Type

Off-grid Solar PV systems may be categorized into the following classes based on their size and functionality;

a) Solar PV Lanterns- These are portable solar systems characterized by one lamp with a PV module mounted at the back as one unit.
b) Portable Lighting Systems – These are ready made solar PV systems often characterized by 2-4 bulbs that also allow for phone charging.
c) Solar Home Systems- these are customized solar PV systems that are sized based on the needs of the user and permanently mounted on rooftops or customized support structures.
d) Off-grid Minigrids- these are solar poor pants designed to serve more than one household who pay the developer for the energy used.

Solar lanterns and lighting systems allow for ease of relocation since they are usually designed to be portable while home systems and minigrids confine the user to a specific location. The ability to be mobile comes with the limitation of capacity since beyond a given capacity, the system becomes too bulky to be conveniently moved from one location to another.

PV Mounting and Roofing Techniques

Solar PV modules are popularly installed on roof tops for ease of illumination by sunlight. This may not be feasible in off-grid areas where roofing structure designs are culturally informed and may be made of grass, mud or makeshift tents which may not be ideal for permanent installation of heavy PV modules.

There is need for an independent structure that can safely secure the solar PV modules to ensure they live up to their intended service life. This should be factored in at the design stage to ensure the systems are functional in such circumstances.

Such a structure may need to be mobile within rough terrain in off-grid areas thus limiting the number of PV modules and battery banks that can be safely moved from one location to another.

Holloway et al., (2011) carried out a study to measure the portability of mobile PV systems for military use. The study established 17 rubrics to evaluate the ability of a PV system to be conveniently assembled, deployed and redeployed while meeting the required energy demand in unfavorable off-grid conditions and terrain. The results indicated that the PV size has a direct relationship with its portability in terms of weight, dimensions and volume. This relationship was evaluated through the power density metric and validated by comparing a mobile PV system alongside an equivalent diesel generator.

2.4 Adaptability factors in existing sizing frameworks

There are six categories of solar PV sizing frameworks that are currently in use in the energy industry. These frameworks, which differ in reliability and simplicity, describe the approach designers use to determine the optimum sizes of individual system components to meet a given load demand (Mellit, 2010).

Sadio et al., (2018) and Khatib et al., (2016) reviewed these frameworks as being intuitive, numerical, and analytical in nature while others adopt Artificial Intelligence to solve the sizing problem. Some frameworks have been packaged as commercial computer software tools while others deploy elements of the first five categories to arrive at appropriate equipment sizes as illustrated in **Figure 2-2**.

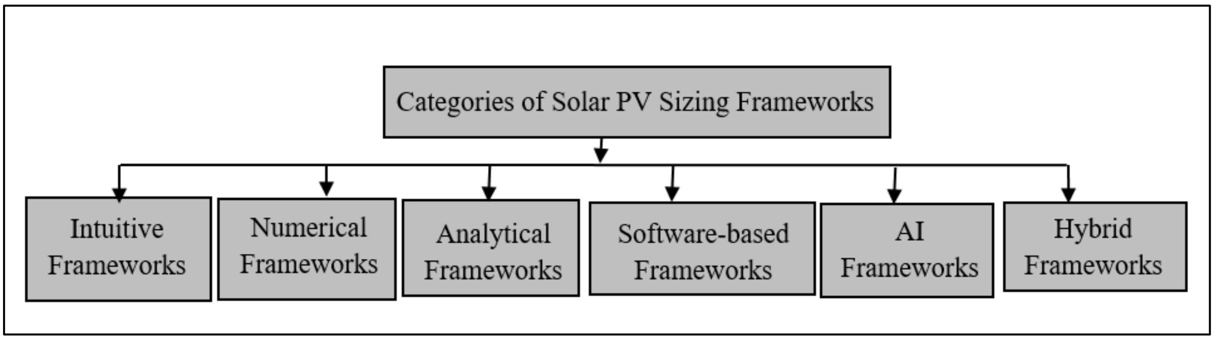


Figure 2-2 : *Categories of solar PV sizing frameworks.*

2.4.1 Intuitive Frameworks

These frameworks are based on simple, experience-based calculations to determine the sizes of individual components while disregarding the relationships between individual system components and the dynamic nature of weather parameters. This makes intuitive frameworks inappropriate for accurate solar PV sizing leading to costly or unreliable solar PV systems (Muhsen 2019). However, intuitive frameworks are ideal for estimating system sizes prior to detailed analysis by other frameworks (Shukla et al., 2016).

To simplify calculations, intuitive frameworks consider the month with the least solar irradiation or the monthly average irradiation in the sizing process. This average together with the maximum daily load demand ensure sizing is done for the worst possible scenario which may result in an oversized system (Sadio et al., 2018).

In general, intuitive solar PV sizing frameworks take the steps in **Figure 2-3** as discussed by Muhsen et al., (2019), Sadio et al., (2018) and Shukla et al., (2016).

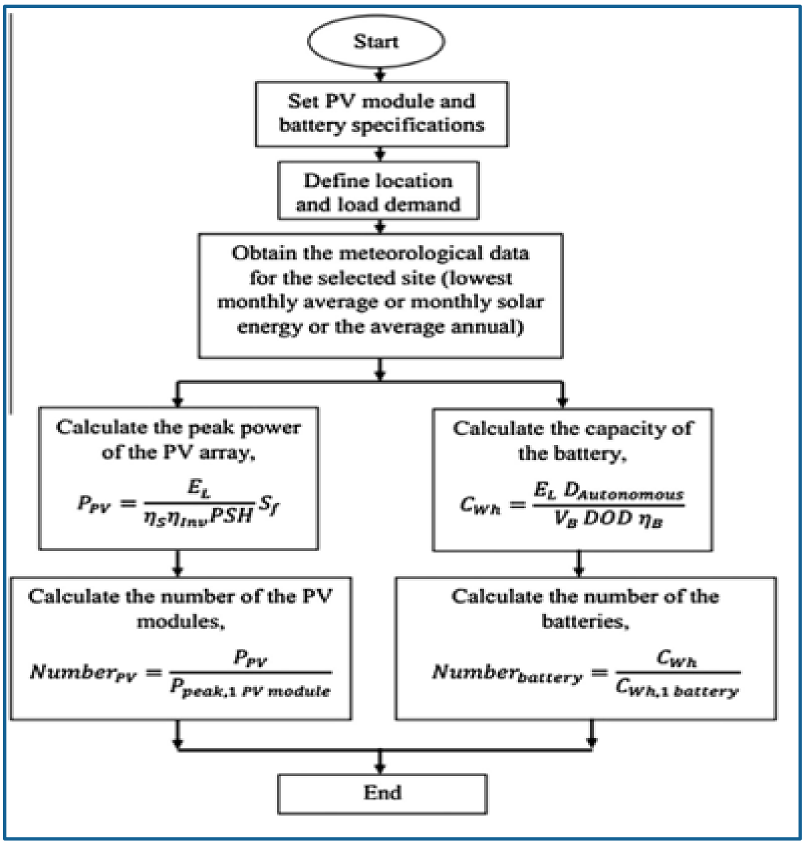


***Figure 2-3**: Intuitive solar PV sizing framework*

Steps in Intuitive solar PV sizing framework

Step 1: Set PV and solar battery specifications.

In this step, the designer has to decide the specification of the solar PV modules and battery specifications based on what is available in the market.

Step 2: Define the location and the load demand.

In this step, the designer determines the location where the solar PV system will be used together with the energy demand based on the electrical equipment in use and the usage pattern.

Step 3: Obtain the meteorological data for the selected location.

The designer at this stage studies the weather patterns at the location where the system will be located with the main interest being the temperature and solar irradiation. To simplify calculations, the average temperature and solar irradiation for a period of 12 months is used. Alternatively, the designer can use the lowest monthly average to design the system from the worst-case scenario.

Step 4: Determine the Maximum power requirement

The maximum power required to be harnessed by the PV array is calculated by considering the daily energy demand by the users, the efficiency of the equipment, and the peak sunshine hours at the location. This maximum power required represents the size of the PV array required and can be calculated by *(2-1)* below:

$$Ppv = \frac{El * SF}{ns.ninv.PSH}$$

(2-1)

where:

E_l is the energy consumption per day.

ηs and ηinv are the system and inverter efficiencies which represent resistive losses.

PSH is the peak sunshine hours for the site location.

SF is the safety factor.

Equation *(2-1)* above can be rewritten as follows:

$$Ppv = \frac{El}{0.65.Ig}$$

(2-2)

where:

I_g represent the average daily solar irradiation in kwh/m2/day and the factor 0.65 compensates for system losses due to equipment inefficiencies, PV cell temperature losses and resistive losses.

Step 5: Calculation of the total number of PV modules required.

Having determined the specifications of the PV modules to be used in step 1 together with the maximum power required from the PV modules as calculated in step 4, the number of PV modules required is calculated by (2-3).

$$Number\ of\ PV\ modules\ = \frac{Ppv}{Ppeak, 1\ module}$$

(2-3)

where:

$\mathbf{P_{pv}}$ is the total power required from the PV array.

$\mathbf{P_{peak,\ 1\ module}}$ is the maximum power of one PV module as determined in step 1.

Step 6: Determination of the battery storage capacity

The battery capacity required for the system is calculated by (2-4).

$$Cwh = \frac{El.Dautonomous}{VB.DODnb}$$

(2-4)

where:

$\mathbf{E_l}$ is the energy consumption per day

$\mathbf{V_b}$ is the battery voltage

$\boldsymbol{\eta_b}$ is the battery efficiency

DOD is the depth of discharge.

$\mathbf{D_{autonomous}}$ is the number of autonomous days desired.

Step 7: Number of battery units

Having determined the specifications of the battery units to be used in step 1 together with the maximum storage capacity required as calculated in step 6, the number of battery units required is calculated by (2-5).

$$Number\ of\ battery\ units\ = \frac{Cwh}{Ppeak, 1\ module}$$

(2-5)

Where:

C_{wh} is the total power required from the PV array.

$C_{wh,1\ battery}$ is the maximum storage capacity of one battery as determined in step 1.

Several scholars have adopted an intuitive approach in sizing solar PV systems as discussed below.

Ahmad, (2002) , while sizing a standalone PV system in Egypt used an intuitive approach to determine the size of the PV array and the battery storage capacity using simple mathematical equation similar to those discussed in this section. The process started by determining the average daily load demand and the average solar irradiation for specific locations. Subsequently, the size of the inverter and the charge controller were selected based on the expected maximum demand and the expected useful life. However, the study did not consider the system reliability in its analysis which may have led to over or under sizing.

Al-Salaymeh et al., (2010) used an intuitive approach to size standalone solar PV systems in Jordan. The approach used average load demand and meteorological data to size the components. The author used 10% of the total demand and five days of autonomy to size the battery capacity using simple calculations. The PV array was determined by considering the peak sunshine hours in specific locations. In this study, economic and socio-cultural aspect were not considered.

2.4.2 Numerical frameworks for sizing solar PV systems

Numerical frameworks for sizing solar PV systems are based on simulations at specified time intervals usually hourly or daily time periods. These frameworks first determine the systems energy balance on a deterministic or stochastic basis.

Deterministic calculation of the energy balance disregards the uncertainty of the solar radiation because this data is usually not available. However, stochastic determination of the energy balance considers this uncertainty which makes it more accurate than the deterministic method.

Numerical frameworks have found application in several computer simulations where subsequent simulations determine the battery state of charge and the system energy balance (Khatib et al., 2016). Based on these two parameters, the cost and technical performance of each configuration is recorded and the cheapest configuration that meets a preset reliability index is selected (Muhsen et al., 2019).

The effectiveness of these frameworks depends on the complexity of the underlying mathematical models and the accuracy of the weather data. However, the major disadvantage of these frameworks is the long runtime and meteorological data that is needed (Ayop et al., 2018; Bouabdallah et al., 2015; Ibrahim et al., 2017; M. Lee et al., 2014).

Figure 2-4 illustrates the general flow that numerical frameworks take in sizing solar PV systems as discussed by Lorenzo, 2019.

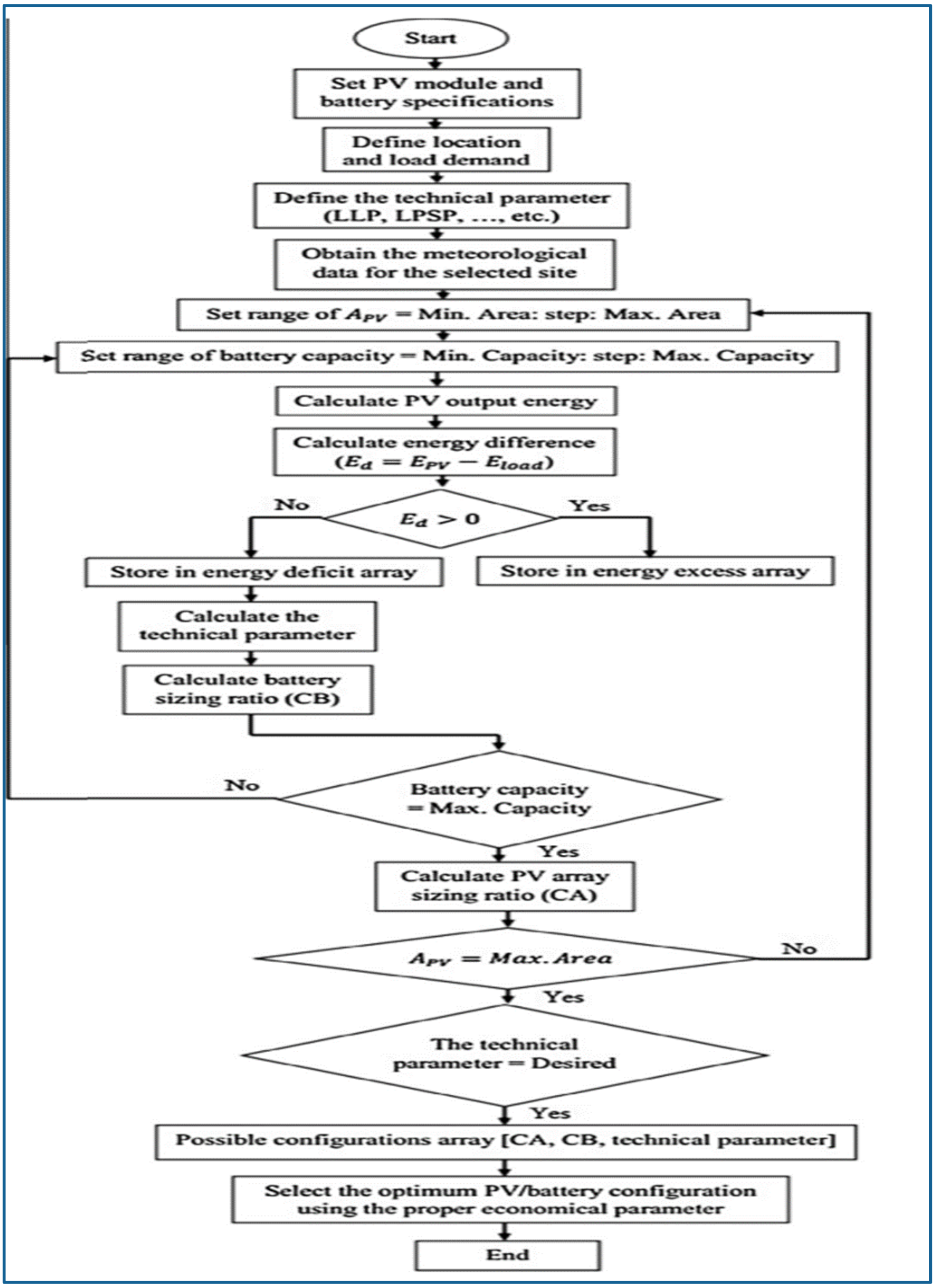


Figure 2-4 *: Numerical solar PV sizing framework*

Numerical sizing approach starts by defining the efficiencies of individual system components followed by determination of the daily load demand and the solar radiation levels at the specific location. The optimum PV array is determined from a set of PV array sizes available. The energy difference is then calculated which determines the matrices of energy deficit and energy excesses.

The Loss of Load Probability (LLP) is determined at each battery and PV configuration and stored in matrices. The appropriate size of the PV array and the battery capacity are obtained at the desired LLP by plotting the LLP- PV array size curve and the battery capacity – PV array size curve. The optimum sizes are determined based on the minimum capital cost.

The inverter capacity can be calculated by considering the maximum load and a safety factor or 25% as shown in (2-6) below (Sadio et al., 2018).

$$Pn,inv = 1.25\ Plmax \tag{2-6}$$

where:

$P_{n,in}$ is the inverter capacity

P_{lmax} is the maximum power at peak consumption.

Erdinc et al., (2015) presented a strategy for sizing solar PV systems based on demand response. The author deployed a techno-economic methodology together with a mixed integrated linear program (MILP) framework to size system components. A smart home demand was then used to validate the framework. The niche of the study was in considering the variability of the daily load demand.

Mandelli et al., (2016) proposed a sizing framework for off grid PV systems in Uganda. The author used the average daily load demand and meteorological data to size the system components. The Least Cost of Energy (LCOE) was the objective function used to determine the battery storage capacity and the PV array size. The battery storage was modelled using stochastic approach while the PV array was modelled using a regression approach.

Sadio et al., (2018) developed a new numerical sizing framework that used the average meteorological data and the average load demand for an off-grid area in Senegal. In the framework development, the author used an intuitive approach first to set the system capacity range followed by a deterministic numerical algorithm to size the system components. The study used the Total Life Cycle Cost (TLCC) and the Average Loss of Power Supply Probability (ALPSP) to validate the framework. The results showed that the developed framework reduced the battery capacity by 25% and the system cost by 35%.

Nordin & Abdul Rahman, (2016) developed a new numerical sizing framework in Malaysia that is based on the ampere- hour approach for sizing standalone solar PV systems. The study used LPSP to determine the PV array and battery configuration and proposed an optimum configuration based on the system levelized cost of energy (LCOE). The optimum design was compared with three other proposed designs and found to have improved in accuracy.

This study has identified that numerical frameworks are the most commonly used methods to size solar PV systems due to their accuracy and reliability. The probabilistic approach is also preferred in these frameworks over the deterministic (stochastic) approach due to the uncertain nature of the meteorological data. (Ibrahim et al., 2017; Mandelli et al., 2016; Nordin & Abdul Rahman, 2016; Okoye & Solyalı, 2017; Perea-Moreno et al., 2018; Sadio et al., 2018; Sarhan et al., 2019)

It has been established that the general flow of these frameworks is to determine the capacity of PV modules and the corresponding battery storage capacity. Each pair of these capacities is then simulated to determine the optimal configuration at a specific level of reliability by considering the hourly meteorological data and the objective function which is usually the system cost.

The current – voltage curve at different reliability conditions are used to determine the optimal system configuration (Okoye & Solyalı, 2017; Sadio et al., 2018; Sarhan et al., 2019).

2.4.3 Analytical frameworks for sizing solar PV systems

Analytical sizing frameworks utilize historical data initially obtained from numerical methods of sizing solar PV systems. This data is then used to statistically derive mathematical models expressed as a function of system reliability which are then used to size new systems. These frameworks present a convenient method to design solar systems as they avoid lengthy simulations (Muhsen et al., 2019).

Analytical frameworks are however not suitable for sizing reliable systems since they rely on assumptions at the analytical stage where coefficients of the mathematical models have to be assumed. Since these assumptions are location dependent, analytical approach to sizing solar PV systems is considered specific rather than general in nature (Jakhrani et al., 2012; Okoye & Solyalı, 2017).

Figure 2-5 shows the sizing process for analytical frameworks.

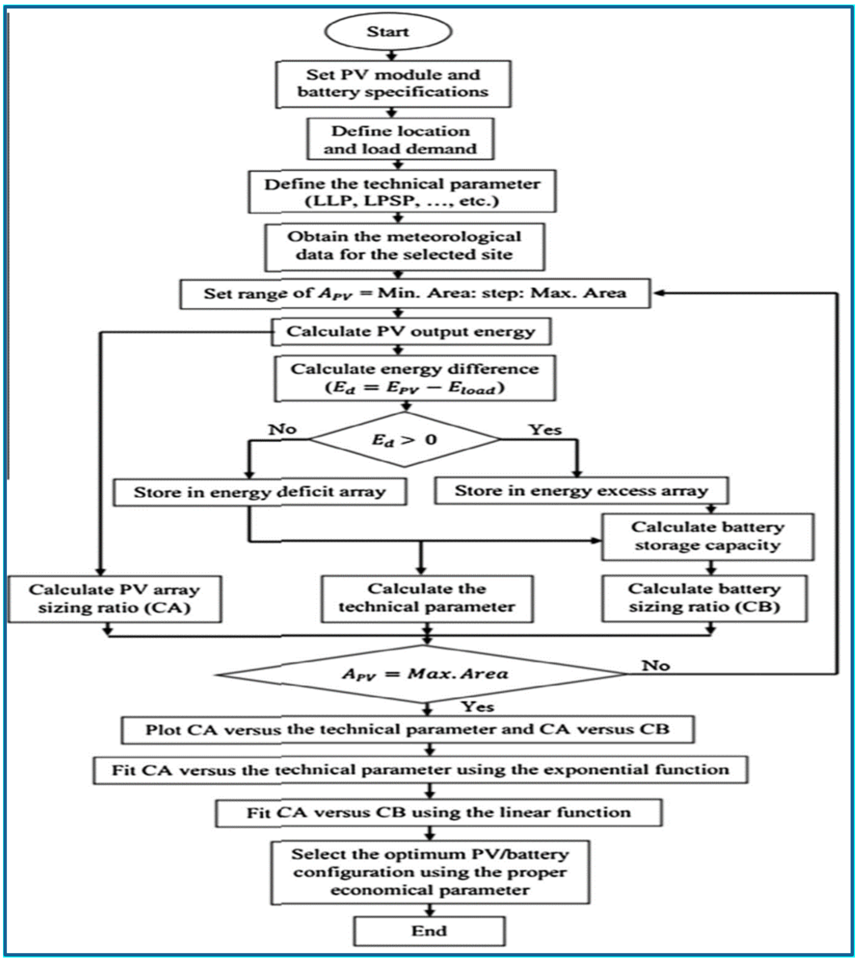


***Figure 2-5**: Analytical solar PV sizing framework.*

Hontoria et al., (2005) developed an analytical framework for sizing solar PV systems using an improved neural network technique called “Multilayer Perception” where battery storage capacity, PV capacity, LOLP were considered. The results showed an accurate relationship between the PV capacity and the battery storage capacity for a given LOLP.

Jakhrani et al., (2012) developed an analytical sizing framework for sizing standalone PV systems where two major indices, that is energy reliability and systems cost, as a function of battery capacity and PV array capacity were considered. The results indicated that for any given value of LLP, optimal system sizes could be obtained from the graph of PV array and battery storage capacity by minimizing system cost.

Bortolini et al., (2014) proposed a framework for optimizing the battery and PV array combination in a grid connected system design in Italy. This framework was based on an analytical approach which used hourly meteorological data and load demand data with the battery state of charge (SOC) as the objective function.

2.4.4 Commercial software tools for sizing solar PV systems

There are various commercial software tools that are used for sizing solar PV systems in the energy industry. Some of these tools include Hybrid Optimization Model for Electric Renewables (HOMER), PVsyst and PV Watts (Khatib et al., 2012).

HOMER is a commonly used software that utilizes meteorological data and hourly load demand data to simulate the battery and PV module configurations (Sinha & Chandel, 2014).

Table 2-1 presents a summary of the functions, inputs and outputs of some of the commonly used software with the focus of investigating the extent to which socio- cultural and economic factors have been integrated in their approach to solar PV sizing. This analysis is therefore important as it gives an indication of how systems developed by a given framework are meeting the needs of the community (Lian et al., 2019).

Table 2-1 *Commercial software tools for sizing solar PV systems*

Sizing Tool	Functionality	Inputs	Outputs
PV GIS	Financial Modeling Performance analysis PV systems sizing	Location & radiation Technology (Crystalline, CdTe)	Energy cost Monthly and annual energy yields
System Advisor Model (SAM)	Financial Modeling Performance analysis PV System sizing	Location and financial data PV module parameter Inverter parameters	PV system design System losses, depreciation Capital cost
PV Syst	Modeling Optimization Economic Analysis PV systems sizing	Load, location & metrological data PV type, orientation Inverter type	
PV Online	Modeling Performance Analysis PV systems sizing	Climatic data System size (kWp), inverter data PV type, orientation, tilt angle Unit cost of electricity	Power of PV field Feed in payment Performance ratio Annual payment
PV Watts	Geographical Interface	Location data	Annual and monthly energy needs

	PV systems sizing	PV type, orientation, angle, azimuth Installation type , system size Inverter efficiency Unit cost of electricity	Solar radiation Capacity factor Monthly energy cost Annual energy cost
PV SOL	Modeling Optimization Simulation PV systems sizing	Location data Annual energy consumption Load data Inverter &PV Modules data	Performance ratio Annual PV energy Solar Fraction Owner power consumption
HOMER	Sensitivity analysis Techno economic analysis	Components capacity and costs Socio economic assessment Load assessment Energy source assessment	Cost of Energy (LCOE) Energy shortage/excess Net present cost(NPC) Capital cost Optimal system configuration

Analysis of the seven frameworks as summarized ***Table 2-1*** revealed a common functionality of PV system sizing. In their basic form, these frameworks are able to determine the size of various solar PV equipment given various input parameters such as load, location and meteorological data. Data on equipment specifications such as inverter efficiency and PV module type are also common across the seven frameworks. Other auxiliary functions include system optimization, financial modeling, and performance analysis.

The requirement for financial data as an input parameter specifically in System Advisor Model (SAM) integrates the economic factor of solar PV sizing. This input allows development of solar systems while keeping in track the economic viability. This is also the case for the use of unit cost of energy as an input parameter in PV Watts and PV GIS. This constraint ensures that the energy generated is affordable to the intended market. The study revealed the provision to include socio- economic data as an input in HOMER, however this data is not specific to off-grid communities and is intended to supplement other key inputs such as load data.

In general, the seven frameworks lay more emphasis on techno –economic factors in solar PV sizing with no evidence to indicate socio-cultural factors specific to off-grid areas have been considered. This can be observed by the technological and economic parameters used as inputs to the frameworks. There is however no indication that these techno – economic factors are directly targeting off-grid communities.

In all the seven frameworks, the load data was revealed to be the key input to sizing the solar PV systems. This presents the challenge of using these frameworks in off-grid areas where electrical loads may not be available in the first place. This challenge was observed by Lian et al., (2019) who noted that the requirement of load data as the key input is ineffective in circumstances where there is lack of basic data. Therefore, there is need for load forecasting during sizing of solar PV systems to predict or fill the gaps in data availability.

2.4.5 Artificial intelligence frameworks for sizing solar PV system

Artificial intelligence frameworks are used in solar PV sizing to overcome the challenge of unavailability of meteorological data which is a common scenario in off-grid areas. The frameworks can handle the nonlinear fluctuation of solar insolation and have predictive functionality such as genetic algorithm (GA) and artificial neural network (ANN). These frameworks also have searching functionality such as tabu search (TS) and fuzzy logic (FL) which may not be available in other frameworks (Sadio et al., 2018).

In AI frameworks, ANNs are trained using historical data obtained from other systems in a specific region. Here, no mathematical derivations are required as was the case for analytical frameworks. However, these frameworks require long term data to develop and train and is generally a trial-and-error approach which is time consuming. This imply that AI frameworks are case specific which may not find application in other cases (Muhsen et al., 2019).

Khatib & Elmenreich, (2014) presented a sizing framework based on analytical and machine learning approaches to resolve the problem of finding coefficients in traditional analytical frameworks. In their study, generalized artificial neural network (GRNN) were used to optimize the system rather than mathematical formulas which are used in traditional analytical frameworks. Hourly load and meteorological data were also used. The results indicated that the new method is more accurate with an error of 0.6% in predicting the sizing curve.

2.4.6 Hybrid frameworks for sizing solar PV systems

Hybrid frameworks for sizing solar PV systems were developed to overcome the disadvantages of the previous frameworks. They are a combination of two or more frameworks intended to reduce execution time and enhance convergence to the optimal configuration given certain parameters. Hybrid methods are considered appropriate since most sizing problems are multi objective in nature (Upadhyay & Sharma, 2014).

Nikhil & Subhakar, (2013) developed a hybrid framework for sizing solar PV systems in India by combining the analytical and iterative approaches on a MATLAB platform. The study was based on the loss of load probability (LLP) and used hourly load demand data and meteorological data to optimize on reliability. The authors incorporated an iteration mechanism to determine optimum configuration for the PV array and the battery storage capacity. The results were validated using other sizing frameworks and experimental data.

Ridha et al., (2020) developed a hybrid sizing framework by considering techno- economic parameters to determine the optimal system configuration. The framework used an intuitive approach to estimate the initial capacity of the PV array and the battery storage capacity followed by an iterative method to determine a range of possible optimal configurations. The study then used a pareto envelope-based selection algorithm (PESA) to determine the optimal configuration. The results demonstrated that lead acid batteries led to more reliable and cost-effective systems compared to other type of batteries.

Hlal et al., (2019) proposed a multi objective hybrid sizing framework which used cost of energy (COE), battery life cost, and Loss of load probability (LLP) to determine the optimal system size. The study used a non- dominated sorting genetic algorithm (NSGA-II) to meet the load demand at the lowest system cost and the highest level of reliability. The results indicated that for the batteries being studied, the optimal depth of discharge (DOD) was 70% at 0% LLP and a cost of 0.2USD/kWh.

Habib et al., (2017) developed an analytical and computational sizing framework. The study utilized solar energy data to determine the optimal switch on and switch off times to maximize utilization. Data from Saudi Arabia, California and San Diego were used to test the framework and the results indicated improved system utilization to 73%.

2.4.7 Research Gap

Table ***2-2*** shows a summary of the sizing frameworks discussed in this section and how they integrate economic and socio- cultural factors in their approach. The findings identify the gaps present in view of these factors.

Table 2-2 *Summary of existing solar PV sizing frameworks*

Framework	Sizing Factors considered	Findings in the context of off grid areas	Reference
Intuitive	Available equipment, location data, load data, average/lowest meteorological data.	Mounting techniques, nomadism, household income, systems quality, licensing requirements, and demand variability are not factored at the sizing stage. Assumes electrical load data exist.	(Ahmad, 2002) (Al-Salaymeh et al., 2010)
Numerical	Available equipment, location data, load data, hourly/daily meteorological data, Reliability index, min/max PV area available, min/max battery capacity.	Mounting techniques, nomadism, household income, systems quality, licensing requirements, and demand variability are not factored at the sizing stage. Assumes electrical load data exist.	(Erdinc et al., 2015) (Mandelli et al., 2016) Sadio 2018 Nordin et al 2016
Analytical	Available equipment, location data, load data, meteorological data. Reliability index, min/max PV area available, min/max battery capacity	Mounting techniques, nomadism, household income, systems quality, licensing requirements, demand variability, repair and maintenance are not factored at the sizing stage. Assumes electrical load data exist. Assumes data on similar systems exist.	(Bortolini et al., 2014) Hontoria et al. 2005 Jakhrani et al. 2012

Software Tools	Location data, available technology, tilt angle, socio- economic assessment, meteorological data	Nomadism, and household income are not factored at the sizing stage. Assumes electrical load data exist. Population distribution factored is as cost of distribution. Mounting techniques factored in (roof mounted or ground mounted) System quality factored in as reliability index. Demand variability factored in as safety factor.	(Sinha & Chandel, 2014
AI Frameworks	Historical data, future demand (predictive)	Security, nomadism, household income, repair and maintenance are not factored at the sizing stage. Assumes electrical load data exist. Population distribution factored is as cost of distribution. Housing techniques factored in as mounting techniques (roof mounted or ground mounted) System quality factored in as reliability index. Demand variability factored in through predictive algorithms.	Khatib 2014
Hybrid Frameworks	Combination of various factors depending on designers' objectives.	Security, nomadism, household income, repair and maintenance are not factored at the sizing stage. Assumes electrical load data exist. Various factors considered based on designers' objectives.	Nikhil & Subhakar (2013) Hussein Mohammed Ridha 2020 Hlal 2019 Habib 2017

The frameworks discussed in this study indicate overemphasis on technical and economic aspects of solar PV system sizing by designers. Moreover, this study has identified that where economic factors are considered, the focus is on minimizing the project cost at the general level which is different from a focus on the ability of individual users to pay.

This study has also identified that existing frameworks tend to rely on meteorological data which varies across different locations. This imply that systems developed through these frameworks must be used within the specified location. This will present an adaptability challenge for nomadic off-grid communities which move from one location to another due to cultural, economic and security concerns.

It is observable that among the six frameworks, numerical frameworks present an accuracy advantage due to the iterative approach and its linear functions. However, these frameworks still rely on data on ambient temperature and solar radiation which may not be readily available.

The technical challenges associated with all the six frameworks can be summarized as follows:

a) *Availability of Data*

   Existing sizing frameworks rely on availability of hourly or daily meteorological data and load demand data to determine the required sizes of system components. This data may not be readily available in off-grid areas which leads to estimation resulting in inaccuracy. The overall effect is that systems designed by these frameworks are not adaptable to the site locations.

b) *Load forecasting*

   Reliance on hourly or daily load demand data call for a forecasting function which these frameworks do not have. Introduction of this function will require accurate data which is not always available as discussed above.

c) *Computation time*

   While intuitive frameworks are simple and require less computation time, they present the challenge of inaccuracy. Numerical and analytical frameworks are more accurate but require more computation time.

This study has identified that apart from the software tools which are prominent in sizing large scale PV systems, most home systems are sized using numerical frameworks (Khatib 2016). The AI frameworks are faster and are used to improve the application of other frameworks, however, they take time to train.

2.5 Development of a Sizing Framework

The objective of this study is to develop a solar PV sizing framework that will be able to overcome the challenges of existing sizing frameworks as discussed in section 2.4.7. These challenges can be overcome by focusing on adaptability factors that make off-grid areas unique in terms of solar PV system adoption, deployment, use and maintenance in off-grid areas.

2.6 Validation of Developed Framework

The performance of Solar PV systems in meeting the required energy needs of the community can be evaluated based on a number of indicators which can be categorized into reliability indicators or economic indicators. These indicators have been incorporated by various sizing frameworks which not only seek to determine design the solar PV system but also to analyze its performance. In this study, these indicators will be used to determine whether the developed framework, having integrated socio-cultural factors, is able to size solar PV systems that are technically reliable and economically viable.

Reliability indicators are metrics used to evaluate whether the solar system is technologically meeting the energy demand as required. On the other hand, economic indicators evaluate at what cost is this reliability attained. These indicators were studied by Kumar, (2017) and Lian et al., (2019) as discussed below.

2.6.1 Reliability Indicators

Reliability of solar systems is affected by the intermittent nature of solar radiation. This fact needs to be considered at the designing stage to ensure the developed system can meet the energy demand. While there are various methods to quantify the reliability of a solar PV system, the Energy difference (E_d) which is the difference between the energy demand (E_l) and the energy supplied by the photovoltaic system (E_{pv}) has been used by various scholars and has been adopted in this study as discussed in section 4.5.2.

2.6.2 Economic Indicators

There are various indicators that are used to measure the economic value of solar PV systems such as Levelized cost of energy (LCOE) and the Life Cycle Cost (LCC) as discussed by Lian et al., (2019) and Sadio et al., (2018). In this study, the LCOE has been adopted to evaluate the economic viability of solar systems as discussed in section 4.5.2.

2.7 Conceptual Framework

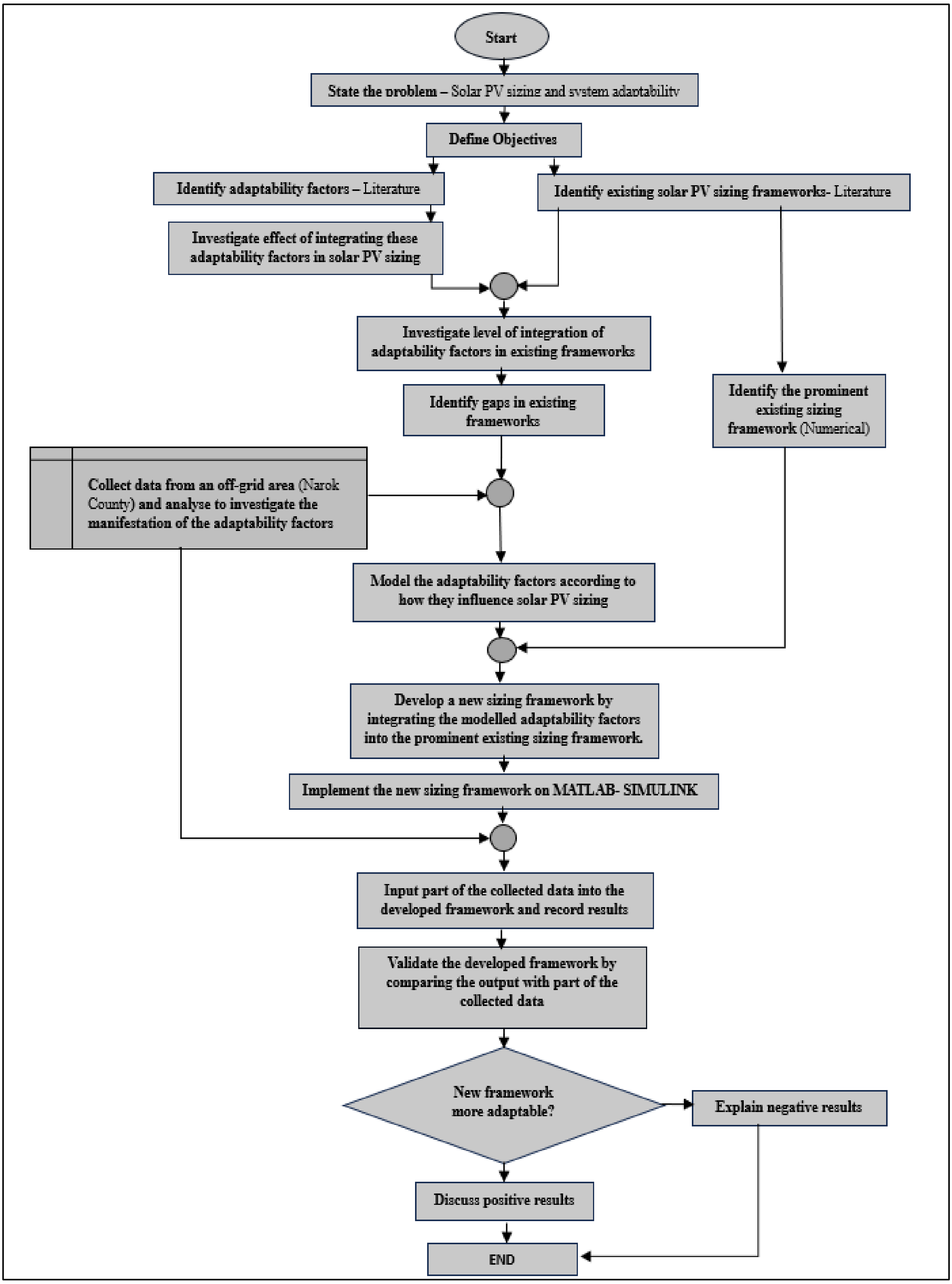


Figure 2-6 : *Conceptual framework.*

3. Chapter Three: Methodology

3.1 Introduction

Solar PV sizing is the process of determining the capacities of individual components of a solar system that can be deployed to reliably meet a given load demand at the lowest cost possible. The components include solar PV modules which harness solar radiation from the sun, battery storage packs which store the harnessed energy, inverters which convert the stored energy from DC to AC and charge controllers which regulate battery charging.

The objective of solar PV sizing is to ensure that the installed system capacity can meet the required load demand and avoid the subsequent cost that comes with unavailable electricity supply. This objective must be met at the lowest possible cost without compromising on system quality.

There exist several sizing frameworks currently in use in the market today but as discussed in section 2.4, these frameworks tend to focus more on technical parameters in their approach while disregarding fundamental adaptability factors that will determine whether the solar system will be adaptable in off-grid areas or not.

This study intends to develop a solar PV sizing framework that incorporates these adaptability factors at the design stage to ensure that the solar systems being designed are functional and affordable to off-grid communities.

The focus of this chapter is to outline how this framework will be developed and validated. The first section outlines the approach used to develop the sizing framework while the second section of describes how data will be collected, analyzed and used to validate the developed framework.

3.2 Research Philosophy

This study takes a positivistic approach to solve the problem of sizing solar PV systems adaptable to off-grid areas. This is because the reality of how effective existing solar PV sizing frameworks address the challenges unique to off-grid areas is independent of the researcher and insight into this effectiveness can be obtained through objective observation and measurement. Therefore, the researcher expects to get concrete absolute answers to the research questions.

The focus of the study will be to identify unique adaptability factors that affect the sizing process of systems intended for use in off-grid areas. A causal analysis will then be carried out to establish the relationship between these factors and solar PV sizing.

A detailed analysis of existing sizing frameworks will then be carried out to establish the extent to which they integrate these factors and as a result the research gap will be identified. The new sizing framework to be developed will build on existing frameworks and integration of the adaptability factors. The developed framework will then be tested against the existing frameworks to establish whether the adaptability problem has been solved.

3.3 Framework Development Methodology and Research Design

3.3.1 Research Design

This study adopted a quasi-experimental approach. The study relies on secondary data collected by Kenya National Bureau of Statistics (KNBS) during the 2019 national household census and data collected in Kenya by World Bank during the Multitier Framework (MTF) study caried out in the same period. The focus of the study is to uncover the adaptability challenges of solar PV systems developed through existing sizing frameworks. By studying these challenges, a new sizing framework is developed and used to size solar PV systems. The economic and technical characteristics of the newly sized solar PV systems are compared to the characteristics of the existing solar PV systems to determine whether the adaptability challenges have been overcome.

A desktop review of the adaptability factors affecting solar PV sizing was carried out in section 2.2 and 2.3 with a specific focus of identifying the factors for integration into the solar PV sizing process.

Consequently, another desktop review was carried out in section 2.4 to identify existing solar PV sizing frameworks and their level of integration of the adaptability factors discussed in the preceding section. The study identified the adaptability gaps in the existing frameworks with the objective of developing a new sizing framework that fills these gaps.

Secondary data from on household income and energy consumption in Narok County in Kenya was obtained from the Kenya National Bureau of Statistics (KNBS) census 2019 and the World Bank Multitier Framework (MTF) survey 2019 for purposes of validating the developed framework. This area was chosen as it contains majority of the adaptability factors of an off-grid area as envisioned in this study.

The data was used to determine whether the adaptability factors identified in the literature review actually manifest at the household level and their impact on the adoption, deployment and use of solar PV system. A new sizing framework was then developed by integrating the identified adaptability factors to the Numerical sizing framework which is currently being used in the market. Part of the data on the household income was used as input to the developed framework to size sample systems for comparative analysis.

3.3.2 Framework Development Methodology

Development of the new solar PV sizing framework was be achieved by adopting the numerical sizing framework as discussed in section 2.4.2 with modification to integrate the adaptability factors modelled in section 2.2 and 2.3.

Modification of the Numerical Sizing framework

The requirement to define the load profile was replaced by household income which was used to estimate the load demand. This will ensure off-grid households which do not possess any electrical loads can be accommodated by the new framework.

Location data was replaced by data on the highest temperature and lowest solar irradiation since the resultant system may need to be moved from one location to another and location specific meteorological data may not be appropriate.

Definition of desired LCOE was introduced as an input to ensure the ability of the household to pay for the solar system is envisioned from the onset. This desired LCOE was then compared with the actual LCOE at the end of the computation and the feedback used to iterate the model for optimal sizing.

The PV array output energy was calculated by *(4-14)* while *(2-1)* was adopted to calculate the array capacity. Equation (2-4) was adopted to determine the battery capacity while (2-3) and (2-5) was used to calculate the number of PV modules and battery units respectively.

Starting with the minimum battery capacity and minimum PV array area, iterations were carried out and analyzed at every incremental step. The LCOE was then computed at the end of each step using modified equation *(4-11)* and stored successively. The optimum system configuration was selected with the objective of attaining the optimal system size while minimizing the LCOE. This ensured maximum reliability improvement with minimum increment in the system cost.

3.4 Data Collection

3.4.1 Data Sources

This study used secondary data acquired from publications by scholars in the same research domain, websites, governmental and non-governmental publications. Data from the Kenya National Bureau of statistics (KNBS – 2019 census) and the World Bank Multitier Framework (MTF) survey 2019 were used to model adaptability factors and validate the new framework.

3.4.2 Study Area

This study is based in Kenya, Narok County which is located along the Great Rift Valley and is reported to have a population of 1,421,932 distributed within 238,115 conventional households (*KNBS 2019*).

Majority of this population comprise of the Masai community who are nomadic pastoralist and rely heavily on fossil-based sources to meet their energy needs. This informed the choice of the region as it projects all of the adaptability factors discussed in this study in section 2.2 and 2.3.

3.4.3 Target Population

This study intends to draw conclusions on solar PV sizing for rural off-grid areas characterized by economic and mobility factors such as low income, nomadic culture and roofing structures which limit installation of solar systems. The developed sizing framework can be applied anywhere across the globe as long as the household portrays these factors as is the case for households in Narok County.

Inferences should be limited to these factors since the objective of the study is to develop a solar PV sizing framework that integrates them at the design stage to enhance system adaptability in off-grid areas.

3.4.4 Sampling Design and Sample Size

Preliminary studies indicated that Narok County has a population of 1,421,932 distributed within 238,115 conventional households where 19.2 % have access to grid connection.

This study relied on preprocessed data from the Kenya National Bureau of Statistics (KNBS) 2019 census which covered the entire population. More specific raw data was obtained from the World Bank Multitier Framework (MTF) 2019 survey which used random stratified sampling to select 215 household across the seven sub counties to participate in the survey. Due to this small sample size, this study adopted the entire sample size for analysis.

3.4.5 Data Collection Instruments

The primary data collection instrument for both KNBS 2019 census and the MTF survey a guided questionnaire administered by trained enumerators. However, in some cases, the enumerators were required to observe and record the findings. The data was recorded through mobile tablets and transmitted to a central data base for analysis.

3.4.6 Unit of Analysis

The unit of analysis for this study is the household which is defined as a group of people residing in the same compound or homestead, which could include one or multiple dwelling units, and they have a common household head with a common cooking and lighting arrangement.

3.4.7 Input parameter description

The proposed sizing framework used household income on energy as the major input to size standalone solar PV systems. This is a change from existing sizing frameworks which use load data and meteorological data as the major inputs. This was done with the objective of developing a sizing framework that responds to the ability of the community to pay for the solar systems at the design stage.

Other input parameters to the developed framework are the highest temperature and lowest solar irradiation of the region where the solar PV system will be used. This approach was adopted to ensure the resultant solar PV system is sized from the worst scenario but within reasonable conditions that it will be subjected to.

The developed framework also requires the user to specify the desired LCOE values to ensure the solution converges faster to reduce calculation time.

3.4.8 Simulation and data collection procedures

This study involved development of a solar PV sizing framework as implemented on MATLAB and SIMULINK. MATLAB is a numeric and computing platform that is used by engineers and scientists to develop algorithms, program, and create models for data analysis. The platform allows for iterative analysis and design processes through a programing language that expresses matrix arrays and mathematical relations directly.

On the other hand, Simulink is a MATLAB-based graphical block diagram design environment that is used to design and simulate systems with multi-domain models. This environment then allows designers to transfer these models into actual hardware platforms for deployment without writing codes in machine language.

The framework developed in this study is a step wise process for sizing solar PV systems and is presented in form of a flow diagram with modelling equations at each step. The sizing process requires iterations to arrive at an optimal solution thus making MATLAB and Simulink ideal platforms for implementation.

To validate the developed framework, data on household income from Narok County was used as input to this framework to size solar PV systems. The program was run and results recorded for comparative analysis. This analysis involved comparison between household income, computed system cost and LCOE. The energy difference between the energy demand and energy generated was also recorded to determine whether the sized system was meeting the energy demand.

3.5 Data Preparation

Due to the large size of the data sets obtained, the study narrowed the results to the study area by filtering the Narok County data from that of the entire country. While the KNBS census data contained preprocessed data on various household parameters, the MTF data was still raw constituting responses from 215 households spread across the seven sub counties.

3.5.1 Data cleaning

The data was cleaned by removing outliers and filling out the missing data through imputation, interpolation and carrying forward previous observation to ensure data completeness. Prior to removal, the outliers were first interrogated to determine whether they hold any critical information in the context of other data entries.

3.5.2 Data Labelling

The data sets were relabeled to replace the questionnaire codes with descriptive titles for ease of analysis. Images on population distribution, color plots on temperature and irradiation were obtained and labelled according to their purpose, location and period. Tables on household income were relabeled to indicate the specific sub location within the wider Narok County.

3.6 Data Analysis

Inferential analysis was used to measure the relationship between the identified adaptability factors and solar PV sizing. This ensured that only the factors which have a substantial effect on solar PV sizing are modelled and integrated in the new sizing framework.

Exploratory data analysis was conducted to understand economic condition of households in Trans Mara East Sub County. Graphs, color plots were also analyzed to get an overview of the meteorological data of the Sub County.

Data from Energy explorer was analyzed to understand energy utilization and population distribution in the region. Collectively, exploratory data analysis and descriptive analysis confirmed the Sub County is indeed an off-grid area with low-income households and limited access to electricity.

3.7 Assumptions

The study assumed various technical and economic parameters regarding the PV modules, battery banks and inverter specifications as shown in **Table 3-1** below. These assumptions were informed by available technologies in Kenya at the time of the study.

Table 3-1 *Equipment specifications*

	Description	**Value**
	PV Module Specifications	
1	PV Module capacity	450W
2	PV Module price	Ksh. 15750
3	PV module efficiency	22%
4	Type of PV cell	Mono-crystalline
5	Nominal cell temperature	45+/- 1˚C
6	PV module expected lifetime	25 Years
	Battery Specification	
1	Battery capacity	5kwh
2	Battery type	Lithium
3	Battery unit price	Ksh. 372,400
4	Battery nominal voltage	48v
5	Depth of discharge	90%
6	Battery efficiency	90%
7	Nominal cell temperature of battery	45+/- 1˚C
	Inverter Specifications	
1	Inverter capacity	5kw
2	Inverter type	Hybrid- MPPT
3	Inverter efficiency	
4	Inverter expected lifetime	
5	Inverter nominal voltage	48VDC/ 230VAC

3.8 Research Quality

3.8.1 Research Reliability

The researcher ensured the reliability of the results by running multiple simulations which were based on various input scenarios derived from the test data. Since the same MATLAB program was used in all these scenarios, the reproducibility and hence the reliability of the sizing framework was assessed. Consistency was checked by varying input data on temperature and irradiation and also on household income.

3.8.2 Research Validity

The researcher ensured the correctness of the results by cross checking the findings against established theories on solar PV sizing. These theories relate to the relationship between solar PV output and temperature of the site location, household income and electricity consumption, and the relationship between irradiation and energy output.

Methodically, the developed solar PV sizing framework is a modification of the numerical PV sizing framework which is widely used in development of commercial solar PV sizing softwares. Modifications were made by modelling off-grid adaptability factors based on established formulas such as LCOE.

3.9 Risk Analysis

The study acknowledges the inadequate data on energy expenditure in Narok County. In this case, the risk was averted by using complimentary data from two different surveys.

There was also the risk of generalization on the application of the developed framework. This was averted by providing an elaborate definition of an off-grid area where the framework should be used. This will ensure that the resulting systems sized by the developed framework are appropriately contextualized.

3.10 Data Analysis and Presentation

The data analysis and results presentation of this study were be divided into two parts which are;

Identification analysis which used data to identify which adaptability factors identified in the literature review manifest at the study area and to what extend it affects adoption, deployment and use of solar PV systems.

Validation analysis which entailed comparing the size, cost and reliability of systems sized through the developed framework against household income and existing solar PV systems to determine whether economic, technical, location and mobility adaptability have been achieved.

3.11 Ethical Consideration

This study relied on publicly available data which was acquired voluntarily without infringement into the rights of the participants. The data on household income was acquired by the Kenya National Bureau of Statistics (KNBS) and the World Bank which are reputable agencies that adopts universal standards in data collection to avoid bias.

The MATLAB software used for simulations was legally acquired by Strathmore University which subsequently avails the same to its researchers for use in their studies. This also applies to the literature works cited which were either publicly available or accessed through the university library portal.

The methods adopted were further reviewed by the Ethical Review committee that is mandated by the National Commission for Science, Technology & Innovation (NACOSTI) to crosscheck research proposal for ethical concerns before they can be conducted. The institution certified the methods in this study as ethical and issued a certificate to this effect as attached in the appendices.

4. Chapter 4: Data Analysis

4.1 Introduction

This chapter presents the results of the research questions that were set out for investigation in ***Section 1.5***. The chapter presents results to confirm whether the adaptability factors identified in the literature review manifest in the study area. Further, results on the framework validation are also presented to confirm whether the developed framework overcomes the adaptability challenges of existing frameworks.

4.2 Data collected and Data sources

Data used in this study was obtained from the Kenya National Bureau of Statistics (KNBS) census 2019 and the World Bank Multitier framework (MTF) survey conducted through the Energy Sector Management Assistance Program (ESMAP) between 2019 and 2021 to capture social, economic and demographic dimensions of households in Kenya.

While the KNBS 2019 census was broader capturing a larger information base, the MTF survey was focused on household energy utilization and how it is affected by social and economic factors. The survey also included a meteorological survey on specific counties including Narok County where devices were installed to measure weather parameters over a period of time.

The KNBS data contained information on number of households in the target area, their sources of cooking and lighting energy, and the nature of the roofing material. On the other hand, the MTF data targeted 215 households but captured additional information on household income, the type of solar system in use, the cost and mode of acquisition of the solar system and the problems experienced while using the system.

This study obtained these sets of data from the online platforms where they have been made accessible to the general public.

4.3 Data Preparation Techniques

Due to the large size of the data sets obtained, data reduction was done by aggregating the data based on county basis. This was done by filtering using the location filter criteria. The data for Narok County was then extracted from the entire data set. Since this data was collected independently from other areas in the country, this filtering and sorting did not affect the data analysis.

The data was cleaned by removing outliers and filling out the missing data through imputation, and carrying forward previous observation to ensure data completeness. These outliers were mainly exaggerated figures with additional zeros as compared to other data entries. Prior to removal or replacement, outliers were first interrogated for their uniqueness in the context of the specific household to determine whether they hold any critical information.

The data sets were then relabeled where the questionnaire codes were replaced by simple descriptive titles for ease of analysis.

4.4 Data Analysis and Framework Development

4.4.1 Phases for Data Analysis and Framework Development

Data analysis and framework development in this study followed the following phases:

Phase 1: Adaptability factors identification and their Effect on Solar PV Sizing

This phase was aimed at answering *research question 1* which was meant to identify the adaptability factors unique to off grid areas and analyze how they affect solar PV sizing.

a) *Identification of adaptability factors*

   Factor analysis technique was used to identify key factors that affect adaptability of solar PV system. These factors were identified as economic, technical, location and mobility factors. By using filtering mechanism, the adaptability factors were isolated for further analysis.

   Descriptive data analysis was then used to determine the level of manifestation of these adaptability factors in the study area.

b) *Determination of the effect of the adaptability factors on the solar PV sizing*

   To determine the cumulative effect of the identified adaptability factors, multiple regression analysis was used to relate data on each of the adaptability factors to the corresponding solar PV sizes.

Phase 2: Creating Solar PV Sizing Modelling Equations

This phase entailed modelling equations that relate the identified adaptability factors to solar PV sizing. This was done by considering the various ways these factors manifest in solar PV sizing and establishing relationships through equations.

Phase 3: Development of the Adaptable Solar PV Sizing Framework

In this phase, the created model equations in Phase 2 were used to modify the existing Numerical sizing framework discussed in *chapter 2.4.2* by integrating them within the sizing process to develop the new adaptable solar PV sizing framework.

Phase 4: Framework validation

This phase of data analysis involved comparison of data collected from the field and data generated from the developed framework to determine whether this framework has actually treated the adaptability challenges arising from existing frameworks.

4.5 Results for Data Analysis and Framework Development

4.5.1 Phase 1 Results: Adaptability Factors Identification and their Effect on Solar PV Sizing

These results answer *research question 1* which was set out in ***Section 1.5*** as follows:

> ***Research Question1:*** *What are the solar PV adaptability factors unique to off-grid areas and how do they influence solar PV system sizing?*

In this section, data is analyzed to determine how economic factors (household income), technical factors (system utilization and equipment degradation), location factors (irradiation and temperature), mobility factors (mounting techniques) and constraint factors (system quality) have manifested within the households of Narok County and how they have impacted the sizes, the deployment and usage of solar PV systems.

4.5.1.1 Economic Factors

Household Income in Narok County

To determine the economic ability of the household in rural and urban areas and the impact of electricity on this ability, the respondents were asked to state their economic activity and their average monthly income. The results of this questions are summarized in **Figure 4-1**.

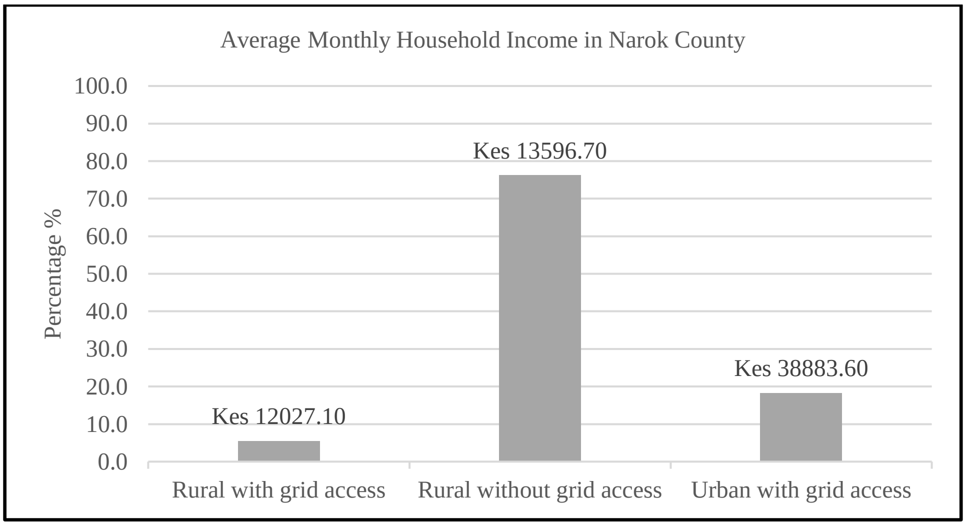


Figure 4-1 *Average Monthly household income in Narok County.*

It is observed that households in urban areas with grid access have a higher monthly income averaging at Ksh. 38,884 while household in rural areas with grid access have the least monthly income averaging at Ksh. 12,027. It is also observed that there is no big difference between the monthly income of households in rural areas with grid access and those without grid access which have an average monthly income of Ksh. 13,596.

Information on monthly household income will inform development of a new sizing framework that results in systems that are affordable to communities in off-grid areas.

Cost of Solar systems and solar devices in Narok County

To determine the cost of solar devices already in use in Narok County, the respondents were asked to state the amount they paid upfront for the devices and the amount they pay monthly in case of an installment arrangement. The results recorded are summarized in **Figure 4-2**.

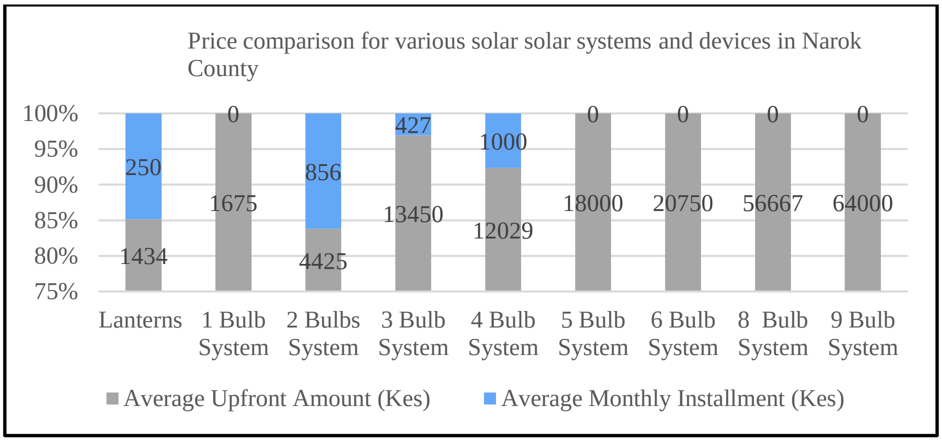


Figure 4-2 *Price comparison for various system sizes in Narok.*

The results indicate that upfront payment was the most common mode of purchase for the solar devices. Installment plans are also available but also require down payment. However, these plans are limited to smaller systems between 1-4 bulbs with suppliers opting for upfront payment for larger systems of between 5-9 bulbs. This information gives insight into the system size and the most effective payment mode in the market.

The results also indicated that a majority of the solar devices accounting for 92% were acquired through an installment plan while upfront payment accounted for 8% of the devices as summarized in **Figure 4-3**.

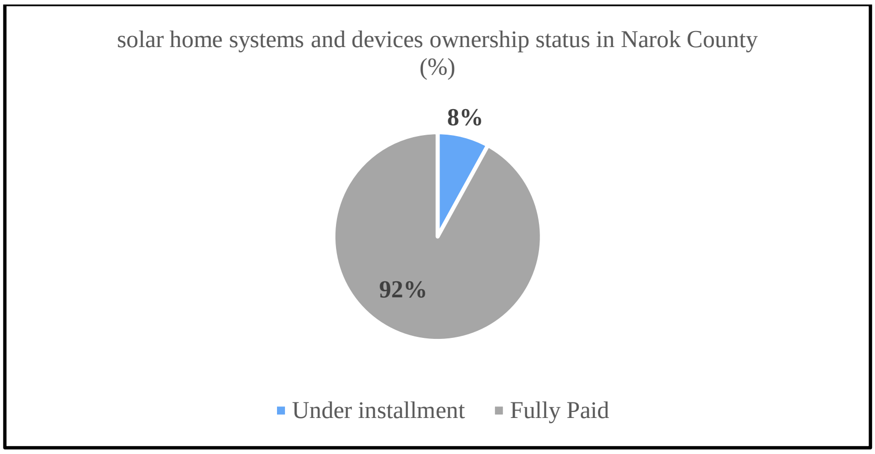


***Figure 4-3** Solar home systems and devices ownership status.*

There were no rental agreements recorded among the respondents with a negligible number reporting that they received their systems for free. This information gives insight into the effectiveness of various payment methods targeted by existing sizing frameworks.

4.5.1.2 Technical Factors

Projected increase in energy demand

The researcher sought to determine how the energy demand will increase once a system is deployed for use in Narok County. This is in view of the fact that some households do not have electrical appliances but are targeted for transition to solar energy. The respondents were asked to list electrical appliances they would like to acquire in the foreseeable future given electricity access. The responses were recorded and the results summarized as presented in **Figure 4-4**.

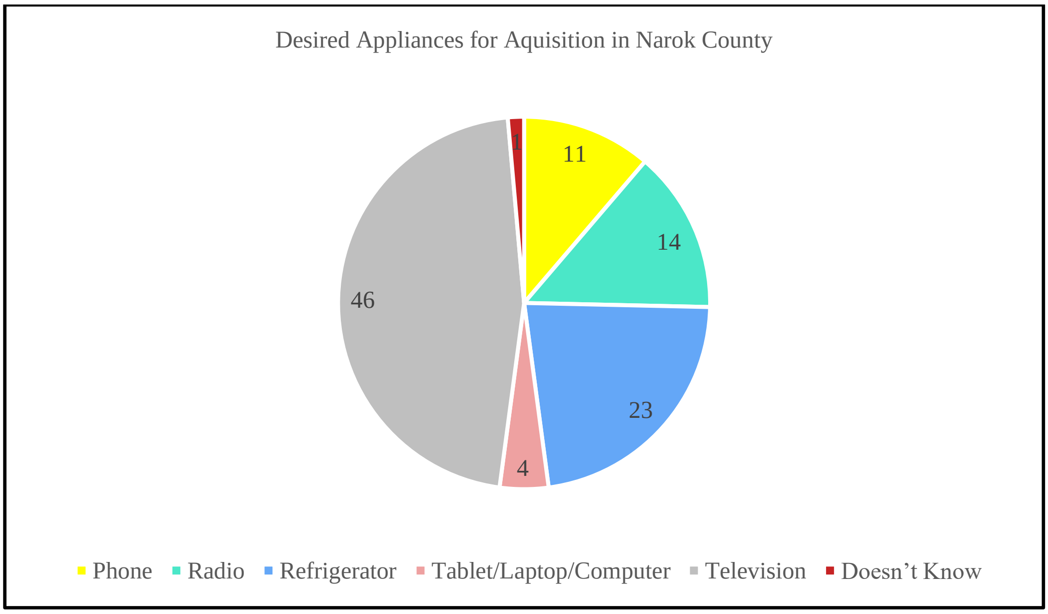


***Figure 4-4**: Desired appliances for acquisition by households in Narok.*

The results indicate that the most desired appliance for acquisition is the television set which was preferred by 46% of the population. The refrigerator was desired by 23% of the respondents while another 14% desired to acquire a radio. The mobile cell phone was the least desired appliance accounting for 11% of the respondents.

These results inform solar PV sizing by projecting future energy consumption which should be factored in at the sizing stage.

Quality assessment of solar PV systems in Narok County

The researcher sought to assess the level of satisfaction from the use of solar devices the results of which are summarized in **Figure 4-5**.

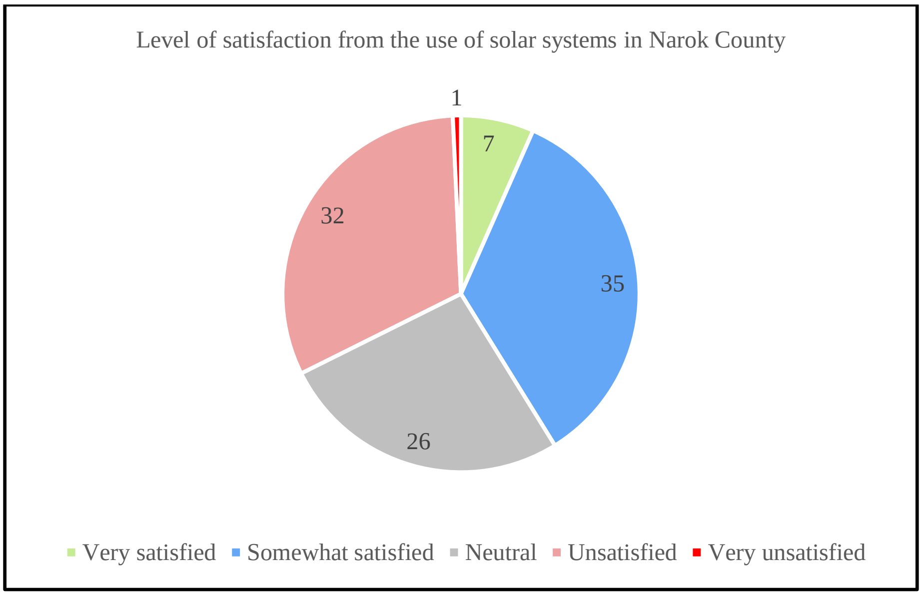


Figure 4-5*: Performance assessment of solar systems in Narok.*

The results indicate a form of evenness between average satisfaction, dissatisfaction and neutrality. Households that were somewhat satisfied with the performance of their solar systems accounted for 35% of the population with 32% reporting to be unsatisfied with the performance of their systems. Those who could not comment on the performance were 26%. It is observed that 7% of the respondents were very satisfied with their systems while 1% were very unsatisfied with their systems.

These results give insight into the general perception on the performance of solar systems in off-grid areas. It also gives indications on whether the current sizing frameworks are developing systems that meet the needs of communities in off-grid areas.

Further, the respondents were asked to state the number of years they have used the solar device and the results were recorded and summarized in **Figure 4-6**.

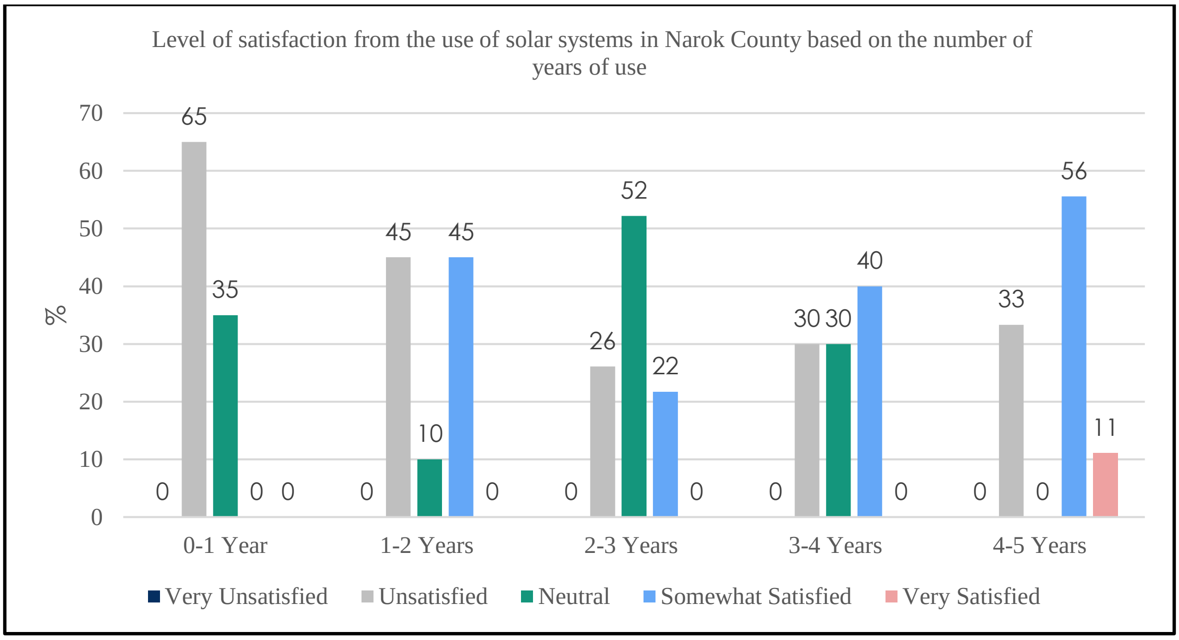


Figure 4-6*: Level of satisfaction and years of solar PV usage in Narok.*

It is observed that a majority of those who reported to be unsatisfied with their systems had used the systems in under two years while those who were somewhat satisfied with their systems had used the systems for over two years. All respondents who reported to be very satisfied with their systems had used them for over four years. Respondents who were neutral about the performance of their systems was highest between 2-3 years of usage but the number diminished as the years progressed.

These results give insight into the performance of solar systems in off-grid areas and the timeline for which they happen. Further investigation is done to determine how this performance can be improved at the sizing stage.

4.5.1.3 Location Factors

Solar Irradiation in Narok County

Data on the solar irradiation in Narok County recorded every minute between 4th December 2019 and 31st December 2021 was acquired for Analysis. The data was collected by GeoSUN Africa for World Bank using two different pyranometers for comparison. The summary for the last month is shown in **Figure 4-7**.

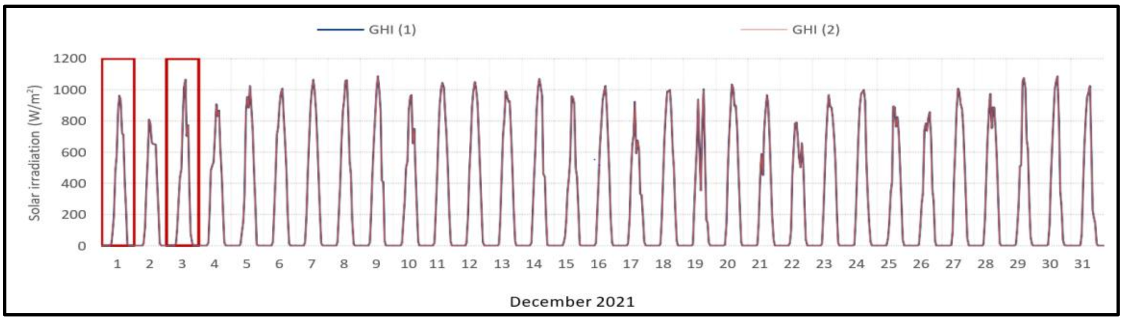


***Figure 4-7**: Narok County Solar irradiation for December 2021*

It is observed that the maximum daily average irradiation recorded for the month was 7.7kW/m^2 while the least recorded daily average was 5.55kW/m^2. The average irradiation for the month was recorded as 6.72kW/m^2

Data on variation of irradiation within the region will inform development of the sizing framework to develop systems that are adaptable to changing solar insolation due to the nomadic nature of the community and weather variations.

Air temperature in Narok County

Data on temperature in Narok County recorded every minute between 4th December 2019 and 31st December 2021 was acquired for Analysis. The data was collected by GeoSUN Africa for World Bank and compared to satellite data for the same region. The summary for the last month is shown in **Figure 4-8**.

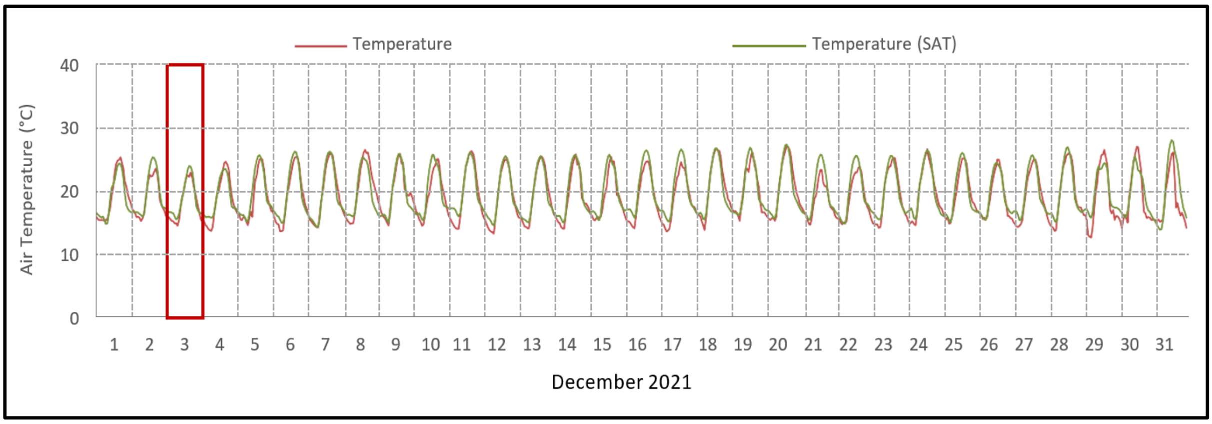


***Figure 4-8**: Narok County temperature for December 2021*

It is observed that the highest daily average temperature for the month is 20.68^{O}C while the least recorded daily average is 18.23^{O}C. The average temperature was recorded as 19.33^{O}C.

Data on variation of temperature within the region will inform development of the sizing framework to develop systems that are adaptable to changing temperature exposure due to the nomadic nature of the community as compared to sizing location specific systems.

4.5.1.4 Mobility Factors

Types of Solar system sizes in Narok County

To determine the type of solar devices already in use in Narok County, the enumerators requested the respondents to show them the devices where the number of bulbs were used as the benchmark to determine the system size. In this case, lanterns were categorized as those devices which have one bulb with a solar PV module attached at the back as one unit. The other devices were categorized based on the number of bulbs that are separable from the PV module and the results recorded as summarized in **Figure 4-9**.

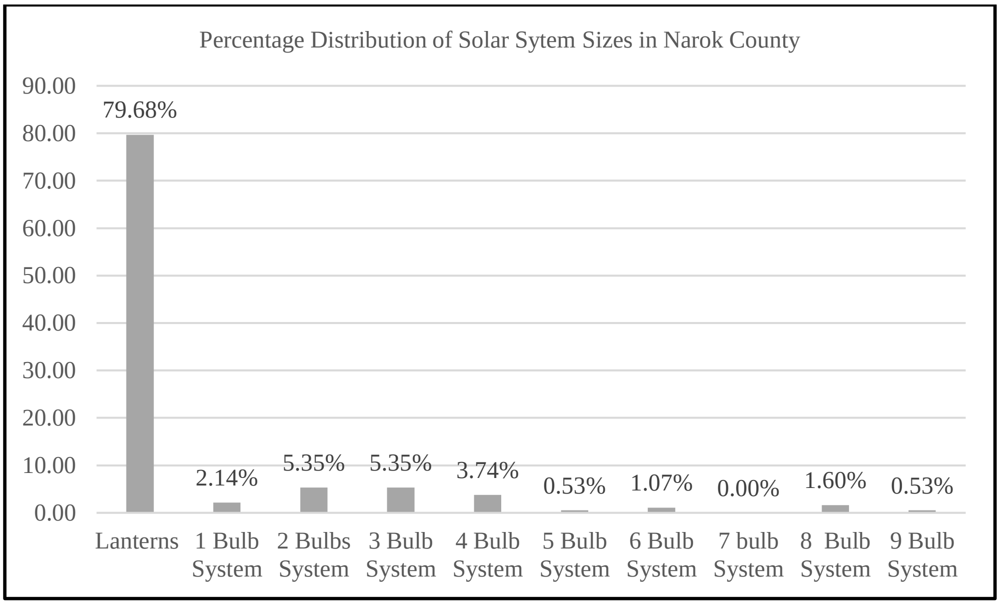


Figure 4-9 *Distribution of solar system sizes in Narok*

It is observed that the most common type of solar device in use in Narok County is the lantern which was found to be used in 79.6% of the households. Lighting systems with 1-3 bulbs are also popular but the usage of systems with more bulbs diminishes from 4-9 bulbs. This information gives insight into the system sizes that are needed by off-grid communities.

Roofing Material and solar PV systems in Narok County

Data on the roofing material in Narok County was acquired from KNBS census 2019 and the results presented in **Figure 4-10.**

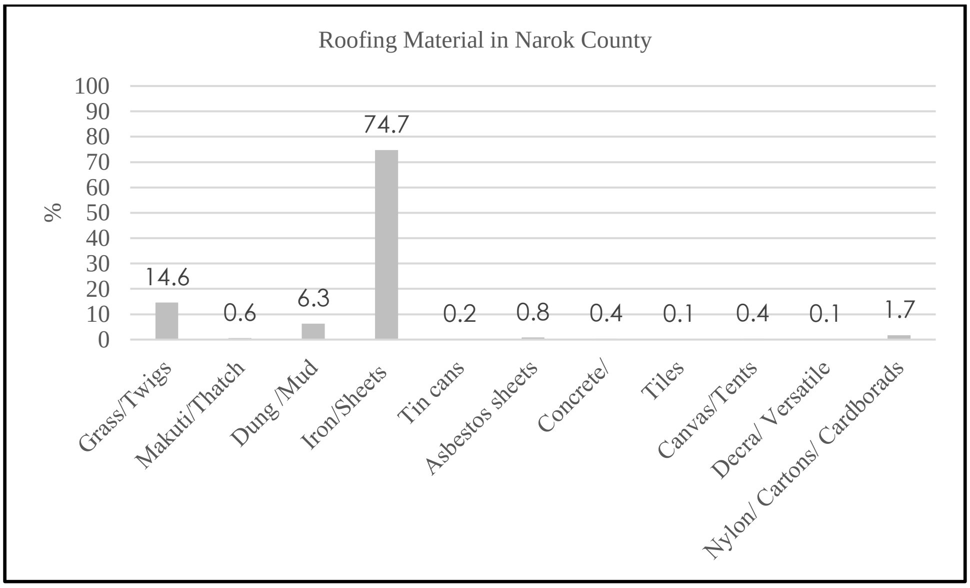


Figure 4-10*: Distribution of roofing material for Narok County.*

The results indicate that iron sheets are the most common roofing material in Narok accounting for 74.7% of the households Grass and twigs are the second preferred roofing material while dung/mud followed at 6.3%. This information gives insight into the effectiveness of sizing solar PV systems to be mounted on rural rooftops.

The researcher sought to establish the relationship between roofing type and solar device in possession in Narok County. Enumerators observed and recorded the roofing type and the type of the solar system the results of which are summarized in **Figure 4-11**. In this case, a solar lantern is defined as a solar device with one lighting point with the solar PV module attached to the back.

The solar lighting system comprise those devices used for lighting only with 1-10 separable lighting points. On the other hand, a solar home system is defined as a solar system capable of powering other electrical appliances apart from lighting such as television sets.

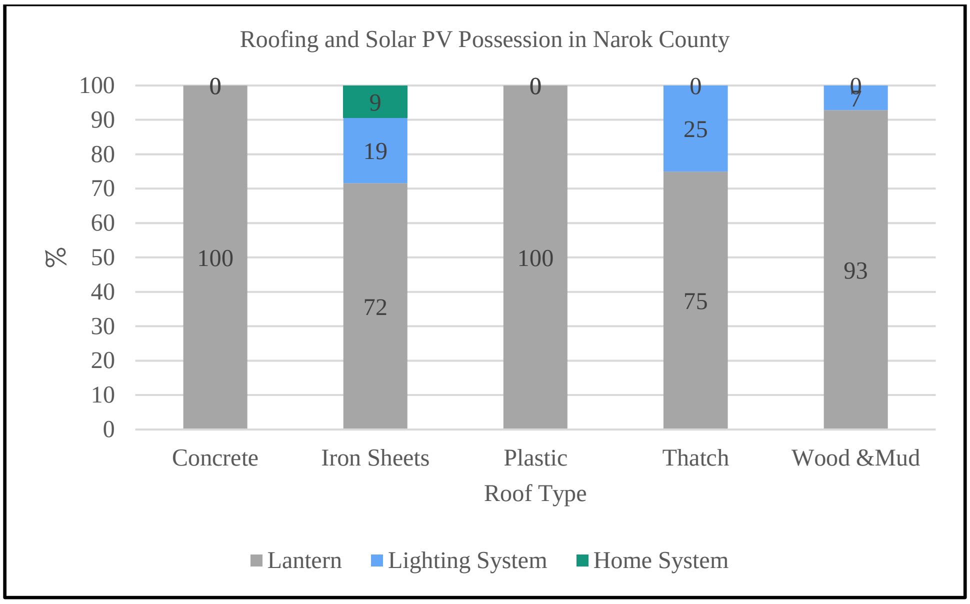


***Figure 4-11**: Comparison between roofing material and solar system possession in Narok.*

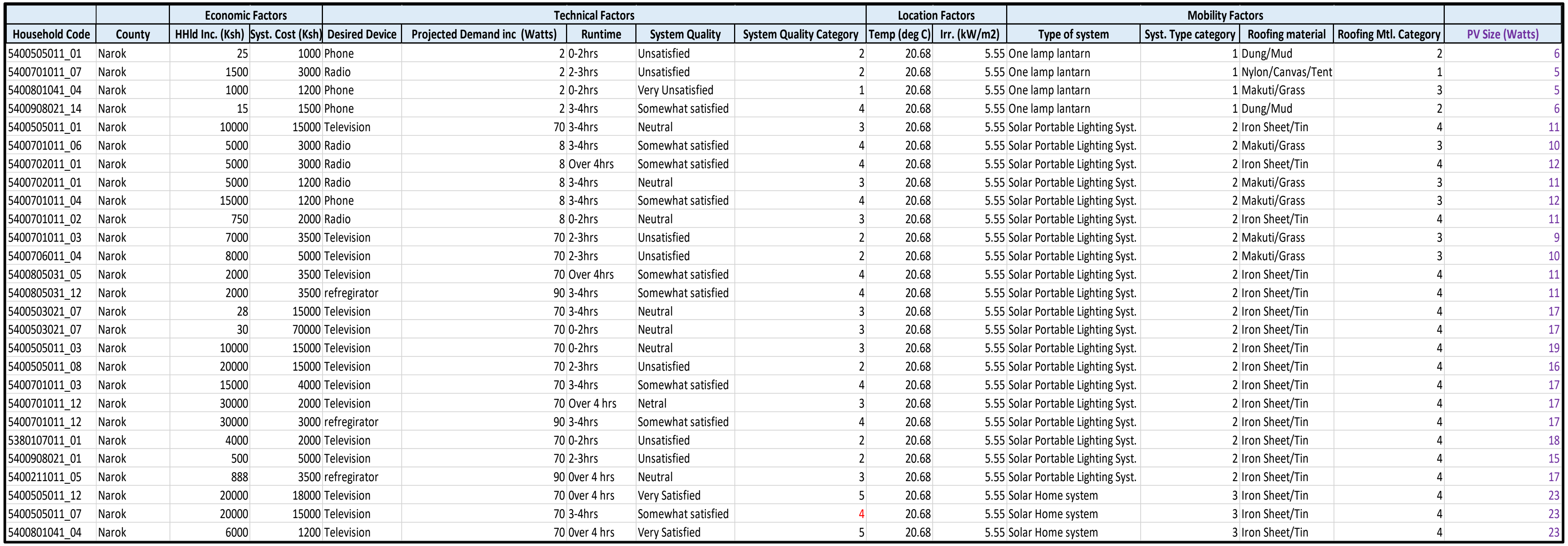
It is observed that all home systems were reported to be owned by household with iron sheet roofing with lanterns being the most common means of lighting across all roof types.

The comparison between the three system sizes and where they have found adaptation with regard to roof types will inform sizing of solar systems for off-grid areas characterized by traditional roofing techniques.

4.5.1.5 Effect of Identified Adaptability Factors on Solar PV Sizing

The study sort to identify the effect of the identified adaptability factor on solar PV sizing through multiple regression analysis. Data on the various factors was arranged as shown in **Figure 4-12** and analyzed.

The results of the regression analysis are summarized in **Table 4-1**.



		Economic Factors		Technical Factors					Location Factors		Mobility Factors				
Household Code	County	HHld Inc. (Ksh)	Syst. Cost (Ksh)	Desired Device	Projected Demand inc (Watts)	Runtime	System Quality	System Quality Category	Temp (deg C)	Irr. (kW/m2)	Type of system	Syst. Type category	Roofing material	Roofing Mtl. Category	PV Size (Watts)
5400505011_01	Narok	25	1000	Phone	2	0-2hrs	Unsatisfied	2	20.68	5.55	One lamp lantarn	1	Dung/Mud	2	6
5400701011_07	Narok	1500	3000	Radio	2	2-3hrs	Unsatisfied	2	20.68	5.55	One lamp lantarn	1	Nylon/Canvas/Tent	1	5
5400801041_04	Narok	1000	1200	Phone	2	0-2hrs	Very Unsatisfied	1	20.68	5.55	One lamp lantarn	1	Makuti/Grass	3	5
5400908021_14	Narok	15	1500	Phone	2	3-4hrs	Somewhat satisfied	4	20.68	5.55	One lamp lantarn	1	Dung/Mud	2	6
5400505011_01	Narok	10000	15000	Television	70	3-4hrs	Neutral	3	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	11
5400701011_06	Narok	5000	3000	Radio	8	3-4hrs	Somewhat satisfied	4	20.68	5.55	Solar Portable Lighting Syst.	2	Makuti/Grass	3	10
5400702011_01	Narok	5000	3000	Radio	8	Over 4hrs	Somewhat satisfied	4	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	12
5400702011_01	Narok	5000	1200	Radio	8	3-4hrs	Neutral	3	20.68	5.55	Solar Portable Lighting Syst.	2	Makuti/Grass	3	11
5400701011_04	Narok	15000	1200	Phone	8	3-4hrs	Somewhat satisfied	4	20.68	5.55	Solar Portable Lighting Syst.	2	Makuti/Grass	3	12
5400701011_02	Narok	750	2000	Radio	8	0-2hrs	Neutral	3	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	11
5400701011_03	Narok	7000	3500	Television	70	2-3hrs	Unsatisfied	2	20.68	5.55	Solar Portable Lighting Syst.	2	Makuti/Grass	3	9
5400706011_04	Narok	8000	5000	Television	70	2-3hrs	Unsatisfied	2	20.68	5.55	Solar Portable Lighting Syst.	2	Makuti/Grass	3	10
5400805031_05	Narok	2000	3500	Television	70	Over 4hrs	Somewhat satisfied	4	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	11
5400805031_12	Narok	2000	3500	refregirator	90	3-4hrs	Somewhat satisfied	4	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	11
5400503021_07	Narok	28	15000	Television	70	3-4hrs	Neutral	3	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	17
5400503021_07	Narok	30	70000	Television	70	0-2hrs	Neutral	3	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	17
5400505011_03	Narok	10000	15000	Television	70	0-2hrs	Neutral	3	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	19
5400505011_08	Narok	20000	15000	Television	70	2-3hrs	Unsatisfied	2	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	16
5400701011_03	Narok	15000	4000	Television	70	3-4hrs	Somewhat satisfied	4	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	17
5400701011_12	Narok	30000	2000	Television	70	Over 4 hrs	Netral	3	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	17
5400701011_12	Narok	30000	3000	refregirator	90	3-4hrs	Somewhat satisfied	4	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	17
5380107011_01	Narok	4000	2000	Television	70	0-2hrs	Unsatisfied	2	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	18
5400908021_01	Narok	500	5000	Television	70	2-3hrs	Unsatisfied	2	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	15
5400211011_05	Narok	888	3500	refregirator	90	Over 4 hrs	Neutral	3	20.68	5.55	Solar Portable Lighting Syst.	2	Iron Sheet/Tin	4	17
5400505011_12	Narok	20000	18000	Television	70	Over 4 hrs	Very Satisfied	5	20.68	5.55	Solar Home system	3	Iron Sheet/Tin	4	23
5400505011_07	Narok	20000	15000	Television	70	3-4hrs	Somewhat satisfied	4	20.68	5.55	Solar Home system	3	Iron Sheet/Tin	4	23
5400801041_04	Narok	6000	1200	Television	70	Over 4 hrs	Very Satisfied	5	20.68	5.55	Solar Home system	3	Iron Sheet/Tin	4	23

Figure 4-12: *Adaptability factors data excerpt*

Table 4-1: Regression Analysis shows a summary of the multiple regression analysis for the various adaptability factors identified in this study.

Table 4-1: *Regression Analysis*

Regression Statistics	
Multiple R	0.831340184
R Square	0.691126501
Adjusted R Square	0.663872957
Standard Error	6.865998635
Observations	38

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	3586.437291	1195.479	25.35914	8.48053E-09
Residual	34	1602.825867	47.14194		
Total	37	5189.263158			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	6.191067643	2.327388907	2.660092	0.011832	1.461244315	10.920891	1.46124431	10.92089097
Household Income (Ksh.)	0.000287699	0.000139391	2.063971	0.046719	4.42241E-06	0.00057098	4.4224E-06	0.000570976
System. Cost (Ksh)	0.000372181	5.97963E-05	6.224148	4.41E-07	0.00025066	0.0004937	0.00025066	0.000493701
Projected Demand inc after acquisition (Watts)	0.09178957	0.038935003	2.357508	0.024294	0.012664123	0.17091502	0.01266412	0.170915016

The regression analysis indicated that the economic factors of household income and system cost were the key factors in predicting solar PV size. The projected increase in demand which is a technical factor was also found to be important in predicting the size of the PV system. Through an iterative process, the other adaptability factors were found to have lower significance in predicting the size of the solar PV system and were successively eliminated from the model.

These factors include location factors of temperature and irradiation which registered the same value for each household. However, it is important to note that these parameters will have a significant input when comparing household from different geographical locations where temperature and irradiation substantially varies.

The other factors which did not present a substantive impact on the solar PV size are the mobility factors of roofing material and system type as summarized in below.

Table 4-2: *Effect of Adaptability factors on Solar PV sizing*

Economic Factors		**Technical Factors**		**Location Factors**		**Mobility Factors**		
Hhld. Inc.	*Syst. Cost*	*Inc. in demand*	*Syst. Quality*	*Temperature*	*Irradiation*	*Syst. Type*	*Roofing Mtl.*	
YES	YES	YES	NO	NO/YES	NO/YES	NO	NO	**PV Size**

The adaptability model is shown in *(4-1)* below:

$$Y = 6.19 + 0.000287X1 + 0.000372X2 + 0.091789X3 \tag{4-1}$$

where;

X1;- is the household income in Ksh.

X2:- is the solar PV system cost in Ksh.

X3:- is the projected increase in demand after acquisition of new equipment (watts).

The analysis also indicated that 64% of the observations of the dependent variable are explained by the independent variables. Further the significance value of less than 0.05 indicate the model is reliable.

The analysis established a positive correlation between the system cost, household income, energy demand and PV system size as shown in **Figure 4-13**, **Figure 4-14** and **Figure 4-15** below.

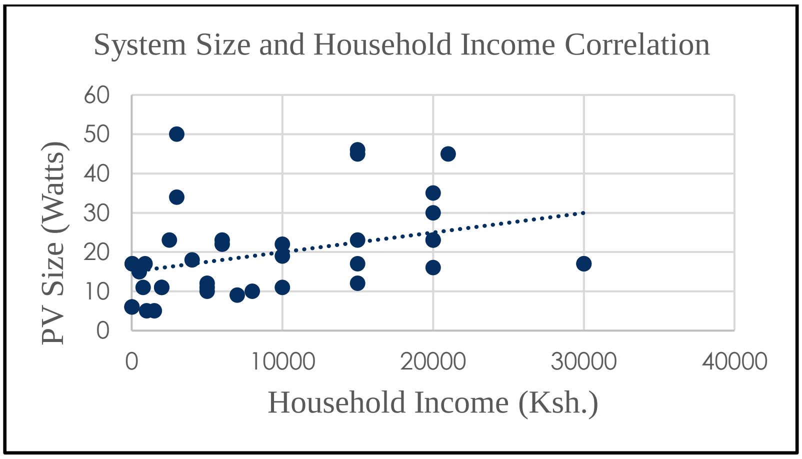


***Figure 4-13**: System size and household income correlation.*

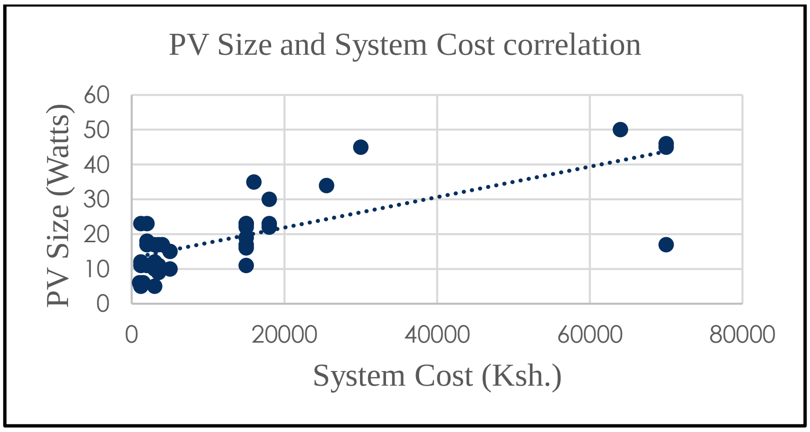


***Figure 4-14**: System cost and size correlation.*

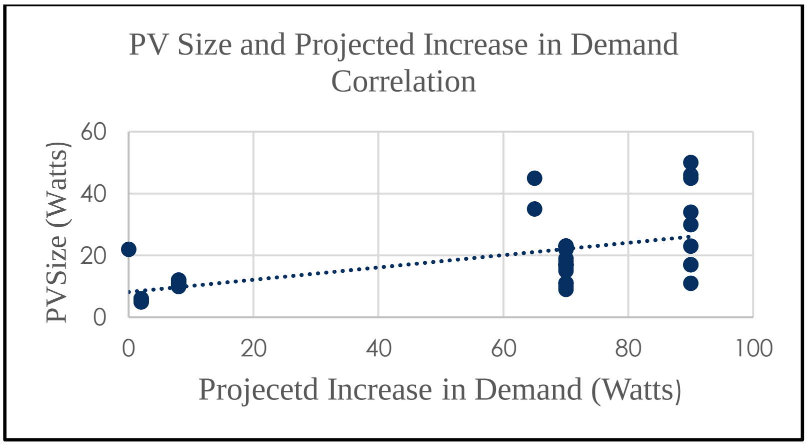


***Figure 4-15**: Energy demand and system size correlation.*

4.5.2 Phase 2 Results: Creating Solar PV Sizing Modelling Equations

4.5.2.1 Equations for Economic Factors

Manifestation of household income and system cost in solar PV sizing

Household income has a direct relation to the final cost of energy that can be charged to the end user which is represented by the levelized cost of energy (LCOE). If this cost is too high compared to the disposable income available for energy in each household, then the developed PV system will be unaffordable.

LCOE represents the unit cost of energy in Ksh/kWh and is derived by dividing the total cost of installation, operation, and maintenance to the total energy generated by the solar system over its useful life as shown in (4-2) (Li, 2018).

$$\text{LCOE} = \frac{\sum_{t=1}^{n}\{(It + (O + M)t)\,/(1 + r)^{t}\}}{\sum_{t=1}^{n}\{Et\,/(1 + r)^{t}\}}$$

(4-2)

where:

It is the initial investment cost.

(O & M)t is the operation and maintenance expenditure in year t.

Et is the electrical energy generated in year t (kWh)

r is the percentage discount rate.

n is the system lifetime in years.

For affordability, the World Bank recommends that the total energy expenditure on energy per day should be less than or equal to one 5% of the daily household income as shown in (*4-3)* and *(4-4)*.

$$k(LCOE) \leq \frac{Household\ income}{0.02}$$

(4-3)

$$\mathrm{k}\left\{\frac{\sum_{t=1}^{n}\{(It + (O + M)t)\,/(1 + r)^{t}\}}{\sum_{t=1}^{n}\{Et\,/(1 + r)^{t}\}}\right\} \leq Hinc/0.02$$

(4-4)

where:

k is number of electricity units used per day in kWhr.

$\mathbf{H_{inc}}$ is daily household income in Ksh.

The objective is to arrive at a system size for which the cost of energy is less or equal to 5% of the household income at the best possible reliability index.

4.5.2.2 Equations for Technical Factors

Manifestation of demand and energy utilization in solar PV sizing

Investors and solar PV developers must predict the change in energy demand in relation to the system maximum capacity. This reduces the risk of sizing a large system with a high capital investment only to be underutilized by the users or a system too small to meet the growing demand.

Energy demand and utilization in solar PV system sizing is represented by the capacity utilization factor CUF. This parameter indicates the actual annual energy generated as a ratio of the energy generated if the plant was operated at full capacity, 24hours a day, for 365 days.

CUF is given by *(4-5)* below (Li, 2018).

$$\mathrm{CUF} = \frac{Et}{Po * 365 * 24}$$

(4-5)

where:

Et = energy generated in Kwh in a given year, t

Ppv =rated capacity of the system in kW

The value of CUF is dependent on the number of clear sunny days, the incident irradiation, and the PV technology in use(V. Sharma et al., 2013). This parameter subsequently has a direct impact on LCOE (Kottek et al., 2006)

Since at design stage, we do not know the actual energy that will be generated, we need to determine a suitable CUF.

Electrical energy generated in a given year (Et) is a product of the solar PV system rating and the system utilization factor (CUF) as shown by *(4-6)-(4-8)*.

$$Et = Ppv * CUF$$

(4-6)

But,

$$Ppv = \frac{El * SF}{ns.ninv.PSH}$$

(4-7)

Therefore,

$$Et = \frac{El * SF * CUF}{ns.ninv.PSH}$$

(4-8)

Equation (4-2) can be used to modify the LCOE as shown by *(4-9)*:

$$\text{LCOE} = \frac{\sum_{t=1}^{n}\{(It + (O + M)t)\,/(1 + r)^{t}\}}{\sum_{t=1}^{n}\{\ \frac{El * SF * CUF}{ns * ninv * PSH * (1 + r)^{t}}\}}$$

(4-9)

where,

SF= safety factor for increasing demand usually 30%

It = initial investment cost

(O & M)t = 0&M expenditure in year t

R = percentage discount rate.

n = system lifetime in years

El: is the energy consumption per day,

ηs and ηinv = are the system and inverter efficiencies which represent resistive losses.

PSH = is the peak sunshine hours for the site location.

Predicting energy demand and utilization should also be done with the consideration that he equipment to be used will be affected by degradation over the period of their useful life. In solar PV sizing, equipment degradation is measured by the rate of degradation (DR) which affect the cost of repair and maintenance in LCOE as shown in *(4-10)* and *(4-11)*.

$$\mathrm{DR} = \frac{(Pnominal - Present) * 100}{Pnominal * Age\ of\ operation}$$

(4-10)

Where:

P$_{\text{nominal}}$ = Power rating of the system

P$_{\text{present}}$ = Power generated presently by the system

Globally, the reported degradation rates for different solar PV technologies are as follows:

mc-Si: 0.4–2.7 %/year

pc-Si: 0.53–4.6 %/year

a-Si: 1.2–2.28 %/year

CdTe: 0.8–5.5 %/year

CIGS: 0.8–5.1 %/year

a-Si/µc-Si: 1.7–2.7 %/year

HIT: 0.36–1.5 %/year

Degradation successively increases the O&M cost in LCOE. In this study we shall assume the use of monocrystalline technology (mc-Si) which has a worst case reported DR of 2.7%/year.

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n}\{(It + ((O+M) * 0.027n)t)\,/(1+r)^t\}}{\sum_{t=1}^{n}\{\frac{El * SF * CUF}{ns * ninv * PSH * (1+r)^t}\}}$$

(4-11)

Where:

It = initial investment cost

(O & M)t = O&M expenditure in year t

Et = electrical energy generated in year t (kWh)

R = percentage discount rate.

n = system lifetime in years.

4.5.2.3 Equations for Location Factors

The regression analysis done in the previous section indicated that location factors were not relevant in predicting the size of the solar PV system. However, interpreting these results in the context of these study, temperature and irradiation were not relevant since it was not practical to record these parameters for individual households and therefore a blanket value from the local meteorological station was used for all households.

In view of this interpretation, this study has included temperature and irradiation in the development of the new sizing framework since these parameters are key in determining the maximum solar energy that can be harnessed from the sun as discussed in the literature review.

Manifestation of Temperature and Irradiation in Solar PV sizing

Frequent movement in the case of nomadic communities implies changing temperature and irradiation data. These two aspects have a direct impact on the efficiency and energy output of solar PV modules as shown in *(4-12)* and *(4-13)*.

$$Epv = G * Apv * nc$$

(4-12)

where:

E_{pv}= PV output energy

G= irradiation at the specific location

A_{pv}= PV area in m^2

n_c= efficiency of PV cell

$$nc = nstc[1 - Bstc(Tc - Tstc)]$$

(4-13)

Where:

n_c = efficiency of photovoltaic cell

n_{stc}= efficiency of photovoltaic cell at standard test conditions (G_{stc} = 1000w/m2; T_{stc} = 25 ^oC)

B_{stc} = Temperature coefficient = 0.004 K^{-1} for crystalline silicon modules.

T_c= cell temperature

Equation *(4-12)* and *(4-13)* can be combined to obtain a modified equation as shown below:

$$Epv = G * Apv * \{nstc[1 - B(Tc - Tstc)]\} \tag{4-14}$$

Where:

G= irradiation at the specific location (worst case scenario)

nstc= efficiency of photovoltaic cell at standard test conditions (Gstc = 1000w/m2; Tstc = 25^{o}C)

Bstc = Temperature coefficient = 0.004 K^{-1} for crystalline silicon modules.

Table 4-3: *Summary of model equations formulation.*

Adaptability Factor	Manifestation in PV Sizing	Sizing Parameter	Initial Equation	Modified Equation
Economic Factors ***Household Income***	Cost of Energy	LCOE	$\text{LCOE} = \frac{\sum_{t=1}^{n}\{(It + (O+M)t)\,/(1+r)^{t}\}}{\sum_{t=1}^{n}\{Et\,/(1+r)^{t}\}}$ **It** = initial investment cost **(O & M)t** = 0&M expenditure in year t **Et** = electrical energy generated in year t (kWh) **R** = percentage discount rate. **n** = system lifetime in years	For affordability: $LCOE \leq Household\ income$ Objective is to arrive at a system size for which LCOE is less or equal to a third of the household income at the best possible LPSP.
Technical factor ***Energy demand and System utilization***	System capacity	CUF	$\text{CUF} = \frac{Et}{Ppv * 365 * 24}$ **Et** = energy generated in kWh in a given year, t **Ppv** =rated capacity of the system in kW $\text{LCOE} = \frac{\sum_{t=1}^{n}\{(It + (O+M)t)\,/(1+r)^{t}\}}{\sum_{t=1}^{n}\{Et\,/(1+r)^{t}\}}$ Since at design stage, we do not know the actual energy that will be generated, we need to determine a suitable CUF. Electrical energy generated in year t (kWh) (Et) = solar PV system rating* utilization factor (CUF). $Et = Ppv * CUF = \frac{El * SF * CUF}{ns.ninv.PSH}$	$\text{LCOE} = \frac{\sum_{t=1}^{n}\{(It + (O+M)t)\,/(1+r)^{t}\}}{\sum_{t=1}^{n}\{\frac{El * SF * CUF}{ns * ninv * PSH * (1+r)^{t}}\}}$ Where **SF**= safety factor for increasing demand usually 30% **El**: is the energy consumption per day, **ns and ninv =** are the system and inverter efficiencies which represent resistive losses. **PSH =** is the peak sunshine hours for the site location.
	Rate of degradation	DR	$\text{DR} = \frac{(Pnominal - Present) * 100}{Pnominal * Age\ of\ operation}$ Pnominal = Power rating of the system Present = Power generated presently by the system Globally, the reported degradation rates for different technologies: mc-Si: 0.4–2.7 %/year pc-Si: 0.53–4.6 %/year	Relation between DR and O&M cost. Degradation successively increases the O&M cost. In this study we shall use mc-Si technology – Worst case DR= 2.7%/year $\text{LCOE} = \frac{\sum_{t=1}^{n}\{(It + ((O+M) * 0.027n)t)\,/(1+r)^{t}\}}{\sum_{t=1}^{n}\{\frac{El * SF * CUF}{ns * ninv * PSH * (1+r)^{t}}\}}$

Location factors	Irradiation	PV output	$Epv = G * Apv * nc$ Epv= PV output energy G= irradiation at the specific location Apv= PV area in m2 nc= efficiency of PV cell	$Epv = G * Apv * \{nstc[1 - B(Tc - Tstc)]\}$ **nstc**= efficiency of photovoltaic cell at standard test conditions (Gstc = 1000w/m2; Tstc = 25°C) **Bstc** = Temperature coefficient = 0.004 K^{-1} for crystalline silicon modules.
	Temperature	PV output	But: $nc = nstc[1 - Bstc(Tc - Tstc)]$ **Tc**= cell temperature	

4.5.3 Phase 3 Results: Development of the Adaptable Solar PV Sizing Framework

This section presents the results of research question 3 which was set out in ***Section 1.5*** as follows.

> ***Research Question 3****: How can we develop a sizing framework to overcome these adaptability challenges?*

A solar PV sizing framework adaptable to off-grid areas was developed in this study by using the model equations developed *in Phase 2* to modify the Numerical solar PV sizing framework discussed in Chapter 2.4.2 and presented in **Figure 2-4**. The modified framework is then implemented on MATLAB SIMULINK and the process layout presented in this chapter as shown in **Figure 4-16** and **Figure 4-17**.

Flow Chart for the Developed Framework

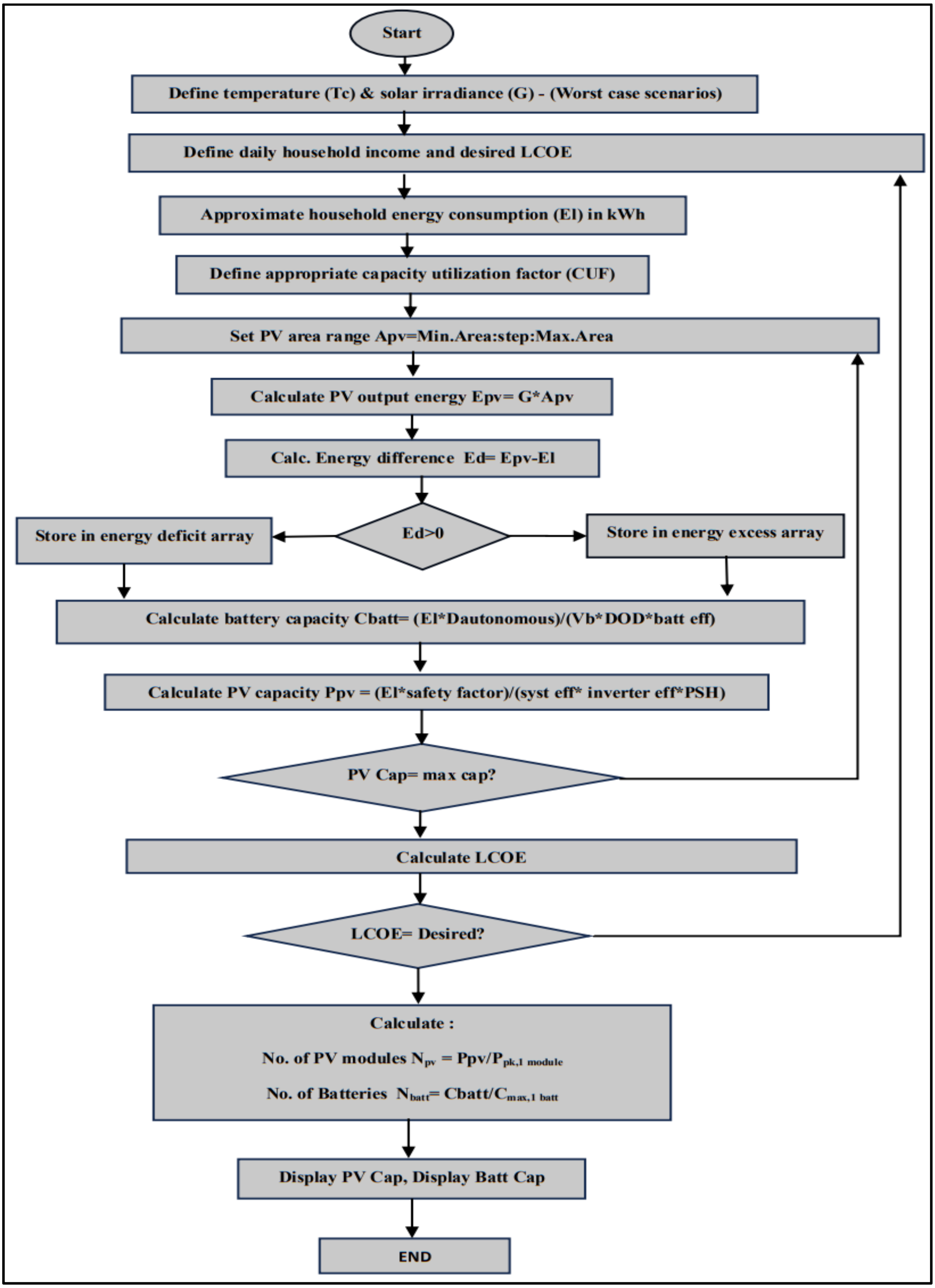


Figure 4-16*: Framework Development Flowchart*

MATLAB- Simulink Implementation of the Developed Framework

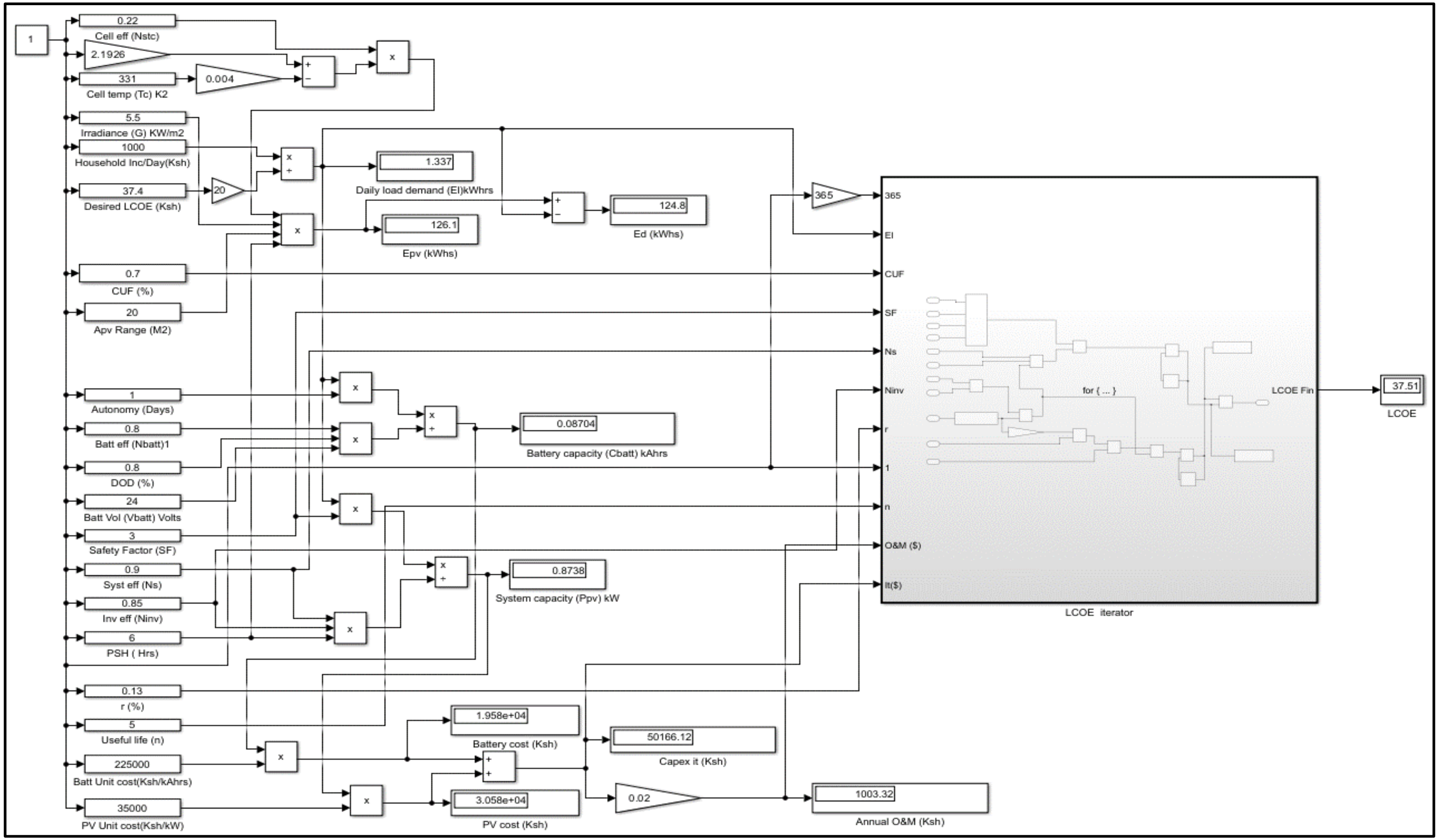


Figure 4-17: Framework Implementation on MATLAB- SIMULINK

Key

Table 4-4 *Framework Key*

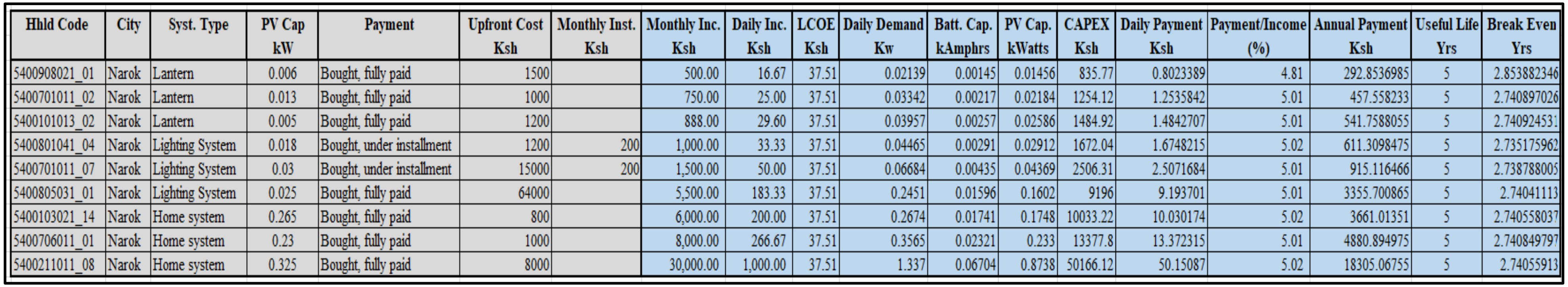
Inputs	Input Code	Modular Functions	Main Outputs	Auxiliary Outputs
Cell Efficiency	N_{stc}	Actual Least Cost of Energy (LCOE) Function Capacity utilization Factor (CUF) Function PV Output Energy (E_{pv}) Function Battery Capacity (C_{batt}) Function PV Capacity (P_{pv}) Function No. of Battery Units (N_{batt}) No of PV modules Function Daily load demand (El) Function Energy Difference (Ed) Function	PV Capacity (P_{pv}) Battery Capacity (C_{batt})	Total Battery cost Capex (It) Total PV cost Annual O$M cost
Cell Temperature	T_c			
Irradiation	G			
Daily Household Income	HH_{inc}			
Desired Least Cost of Energy	$LCOE_{des}$			
Capacity Utilization Factor	CUF			
PV area range	APV			
Autonomy Days	D			
Battery Efficiency	n_{batt}			
Depth of Discharge	DOD			
Battery Voltage	V_{batt}			
Safety Factor	SF			
System Efficiency	n_s			
Inverter efficiency	n_{inv}			
Peak Sunshine Hours	PSH			
Rate of return	r			
Useful life	n			
Battery unit cost				
PV unit cost				

4.5.4 Phase 4 Results: Framework Validation

This section presents the results of research question 4 which was set out in ***Section 1.5*** as follows.

> ***Research Question 4***: *How can we measure the performance of the developed framework in overcoming the adaptability challenges?*

To validate whether the developed framework has overcome the adaptability challenges encountered by existing frameworks, part of the data from Narok County was used as test inputs into the developed framework as implemented on MATLAB - SIMULINK and the results presented in this chapter for comparison.



Hhld Code	City	Syst. Type	PV Cap kW	Payment	Upfront Cost Ksh	Monthly Inst. Ksh	Monthly Inc. Ksh	Daily Inc. Ksh	LCOE Ksh	Daily Demand Kw	Batt. Cap. kAmphrs	PV Cap. kWatts	CAPEX Ksh	Daily Payment Ksh	Payment/Income (%)	Annual Payment Ksh	Useful Life Yrs	Break Even Yrs
5400908021_01	Narok	Lantern	0.006	Bought, fully paid	1500		500.00	16.67	37.51	0.02139	0.00145	0.01456	835.77	0.8023389	4.81	292.8536985	5	2.853882346
5400701011_02	Narok	Lantern	0.013	Bought, fully paid	1000		750.00	25.00	37.51	0.03342	0.00217	0.02184	1254.12	1.2535842	5.01	457.558233	5	2.740897026
5400101013_02	Narok	Lantern	0.005	Bought, fully paid	1200		888.00	29.60	37.51	0.03957	0.00257	0.02586	1484.92	1.4842707	5.01	541.7588055	5	2.740924531
5400801041_04	Narok	Lighting System	0.018	Bought, under installment	1200	200	1,000.00	33.33	37.51	0.04465	0.00291	0.02912	1672.04	1.6748215	5.02	611.3098475	5	2.735175962
5400701011_07	Narok	Lighting System	0.03	Bought, under installment	15000	200	1,500.00	50.00	37.51	0.06684	0.00435	0.04369	2506.31	2.5071684	5.01	915.116466	5	2.738788005
5400805031_01	Narok	Lighting System	0.025	Bought, fully paid	64000		5,500.00	183.33	37.51	0.2451	0.01596	0.1602	9196	9.193701	5.01	3355.700865	5	2.74041113
5400103021_14	Narok	Home system	0.265	Bought, fully paid	800		6,000.00	200.00	37.51	0.2674	0.01741	0.1748	10033.22	10.030174	5.02	3661.01351	5	2.740558037
5400706011_01	Narok	Home system	0.23	Bought, fully paid	1000		8,000.00	266.67	37.51	0.3565	0.02321	0.233	13377.8	13.372315	5.01	4880.894975	5	2.740849797
5400211011_08	Narok	Home system	0.325	Bought, fully paid	8000		30,000.00	1,000.00	37.51	1.337	0.06704	0.8738	50166.12	50.15087	5.02	18305.06755	5	2.74055913

Figure 4-18: *Framework validation.*

It is observed in **Figure 4-18** that households are able to acquire more reliable solar PV systems than they currently have. A household with a daily income Ksh. 16.67 which currently owns a solar PV system rated at 6watts will now be to own a bigger system rated at 14.56 watts with a battery capacity of 1.45Amphours.

This ownership comes at a daily cost of Ksh. 0.80 which is 4.8% of daily household income. This is within the industry standard which stipulate that an energy source is considered affordable if it does not exceed 5% of the household income. This observation is the same across various households with different levels of incomes.

If the household is to rent the system from an investor, the LCOE to be charged should be Ksh. 37.5/kWh. This value does not change with household income which is the key input to the framework. However, simulations indicated that this amount changes with a change in other parameter such as peak sunshine hours, efficiency and capacity utilization factor. In this scenario, we observe that the investor will be able to recover the investment in less than three years beyond which the investment will be profitable.

This analysis indicate that the developed framework enables sizing of solar PV systems that are more reliable than what the households already own and at a cost that is more affordable to these households while enabling investors to recoup their investments within reasonable time.

5. Chapter Five: Discussion

5.1 Introduction

This chapter discusses the results obtained in chapter 4 by comparing the findings on solar PV sizing in off-grid areas with the literature discussions in chapter 2. The differences between what existing sizing frameworks target and what the data from the indicate are also discussed in this chapter.

5.2 Adaptability Factors

5.2.1 Economic Factors

The role of household income and system cost in solar PV sizing

Energy affordability is directly related to the household income. According to the World Bank recommendation, an energy source is considered affordable if its cost does not exceed 5% of the household income. Results on household income in Narok County as summarized in **Figure 4-1** Average Monthly household income in Narok County. indicate that an off-grid household in Narok County has an average monthly income of Ksh. 13,596.70. This imply that for economic adaptability, a solar PV solution will be considered affordable if its monthly cost does not exceed Ksh. 679.84.

Mugisha et al., (2021), while conducting a study in Rwanda made an observation that low-income has discouraged investors and entrepreneurs in the energy industry from venturing into off-grid areas as there is no guarantee that they will recoup their investment within reasonable time. The study further revealed that most households are not aware of the available solar solutions and financing programs to purchase them. It was reported that there are savings and credit societies offering facilities to enable households to subscribe to local mini-grids but the community has no confidence and awareness to engage in these programs.

This study has revealed that this is not the case in Narok County where households heavily rely on solar energy to meet their lighting needs followed by paraffin at 37.7% and 9.9%

respectively. The results indicate a community that is already embracing solar energy as a better alternative to traditional fossil-based sources of energy.

The question that follows is whether these PV systems already in use in Narok County are adaptable to the needs of this community. This adaptability relates to the economic ability of the community, technical adaptability, mobility and location adaptability.
Data obtained in this study indicate that household in Narok County spend between Ksh.150 to Ksh.550 on paraffin for lighting purposes. This is in comparison to households which have grid connection which spend an average of Ksh. 800 every month to pay the total electricity bill. This economic insight indicates that while urban communities connected to the grid pay more on electricity bill than the off-grid counterparts, the urban communities are able to get more value as the bill covers other energy uses beyond lighting such as television sets, radios and fridges.

It is important to factor in this information while developing a solar PV sizing framework for this region to ensure economic adaptability. The sizing framework should be able to take in household expenditure as an input to ensure the resulting PV system does not have a monthly cost exceeding the monthly energy expenditure of the household.

Further insight into the economic ability of the off-grid community in Narok County indicate that 92% of the households relying on solar devices for lighting purposes acquired then by paying upfront while 8% acquired them through an instalment payment plan as seen in **Figure 4-3** where no records of rental agreement were reported .These results indicate that investors are still shying away from investing in solar solutions in this region.

The implication of this finding is that there is need for a solar PV sizing framework that can factor the ability of the community to pay while at the same time provide a mechanism for the investors to recoup their investment within reasonable time in a community characterized by a nomadic culture.

Results already indicate that payment by installation is not a popular payment mode in this region and that rental agreements have not been explored by investors in this region. While upfront payment is the most common method of payment, this study has revealed that 79.68% of the households are purchasing small lanterns which they are able to afford as summarized in **Figure 4-9** and **Figure 4-2**. As will be discussed later in this chapter, while household are able to pay upfront for these small systems, these systems are not meeting their basic functional requirements. In view of these results, it is the proposal of this study to develop a sizing framework that will make rental agreements a viable option for investors in these regions.

These agreements however should be limited to medium sized solar systems that are not hindered by costly set up regulations. Cross & Murray, (2018) observed that regulations have a significant impact on the cost of the solar PV system which is one of the main impediments to acquisition of quality solar systems. This observation has been validated by the findings of this study. Larger system sizes in the range of mini-grids attract costly procedures related to license acquisition. This cost is eventually transferred to the community which is already burdened with low income. Therefore, it is important to size solar systems that avoid set up hurdles such as license and land acquisition which increase the unit cost of energy being charged to the community. This can be achieved by sizing smaller systems that do not exceed the limits that require license acquisition.

5.2.2 Technical Factors

Growing energy demand and solar PV sizing

The technical reliability of a solar system is dependent on its ability to meet the current energy demand and keep track of the increasing energy demand as the community appreciates the benefits that come with electrification.

While it has been observed that the main energy need for communities in off-grid areas in Narok County is lighting, it is important when developing a sizing framework for this region to provide a forecasting approach to ensure the system will remain technically reliable as the community starts to increase their loading. This is in contrast with the current PV frameworks which size solar systems based on existing loads with a small estimated margin for future load increment.

Bamundekere, (2019) observed that economic prosperity brings about increased energy demand in off-grid areas by enabling communities to have access to information through mobile telephony, radios, and television. The study revealed that a majority of the households purchased radio and television devices for the first time when the local mini-grid solar capacity was increased to 8.5 megawatts.

The results on desired appliances from Narok County presented in **Figure 4-4** agree with this study indicating that 46% of the households desired to acquire a television set in the near future followed by 23% who desired to acquire a refrigerator. Another 14% desired a radio while 11% intended to acquire mobile cell phone devices given increased solar PV capacity.

These results indicate that standard small size solar systems in the range of lanterns and solar lighting systems are no longer adaptable to the aspirations of the communities living in these off-grid areas. The devices these communities intend to acquire are AC devices while the current sizing frameworks are resulting in DC systems mainly used for lighting and phone charging.

Comparing these results with the average monthly income, an off-grid household with an average income of Ksh.13,359.70 will be able to afford a small 21-inch television set within one year given the right size of solar PV system to supply the electricity. This television set retails at an average price of Ksh.9,200 depending on the brand and is averagely rated at

50watts. Other devices such as radios and cell phone devices are cheaper except for the refrigerator which may take a longer period for the household to acquire.

This imply that the sizing framework adopted should forecast this increasing demand within a reasonable range guided by the ability of the household to pay to ensure the resulting system is technically reliable but also affordable.

System Quality and solar PV sizing

Solar PV sizing has an end objective of delivering a system that will meet the energy demand of the household and keep track of increasing demand without compromising on the performance expectation. Results obtained in **Figure 4-5** indicate that 32% of the households which owned a solar device were unsatisfied with its performance while 35% were somewhat satisfied with their systems. Another 26% were neutral on their assessment while 7% were very satisfied. Only 1% reported that they were very unsatisfied with their systems.

These results agree with the findings of Mugisha et al., (2021) in Rwanda where it was reported that solar lanterns which do not meet global certification standards and performance expectations

have increased by over 15%. A similar situation was also observed in Kenya by Cross & Murray, (2018) where families have been left in the dark after investing in substandard solar solutions which fail within the first year of use. This problem of substandard solar products finding a ready market in off-grid areas has also led to counterfeiting of major solar brand in the market which discourages investors.

The problems associated with low quality solar PV systems include battery performance, inability to power large appliances, breakdowns, and less runtime. To develop a sizing framework that intends to address some of these problems at the sizing stage, it is important to determine at what time within the period of use these problems occur. This will give a better insight into the responses received during the performance assessment.

Results presented in **Figure 4-6** indicate that all respondents who reported to very satisfied had used their solar systems over 4 years. We also observe that none of the respondents reported to be satisfied or somewhat satisfied with their systems in the 1st year of use. This is an indication of a community that has interacted with solar systems and is aware that challenges usually develop in the later years of use.

Therefore, developing a solar PV sizing framework goes beyond establishing the required size but also choosing quality equipment that will ensure durability over a long period of time. This quality control can only be established at the sizing stage a factor left out by the current sizing frameworks.

5.2.3 Location Factors

Irradiation and solar PV sizing

Assessment on the quality of the irradiation in Narok County indicates a region with a good potential for harnessing solar energy. The daily average value of 6.72kW/m^2 is globally considered to be above average as indicated in **Figure 4-7**.

The existing solar PV sizing frameworks as discussed in this study in chapter 2 take solar irradiation as part of the key inputs. However, they require comprehensive records of this data at a specific location over a period of time to size solar PV systems, usually this data is not available. While this approach maximizes on the potential energy to be harnessed, it restricts the developed system to the specific location in which it was sized.

Considering communities in Narok County are nomadic in nature, sizing a solar system restricted to one area will lead to a location adaptability challenge. Therefore, this study proposes to develop a solar PV sizing framework that will take into account solar irradiation as an input but allow for location flexibility by utilizing only the least recorded irradiation in the region.

This is a worst-case scenario sizing approach that is informed by data from the target location. In this case, the data that will be used in Narok County is 5.55W/m^2. This approach minimizes the need for comprehensive data on irradiation during the sizing process and also allows the developed system to be relocated anywhere within the region without compromising on energy output due to changing irradiation.

Since this study proposes a rental agreement approach to provide solar solutions to off-grid communities, a sizing framework that is not limited by changing irradiation is ideal for location adaptability. This approach allows the investor to relocate the system as need be without having to redesign the system due to changing irradiation.

Temperature and solar PV sizing

The output of a solar PV module is affected by temperature exposure. Higher temperatures tend to reduce the efficiency of these modules which reduces the maximum energy that can be harnessed from a unit area (Nasrin et al., 2018).

Data presented in **Figure 4-8** indicate that the maximum daily average air temperature recorded was 20.68^{O}C, while it would have been prudent to size solar PV systems for this region using this worst-case scenario, this study has distinguished air temperature from cell temperature in chapter 2.

Air temperature is the temperature around a solar PV cell while cell temperature is the actual temperature of the cell that affects its energy output. In this study, the developed framework will not use air temperature to size solar PV systems but instead will use the worst tolerable temperature specified by the PV module manufacturer. This is because the temperature change is not only dependent on the location and the air temperature but how it is mounted and the allowance for free air circulation to allow for natural cooling.

This approach is in contrast with the current sizing frameworks that rely on comprehensive data on air temperature for a specific location to size solar PV system. Design from worst case scenario allow the system to meet the energy demand at its highest temperature exposure throughout its lifetime regardless of the location and the changing temperature due to relocation.

5.2.4 Mobility Factors

Roofing material, mounting technique and the sizing process

Results on roofing material in Narok County indicate that the most common roofing material in urban areas is corrugated iron sheets accounting for 74.7% of the houses as indicated in **Figure 4-10**. However, grass and twigs are common in rural off-grid set up accounting for 14.6% of the houses followed by mud and dung at 6.3%.

Understanding the nature of the roofing material has an implication on the size and number of PV modules since most household systems are presumed to be mounted on the rooftops by the current sizing frameworks. These is one of the ways to reduce the cost of installation since ground mounting has an additional cost implication.

Further insight into the relationship between system size and roofing material indicated that all home systems, which are larger in size than lighting systems and lanterns, were installed in houses with iron sheets as indicated in **Figure 4-10**. The lanterns found application across all roofing types due to their small size and ease of deployment. These findings agree with the observation of Holloway et al., (2011) on the need to factor in size and mounting techniques for systems intended to be mobile.

Since off-grid areas are characterized by traditional roofing material, it is important to consider this factor at the sizing stage since solar PV modules are delicate and the larger the system size the more the weight exerted on the roofing structure.

The cultural practice in the nomadic Maasai community of Narok County attach great value on the roofing of traditional houses. This is observed from the unique design of the traditional manyatta shelter that is prescribed to be built by women only. This imply that deploying solar PV modules on such structures may be disrupting cultural norms that have been valued for ages.

This study therefore proposes a sizing framework that will size PV systems to be owned by the investor and mounted on mobile structures that can be relocated to various locations. The community remains with the option of renting the energy service which they can opt out at any time. This form of mounting does not tie the investor at any specific location and is free to relocate with the nomadic community if need be or move to another location where the market is more lucrative.

6. Chapter Six: Conclusions and Recommendations

6.1 Conclusion

The adaptable solar PV sizing framework developed in this study demonstrated that by factoring in unique off-grid factors, PV systems which are more economically adaptable to the needs of communities in these areas can be sized. The new framework demonstrated the ability to size more reliable solar PV systems at a cost that is less than 5% of the household income a challenge that existing sizing frameworks could not adequately address. The new framework further demonstrated the ability to size these systems at favorable terms to investors by enabling a break-even period of less than 3 years.

The findings of this study have emphasized the need to size solar PV systems for off-grid areas differently from sizing for other areas. The focus should be on unique factors that will make the developed system to be adaptable to these areas in terms of pricing, ownership and mode of payment, ease of deployment, relocation and functionality.

The study has summarized these unique factors as being economic in nature, technical, location and mobility oriented while others serve to constrain the sizing process. Through data, it has been established that these factors are actually manifest in off-grid Narok county as an example of other similar areas and that these factors have had an impact on the acquisition, deployment and use of solar PV systems in Narok County.

However, the study has identified that household income, system cost, and system type are the predominant adaptability factor that if not factored in at the sizing stage will result in a solar PV system that cannot be adoptable to off-grid areas. Once these factors have been addressed and the system has been acquired, other location and mobility factors can then be addressed.

6.2 Recommendations

In view of the findings of this study, the following recommendations will assist hasten the transition to renewable energy in off grid areas through solar energy:

a) Investors should be at the front in seeking to open the solar energy potential in off grid areas by actively engaging communities in these areas to understand their unique needs that should be tailored to solar PV solutions
b) Due to the low household income in these areas, this study recommends the rental agreements as a more viable payment plan over the PAYGO systems.
c) While there is evidence of growing awareness and adoption of solar PV systems in off-grid areas, there is need for awareness to demystify misconceptions about the potential of solar energy. This need has been created by suppliers of substandard solar devices that have ruined the expectation of users on the potential of the technology.
d) Investors should leverage on local institutions and structures such as the livestock value chain to create awareness on their solutions and enhance productive use of renewable energy for deeper market penetration.
e) The government should enforce legislation on e-waste and quality clearance to crack down on substandard solar products that have found a dumping site in off-grid areas to their cheap price.

6.3 Future Study

This done has developed a framework for sizing a solar PV system for off-grid areas. However, there is need to test this framework in the market to determine the market response. Special focus should be on the rental agreement model and how it can be used alongside this framework to increase energy accessibility in off-grid areas.

Further studies should be carried out to determine how this framework can be modified to find application in urban informal settlements characterized by similar factors such as low household income and a market shun by investors.

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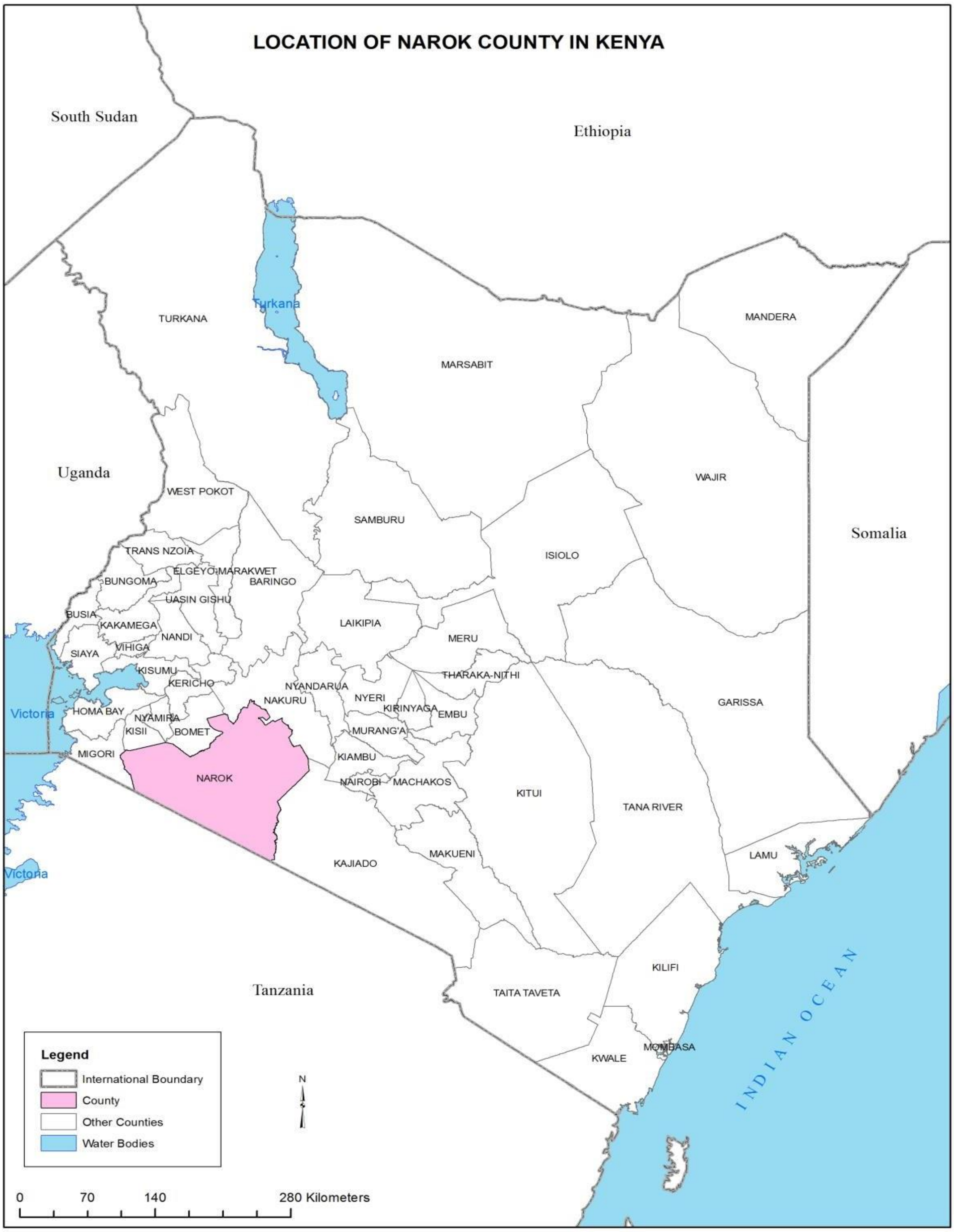
APPENDICES

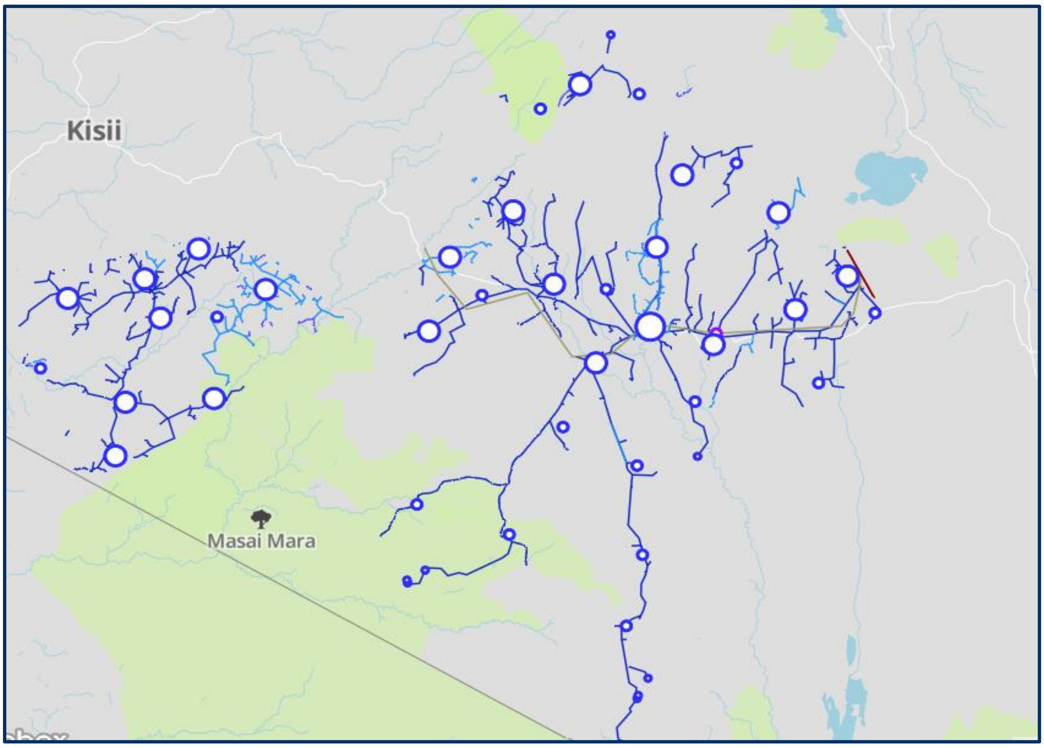
Appendix A: Narok County



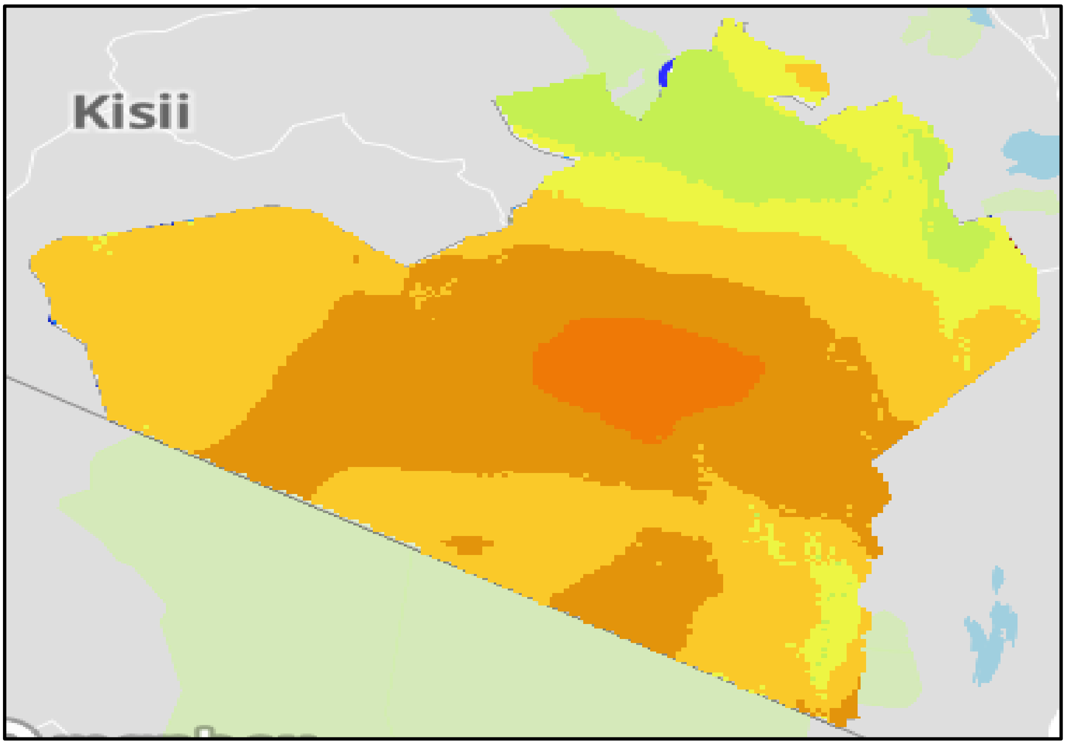
Prepared by: The Kenya National Bureau of Statistics: Cartography\GIS Section:
Source: 2009 Population Census

This map is not an authority on delineation of boundaries

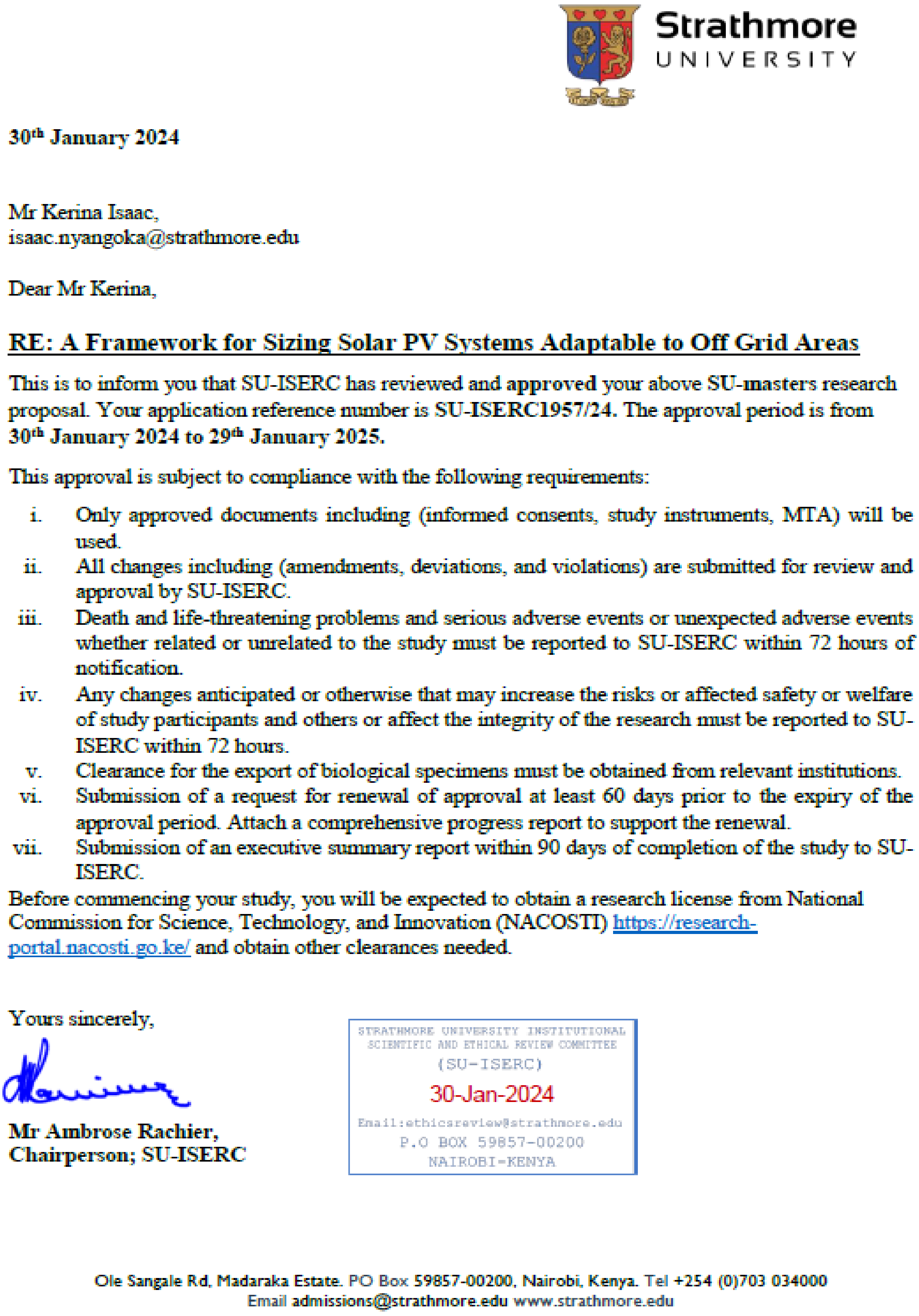
Appendix B: Grid Infrastructure in Narok County



Appendix C: Global Horizontal Irradiation for Narok County



Appendix D: Ethical Approval



Strathmore
UNIVERSITY

30th January 2024

Mr Kerina Isaac,
isaac.nyangoka@strathmore.edu

Dear Mr Kerina,

RE: A Framework for Sizing Solar PV Systems Adaptable to Off Grid Areas

This is to inform you that SU-ISERC has reviewed and **approved** your above SU-masters research proposal. Your application reference number is **SU-ISERC1957/24.** The approval period is from **30th January 2024 to 29th January 2025.**

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

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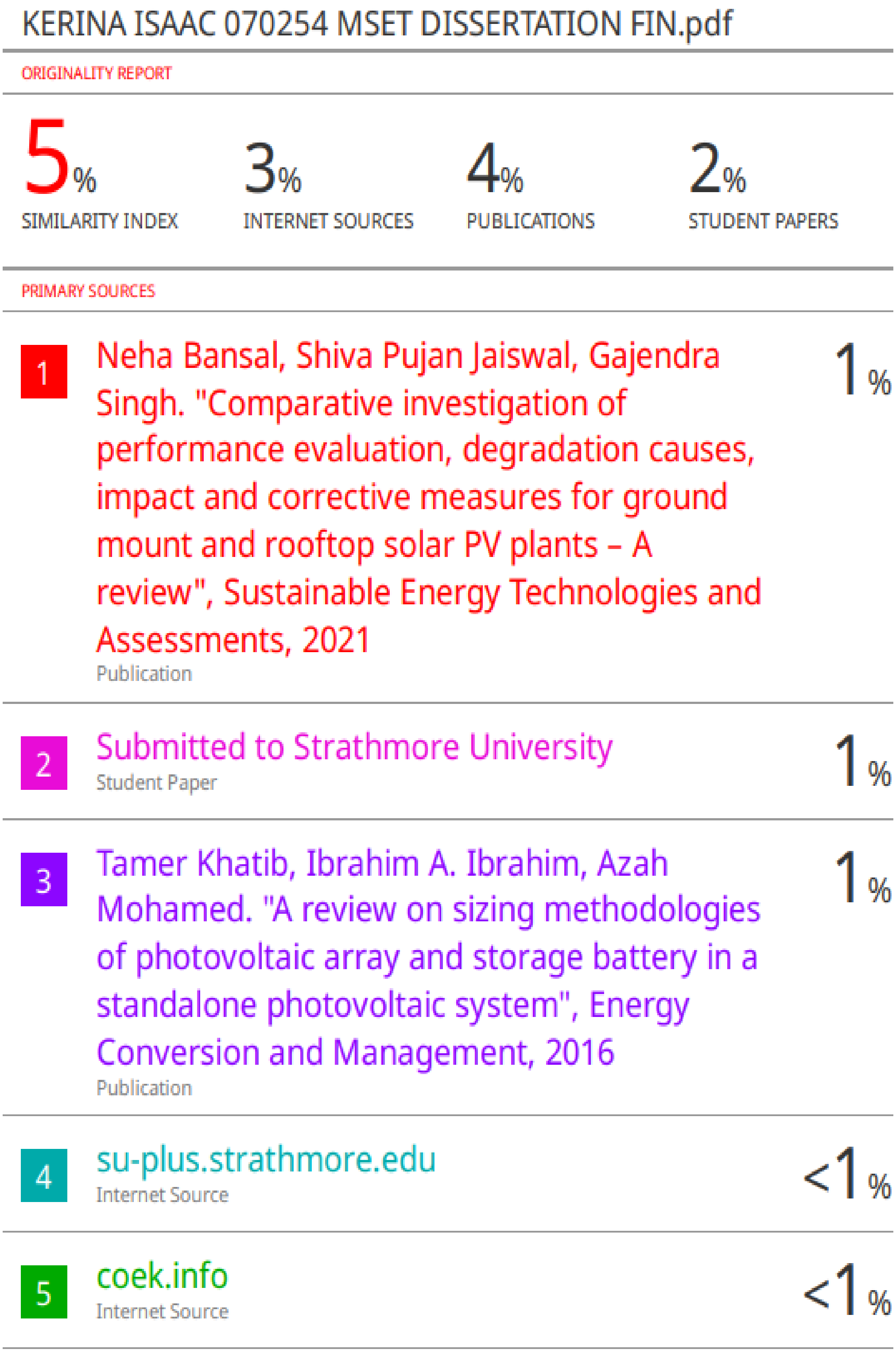
Appendix E: Originality Report



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