IN SITU TECHNO-ENVIROECONOMIC ANALYSIS OF A ROOFTOP PHOTOVOLTAIC (PV) BACKUP SYSTEM IN THE TROPICAL CLIMATE

BY

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DECLARATION

Declaration by the Candidate

This thesis is my original work and has not been presented for a degree in any other University. No part of this thesis may be reproduced without the prior written permission of the author and/ or University of Eldoret.

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

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DEDICATION

To my Dad George Sirma Kosgei for his unconditional love, advice and support. To my dear wife Sellah Jesang, for her love and care and to my lovely children Abigael Jelagat and Abijah Jelimo.

To the faculty and staff and colleagues of the University of Eldoret, Physics department.

To my mentor and friend, Mr. Mbeche Fanuel, I couldn’t have done this without you. To my friends and neighbours, thank you all for your support along the way.

Above all, I dedicate this work to our almighty God who showers us His blessings in our everyday lives, especially for the strength, courage, patience, wisdom, time, and guidance in realization of this work.

ABSTRACT

Solar PV generators are increasingly being deployed in the built environment as stand-alone or backup power systems to supply electricity either solely or during power outages respectively. Diesel generators (DGs) are applied routinely as standby power systems by many enterprises and institutions, especially in developing countries where power outages are real and frequent due to unstable national grids. The current pursuit of low-carbon and sustainable source of energy places photovoltaic (PV) power system in advantageous position as a substitute for a DG backup system. An existing off-grid 780 Wp PV system installed as a backup power supply in a learning institution in western part of Kenya was studied both experimentally and theoretically. Technical, economic and environmental analyses were carried out to determine its performance under the local outdoor conditions at the site for a period of one year in 2020. Irradiance estimation models were also validated by experimental data to determine appropriate model(s) for the site. Plane-of-array (POA) solar radiation was measured with solar cell sensor installed at the surface of PV modules and a charge controller/inverter unit with the capability to measure and log real time output current (I) and voltage (V) was used to generate I-V characteristic data. PVsyst software was used to simulate the PV system and generate optimized theoretical results for the site which were compared with experimental results. Available energy was determined as 3202.80 kWh/year, average array efficiency of 11.71%, FF of 0.66, array yield of 4.89 kWh/kW, reference yield of 5.51 kWh/kW, capacity factor as 19.8%, annual average performance ratio (PR) as 76.0%, and average array losses as 0.54 kWh/kW. Economic results for the PV system show that the payback time (PBT) is~ 6.38 years, LCC of $3057.93, levelized cost of energy (LCOE) of0.045 $/kWh and operation and maintenance (O&M) is17.32 $/year. For the diesel generator (DG),PBT was 4.25 years and O&M was 262.80 $/year for a lifespan of 5 years and assuming that it operates 2 hours per day of blackouts, LCC of $7792.75 and LCOE of 0.324 $/kWh. Environmental results show that the total annual amount of CO_2 emissions avoided when PV is used instead of DG power backup system was 5.84 tCO_2/year giving an average cost parameter (penalty for CO_2 generation) of $9.62. Simulation results gave the available energy as 3746.40 kWh/year, reference yield of 5.55 kWh/kW, array yield of 4.18 kWh/kW, array losses of 0.61 kWh/kW, capacity factor as 21.23%, FF as 0.68, PR as 73.6% and PV array efficiency of 13.19%. The average amount of CO_2 emission avoided was 7.95 tCO_2/year with annual environmental cost of $116.18. Angstrom-Prescott and Iqbal models were found to be the most accurate for the site having the lowest values of mean absolute percentage error (MAPE) of 8.5% and 8.9% and root mean square error (RMSE) of 0.252 and 0.302 respectively. In conclusion, technically, the low FF (<<1) indicate that the system is not operating at its optimum, which can be attributed to how the PV system was installed. The LCOE results show that PV power is cheaper by a factor of seven than that of the diesel generator, and the amount of CO_2 avoided is at least 0.44 tCO_2/month. The PV power presents net benefits over diesel power in all performance indices evaluated, and hence can be used as a reliable and affordable replacement for DG backup systems in tandem to the global quest to transition to clean and sustainable energy sources and attainment of the SDGs 7 and 13.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Module area (m^2)
a-Si	Amorphous Silicon
BOS	Balance of system
CF	Capacity factor
CO_2	Carbon dioxide
COVID	Corona-virus disease
CSP	Concentrating solar power
CSV	Comma-separated values
DAQ	data acquisition systems
DG	Diesel generator
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
E_{Dc}	DC output energy (kWh)
FF	Fill Factor
FiT	Feed-in Tariff
G_t	Measured solar irradiance (W/m^2)
GHG	Greenhouse gases
GHI	Global Horizontal Irradiance
I_{mp}	Nominal current (A)
I_{sc}	Short-circuit current (A)
I_{max}	Maximum current (A)
I_{mp}	Maximum power current (A)
IEC	International Electrotechnical Commission

IEEE	Institute of Electrical and Electronic Engineers
IRENA	International renewable energy agency
J_{sc}	Short-circuit current density
KAM	Kenya Association of Manufacturers
KenGen	Kenya electricity generating company
KOSAP	Kenya Off-Grid Solar Access Project
KPLC	Kenya power and lighting company
KNBS	Kenya national bureau of statistics
KTTI	Kaiboi Technical Training Institute
L_A	Array capture loss (kWh/kW)
LCE	Life cycle emissions
LCOE	Levelized cost of energy
MAPE	Mean absolute percentage error
MBE	Mean bias error (MBE),
MPPT	Maximum Power Point Tracking
NPV	Net present value
P_0	Module rated power (W)
P_{max}	STC power rating (W)
pc-Si	Poly-crystalline silicon
POA	Plane of array
PPA	Power Purchase Agreement
PR	Performance ratio
PSH	Peak Solar Hour
PV	Photovoltaic
PV/T	Photovoltaic/Thermal

PWM	Pulse Width Modulation
R^2	Coefficient of determination
R&D	Research and Development
R_s	Series resistance
R_{sh}	Shunt resistance
RES	Renewable energy sources
RMSE	Root mean square error
ROI	Return on investment
SDG	Sustainable Development Goals
SE4All	Sustainable Energy for All
SHC	Solar heating and cooling
SHS	Solar home system
SDHW	Solar domestic hot water heating system
SSA	Sub-Sahara Africa
STE	Solar thermal electricity
STC	Standard Test conditions
t-stat	*t*-statistic method
TC	Thermal collector
T_c	Cell temperature (^{0}C)
T_{amb}	Ambient temperature (^{0}C)
T_{NOCT}	Nominal operating cell temperature (^{0}C)
V_t	Thermal voltage (V)
V_{mp}	Maximum power voltage (V)
V_{max}	Maximum voltage (V)

V_{oc}	Open circuit voltage (V)
VRB	Vanadium Redox Battery
WEO	World economic outlook
Y_A	Array yield (kWh/kW)
Y_r	Reference yield (kWh/kW)
η_{cell}	Cell efficiency (%)
β	Cell temperature parameter (K^{-1})
η_{Array}	PV array efficiency (%)
η_{ref}	Reference module efficiency (%)

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CHAPTER ONE

INTRODUCTION

1.1 Background

Energy is an essential resource globally for economic, social development and improvement of quality of life. However, energy creation and use have far-reaching consequences, affecting big themes such as climate change and geo-political factors, as well as many more "trivial" elements of our daily lives.

Energy is an essential resource globally for economic and social development in any country. Efficient use of energy comes with benefits such as industrial development and improvement of the standards of living. On the contrary, energy generation and use have far-reaching consequences, which have created the present big themes such as climate change and geo-political factors, as well as many more "trivial" elements of our daily lives. Several important aspects of energy are currently experiencing a period of transformation. These include energy production (with regards to both fossil fuels and renewable energy sources); transportation and distribution (e.g., electricity and distribution networks); consumption (including demand-side management and energy efficiency); and energy security and access (Kristie *et al.*, 2019). Energy transitions also play a crucial role in climate change mitigation. Energy technologies are developing rapidly, allowing new and more efficient ways to deliver energy on varying scales. Globally, energy is evolving from a centralized system, with large production plants, to a distributed system, in which an individual becomes a "prosumer", both producing and consuming energy(World Bank, 2021). As a result, consumers have an increasingly important role to play in improving the efficiency of these systems.

Electricity, from a practical viewpoint, catalyzes economic productivity and industrial growth and is central to the operation of any modern economy and livelihood. Provision of electricity is now considered globally as a necessity along with food and water (Hemza *et al.*, 2019). However, universal access to electricity is highly skewed with the majority if not all households in developed countries connected to grid electricity, and vice-versa in the developing and transitioning economies like Africa and South Asia (Corfee-Morlot *et al.*, 2019; World Bank, 2019). The percentage of people with access to electricity has been steadily increasing over the last few decades where a rise of more than 50% of new connections has been realized between the year 2000 and 2021 (World Bank, 2021). Electricity is a high quality and versatile form of energy and lack of access to it leads to adverse socio-economic consequences. According to the World Bank technical report (ESMAP, 2007), lack of access to electricity services entrenches poverty, constrains the delivery of social services, limits opportunities for women and girls and erodes environmental sustainability at the local, national and global levels. The lack of universal access to electricity by all in the world, prompted global agencies such as the United Nation (UN), the World Bank Group and others to come up with strategies to provide electricity for all at the start of this millennium or 21st century (IEA, IRENA, UNSD, WB, WHO, 2021).

Global campaign for universal electrification across the world begun with the Millennium Development Goals (MDGs) in 2000 at the beginning of 21st century. However, the MDGs initiative did not capture explicitly energy sector unlike its predecessor, the Sustainable Development Goals (SDGs) which has a substantive agenda on energy, SDG 7 (Kumar *et al*., 2016). The 17 SDGs, cover everything from energy and climate; to water, food and ecosystems; to health and poverty; to jobs and innovation; education, gender equity, among a number of other objectives (McCollum *et al*., 2018). The SDG 7 is subdivided into three distinct, but related targets or pillars to be achieved by the year 2030 (UN, 2015; McCollum *et al*., 2018; Nerini*et al*., 2018; Warner and Jones, 2017). The SDG Target 7.1 is to ensure universal access to affordable, reliable, and modern energy services (7.1.1 focuses on the proportion of the population with access to electricity and 7.1.2, on the proportion relying primarily on clean fuels and technologies for cooking). Target 7.2 is to increase substantially the share of renewable energy in the global energy mix, while Target 7.3 is to double the global rate of improvement in energy efficiency (UNDP, 2015). Another global initiative for universal access to electricity is the Sustainable Energy for All (SE4All) of 2012 (AfDB, 2015). The SDG 7 is a fundamental objective to sustainable development, because all the other SDGs are intrinsically linked to energy. This means that the efforts undertaken to achieve its targets may either facilitate or compromise achievement of the targets of other SDGs. Since Kenya is a UN member, it is obliged to ratify the SDG goals, and the country employed institutional approach to achieve the SDG targets within the specified time frame. The country established the Rural Electrification Authority (REA) in 2006 and national development blue print document prominently called ‘Kenya Vision 2030’ (GoK, 2007). The REA was tasked to hasten rural electrification in the country through extension of national grid in order to promote sustainable socioeconomic development by 2030 (Roche & Blanchard, 2018). Following the enactment of Energy Act of 2019 (Act, EPRA, 2019), REA has been transformed to Rural Electrification and Renewable Energy Corporation (REREC) and its mandate expanded to include also Target 7.2. Thus, REREC is tasked with implementing rural electrification projects (Target 7.1.1) and spearheading Kenya’s green energy drive (Target 7.2).

Reliable supply of electricity is crucial for both modern livelihood and economy. Electrical power outages lead to a variety of negative business outcomes, such as reduced sales (loss of revenue), damaged machinery (reduce productivity), data loss, loss of customers, and product spoilage (Maende and Alwanga, 2020). In addition, it disrupts daily life; interfere with services such as lighting, refrigeration and air conditioning as well as causing tragic consequences to critical health and social services, such as life-saving medical devices and to the extreme end loss of life. Power outages in developing countries are rampant and are made worst with increasing severe weather events and disasters as well as aging grids (Farquharson *et al.*, 2018). The World Bank Enterprise Surveys report that most enterprises in Africa encounter regular power outages, which could number to as high as 100 times in a month (The World Bank, Enterprise Surveys, 2018). The grid electricity is vulnerable to a range of mechanical, operational, environmental, and human-related hazards (Preston *et al*., 2016). Mechanical faults, line shorts, fires, and human interference are common causes of outages during transmission.

Power outages have compelled many businesses, institutions and even individuals to seek self-generation options. The widely adopted option, in developing countries mainly, is the diesel generators (portable or immovable) because they are readily available and have a relatively low initial investment cost, but carry health and environmental risks (Babajide and Brito, 2021). In addition, the cost of running diesel generator can be quite high, especially in countries where gasoline prices are high. Solar photovoltaic systems offer a cleaner viable option for the African continent because it is endowed with abundant solar resource throughout the year. This solution is suitable for individuals and businesses alike because of its modularity and do not incur high running cost unlike the traditional DG, but has not been embraced in the

African continent, including Kenya. Therefore, for decision makers or prospective consumers to make informed choices, it is important to understand the cost and reliability associated with Solar PV backup power in order to be accepted as a possible replacement of the present fuel-power generators.

1.2 Electricity Generation from Solar PV Systems

The sun is the driving force for all atmospheric processes, and every known form of energy, except nuclear and geothermal energy, originates from the sun, either directly or indirectly. Solar energy refers to energy that is directly attributed to the light of the sun or the heat that sunlight generates (Timilsina *et al*., 2011). It is a huge resource and is considered as the only inexhaustible renewable energy (RE) source because it will last as long as the sun exists and has minimal impact on the environment (Freris and Infield, 2008). It can be harnessed using modern technologies to provide the two widely sought forms of energy viz electricity and heat energy. Since solar energy is dilute (spread throughout the earth's surface facing the sun) and intermittent (not available at night and non-steady during the day), it needs to be collected, concentrated and stored for it to be useful. Solar collectors are devices used to collect and concentrate solar energy to make it adequate and available continuously. Two commonly used types of solar collectors are photovoltaic (PV) and solar thermal collector (TC).

The PV converts sunlight directly into electricity while TC converts sunlight into heat energy through a working fluid (water or air or any other heat transfer fluid). These two technologies are available commercially and have been deployed all over the world but to different degrees with developed countries leading the developing countries. The skewed deployment has been attributed to technological, financial and institutional barriers, which are experienced mainly in developing countries (Timilsina *et al*., 2011). The PV applications have been growing exponentially across the world, with installed capacity of more than 750 GW by the end of 2020, and now contribute ~3% of total electricity in the world (IEA PVPS, 2020). The present development in PV is characterized by ongoing research that aim at increasing the low field efficiencies of about 15% to 20% currently in order to reduced PV electricity cost and expand its applications globally.

Photovoltaic has the potential to provide electricity in every corner of Kenya, both in urban dwellings and remote rural villages(Kiprop *et al*., 2018). PV can promote development across all sectors of economy, especially in regions with enough solar radiation to meet electricity needs and cost of the consumers (Jiménez-Castillo *et al*., 2019). PV applications are usually classified as either solar home system (SHS), mini-grid, grid-connected or hybrid system (PV-thermal power, PV-wind, or PV-hydro). However, SHS and mini-grid systems can play important role in rural electrification in any country (Barnes and Foley, 2004). The SHS has been cited in literature as having provided individual solution, while mini-grid can offer a collective solution at a relatively lower cost. In addition, the mini-grid can facilitate basic needs as well as productive use of electricity, and hence promoting local economic engagements (Bhattacharyya and Palit, 2016). For these PV systems to be competitive, they should be able to supply reliable electricity to support income generation activities for the poor on a regular basis. Grid-connected PV system consists of a large number of PV modules interconnected in series-parallel to form a PV array that can generate a great amount of electricity (hundreds of kW to MW), which is then fed to the national grid (Felten *et al.*, 2006). Hybrid PV system, on the other hand, consists of a PV generator combined with convectional electricity generation plants such as thermal power (fossil fuels), wind generator or mini-hydropower plants. In hybrid systems, generators are fused together to complement each other with respect to time mainly and hence supply more reliable and stable electricity than the individual system throughout the year (Kougias *et al*., 2016).

Solar electricity can be cost competitive in many electricity markets today if solar panels can perform to warranted specifications for at least the length of their warranty, which is typically 25 years. But it can be difficult to identify which PV modules will meet their warranted performance level, and hence the need for long term outdoor performance test of different PV technologies at the site of application (Olchowik *et al*., 2006; Kurtz and Jordan, 2013; Bashir *et al*., 2014). Power output of a PV module is reported by manufacturers at standard test conditions (STC), which are defined by international standard IEC 61836 as one-sun irradiance of 1000 W/m^2, cell temperature of 25°C, air mass 1.5 and normal incidence (IEC TS 61836, 2016) or PVUSA Test Conditions (PTC) with same irradiance but ambient temperature (T_{amb}) of 20 ºC (Topic *et al*., 2011).However, these conditions cannot be experienced under realistic outdoor operation anywhere in the world. In real installed PV systems, the module output is strongly affected by various environmental conditions such as irradiance, temperature, spectral effects, angle of incidence, wind speed and direction. In addition, different PV technologies have different patterns of behaviour with respect to each climatic factor on amount of energy produced. Hence, modules of different technologies may be more suited to certain specific climate (Carr& Pryor, 2004). In order to help PV users to make more accurate performance predictions and assist them in system planning and financing, it is important to evaluate or predict the performance of the module at the local climatic conditions.

Monitoring of outdoor performance of a PV module is challenging because the operating outdoor weather conditions change simultaneously making it difficult to investigate the effect of one parameter independently. In most cases, these changes are intertwined to one another and it becomes difficult to separate the contribution of each effect on the overall performance of the PV module. In tropical regions, weather conditions tend to be constant throughout the year except during rainy season where some days are fully or partially overcast. The temperature affects the performance of PV module either negatively or positively depending on the cell technology. The effect of air mass is due to the filtering of incident solar radiation beam by atmospheric constituents, which affect its spectral distribution (Chantana *et al.*, 2020). Since these factors vary geographically and seasonally as well as time of the day, it is important to investigate experimentally or model their effects on different PV technologies in order to characterize them and hence help the users purchase cost-effective modules for the site.

A wealth of literature on performance of solar off-grid PV, either SHS or mini-grid or hybrid systems is available in various journals, technical reports and conference proceedings. This is due to the growing share and relevance of PV as a future clean and sustainable energy system throughout the world. However, their performance in different climates or geographical locations over extended period of time is not completely established (Guerra *et al*., 2017). The data collected during the operation of PV systems are of great interest in determining the system performance, which will help to detect malfunctions and to optimize the system. For instance, field studies have reported that one PV system was oversized by more than 40%, a rural electrification project in Laos reported 65% of solar home systems were not operating, and another project at Guatemala reported that 45% of solar home systems ceased to operate after five years of installation (Jiménez-Castillo *et al*., 2019).

The installation of a solar PV power system to either replace or offset a portion of electricity generated from DGs has been cited as an option to consider for remote residential homes in Nigeria (Ani, 2016).However, this author observed that complete replacement of DGs with PV systems may not be feasible during rainy season, and recommended the use of PV/diesel hybrid systems. It is noted that combined solar/diesel system is more reliable and cost effective, but it must be sized optimally. The DG component is operated only during low irradiance wet seasons, and hence reduces fuel consumption, which in turn reduce fuel cost and CO_2 emission. The merit of a PV power backup system is that it will accord the institutions or individuals an opportunity to contribute towards the global quest on low-carbon and sustainable sources of energy. Additionally, unlike a DG that is operated only during power outages, a PV system has the potential of producing electricity continuously, whether grid is on or off. Therefore, it can free up the limited utility electricity, and hence assist in stabilizing up the grid, contribute to energy diversity and security with little burden on the government.

1.3 Progress in solar PV Technology

The development in solar PV technology has been growing very fast in recent years due to technological improvement, cost reductions in materials and government support for renewable energy-based electricity production. The cost of PV systems has been declining steadily and significantly over the past recent decades, and this cost decline has been attributed to intense research, technological development and market growth spurred by government subsidies (Lang *et al.*, 2016). The efficiency of solar cell is one of the important driving parameters which are required to establish and make this technology competitive in the market. The decreasing module costs combined with increasing efficiencies have resulted in a compound decrease in the cost of electricity from PV modules (Fukushima Renewable Energy Institute, 2014; Shubbak, 2019). In addition, the robust growth is backed up by continuous reduction in cost per watt where currently on average the cost is below a dollar per watt in the United States (US) and for a PV system it is slightly above a dollar per watt (Fu *et al.*, 2020). The growth is further attributed to the realization of levelized costs of electricity (LCOE) that are now generally very low compared to other energy sources (Jordan and Kurtz, 2013).

According to International Energy Agency (IEA) report of 2019, PVs have been gaining an increasing market share over the last few decades and is one of the fastest growing renewable energy technologies expected to play a major role in the future global electricity generation mix. As a result, global PV capacity is projected to increase from 700 GW to 880 GW in a span of five years from 2020 to 2025 (IEA, 2019). Figure 2.1 shows the trend of annual PV installations in leading world markets from the year 2000 to 2020, indicating clearly the rapid growth in the last 2010 to 2020 decade. The installed PV systems in this market increased by 156 TWh or a 23% growth in 2020 as compared to 2019. This placed the PV sector in the second position behind wind and ahead of hydropower in the annual growth of electricity generation from renewable energy sources. The growth of solar PV in major world markets from 2019 to 2020 includes 45% in United States, 75% in China, and 15% in European Union. In the emerging world markets, Brazil continued to lead Latin America’s solar PV capacity where annual installed capacity increased by 58% to reach 3 GW in 2020 as compared to 2019. However, despite the increasing generation of electricity from solar PV, it accounts for only 3.1% of global electricity generation, trailing behind hydropower and onshore wind, but ahead of bio-energy in 2019.

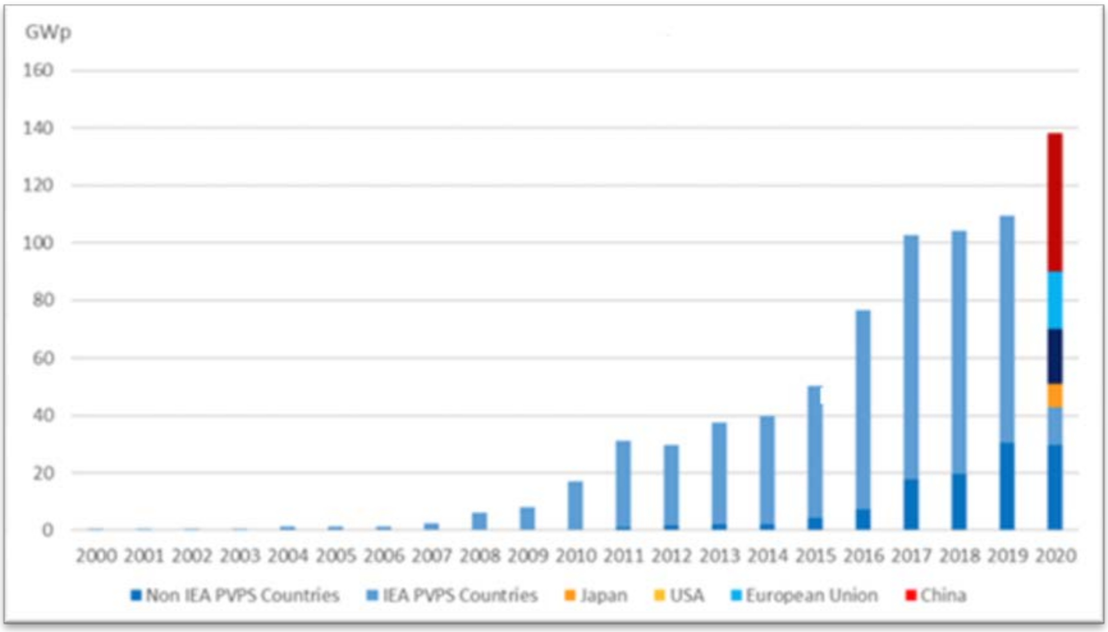


Figure1. 1: Annual PV installations globally (Source: IEA, 2019).

Kenya has a huge potential for PV since it is located astride the equator, hence endowed with a high level of solar insolation with large part of the country receiving average insolation ranging from1900 kWh/m^2 to 2500 kWh/m^2 (Oloo *et al.*, 2015; Kiplagat *et al.*, 2011; SolarGIS, 2013; Jacobson, 2007; Rabah, 2005). Due to the huge abundance of solar irradiance in Kenya, PV systems offer a cleaner and viable solution for both primary (sole supply) and secondary (backup system) electricity generation (Jacobson, 2007; Rabah, 2005; Mohandes *et al.*, 2019).The most common PV systems in the country are the solar home system (SHS) and constitute the largest percentage of the installed capacity (Simuyu *et al.*, 2014).Currently, the country is considered as among the most active PV market in the African continent, with an estimated 250,000 rural households using SHS and annual PV sales estimated to be between 25,000 to 30,000 PV systems. With a recent major government decision to reinstate the VAT exemptions will support the increased uptake of the solar products and significantly contribute towards the achievement of universal access to electricity in the country. PV is projected to grow at 15% annually in Kenya, but this is still marginal compared to its potentials, (ERC, 2019).

1.4 Statement of the problem

Accessibility to reliable and efficient supply of electricity is regarded as a key conduit for economic growth and development across the world. However, majority of African countries, Kenya included, experience numerous power outages. The costs of a power outage to a business can be substantial, including product losses, revenue, productivity, customers and even loss of life (in case of medical facilities). With increasing severe weather events and disasters triggering greater numbers of costly power outages, there is a growing interest in independent generators that can provide reliable electricity whenever power outages occur. The widely used power backup systems are the conventional DG power systems that can reliably bridge the gap during power blackout, but are associated with pollution effects through CO_2 emission due to fossil fuel used and noise as well as high fuel cost. These adverse effects of diesel backup systems prompt for gradual replacement of these fossil powered systems with clean alternatives that conform to SDG 7 and 13 targets. The current pursuit of low-carbon and sustainable sources of energy makes PV power backup systems ideal substitute for a diesel backup system because they are clean, low noise pollution and reliable. However, due to intermittent and irregular nature of PV power generation, there is a need for monitoring PV power output, and generated data on its performance has a wealth of information for diverse stakeholders (consumers, vendors, manufacturers, governments, etc). Most PV systems are installed in the built environment, most notably on the rooftops of residential, commercial, and industrial buildings. Thus, in many cases, module orientation (i.e., tilt and azimuth) of these PV systems are not optimized, because they are installed at heterogeneous tilt and azimuth angles, often determined by roof characteristics, especially for pitched roofs. Consequently, they are not operating optimally as it should be, and hence there is a need to perform assessment of technical, economic and environmental performance of PV systems to showcase its viability as power backup over DGs, and hence enable stakeholders make informed decision on its adaptability. The technical, economic and environment analyses are done on an already installed solar PV system at Kaiboi Technical Training Institute (KTTI) in western part of Kenya as a case study for possible substitute of the DG backup systems.

1.5 Research Objectives

1.5.1 General objective

To carry out technical, environmental and economic analysis of an installed off-grid PV system at KTTI, in western region of Kenya as a possible substitute for diesel backup generator.

1.5.2 Specific objectives

The specific objectives of this research are:

1. To determine the solar irradiance model(s) that best fit the solar radiation data collected at the site.
2. To evaluate in-situ outdoor electrical performance of the PV power system, both experimentally and theoretically.

3. To perform comparative economic analysis of electricity generation from the solar PV system relative to that of a similar diesel backup generator.
4. To calculate the amount of the CO_2 emission avoided or mitigated when solar PV power system replaces a similar diesel backup generator.

1.6 Justification of the study

Many countries throughout the world are increasingly incorporating locally available renewable energy (RE) into their energy supply mix. This trend is informed mainly by the perceived scarcity of fossil fuels and increasing restriction on their use as a result of their adverse effects on climate change. Kenya is endowed with high solar irradiance (average of 5 $kWh/m^2/day$) (Oloo *et al.*, 2015; Kariuki and Sato, 2018) throughout the year, hence huge potential which can be exploited to generate green electricity for every household throughout the country. The PV technology allows electricity to be obtained from solar radiation with minimal or no impact to the human-beings and environment, unlike the diesel which has health and environmental hazards. Deployment of PV backup systems has the potential to supply a significant share of the energy demand and to make a positive impact on combating climate change and global warming. However, a major part of PV electricity production is characterized by a large degree of intermittency driven by the natural variability of climate factors such as air temperature, wind velocity, solar radiation, and precipitation. Consequently, it is beneficial to investigate the performance of any PV technology installed under the local weather conditions, because the generated data on energy yield can be consumed by different stakeholders for optimization of power flow management, evaluation of profitability by the private PV power producers and detection of system anomaly. In addition, PV power backup systems will enable the enterprises and institutions to operate their business and operations smoothly with low operational costs, and also enable them to contribute to the increase use of green energy at individual level and hence synergize with the government in the achievement of SDG 7 and its ripple effect on the other interconnected SDGs.

1.7 Significance of the study

The benefit of this study is that it will showcase to the decision makers in institutions or individual entrepreneurs and governments to make informed decision on affordably replacing the DG backup system with PV power backup system. The experimental data collected on solar irradiance and electrical performance of the PV system are important to solar energy community. The developers of simulation models will use radiation data to validate their models and electrical measurements will be useful for degradation analysis for the PV modules. Further, the economic and environmental analyses will guide the consumers on the initial/ running cost and environment impact respectively for each backup system.

1.8 Scope and Limitations of the study

The findings from this study are based on the local outdoor climatic conditions measured at Kaiboi Technical Training Institute (KTTI) in western region of Kenya collected for the year 2020, which may and may not be replicated in subsequent years. Consequently, generalizing the results to other years or places may be subjected to variations.

1.9 Thesis organization

The thesis is structured as follows:

- Chapter two presents background of PV theory, PV power system and literature review.
- Chapter three presents methodology and materials. It covers experimental setup, instrumentation and analytical techniques used to generate results.
- Chapter four presents the results and discussions, based on the four objectives.
- Chapter five presents the conclusions and recommendations.

CHAPTER TWO

THEORY AND LITERATURE REVIEW

2.1 Introduction

This chapter presents a brief overview of electricity scenario in Kenya, solar radiation, photovoltaic theory and literature review. Photovoltaic theory focuses on available conversion technologies, PV cell structure and operations, applications and the available PV system configurations. Literature review on technical, economic and environmental performance analysis of PV systems are presented.

2.2 Electricity in Kenya

Electricity generation in Kenya is largely dominated by renewable energy sources (RES) which comprise of hydro, geothermal, wind and solar resources. Figure 2.1 presents the installed proportion trend of electricity generated by source from 2016 to 2020 where their corresponding data is given in Appendix I which include their effective capacities (KPLC, 2020 and Economic survey, 2021).

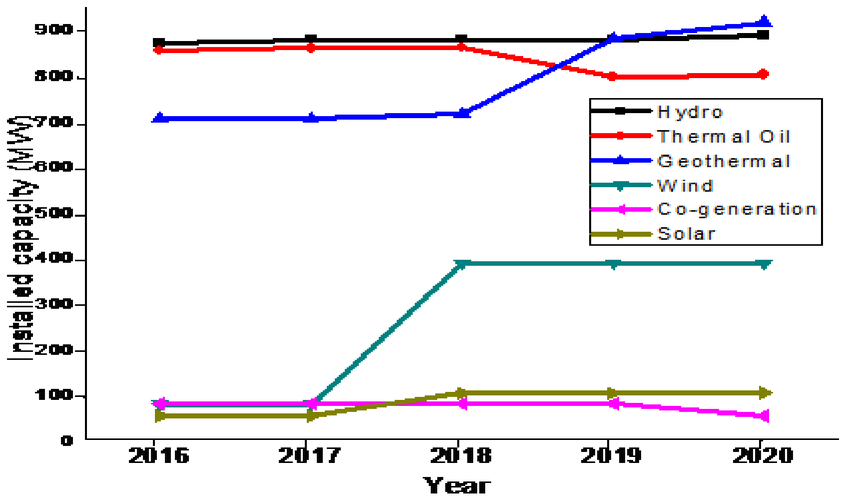


Figure 2.1: The proportion trend of electricity generated by source from 2016 to 2020 (Source: Economic survey, 2021; KPLC, 2020)

As can be seen from Figure 2.1, the geothermal installed capacity of electricity remained at a constant capacity about 712.5 MW from 2016 to 2018 since there was no additional well. With an additional Olkaria V well in 2019, there was an increase in capacity by 4.2% to 863.1 MW from 2019 to 2020. In addition, geothermal effective capacity declined by 10.9 MW to 805.1 MW in 2020. In addition, the Kenyan Government through KenGen has four ongoing geothermal projects with a total estimated capacity of 314 MW. Similarly, wind installed capacity of electricity showed a sharp rise in 2018 to about 400 MW as a result of commissioning of new wind power plants e.g., the Lake Turkana wind power plant. Solar energy installed capacity of electricity has as well shown a slight rise from the year 2018 by 3.0% to the current 52.5 MW in 2020. This increase was as a result of commissioning of the Garissa solar power plant with a capacity of about 50.0 MW. This capacity is expected to increase in the near future with more power plants being developed e.g., the Gitaru solar power project with an estimated capacity of 42.5 MW (Economic survey, 2021).

Hydro capacity rose by 7.8 MW to 834.0 MW in 2020 mainly due to favourable rainfall experienced in the year. Its capacity over the previous years has shown slight or no change since there has been any installations of new hydro power plants. Hydropower in Kenya is mainly in the form of dammed hydro power plants with production susceptible to drought. On the other hand, thermal capacity decreased slightly to 749.1 MW in 2020 and has been on downward trend since 2018 in an effort to scale up access to clean energy by replacing it with solar and wind energy sources hence saving the country from heavy expenditure on petroleum imports. Generation of electricity from thermal sources, which is the only non- renewable source in the country accounted for 26.4% of the total electricity generation during the review period where the rest of electricity was generated from renewable sources which accounted for a total 73.6%. Similarly, Co-generation installed capacity dropped from 28.0 MW in 2019 to 2.0 MW in 2020 due to decommissioning of Mumias Sugar power plant in February 2020 following expiry of its Power Purchase Agreement (PPA) (Economic survey, 2021).

The total installed capacity of electricity in the country increased slightly to 2,836.7 MW in 2020 from 2,818.9 MW in 2019. In addition, the total maximum theoretical electric output power has seen a huge increase of 509.7 MW from the year 2016 to 2020. However, effective electricity generation capacity dropped by 1.1 per cent to 2,705.3 MW in 2020. Total electricity generation declined marginally from 11,620.7 GWh in 2019 to 11,603.6 GWh in 2020 (Economic survey, 2021).

Energy demand in Kenya is on the rise due to rapid increase in population as well as growth in the economy and more affordable electronic devises, though a decline was registered in the year 2020 where total domestic demand for electricity reduced by 57.6 GWh to 8,796.4 GWh (KNBS, 2020;Economic survey, 2021;KPLC, 2021). In addition, demand for electricity registered an increase in all categories except large and medium (commercial and industrial) category whose demand reduced by 3.6% to 4,281.0 GWh in 2020. Demand for street lighting and rural electrification categories increased by 16.7% and 7.5% to 74.5 GWh and 611.9 GWh, respectively during the same period. Similarly, demand for domestic and small commercial category increased by 49.0 GWh to 3,829.1 GWh. This was attributed to, possibly, the working from home measures instituted to counter the spread of COVID-19. Large and medium (commercial and industrial) category accounted for 48.7% of the total domestic demand for electricity in 2020, while domestic and small commercial category accounted for 43.5% (Economic survey, 2021; Energy Regulatory Commission, 2020).

Available data shows that the cost of electricity in Kenya is relatively high compared to other countries which result to high cost of locally produced goods (KAM, 2019). The high cost of electricity is attributed to power production plants which operate under low efficiencies as reported by Njeru *et al.*,(2020). For instance, the thermal power plants average efficiency was found to be 70.62% for both the grid connected and the isolated power plants. The mean price of electricity which is inclusive of power production costs, distribution and taxes for the past few years in Kenya is 0.211$/kWh for households and 0.169 $/kWh for business (Economic survey, 2021). Comparatively, in the neighboring countries the household price of electricity in Tanzania is 0.099 $/kWh, in Uganda is 0.189 $/kWh and in Ethiopia is 0.007 $/kWh. Globally, the average price for electricity is 0.136 $/kWh for households and 0.123 $/kWh for businesses respectively (Grant *et al.*, 2020).

During the same review period 2016 to 2020, transmission and distributive losses totaled to 2,790.7 GWh, accounting for 24.3% of the total domestic generation in 2020 (KNBS, 2021; Economic survey, 2021). These losses coupled with frequent power outages act as a decelerating factor on economic growth (World Bank, 2019). In addition, according to Cissokho and Seck, (2013) and George *et al.*, (2019) show that interruption in electricity supply could have serious consequences on consumers and losses which have led to many Kenyan companies lose nearly 10% of their production and on average; firms reported losing 8.6% of the total annual sales due to power outages (Enterprise Surveys, 2016). Power outages in Kenya are partly blamed on poor infrastructural facilities, fraud and vandalism of infrastructures such as transformers and power cables and in extension corruption, politics and poor governance in the power institutions (Pless and Fell 2017; Maende and Alwanga 2020). These power outages experienced in the country according to the World Bank (2013) occur 6.3 times in a month and can last an average of 5 hours which translate to an average of 1.5 hours to 2 hours in a day across the year. During this period of power outages, many businesses, institutions and households look for an alternative source of power as backup solution to these interruptions.

Lack of reliable electricity in Kenya has prompted the need for self-generation and consumption of electricity (Jiménez–Castillo *et al.*, 2019).During power blackouts, DGs, with typical power ratings ranging from ~ 0.1 kW to 100 kW, are usually used by many businesses and institutions to power their operations. The DGs are preferred power backup systems because of their availability, low initial and operational know-how by many users (Research and Markets, 2017; Energy Regulatory Commission, 2018). In addition, the recent push to expand rural grid coverage nationwide has resulted in higher levels of electricity access in Kenya (Lee *et al*., 2014). These authors collected data on spatial and economic factors to determine local electrification rates in the densely populated counties of Western Kenya, and their findings were interesting. They found, to their surprise, that even in an ideal setting, where there is high population density and extensive grid coverage, electrification rates remain very low, averaging 5% for rural households and 22% for rural businesses. They also observed that the pattern holds across time and applies to both poor and relatively well-off households and businesses. An interesting finding from this study is that half of the unconnected households are “under grid,” or clustered within just 200 m of a low-voltage power line, and that the same results may apply across many countries in SSA. Thus, the assumption that majority of the un-electrified are ‘off grid’ is not true and hence this signal for alternative methods for electrification of rural households and enterprises in SSA. In her efforts to achieve universal electrification for all by 2030, the Kenya’s government has rolled out an ambitious flagship rural electrification project called ‘Kenya Off-Grid Solar Access Project (KOSAP)’, and is tasked to increase electricity access using PV systems in 14 underserved counties (KPLC, 2012).

2.3 Solar Radiation

The energy emitted by the sun is called solar radiation and is the earth’s primary natural source of energy, and has been exploited since antiquity to date. Solar radiation is a term used to describe ultraviolet, visible and infrared regions of the electromagnetic spectrum where their wavelengths range from 0.25 µm to 4.5 µm (Goswami *et al.*, 2000). Figure 2.3 shows the spectral distribution of terrestrial and extraterrestrial solar radiation. Extraterrestrial and terrestrial radiation falls between 0.15 µm and 1.20 µm and the radiation of practical importance to the solar energy users falls between 0.15 µm and 2.50 µm, which include infrared used in thermal collectors. Visible radiation wavelengths lie between 0.40 µm and 0.80 µm. The power density emitted by the sun is of the order of 64 MW/m^2 of which ~1370 W/m^2 also known as the solar constant reaches the top of the Earth’s atmosphere with no significant absorption in the space (Duffie and Beckman, 2013).

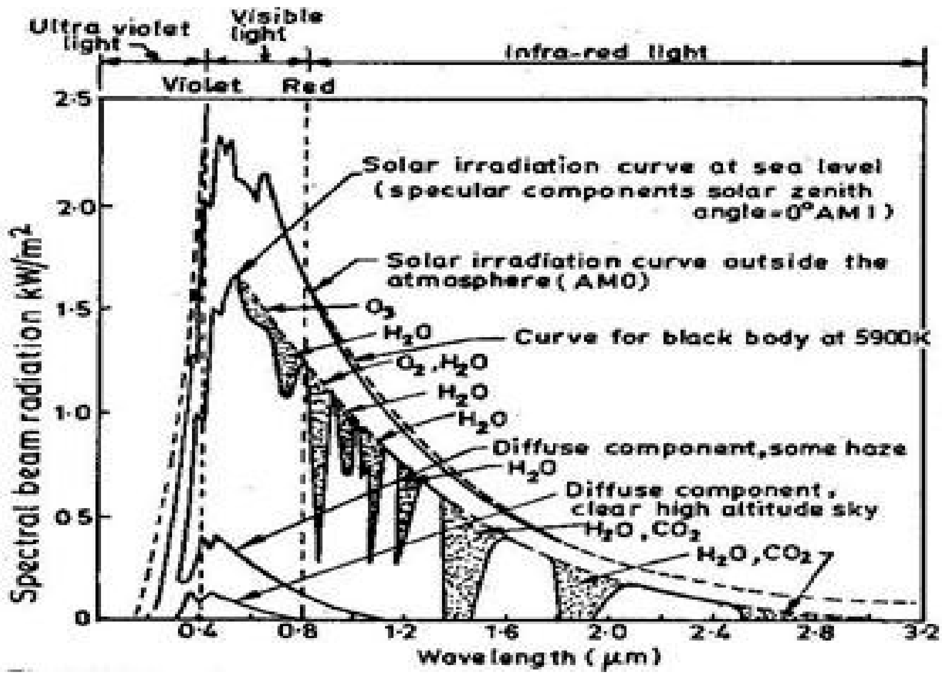


Figure 2.2: Spectral distribution of extraterrestrial radiation. Source: Renewable resource data center(Duffie and Beckman, 2013)

The spectral and intensity distribution of solar radiation is altered as it passes through the atmosphere by absorption, reflection and scattering and the amount of energy absorbed depends on the length of the path in which the solar beam traverses (Shafey and Ismail, 1990). This has important implications in many natural and technological processes, including meteorology, biology, ecology, and energy production. The solar radiation received at ground level by a horizontal surface has a direct component and a diffuse component (Zhang *et al.*, 2014).In addition, for solar energy collectors, there is also a third component called albedo, which is solar radiation reflected to the surface of the collector from the ground/snow, buildings and trees(Rao *et al.*, 1984). The sum of the direct and diffuse components on a horizontal surface is usually called global horizontal radiation (GHI) (Karuppu and Sitarama, 2019; Duffie and Beckman, 2013). Solar harvesting devices are usually mounted on inclined building roofs or inclined on flat roofs; hence the radiation intercepted is different from the GHI. In such cases, the plane-of-array (POA) solar radiation is used instead, and consists of the three components mentioned above. Solar radiation data bases provide the GHI and simulation models have been developed for estimating solar radiation in sites where there are no measurements for both GHI and POA data (Hofmann and Seckmeyer, 2017).

The earth receives about 174 PW which is approximately 70% of solar insolation at the upper atmosphere where some of the incoming radiation is absorbed in the atmosphere by vapor, dust, ozone and some are reflected back into space mostly by clouds (Duffie and Beckman, 2013). Available data show that most of the Earth land mass receive insolation levels of about 3.5 $KWh/m^2/day$ to 7.0 $KWh/m^2/day$ which is substantial and supplies about 0.1% of the world energy consumption (Karuppu and Sitarama, 2019; Hofmann and Seckmeyer, 2017; Duffie and Beckman, 2013). It is estimated that Kenya on average receives solar insolation of about 4.0 $KWh/m^2/day$ to 6.0 $KWh/m^2/day$ (Oloo *et al.,* 2015; Kiplagat *et al.*, 2011; Rose *et al*., 2016). Insolation received at a given location depends upon the relative position between the sun and the earth, time of the day, seasons of the year, local weather and geographical location (Castaner, 2002; Bosch *et al.,* 2010; Museruka and Mutabazi, 2007).

Availability of solar radiation data are beneficial in areas of agriculture, water resources, day lighting and architectural design, solar conversion devices and climate change studies (Katiyar *et al.*, 2010; Al-Kayiem and Mohammad, 2019). In solar energy conversion and utilization devices, data on solar radiation and its components at a given location are very essential for their evaluation and deployment. These data are required in order to design and size a cost-effective solar collector in terms of cost and energy demand of the load at the site. Daily global solar radiation reaching the earth surface at hourly basis (or even sub-hourly) is very important for analysis of performance of solar energy conversion and utilization devices (e.g., PV module), but monthly averaged solar radiation data may be sufficient for agricultural applications (Al-Sanea *et al.,* 2004). Solar radiation data can be obtained from several sources including ground observation, satellite remote sensing, interpolation, and empirical models (Huang *et al*., 2019; Dahmani *et al.,* 2016; Myers *et al.,* 2002). Each method has its merits and deficiencies. The radiation data are specified in units of Wm^{-2} or kWm^{-2} and when integrated over a day, give daily irradiation which is expressed in $MJm^{-2}day^{-1}$ or $kWhm^{-2}day^{-1}$. In addition, solar radiation varies both spatially and temporarily. Thus, for a given site and regardless of type, solar radiation can be quantified with respect to time as hourly, daily, monthly or annual averages (Cucumo *et al.*, 2007).

2.3.1 Ground Observation

Ground observation is the most direct and reliable way to obtain solar radiation at the site of interest, and high-quality instrumentation and maintenance often provides baseline solar radiation data. These stations have been in operation as early as 1964, and in particular, the World Meteorological Organization (WMO) had set up the World Radiation Data Centre to collect, archive and publish global measurements of GHI, and other components (Huang *et al*., 2019).However, these ground stations are few and sparsely distributed across the world due to the high cost of measuring instruments (Sengupta *et al.,* 2015; Myers *et al.*, 2002) and is its weakest point.

Pyranometers (e.g., Kipp and Zonen) are usually used to measure the GHI, and are mounted on flat surfaces (Shenoy *et al.,* 2018). The GHI component may vary greatly depending on the surface elevation, location, time of day, seasons and on other meteorological factors (Awasthi and Poudyal, 2018). For solar energy conversion devices, the pyranometers are also used to measure POA radiation by mounting them on the surface of the collector (Oyelami *et al.*, 2020). The pyranometers come in various models based on type of sensor used, which can be based on either heating effects (thermopiles) or electric effects (PV cell) to generate electric voltage that can detected and measured. Modern digital pyranometer use pyroelectric elements that generate voltage when a change in temperature is detected. Each pyranometer is usually calibrated by the manufacturers, but need to be calibrated at regular intervals to ensure accurate measurements (Tohsing *et al.*, 2019). Another common instrument used for solar radiation measurements is the pyrheliometer, which is used to measure direct or beam solar radiation only (Garg, 1993). A pyrheliometer has a narrow aperture to ensure that only solar radiation from the sun is measured, usually has a full angle of about 0.53^{o} (Frohlich *et al.*, 1973; Duffie and Beckman, 2013).The pyrheliometer needs to be pointed to the sun and is normally used for calibration. The portable pyranometer and pyrheliometer are usually used in conjunction with voltmeter to read the measurements or with data loggers for continuous recording and storage (Jacovides *et al.*, 2006).

2.3.2 Interpolation method

Interpolation method is used to estimate solar radiation in a location where there is no measured data, and is used in conjunction with ground measured data or global radiation maps. This method is used to estimate radiation values at a location between two ground measuring stations and usually uses interpolation with respect to spatial dimensions between the observation stations and area of interest (Longley *et al.*, 2001). However, spatial interpolation is restricted to a radius of 30 km from the station (Al-Sanea *et al.*, 2004 and Ascencio-V´asquez *et al.*, 2020).Interpolation techniques that are usually used include linear regression; nearest neighbor; inverse distance weighting, among others (Pessanha *et al.,* 2021).

2.3.3 Satellite Remote Sensing

Satellite remote sensing has been recognized as a method that offers a unique means to monitor and estimate solar radiation regionally or globally and is better than interpolation and numerical modeling methods. In particular, satellite data are preferable than those of interpolation method, and is usually recommended to be used for locations that further than 30 Km from ground observation stations. The satellite derived data have accuracies that approach those of ground observations(Huang *et al*., 2019). In this method, radiometers mounted on the satellites are used to measure the radiation in space and relay the data to ground stations where they are recorded and archived (Ruiz-Arias *et al.,* 2010).Satellite measurements provide continuous data for all regions of the earth over many years with almost uniform resolution (Cebecauer *et al.,* 2010).

2.3.4 Empirical methods

Solar radiation data in any location on the earth surface can also be generated using numerical or empirical or theoretical models that have been developed over the years. The empirical method is used in cases where measured or satellite data are inaccessible and is usually used in simulation models that are usually utilized in the design and analysis of solar energy conversion devices.Several models with varying degrees of complexity, detail and accuracy have been developed and used in different parts of the world to generate radiation data and its components. These models are based on either empirical correlations or statistical regression between satellite and or ground measurements and various meteorological parameters (Doorga *et al.,* 2019).

The most commonly used meteorological parameters are air temperature (Gairaa and Bakelli, 2013; Bocca *et al.,* 2018), relative humidity (Rao *et al.,* 2012; Qing andNiu, 2018), precipitation (Yu *et al.,* 2019; Maleki *et al.,* 2017), cloudiness cover (Paulescu and Blaga, 2016) and bright sunshine duration (Muneer, 2014). Additional input parameters used are solar altitude, aerosol concentrations and global warming factor (Hocaoglu and Serttas, 2017; Despotovic *et al.,* 2016).The correlation coefficients in each model are site dependent, and hence are adjusted for each location when using them. In this study, four models for predicting GHI were selected and validated with the ground measured data at a site of study to select the most appropriate. These models are Angstrom-Prescott, ASHRAE, Hargreaves-Samanni and Iqbal, which are based respectively on sunshine hours, sky clearness, ambient temperature and the atmospheric transmittance. Each model has got unique merits and demerits depending on the number and availability or ease of determination of predictor variable(s) (Doorga *et al.,* 2009).

Radiation prediction models are expected to estimate as closely as possible the monthly average daily global solar irradiation on a horizontal surface from applicable meteorological parameters (Ulgen and Hepbasli, 2002). The four selected models were chosen because they are diverse and involve input parameters that are easily available or determined at the site. The models considered can be grouped into three categories: sunshine, temperature and hybrid-parameter based models (Hofmann and Seckmeyer, 2017). The Angstrom-Prescott model was developed by Angstrom but was modified by Prescott, hence the name. Prescott simplified the equation by replacing clear sky global solar irradiation with extraterrestrial solar irradiation on a horizontal surface. The Angstrom-Prescott model assumed linear relationship between sunshine duration and solar radiation, but various researchers have reported better coefficients for second order (quadratic), third order (cubic), exponential, power and logarithmic fits (Doorga *et al.,* 2009).Hargreaves-Samanni's model is based on air temperature (maximum and minimum) and most appropriate when data on sunshine hours is lacking. ASHRAE clear sky model offers a simple method and is widely used as a basic tool for solar heat load calculation for air conditioning systems and building designs by engineers and architects (Maleki *et al.*, 2017). Iqbal model takes into account the scattering-transmittance of the atmosphere contributed by ozone, gases, water and aerosol components (Wong and Chow, 2001). In this study, these selected models will be validated by the solar radiation data measured in the study area.

a) Angstrom-Prescott model

This model correlates the daily extraterrestrial, H_o and terrestrial, H_s solar radiation and sunshine duration as having linear relationship (Duffie and Beckmann, 2013; Ångström, 1924; Da-Silva *et al.,* 2017; Tymvios *et al.*, 2005):

$$H_s = H_o\left[a + b\left(\frac{S}{S_o}\right)\right] \tag{2.1}$$

where S is daily number of hours of bright sunshine, S_o is daily number of hours of possible sunshine (daylight between sunrise and sunset), a and b values are regression coefficients to be determined for the site (Duffie and Beckmann, 2013; Sabzipavar *et al.,* 2013). The H_o can be calculated from the equation:

$$H_o = \frac{24}{\pi}G_{sc}\left[1 + 0.33\cos\left(\frac{360n}{365}\right)\right]\left[\cos\delta\cos\varphi\sin\omega_s + \frac{\pi\omega_s}{180}\sin\varphi\sin\delta\right] \tag{2.2}$$

where G_{sc} is solar constant, ω_s is the sunset angle, φ is the latitude angle of the site, δ is the sun declination angle and n is the day number of the year, with n=1 for 1^{st}January and n= 365 for 31^{st} December (Bandyopadhyay *et al.*, 2008). The coefficients *a* and *b* in equation (2.2) is dependent on the site altitude and atmospheric transmittance and are given by Duffie and Beckman, (2013) as;

$$a = 0.110 + 0.235\cos\varphi + 0.323\left(\frac{S}{S_o}\right) \tag{2.3}$$

$$b = 1.449 + 0.553\cos\varphi - 0.694\left(\frac{S}{S_o}\right) \tag{2.4}$$

b) ASHRAE model

ASHRAE clear sky model is given by (ASHRAE, 1985; Wong & Chow, 2001; Al-Sanea *et al.*,2004; Perez *et al.*, 1992; Jamil and Khan, 2014):

$$H_s = G_{sc} e^{(-A/\cos\phi_z)}(\cos\phi_z + B) \tag{2.5}$$

where *A* is the atmospheric extinction coefficient, *B* is the diffuse sky factor, and ϕ_Z is the zenith angle. The coefficient*A* and Cos ϕ_Z can be calculated respectively from (Basharat and Mohd, 2014; Perez *et al.*, 1992; Bakirci, 2009):

$$A = 360(n - 81)/365 \tag{2.6}$$

$$\cos\phi_Z = \cos\delta\cos\varphi\cos w_s + \sin\delta\sin\varphi \tag{2.7}$$

c) Hargreaves-Samanni's model

Hargreaves-Samanni'stemperature-based model is given by (Hargreaves and Samani, 1982; Gavalian *et al.*, 2005):

$$H_s = K_{RS}\left(\sqrt{T_{\max} - T_{\min}}\right)H_o \tag{2.8}$$

where K_{RS} is an empirical coefficient related to atmospheric transmittance, and T_{max} and T_{min} are respectively maximum and minimum temperatures. The K_{RS} is included to account for possible pollution at the site with values of 0.16 (used in this study) and 0.19respectively for inland and coastal sites. The H_o is given by (Despotovic *et al.*, 2016):

$$H_o = \frac{1440}{\pi} G_{sc} E_o \left(\omega_s \sin\varphi \sin\delta + \cos\delta \cos\varphi \sin\omega_s \right) \qquad (2.9)$$

where $E_{0,}$ is the eccentricity correction factor of the earth's orbit and is expressed as (Wong & Chow, 2001):

$$E_0 = 1.0 + 0.033 \cos 2\pi \left(\frac{n-1}{365} \right) \qquad (2.10)$$

d) Iqbal model

Iqbal model is based on atmospheric transmittance and is given by (Iqbal, 1983; Batlles *et al.*, 2000; Wong and Chow, 2001):

$$H = \left(0.9751 G_{sc} E_o \tau_s \cos\theta_z + H_d \right) \left(\frac{1}{1 - \rho_g \rho_a} \right) \qquad (2.11)$$

where the factor 0.9751 is included to show that spectral interval considered is 0.3-3 μm of the electromagnetic spectrum,$\tau_s$is the scattering-transmittance (equal to product of ozone, gas, water and aerosol scattering fractions), and H_d is diffuse component contributed by Rayleigh and aerosols scattering after passing through the atmosphere. The parameters ρ_g and ρ_a are the ground albedo respectively. Evaluation of τ_s, H_d, ρ_a and other parameters are given explicitly by Wong and Chow (2001); Batlles *et al*., (2000) and Despotovic *et al.*, (2016).

e) Sensitivity analysis

Several statistical indicators have been proposed and used to test the accuracy of the solar radiation models. Among them are mean bias error (MBE), root mean square error (RMSE), absolute percent error (MAPE), coefficient of determination (R^2), *t*-statistic method (*t*-stat), among others (Toffalis, 2015; Al-Aboosi, 2020; Doorga, *et al.*, 2019).

The RMSE represents the sample standard deviation of the differences between estimated and measured values and is given as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(H_{i,r} - H_{i,e}\right)^2} \tag{2.12}$$

The MAPE is a measure of relative overall fit, and has the advantage of being scale-independent (Doorga *et al.*, 2019):

$$MAPE = \frac{100}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{H_{i,r} - H_{i,e}}{H_{i,r}}\right)} \tag{2.13}$$

where $H_{i,r}$ and $H_{i,e}$ represent the i^{th} measured and estimated values respectively, and*n* is the number of observations.

2.3.5 Clearness index

Clearness index, K_T is the ratio of the measured solar irradiation in a given location relative to the calculated extraterrestrial irradiation (Woyte *et al.,* 2007).It is a dimensionless quantity and can vary from 0 to 1 and can be determined on hourly, daily or monthly basis (Mellit *et al.*, 2008). The monthly average clearness index is the ratio of monthly average measured daily radiation on a horizontal surface (H) (W/m^2/day) to monthly average daily extraterrestrial radiation on a horizontal surface (H_o) (W/m^2/day) expressed as (Duffie and Beckman, 2013; Bandyopadhyay *et al.,* 2008):

$$K_T = \frac{H}{H_o} \tag{2.14}$$

where H_o is the extraterrestrial solar radiation as expressed in equation (2.2).

Clearness index is useful in characterization of solar energy resource for effective sizing of energy conversion systems and for a predictive purpose (Li and Lam, 2000). Using clearness index, segmentation of a given site is characterized by three types of clusters, namely cloudy (KT < 0.3), partly cloudy ($0.3 \leq$ KT ≤ 0.5) and clear sky/sunny (KT > 0.5) (Harrouni *et al.,* 2005; Al Aboosi, 2020; Lee *et al.*, 2015).

2.4 Solar energy conversion technologies

The available technologies through which solar energy is harnessed presently include the photovoltaics (PV), concentrating solar power systems (CSP), solar domestic hot water heating system (SDHW), solar heating and cooling (SHC) systems and Photovoltaic/ Thermal (PV/T) systems.

The solar heating and cooling (SHC) systems absorb solar radiation and convert to heat energy through heat transfer fluid such as water, air or oil (Faninger, 2010). They are utilized in various applications in commercial and industrial applications. They comprise of solar thermal collectors, heat exchange system, a thermal storage system, and a cooling tower (Luzzi and Lovegrove, 2004). The CSP system also known as solar thermal electricity (STE) uses heat from the sun to run a steam engine, which turn turbine to generate electricity (Collado and Guallar, 2013). They use mirrors to concentrate energy from the sun in order to heat water to steam. The SDHW system uses solar energy for heating where a black absorbing surface absorbs solar radiations and transfers the heat energy to water flowing through it. They consist of solar collector and an insulated storage tank to store hot water to be used latter anytime (Burzynski *et al.,* 2010). Recent development in solar energy utilization is the combination of PV and solar thermal collector to yield hybrid PV/T solar system where heat and electricity are generated simultaneously (Ali *et al.*, 2017, Tonui and Tripanagnostopoulos, 2008, 2007). These systems transfer the otherwise unused waste heat from the PV modules to heat transfer fluid which then channel for useful applications and at the same time cools the cells improving electrical conversion efficiency. The PV/T system attains higher overall conversion efficiency compared to when they operate independently (Kalgirou and Tripanagnostopoulos, 2007).

The PV convert solar radiations directly to electricity through a process known as photoelectric effect, a phenomenon that was first discovered experimentally in 1839 by Bequerel (1839). During his experiments involving an electrochemical cell, he noted that the voltage of the cell increased when its silver plates were exposed to sunlight. It is through this process that PV cells generate voltage and electric current upon exposure to light. The solar PV cells produce direct current (DC) power. Upon this discovery, it opened up a modern application of solar energy for electricity generation and spurred great interest in research and technological development in solar energy field. An explosion of research and development in solar photovoltaics have been witnessed since the oil crisis of the 70s to date when countries who do not produce oil was awakened to the seek alternative energy sources to mitigate against oil crisis in the future. The PV industry has been striving throughout the world in applications and market penetration, which has been attributed to advances in technology (increasing efficiency and reliability), government subsidies (policies), mass production, and the need to switch to low carbon energy sources (Mittag *et al.*, 2019).

2.5 The PV cells

Figure 2.3 shows the structure of a PV cell. As Illustrated in the figure, the PV cell consists of two layers, the p-type semiconductor and the n-type semiconductor that are joined together to form a p-n junction diode (Luceño-Sánchez *et al*., 2019). The n-layer has high electron concentration while the p-layer has high hole concentration, and when they are joined, electrons (holes) diffuse from n-layer (p-layer) to p-layer (n-layer)and fill the holes (electrons) adjacent to the junction and create negatively (positively) charge ions. Diffusion of free charge carriers continue until equilibrium is reached, when the negative (positive) ions on p-layer (n-layer) stop further diffusion of electron (holes). Thus, the region adjacent to the junction is depleted of free carriers and is usually called depletion layer, and no free carriers (electrons or holes) can cross it.

A solar cell is a large area p-n junction diode so as to capture sufficient solar radiation. It is structured such the p-layer forms the top or front layer and is intentionally made very thin as compared to back n-layer in order to allow solar radiation to penetrate into the p-n junction. When light is incident on the p-n junction through the front thin p-layer, light photons absorbed supply sufficient energy to ions in the junction to create a number of electron-hole pairs. If an external circuit is connected across the cell, then the photon generated charge carriers will be separated, and made to flow in opposite directions creating an external current in the process. The amount of current depends on the number of charges created, which in turn depends on the amount of solar radiation incident on the cell (Kumaresh *et al.,* 2014; Boyle, 2004). Typical shapes of solar cells are either square or circular, though other shapes are also possible, with typical dimension of 10 cm x 10 cm and thickness of about 0.3 mm(Archer and Hill, 2001).Solar cells are also provided with metallic contacts attached to the two layers, which are used to collect the photon generated charge carriers and pass them to the external circuit. The front contact collects electrons, hence forms the negative terminal, while the back contact collects the holes and the positive terminal (Luceño-Sánchez *et al.*, 2019).

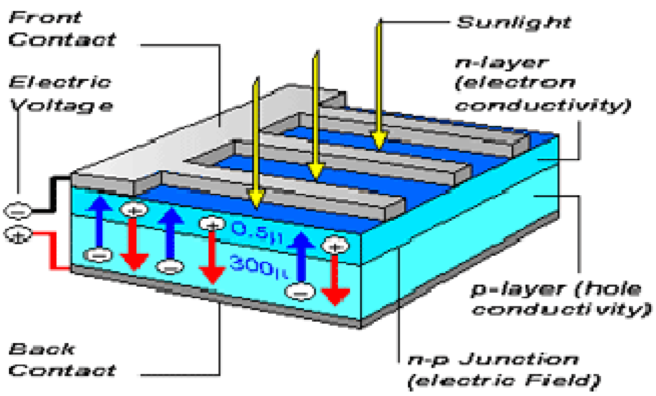


Figure 2.3: Structure of a solar PV cell. **(Luceño-Sánchez *et al.*, 2019)**

Front contacts are plated into grooves in the cell so as to minimize shading of the PV cell surface. The back contact for modules is patterned in order to separate one cell from the next. The characteristics of the material to be used in making of the front and back contacts are those that are good conductors, comparatively cheap, temperature stable and with a smooth surface. The front and back contacts have great influence on efficiency as well as performance of the PV cell (Rached and Mostefaoui, 2008). The entire assembly of the PV cell is encapsulated between thin glass to provide mechanical stability and environmental protection (Hossain *et al.*, 2019).

The art, design and development of solar cells are categorized into three generations, and each generation aims to increase efficiency and reduce cost as compared to the previous one. Figure 2.4 shows classification of solar PV technologies based on the generation.

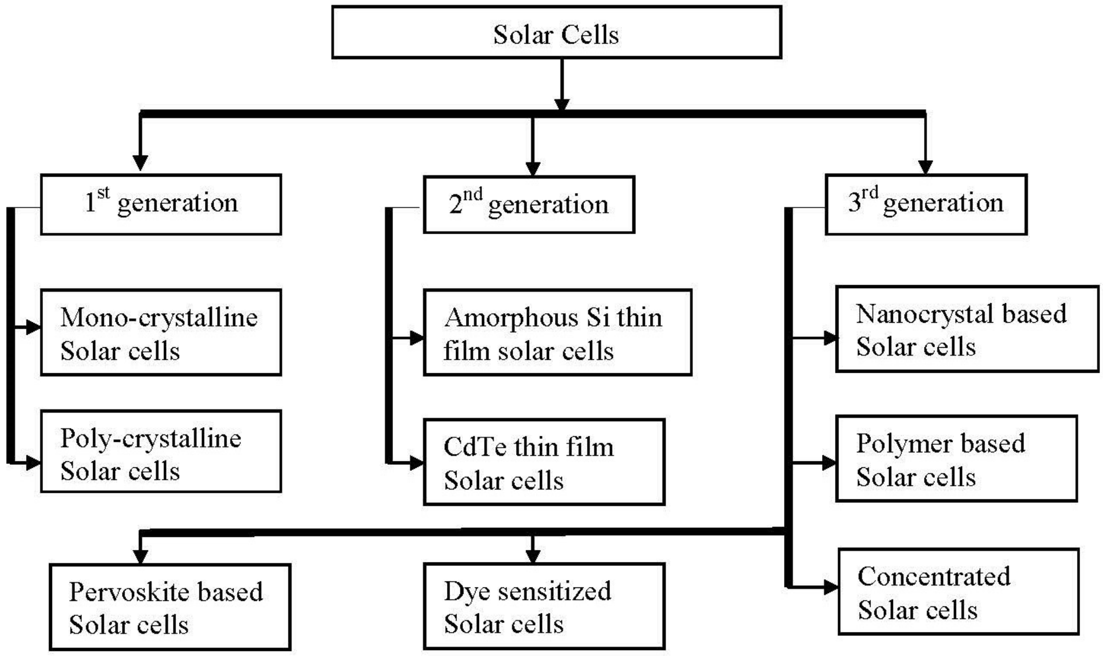


Figure 2.4: Schematic showing the classification of solar PV cells

First generation is based on cells from silicon and is categorized into two subgroups namely the single/ mono-crystalline silicon solar cells and poly/multi-crystalline silicon solar cells (Sampaio and González, 2017). They are solar cells produced from silicon wafers, hence referred to as wafer-based cells and the oldest and most established technology due to high conversion efficiencies. Their popularity is also attributed to easy ways of making an insulating layer on top of silicon by exposing it to oxygen while heating it to form SiO_2 layer which is a strong insulating material (Esmaili and Nasiri, 2009).

Second generation is more economical as compared to the first generation silicon wafer solar cells and they comprise of a-Si thin film solar cells, Cadmium Telluride (CdTe) thin film solar cell and Copper Indium Gallium Di-Selenide (CiGS) Solar cell which offer added advantages like environmental friendliness and lower costs(Choubey *et al.*, 2012; Gorter and Reinders, 2012 and Nikolaidou *et al.*, 2019).For a long period, silicon technology has been leading in manufacturing of PV cells due to its availability but comes with high cost of production that has prompted researchers to come up with thin-film technology as a substitute since their layers are thinner, hence uses less material(McCann *et al.*, 2001). Thin-film technologies are maturing fast and soon may challenge the market share of crystalline Silicon devices though crystalline silicon devices are likely to remain dominant for the next decade because of their abundant availability as compared to thin-film technologies (Green and Emery, 2008; Shah *et al.,* 2014). Solar cells based on thin films constitute ~10% of global PV module market nowadays (Nikolaidou *et al.,* 2019). Generally, thin-film cells are made through fabrication processes, which may reduce manufacturing capital expense and material usage. This category extends from commercial technologies based on conventional inorganic semiconductors to emerging technologies based on nano-structured materials. At the moment, three thin film PV technologies which are developed to commercial phase are hydrogenated amorphous silicon (a-Si:H), cadmium telluride (CdTe) and copper indium gallium diselenide (CuInxGa1−xSe2, or CIGS) (Ludin *et al.,* 2018).

The third generation comprises of nanostructures and organic materials which are relatively expensive but very efficient cells. These types include the Nano crystal-based solar cells, polymer-based solar cells, dye-sensitized solar cells and concentrated solar cells (Nikolaidou *et al.,* 2019*;* Habibi *et al.,* 2014). They are the new promising technologies but are not yet commercially deployed. This generation aim to develop devices with high efficiencies using the thin film method which may lead to an increment in the area cost, but the cost per watt peak would be reduced (Conibeer, 2007; Das *et al.,* 2014; Sethi *et al.,* 2011; Serrano *et al.,* 2009).

2.6 The PV module and array

Figure 2.5 shows a structure of a PV module with 72 PV cells connected in series. A PV module is made of a number of PV cells connected in series or parallel to respectively increase current and produce a higher voltage. Most commercial modules contain 36 PV cells or 72 PV cells connected in series where the36 PV cells modules are commonly used for large power production in the PV industry. These number of cells account for any unexpected reduction in PV module voltage due to temperature, shading and other outdoor operating factors. The output voltage of a PV module is y chosen so as to be compatible with a 12V battery which may require voltage of about 15 V or more to charge. The current output from the PV module is determined by the solar irradiance and the number of PV cells while voltage is dependent on the size of the PV cells and cell temperature (Joseph and Kamala, 2013; El-Adawi and Al-Nuaim, 2007). A single crystal PV cell is often 15.6 × 15.6 cm^2 in size which gives a total current of almost 10 A from a module of 72 PV cells (Yang *et al.*, 2015). In addition, under optimum tilt conditions, the current density from a commercial solar cell is approximately between 30 mA/cm^2 to 36 mA/cm^2 (Green *et al*., 2009).

Tempered glass or some other suitable transparent material encapsulates PV modules on the front surface while the back surface is covered with a thin polymer protective sheet (typically tedlar) which is a water proof material. These materials guarantee protection of the cells within the module from water, dust, mechanical compressions etc. To ensure that the module is well mounted, an aluminum frame holding everything together in a mountable unit is used in all the module edges for mechanical strength. At the back of the module there is a junction box, with wire leads that provide external power extraction line via the charge controller.

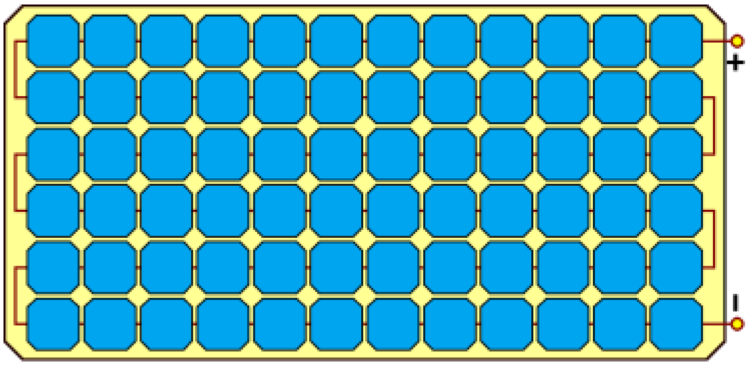


Figure 2.5: Structure of a PV module with 72 cells wired in series. (Source: Müller *et al.*, 2016)

A PV array is constructed from a number of individual PV modules that are connected together either in series or parallel or mixture of the two and usually mounted on the roof or on the ground field. For high power applications, this kind of connection is desirable so as to increase the output power to meet the load demand since a single PV module may not produce sufficient power. To increase the voltage, modules are connected in series and to increase current they are connected in parallel but under outdoor conditions, PV modules in an array should not be connected in series so as to obtain higher power output (Khatoon and Ibraheem, 2014). An entire surface of a PV array would not maintain a uniform irradiance level sometimes due to partial shading which causes a significant power loss (Micheli *et al.*, 2014). To avoid these power losses, blocking diodes are used in series with the PV modules so as to prevent current from flowing back into them and also prevent the fully charged batteries from discharging or draining back through the PV array at night. In addition, bypass diodes are used in parallel with a PV module so as to provide an alternative path to current around the shaded module (Müller *et al.*, 2016).Figure 2.6 shows a PV array consisting of four PV modules. As illustrated in the figure, the PV array produces two parallel branches in which there are two PV panels that are electrically connected together to produce a series circuit.

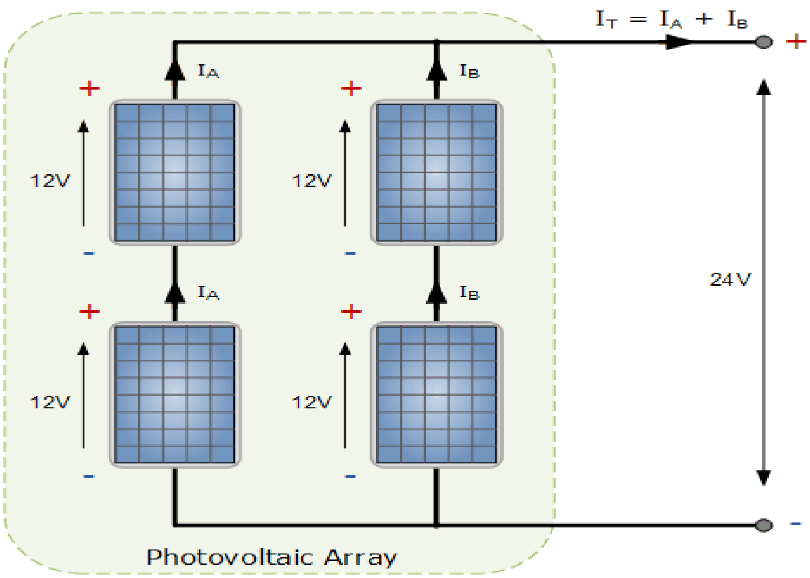


Figure 2.6: Basic structure of a PV array

2.7 PV performance

Characterization of the performance of PV cells/ modules/ arrays can be done either experimentally or theoretically. Experimental method involves setting up a PV circuit and measuring voltage, current, temperature and POA irradiance under different loading and plotting the I-V curve. From the curve, various characteristic parameters can be determined. On the other hand, theoretical analysis involves constituting equations from the equivalent circuit of a solar cell. The commonly used equivalent circuit of a solar cell is the single-diode model and PV module model (Bandou *et al.*, 2013; Ghani *et al.*, 2015; Akinyele *et al.*, 2015).

2.7.1 Single diode model

Figure 2.7 shows a single-diode equivalent circuit model of a solar cell, which consists of a series resistance (R_s), a shunt resistance (R_{sh}), and a linear independent current source in parallel to a diode (Dadjé *et al.*, 2017). This model shows the parameters that are of interest such as the short-circuit current (I_{sc}), open-circuit voltage (V_{oc}) and the PV maximum power (P_{max}) that is expressed as the product of maximum power point voltage (V_{mpp}) and maximum power point current (I_{mpp}) (Ghani *et al.*, 2015; Tian *et al.*, 2012 and Akarslan, 2012). The V_{oc} is voltage measured when the solar cell has no load; hence the current through the cell is zero. Essentially, V_{oc} is the maximum DC voltage while I_{sc} represents the maximum DC current on the I-V characteristics curve. The I_{mpp} and V_{mpp} are values of current and voltage when a PV cell or module is operating at maximum power point respectively (Tian *et al.*, 2012).

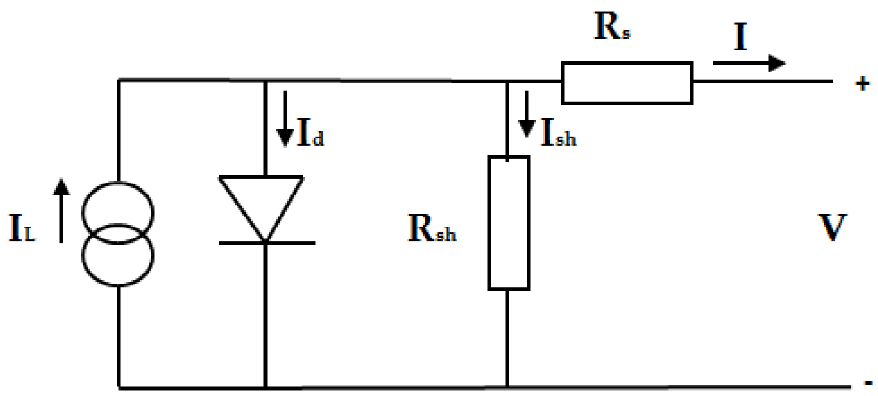


Figure 2.7: Equivalent circuit of a PV cell (Dadjé *et al.*, 2017)

From Figure 2.7, the PV cell output current, I could be estimated by applying the Kirchoff's current law as (Tian *et al.*, 2012; Ghani *et al.*, 2015):

$$I = I_l - I_d - I_{sh} \tag{2.15}$$

where I is the output current, I_l is the solar generated current, I_d is the diode current and I_{sh} is the shunt leakage current.

Employing the Shockley's ideal diode equation I is given as:

$$I = I_o(\exp\left(\frac{V + IR_s}{n_{id}V_t}\right) - 1) \tag{2.16}$$

where

$$V_t = \frac{kT_c}{q} \tag{2.17}$$

and

$$I_{sh} = \frac{(V + IR_s)}{R_{sh}} \tag{2.18}$$

These equations (2.16), (2.17) and (2.18) are then substituted to equation (2.14) where the output current of the solar cell is then represented as (Bandou *et al.*, 2013; Mahmoud *et al.*, 2012):

$$I = I_l - I_{dr}\left(\exp\left(\frac{V + IR_s}{n_{id}}\right) - 1\right) - \frac{V + IR_s}{R_{sh}} \tag{2.19}$$

The five parameters (i.e., I_l, I_{dr}, R_s, R_{sh} and n_{id}) of the model are very useful in the development of the I-V curve for PV performance analysis.

2.7.2 PV module model

For a PV module, with cells connected in series, the same current flow through the cells while voltage is cumulative and is equal to the product of cell's voltage and number of cells (Akinyele *et al.*, 2015). The single-diode model equivalent for a PV module is given by(Tian *et al.*, 2012; Moharil and Kulkarni, 2009; Sangram, 2016):

$$I = I_l - I_{dr}\left(\exp\left(\frac{V_m + \alpha I_m R_s}{n_{id}\alpha V_t}\right) - 1\right) - \frac{V_m + \alpha I R_s}{\alpha R_{sh}} \tag{2.20}$$

where V_m is the module voltage, I_m is the module current and α is the number of modules in an array.

2.8 Solar PV application

Application of PV power systems is usually categorized into either grid-connected or standalone systems as shown in Figure 2.8 and vary greatly in size and application (Bhandari *et al.*, 2015).

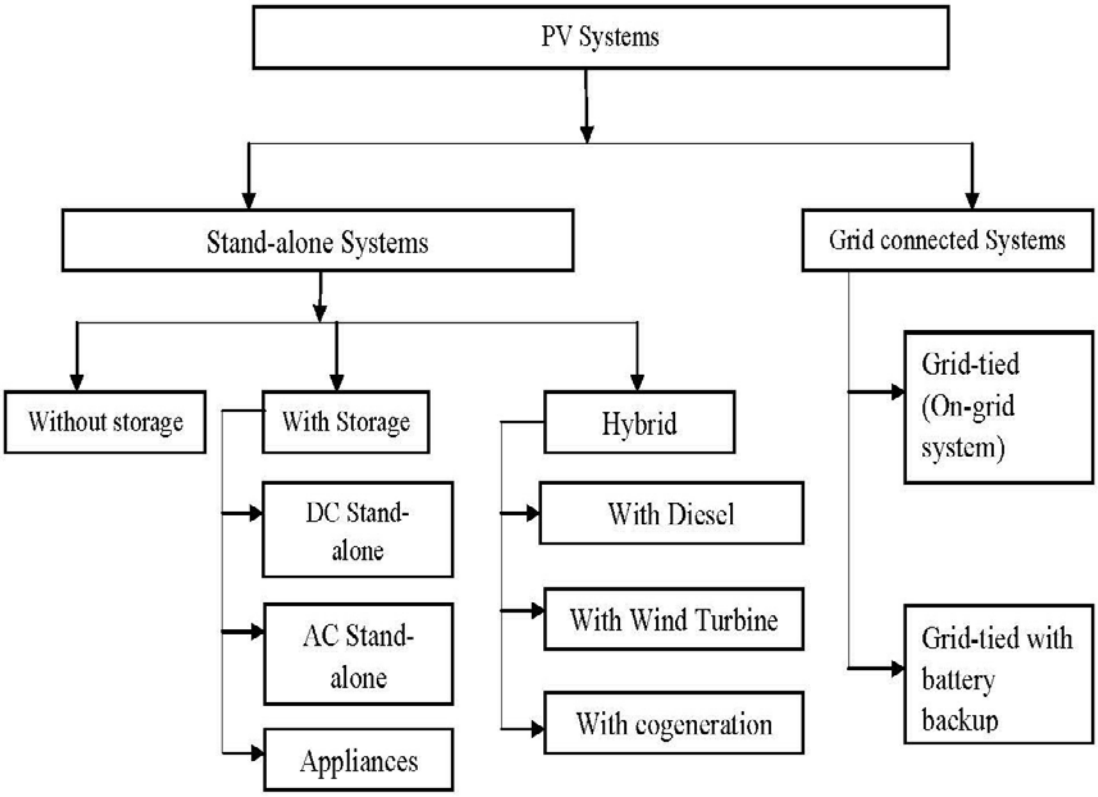


Figure 2.8: Classification of PV systems (Messenger and Ventre, 2003).

A stand-alone system supplies electricity solely to the premise and are broadly classified into hybrid systems, PV with storage systems and PV without storage systems (Messenger and Ventre, 2003; Enerray, 2017). Standalone systems vary widely in size and application from wristwatches or calculators to remote buildings or spacecraft. Those without storage are used to power the loads directly only during sunshine hours making them suitable for applications such as ventilation fans, water pumps and small water pumps for water heating systems or fans in solar air dryers (Ramirez *et al.*, 2018; Weis, 2013). In non-portable applications where weight is not an issue, such as in buildings, batteries are commonly used (Karakaya and Sriwannawit, 2015).

The grid connected systems can be directly connected to the main utility grid where all the power generated is supplied to the grid or can be connected to the utility grid via the locale electrical network where only surplus power generated is supplied to the grid (Elhodeiby *et al.,* 2011). Depending on the solar radiations and the electric energy generated by the PV system, the load can take all of the required energy either from the PV system or can be shared between the PV and the electric grid. Grid connected systems can be enabled through net metering system where producers can sell their surplus electricity to the utility grid and as well buy it during low PV power production (AbdelHady, 2017). Usually, grid connected system does not need battery storage, because all surplus power is transferred automatically to the linked utility grid. These grids connected systems range from small residential and commercial rooftop systems to large utility-scale solar power stations (De-Lima *et al.,* 2017).

2.9 The PV Balance of System

In a PV power system, PV module is the core component and other components needed to avail electricity generated to the loads are called collectively the balance of system (BOS). The BOS included are charge controller, inverters, batteries, wiring and switches. The inverter and the storage systems form the major parts of the subsystem because of their impact on overall PV system efficiency.

2.9.1 Inverters

The inverter is an essential component of BOS subsystem that changes the direct current (DC) from the PV array to alternating current (AC) for use by appliances that operate on AC supply (VignolaFotis *et al.*, 2008). There are two general types of inverters namely, square wave inverters (line frequency switching) and pulse width modulation (PWM) inverters (high frequency switching) depending on the switching techniques used. Nowadays, inverter manufacturers list the overall conversion efficiency in the range of 95% to 98% (Panwar *et al.*, 2017). These efficiencies are obtained under standard testing conditions (STC) for a PV system in which the array is properly sized for the inverter. This conversion efficiency usually affects the overall performance of the PV systems (Saiful *et al*., 2006). This efficiency reduces gradually at full load depending on the solar irradiance and inverter operating temperature (Burger and Rüther, 2006).

The choice of the right type of an inverter for any PV system has a greater influence on the optimum performance of the system to meet the different requirements for any application. Modern inverters have incorporated solar charge controllers with maximum power point tracking (MPPT) capability (Alpesh *et al.,* 2020; Danandeh and Mousavi, 2018). Such a device has a better capacity to maximize the solar energy output at any given irradiance levels.

2.9.2 Energy Storage systems

One of the major challenges of many renewable energy technologies and particularly the PV technology is intermittency nature of its electrical power output. It is due to this feature that they are installed with storage systems capable of smoothing out the fluctuating output power (Akinyele and Rayudu, 2014; Chen *et al*., 2009). Various energy storage technologies are already in existence and are classified into four types (Denholm *et al*., 2010) as shown in Figure 2.9. The electrical energy storage systems include the capacitor storage and superconducting magnetic energy storage systems (Vazquez *et al.*, 2010);The mechanical energy storage systems include the flywheel energy storage, compressed air energy storage and the pumped-hydro storage systems (Young-Min *et al.,* 2012);The chemical energy storage systems include the battery energy storage system (Chen *et al*., 2013);Finally the thermal energy storage systems which includes the aquiferous thermal energy storage, cryogenic energy storage, hot thermal energy storage and pumped-heat electrical storage systems (Kaldellis *et al.*, 2007).

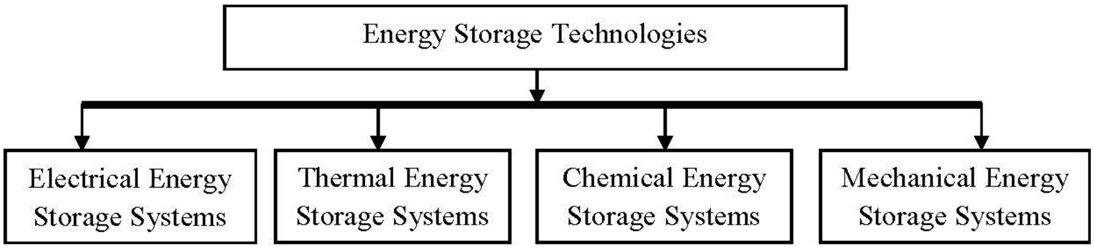


Figure 2.9: Classification of energy storage systems

The studied PV system uses the battery type of chemical energy storage system. Batteries are the most widely used energy storage systems in PV applications and their popularity is driven by their availability in the market, modularity and their high efficiencies compared to other technologies (Akinyele, 2014; Burke, 2007). There are several existing types of batteries which include Lead-acid, Lithium-Ion (Li-ion), Nickel Cadmium (Ni-Cd), Bickel metal Hydride (Ni-MH), Sodium Sulphur (NaS), Zinc Bromide (ZnBr), Sodium-Nickel Chloride (ZEBRA) and vanadium redox (VRB) (Chen *et al.*, 2009).

Traditionally, lead-acid batteries, invented in 1859 by Gaston Planté, are the oldest technology of rechargeable batteries and have been used widely with standalone PV systems. These lead-acid batteries consist of an electrolyte (concentrated solution of sulfuric acid), electrodes that are the positive (lead oxide) and negative (lead) conductors and the primary part of connected cells (Denholm *et al.*, 2010). These batteries are classified as both the flooded or vented types which require frequent distilled water addition to avoid the battery’s electrolyte from depletion and the sealed types that do not require water addition (Young- Min *et al.*, 2012). They have a round-trip efficiency of more than 70% and a life span of 5 - 15 years and a cycle life of about 2000- 2500 cycles with a low self-discharge loss of 0.1 %/day - 0.3 %/day (Denholm *et al.*, 2010). However, they suffer from deep discharging and overcharging and may bring about lots of pollution if improperly discarded, poisoning and leaks contaminating environment and damaging ecosystem.

Lithium-ion is recognized not only in the renewable energy (PV sector) and electronics field but is also well known in the transportation industries (Whittingham *et al*, 2012).Their low self-discharge losses of 0.1 %/day to 3 %/day and round trip efficiency of about 100% with a life span of 5-15 years make them popular among the other battery technologies (Vazquez *et al.*, 2010). Despite these, they are much more expensive upfront compared to lead acid but they are maintenance free and have longer lifespan.

Nickel cadmium electrode material is useful in many different battery technologies that include the nickel-zinc (Ni-Zn), nickel-hydride (Ni-H2), nickel cadmium (Ni-Cd), nickel metal hydride (Ni-MH) and nickel-iron (NiFe). Among these alloys, Ni-Cd and Ni-MH technologies are the most popular and widely used in the industry. These batteries have a life span of ten to twenty years. However, adverse environmental impact of producing cadmium is their major shortcomings (Denholm *et al.*, 2010).

Vanadium Redox Battery (VRB) technology stores energy through the transference of electron between dissimilar ionic vanadium materials (Vazquez *et al.*, 2010). It has a lifespan of 5 to 10 years with a round-trip efficiency of over 85% with small self-discharge loss per day. However, it has an adverse environmental impact of generating toxic remnants (Denholm *et al.*, 2010).

Zinc bromide technology presents a relatively higher performance though expensive compared to the lead acid batteries. It has a life span of 5 - 10 years, cycling capacity of over 2,000, a round-trip efficiency ranging from 72% to 85% and a small daily self-discharge loss (Vazquez *et al.*, 2010; Burk, 2007).

The NaS possesses a high power and energy density of than those of lead acid battery however; the battery operates at a temperature ranging from 300 ˚C to 350 ˚C. This is because an external heating arrangement is a requisite for its efficient operation. It has relatively higher self-discharge losses of about 20%, a cycling capacity of about 2,500 and a life span 10 to 25 years (Diaz- Gonzalez, 2012).

The ZEBRA is a high energy battery technology with electrodes of nickel chloride as the cathode conductor and liquid sodium as the anode conductor. It possesses a high operating temperature property of ~ 300˚C, cycling capacity of over 2,500, self-discharge losses of ~ 15 %/day and life span of between 10 to 14 years. They can be easily recycled and be developed into new batteries (Diaz- Gonzalez, 2012). In addition, this technology possesses a lower energy and power density compared to the NaS battery systems (Lim *et al.*, 2012).

Metal-air technology presents battery system in form of cell technology that uses a metal as fuel while the air serves the purpose of an oxidizing agent (Lim *et al.*, 2012). It is eco-friendly and can also offer cost-efficient energy storage in the future. However, it possesses a low round trip efficiency and a poor recharging capability (Diaz- Gonzalez, 2012). Its cycling capacity is between 100 and 300, even though it has very small self- discharge losses.

Stand-alone PV systems, like any other renewable energy system, are weather dependent and batteries play a role of ensuring continuous and stable power supply during overcast conditions or autonomous days (Hubble and Ustun, 2018). Operation lifetime of a battery is greatly affected by fluctuations in weather conditions because of frequent charging and discharging cycles. As a result, battery performance is affected, life time will be decreased and the maintenance and replacement costs will increase. Use of charge controllers help to safeguard batteries from unnecessary deep and over charging and discharging especially the lead acid batteries hence enhance PV system's performance and minimize associated costs (Kan *et al*., 2006).

2.10 Photovoltaic system performance

Once a PV module or array has been installed in the field, an essential requirement is the understanding of the performance exhibited by the system (De-Lima *et al.*,2017). This is because PV system outdoor performances are different from those described in manufacturer data-sheets which are always obtained at standard test conditions (STC). Use of appropriate performance parameters is vital in the determination of PV system output power over a given specified period and as well facilitates the comparison of PV systems that may differ with respect to design, technology, or geographic location and the prevailing weather conditions at a given location (Gongsin and Saporu, 2020; Beyer *et al.*, 2011 and Okello *et al*., (2015). In addition, It is largely reported that disparities in the performance of PV systems are attributed to various factors such as BOS (Congedo *et al.*, 2013), meteorological factors (D'Orazio *et al.*, 2014 and Pietruszko *et al.*, 2012), solar irradiance (Al-Addous *et al.*, 2017), cell temperature (*Bai et al.*, 2016 and Zaoui *et al.*, 2015) and effects of dust (Fouad *et al.*, 2017 and Chanchangi *et al.*, 2020). Therefore, there is need to determine performance of PV system at site of application and these parameters be investigated. The most significant of these factors that affect the amount of PV power generated by the PV array is the solar radiation incident on the module (Al-Aboosi, 2020).

2.10.1 Efficiency of PV cell/module

The efficiency of solar PV cell/ module is an important parameter normally used in the determination of its performance and its acceptance rate in the energy market. Currently there is a lot of research work going on and new techniques have been developed with the aim of increasing the conversion efficiency (Ghaffarzadeh and Azadian, 2019). An example of such a technique is the tandem solar cells where the light with a shorter wavelength is absorbed by the outermost material with a wide band gap, while the light with a longer wavelength is transmitted through and absorbed by the material with the narrower band gap (Zhu *et al.,* 2020; Aydin *et al.,* 2020). Investigations on PV module efficiency have led to the development and growth of PV technologies for both domestic and commercial use and in extension reduced its prices (Ozden *et al.,* 2017 and Gaglia *et al.*, 2017).

Nominal efficiency measured at STC is always provided by the manufacturers and usually carried out in controlled laboratories. However, under outdoor conditions, these conditions (e.g., solar radiation) are rarely met and vary with location hence varying cell/module efficiency(Ghazi and Ip, 2014). Moreover, the outdoor operating conditions overlap making it complex to analyze each independently to determine the extent of its influence on system efficiency. But solar radiation and temperature, since they directly influence the energy production, which affect PV module efficiency, can be determined individually (Olchowik *et al.,* 2006; Tanesab *et al.,* 2017; Lorenzo *et al.,* 2014 and Louwen *et al.,* 2017).

2.10.2 Effect of solar irradiance on PV performance

Solar irradiance is the most important parameter for assessing a PV plant performance and its measurement is an important exercise for performance evaluation (Salih *et* *al.*,2012). Solar radiation directly affects the PV array current where, as solar radiation increases, the short circuit current, maximum power, and conversion efficiency also increase (Irwanto *et al.*,2010). Development and growth of PV technology has significantly led to the development of methods and technology for solar radiation measurement with the aim of using the data to rate PV system performance on various scales under outdoor conditions. In PV system performance studies, solar insolation data play a significant role in characterization and evaluation of PV modules performance and development of new technologies.

Figure 2.10 shows the effect of varying solar irradiance on the I-V characteristics of a PV module under constant temperature. From the figure, there is a huge impact on output current with a slight change in solar radiation. The output voltage show slight change with increase in solar radiation. There is a point on the curve known as the maximum power point (MPP) where generated power from the PV modules is maximized under given solar irradiance (Yali *et al.*, 2014). This point shifts upwards (vertically) with increasing solar insolation e.g., from 18.4 W for solar radiation of 200 W/m^2 to 100.5 W for solar radiation of 1000 W/m^2.These points of maximum power generated by a PV module are tracked by the Maximum Power Point Tracking (MPPT) schemes also called MPPT trackers incorporated in the inverters (Mohamed *et al.*, 2013; Venkata and Muralidhar, 2016; Emilio *et al.*, 2014 and Mahmoud *et al.*, 2012).

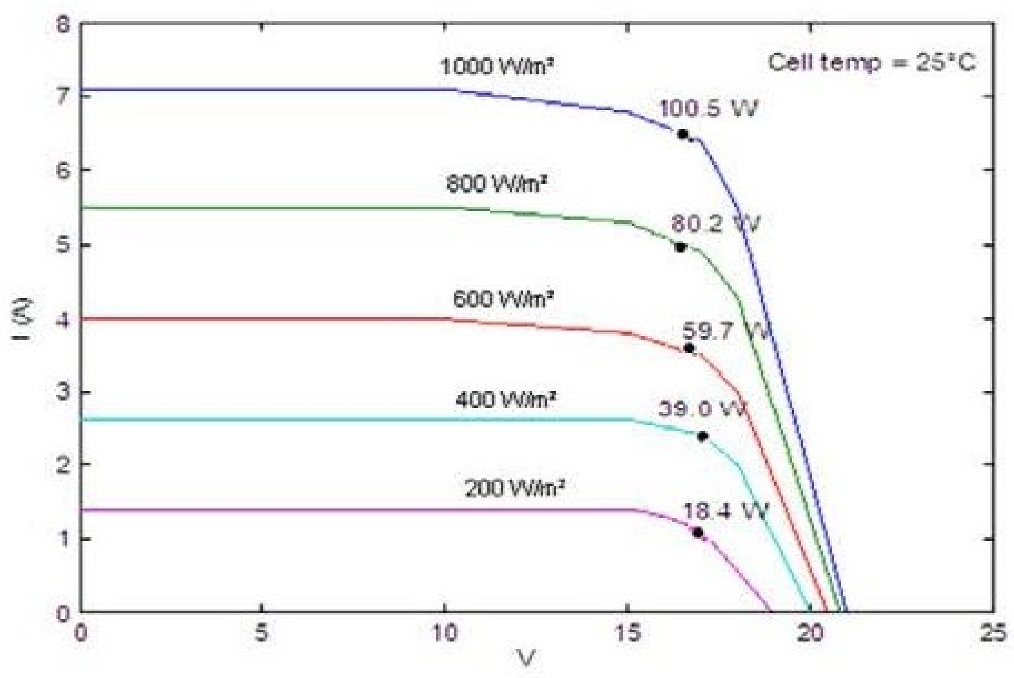


Figure 2.10:TheI-V characteristic at varying solar irradiance under constant temperature (Source: PVSyst simulation software library)

2.10.3 Effect of ambient temperature on PV performance

Ambient temperature is an outdoor operating condition factor that plays an important role in the PV module energy conversion process where its variation affects the module efficiency (Fesharaki *et al.*, 2011; Siddiqui and Bajpai, 2012).Cell/ module temperature which is a factor of ambient temperature and solar irradiance as shown in equation 2.22 affect the performance of a PV module where module performance decreases with increasing cell temperature (Kawajiri *et al.*, 2011). This is because of increased internal carrier recombination in the semi-conductor material caused by increased carrier concentration. Both the electrical efficiency and the power output of a PV module depend on the cell temperature where it can reduce output efficiency by 10% - 15% (Skoplaki and Palyvos, 2009).

The open circuit voltage of a PV module and the fill factor decreases substantially with temperature due to increased thermally excited electrons that begin to dominate the electrical properties of a PV cell. On the other hand, the short circuit current slightly increases with temperature (Thong *et al.*, 2016; Skoplaki and Palyvos, 2009). Thus, the electrical efficiency of a PV module is dependent on temperature and its net effect leads to a linear relation expressed as (Kawajiri *et al.*, 2011):

$$\eta_{\mathrm{mod}} = \eta_{ref}[1 - \beta_{ref}(T_c - T_{ref})] \qquad (2.21)$$

where η_{ref} is the module's electrical efficiency at the reference temperature (i.e., STC), T_{ref} , β_{ref} is the temperature coefficient of silicon and T_c is the PV cell/module temperature. The quantities η_{ref} and β_{ref} are normally given by the PV manufacturer. The PV cell/ module temperature in most cases is not measured but normally evaluated from nominal operating cell temperature, T_{NOCT} (measured under open-circuit conditions), and is expressed as (Anis *et al.,* 1983; Debbarma *et al.,* 2017; Griffith *et al.,* 1991):

$$T_c = T_{air} + (T_{NOCT} - 20)\frac{G(t)}{800} \qquad (2.22)$$

where $G(t)$ is the measured solar irradiance and T_{air} is the ambient temperature.

Figure 2.11 shows the behavior of PV module current and voltage with variations in temperature between 10 ˚C and 70 ˚C, in steps of 15˚C under constant solar irradiance (Mayfield, 2012). The Figure was obtained from the PVSyst simulation software library. From Figure 2.11, the module's voltage decreases as the cell/ module temperature increases, while the current shows little or no increase with temperature at constant irradiance (Irwanto *et al.,* 2010). In addition, there is a drop shift of the MPP point position with increase in cell/ module temperature. Shifting of the MPP point position is largely attributed to changes in the PV cell/ module temperature.

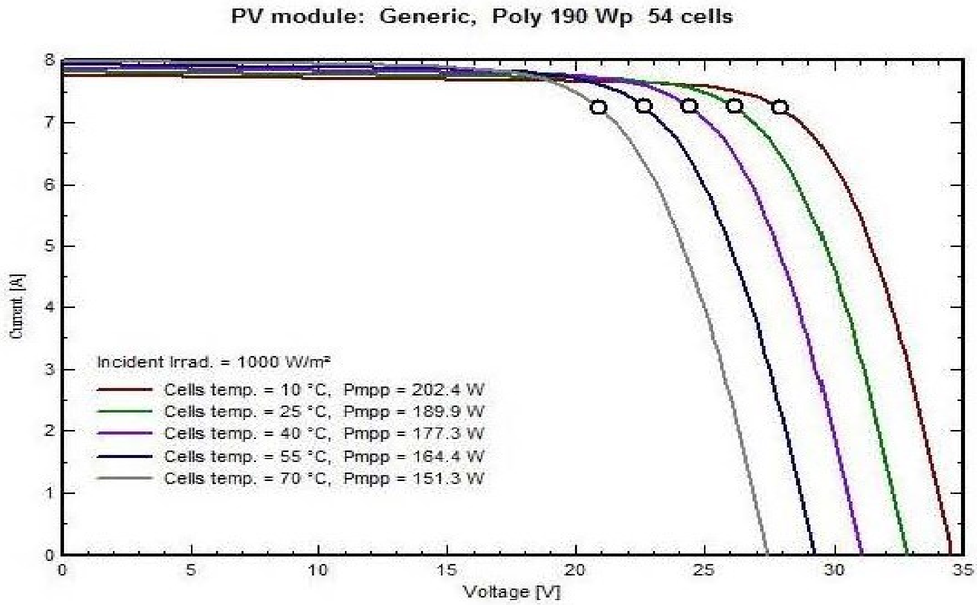


Figure 2.11: I-V characteristics of a PV module at constant solar irradiance (Source: PVSyst simulation software library)

2.10.4 Installation setup and performance

The PV system performance is affected by its design, configuration and BOS characteristics (Díez-Mediavilla *et al.*, 2012). The design (installation setup) is characterized mainly by the PV module tilt angle and orientation (azimuth angle).Tilt angle of a PV module is the angle measured between the PV module and a horizontal surface or the vertical surface representing the *x* or *y* direction respectively. For the PV stand-alone systems with battery storage and permanently fixed, their tilt angle is an angle equal to the latitude of the installation site (Joshua *et al.*, 2014). In addition, Degradation over time of the PV system components decreases the performance of the PV system (Makrides *et al.*, 2014). Degradation technique is used to determine the decrease in maximum power point performance over time and depends on several factors, such as the technology, the operating conditions and the cumulative history of environmental exposure (Phinikarides *et al.*, 2014).

2.11 IEC Standards

Standards for PV module performance evaluation have been developed by the International Electrotechnical Commission (IEC) established in the year 1995 though some countries still have their own national PV standards (Spooner and Harbidge, 2001). The IEC is a worldwide organization for standardization, and its objective is to promote international co-operation on all issues concerning standardization in the electrical and electronic fields. It develops and publishes the international standards for electro- technology for a wide range of technology with the help of experts from various sectors such as academia, industry, and government sector and research laboratories. The IEC standards in PV were developed by TC82 Solar photovoltaic energy systems (Wohlgemuth, 2012).

This International Standard recommends procedures for monitoring of energy-related PV system characteristics such as in-plane irradiance, array output, storage input and output, power conditioner input and output and for the exchange and analysis of monitored data (Mcnutt *et al.*, 2000). The IEC standard 61724 (Photovoltaic system performance monitoring, 1998) basically concentrates on the PV system performance monitoring through methodologies for evaluating performance of the system in respect to site prevailing operating conditions. It provides procedures and recommendations on the PV system performance guidelines for measurement, data collection and analysis (El-Chaar *et al.*, 2011). The IEC/TS 61836 presents definitions, terms and symbols of PV energy systems. The IEC/TS 62257-7 consider the PV system components selection, installation, sizing and operation and maintenance for small renewable energy systems. The IEC/TS 62257-7-1 present technical specifications for small renewable energy systems for their design and development for off grid applications. The IEC/TS 62257-9-1 provide standards for system selection for the right locations considering their technical specifications. The IEC/TS 62257-2 emphasize on methodologies useful for evaluating the socio-economic aspect of stand-alone renewable energy systems from specified energy demand requirements. The IEC/ TS 62257-4 provide technical specifications and recommendations for system selection and design for small renewable energy and hybrid systems with emphasis on user's energy needs (Hibberd, 2011; Wohlgemuth, 2012).

Three of the IEC standards 61724-1 (2021) performance parameters may be used to define the overall system performance with respect to the energy production, solar resource, and overall effect of system losses. These parameters are the final PV system yield, reference yield, and performance ratio. The IEC standard parameters that are used to characterize the performance of solar cells are the peak power (P_{max}), the short-circuit current density (J_{sc}), the open circuit voltage (V_{oc}), efficiency and the fill factor (*FF)* (Al-Aboosi and Al-Aboosi, 2021).

2.12 Literature review

A lot of research work on PV systems has been done and reported in peer reviewed journals, conference proceedings and technical reports. The work includes research on different PV systems, technical performance, economic and environmental performance of PV systems, degradation tests, applications, regional performance tests etc. These work findings are reviewed in this section.

Samoita *et al.,* (2020) explored barriers and solutions for increasing integration of PV systems in Kenya's electricity mix as a means of diversifying and stabilizing electricity supply. In their study, they pointed out a variety of technical, economic, institutional and political barriers which currently restrict further growth of PV technology deployment in Kenya. Key among the technical barriers includes the lack of PV performance information as well as lack of operation know-how of PV systems among potential Kenyan customers. These barriers, as stated by the authors, can be overcome with robust policy regulations, additional investments in education, training, research and development, better regulation of the electricity sector and improved coordination between key actors. Their results may be applicable to other sub-Saharan African countries of whom many are faced with similar challenges.

A research study on techno-economic analysis of off-grid solar PV system for rural electrification in Punjab, Pakistan was discussed by Irfan *et al.*, (2019). The research results reveal that there is an excellent solar irradiance in the rural areas of Punjab for electricity generation. In addition, the authors also found that conventional energy sources are more expensive than the off-grid solar PV system as electricity generation from conventional sources is 0.092 $/kWh, while it is only 0.032 $/kWh for the off-grid solar PV system. The study further reveals that 617,020 metric tons of CO_2 could be mitigated annually by electrifying 100% rural households with the off-grid solar PV system. In their conclusion, the authors suggested essential policy recommendations that would serve as a guideline for the government and stakeholders to maximally deploy the off-grid solar PV rural electrification programs. A similar research has been presented by Omar and Mahmoud, (2018), for a selected number of home systems in Palestine, showing a payback in less than five years for a 5 kW system. Additionally, Allouhi *et al.,* (2016) studied the energy production from two PV technologies in an institutional building in Morocco by evaluating the economic and environmental aspects and comparing them with other PV plants worldwide.

A study has been presented on experimental performance evaluation of a PV array with respect to maximum power voltage, maximum power current, maximum power output, power output losses and fill factor (FF) values by Abdullah *et al.*, (2021). The setup involved a PV array with series configuration of 2×4 PV modules. Their work aimed to provide information on PV array performance as a whole considering site shading effect. Such information is useful for planning and system site installation. Results showed that in the case of the series configuration of a PV array, even if only one PV module fails to generate electricity due to an event of any failure or partial shading, the total amount of power generated is reduced. The power output of a PV array as discussed by Micheli *et al.,* (2014) is a factor of various features such as shading pattern, number and size of modules and wiring scheme of the modules in a PV array. Musanga *et al.*, (2018) reported that output current is a factor of solar irradiance while the module temperature has more effect on the output voltage which in essence the two controls the power output of a PV array. These two operating conditions, most significantly the solar irradiance, provide insight into PV array electrical characteristic performance information.

Nkhonjera and Wu, (2013) in their study on performance analysis of a battery based standalone system (SHS) installed in Malawi to expedite the country's electrification. They considered both low and high insolation sites of Malawi. Results showed that the system is capable of operating annually with a mean performance ratio(PR) of 0.68, PV array production factor of 0.88 and PV performance ratio of 78% which indicate a good system performance. In addition, if the system is under-sized, its performance ratio is reduced considerably and the system becomes less reliable. However, the authors noted that the system is not totally reliable all year round since it cannot meet the demand in 9% of the total yearly operational time if located in high insolation areas and 13% of the year if located in low insolation areas.

Bhuvaneswari *et al.*, (2018) carried out a study on performance analysis of a 15 kW standalone solar PV system installed in Vellore District, Tamil, and reported E_{Dc} ranging from 6,500–7,000 kWh, *PR* of 78%, and utilization factor of 6.97%. In a similar study, Ezenugu *et al*, (2016) carried out performance analysis of stand-alone PV system in a health clinic in Nigeria, and reported annual DC energy output (E_{Dc}) of 5269 kWh/year, *PR* of 58.4%, moderate operating efficiency of 8.83% and average system loss of 7.1%.

Kessaissia *et al.*, (2015) characterized two silicon-based PV modules i.e. monocrystalline and polycrystalline silicon based on site prevailing outdoor conditions. The I-V characteristics were obtained using two mathematical models i.e. the implicit model and the explicit model. In the implicit model, five coefficients were calculated analytically whereas in the explicit model, two coefficients were calculated from experimental measurements. Outdoor conditions considered are solar insolation and temperature in addition to data provided by manufacturers. The results show a strong agreement between the implicit model and the experimental characteristics. In their conclusion, the five parameters model is better and more accurate than the explicit model where it is preferable to use the method according to IEC 891. In a similar study, Bhowmik and Amin, (2019) carried a comparative simulation analysis study of m-Si and p-Si PV modules to study the performance of the modules at the specific tilt angle of 32^o. The parameters measured include solar intensity, output voltage and current, ambient temperature, humidity, wind velocity, output power efficiency and module efficiency. They concluded that m-Si PV module performs better with the module efficiency of around 8.5% higher than that of p-Si PV module. Another comparative study between m-Si and p-Si PV modules at an optimized tilt angle was reported by Cornaro and Musella, (2010). Their results showed that p-Si module is highly stable with an average performance ratio (PR) of 88%.

Olatomiwa *et al.*, (2014), in their study, employed the Hybrid Optimization Model for Electric Renewables (HOMER) tool to simulate hybrid energy systems such as the PV/diesel generator, PV/Wind turbine/ diesel generator and diesel generator only. Using remote telecommunication tower in Nigeria, they focused on the technical and economic assessment of the energy options and also compare the amount of carbon emissions produced by the systems. The peak load and average demand per day of the telecommunication system are 3.3 kWh and 37 kWh respectively. The sizes of PV, diesel generator, and wind turbine are 8.0 kW, 5.5 kW, and 1.0 kW, respectively. The research results reveal that the energy configurations that incorporate renewable energy systems offer the most economical solutions as well as contribute to the reduction of carbon emissions.

A paper on the analysis of PV system based on energy output and carbon credit earned for the climate of Uttah Pradesh, India has been published by Rajput *et al.*, (2017). It focuses on yearly performance of the system whose lifespan is 25 years. Embodied energy and Energy Payback Time (EPBT) is also analyzed for calculation of reduction in CO_2 emission while generating electrical energy. The research results reveal that embodied energy of the installed PV system is 8493.16 kWh and EPBT of the system is 5 years. Reduction in CO_2 emission; when using PV system against the coal-based plant for the generation of electricity is 2.525 tCO_2eq and the monetary saving due to carbon credit is 143162.19 ₹ for life time of 35 years. Further, they recommended that EPBT can be reduced if the output of the system increased further with a greater number of clear days. However, their research did not consider monetary savings due to carbon credit during economic analysis of PV system.

Integration of PV systems into the rooftops of residential buildings offers a considerable amount of clean and renewable energy that could slightly move towards achieving the concept of zero-energy buildings and contribute to lower CO_2 emissions as discussed in a research study by Abdelhafez *et al.*, (2021) in Hail, Saudi Arabia. Results reveal that there is a considerable amount of energy production from the use of all residential rooftops in Hail, reaching more than 346 GWh. In addition, there is a significant reduction in the amount of CO_2 emissions reaching nearly 5.9tCO_2/year. Further, the PR and the system efficiency were affected by tilt angle of the PV module. The efficiency increases with higher tilt angles because with decrease in PV module temperature its efficiency increases. Besides, the results pointed out that the 30^0-tilt angle PV produced the highest amount of energy, whereas the 75^0 tilt PV records the lowest amount of energy though it achieves the best possible efficiency.

González-Mahecha *et al.*, (2019) carried out research on greenhouse gas (GHG) mitigation potential and abatement costs in the Brazilian residential sector. Their findings show that energy efficiency measures in the cooking end-use and solar PV systems would represent together more than 70% of the abatement potential. In addition, the total avoided emissions would be 642 MtCO_2 in Brazil over the period of 2010–2050. In a similar study, Tiwari *et al.*, (2015) carried out enviroeconomic analysis of a stand-alone PV system and their results show that the amount of CO_2 emitted per kWh is approximately 960 g. However, from their findings, this amount rises to 2.0 kg of CO_2 per kWh if transmission losses (40%) and distribution losses (20%) are considered.

An economic analysis of an off-grid PV system designed for household electrification was presented by Ghafoor and Munir, (2015). The paper focuses on a single household application in Faisalabad, Pakistan that requires 1.928 kW of solar PV to support an average daily demand of 5.9 kWh. The results indicate that the system's life cycle cost and the cost of energy are lower than those of conventional systems. However, the study does not consider energy losses, battery state of charge, reliability, load growth and the life cycle impact analyses.

A life-cycle cost (LCC) analysis of various combinations of PV and diesel generators for a school in India was done by Kolhe *et al.*, (2002). Their study drew a conclusion that a stand- alone PV system is the most viable option when the power needs for the school are minimal and that PV systems will become more competitive as their costs decline with improved technology and efficiency.

Liu *et al*., (2017) used measured data from 15 radiation stations to validate different empirical estimation methods of daily solar irradiation over the Tibetan Plateau. The highly rated sunshine- based Ångström model and temperature-based Bristow model were selected for the site application. Their result through calibration indicates that sunshine- based site- dependent models perform better than temperature-based ones. To achieve better performance, the Ångström- type model was improved using altitude and water vapor pressure as the leading factors. However, they inferred that the model should be further validated against observations before its applications in other plateau mountainous regions.

Several computer software tools have been developed and employed to analyze the performance of PV systems in different parts of the world. These tools include PVsyst, SolarMAT, HOMER, among others. The PVsyst software has been used widely by many researchers to simulate and study the performance of PV system and was selected for this study. Spea and Khattab, (2019) designed and carried out performance analysis of stand-alone PV systems using PVSyst software for a location in Egypt. The system studied consists of PV panels, batteries, inverter, and charge controller. They employed PV panels of 450 W and 260 W in their study based on watt-hour demand calculations for comparisons. Their results showed that both PV panels can feed the desired load. A 450W PV panel is better than 260W PV because higher energy conversion efficiency was obtained; higher value of energy produced per year, and occupied a lower area. Kumar *et al.*, (2020) employed PVsyst tool to design and simulate a standalone solar PV system in India. Analysis of performance ratio and losses are reported. Their results showed that the energy required was 1086.24 kWh and the energy available through solar panel was 1143.6 KWh, whereas energy supplied to the user was 1068.12 kWh with average PR for the year was 72.8%. Sifat *et al.*, (2015) designed a 2 kW Stand-alone PV System with backup in Bangladesh Using PVsyst, Homer and SolarMAT software tools. The PVsyst showed mismatch with practical data to a small extent and a good choice for economic analysis while output results generated by SolarMAT has a great similarity with practical data. HOMER would be preferable for hybrid solar system designs.

Ammu *et al.*, (2017), in their study, carried out a cost-effective assessment of PV system as a backup source of power in an Urban Indian context. They compared five different battery technologies and conventional grid backup systems such as inverter-battery versus diesel engine options. Life cycle costing (LCC) and the energy payback time (EPBT) tools were used to determine the economic viability conditions of the battery technologies and the grid backup systems while the net energy ratio (NER) was used to determine their technical aspects. Their results show that Li-ion battery technology has high NER and lowest annualized energy requirement. Further, the two grid backup systems have initial comparable costs with inverter- battery system showing relatively low long term costs and at the same time have high NER.

Ndwali *et al.*, (2020) proposed an optimized operation control strategy of micro grid connected PV system with diesel generator backup system. Their aim was to reduce energy purchased from utility grid and the fuel consumption cost of the diesel generator based on the daily load profile of an Engineering workshop at Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya. Their results show a daily energy saving increase of up to 52.1%, daily cost saving of 20%, and daily generated income of $17. The study did not deal with uncertainties and disturbances associated with micro grid systems.

Rahil *et al*., (2018) presented an economic and environmental analysis of PV energy system as an option to meet the electrical energy demand in a reliable and sustainable manner for regions without grid connection in a remote village in South Africa. The PV systems presented are the PV system with battery storage and PV systems with diesel generator and battery storage. Their results show that the total cost in a PV system with battery storage represents only 26% of the entire PV system. In addition, the PV with Battery system release minimal harmful emissions compared with nearly 6.0 tCO_2/year in the PV with Diesel generator system. Both the systems sufficiently meet the load demand with no interruptions.

Diesel generators are known to have a relatively low initial investment cost compared to PV systems but carry health and environmental risks as reported by Babajide *et al.*, (2021). In their work, they used measured data from a monitoring campaign in Lagos, Nigeria for analysis. Their work addressed making cleaner electricity through solar PV more attainable, increasing access to more reliable power, and reducing or eliminating the use of diesel generators. Their results showed that a cost saving of about 60% - 65% over the project life can be attained by use of PV system in place of diesel generators for backup power generation.

CHAPTER THREE

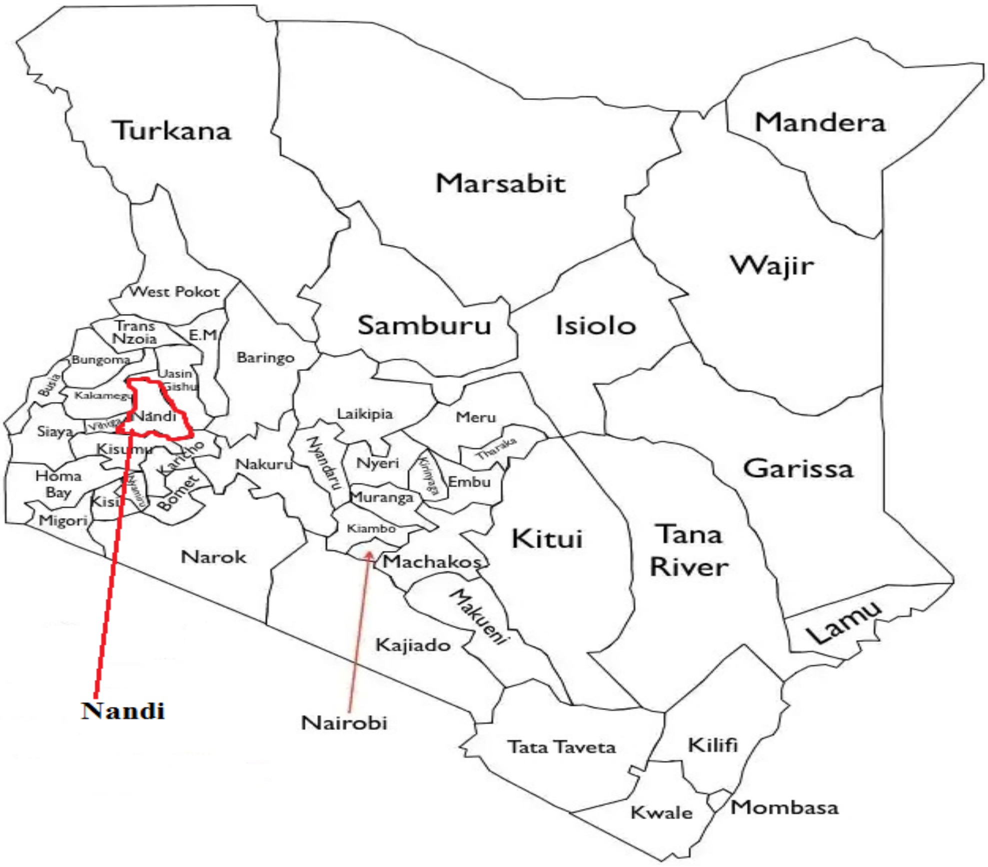
METHODOLOGY AND MATERIALS

3.1 Introduction

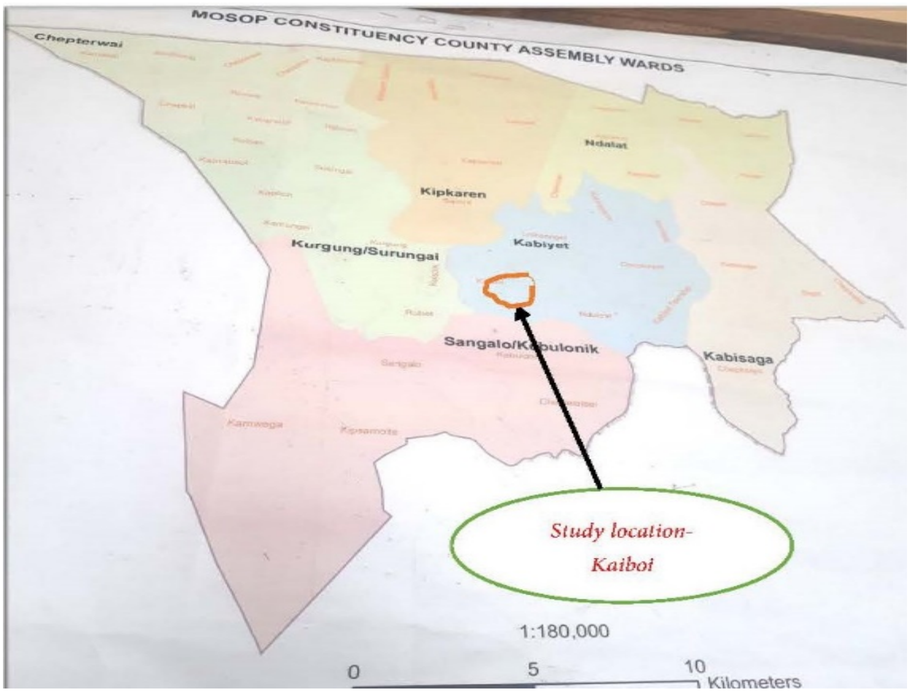
This chapter presents description of the study location, instrumentation and data collection, PV backup system performance parameters and the simulation tool used in this thesis. The study was carried out both experimentally and theoretically.

3.2 Study location

The study was carried out at Kaiboi Technical Training Institute (KTTI) located in Nandi County, western Kenya. Figure 3.1 (a) shows the map of Kenya and the region where the study was carried out. Figure 3.1 (b) shows the map of Mosop constituency in Nandi County and the site location where the study was carried out. The site has geographical coordinates of 0.42 ^{0} N (hence is almost to the equator) and 35.03 ^{0} E with elevation of 1993 m above sea level. The site is located in a flat terrain, hence not affected by terrain shading in the morning or evening. The location experiences moderate to warm temperatures with mean of between 18 ^{o}C to 28 ^{o}C with an average rainfall ranging from 1200 mm to 2000 mm per annum. The location falls within tropical climatic zone, and as such is expected to have abundant solar radiation throughout the year.



(a)



(b)

Figure 3.1: (a) Map of Kenya showing study region - Nandi County; (b) Map of Mosop constituency showing the study site.

3.3 Experimental setup

The experimental system studied was an existing PV power system installed at the social/dining hall of KTTI. The system was installed in the year 2016 and has been operating since then as a power backup system to electrify the appliances in the social/ dining hall whenever power outages occur. Figure 3.2 is a block diagram showing the components and connections of the PV system studied and how it is integrated into the electrical power network of the social/ dining hall as a backup system. The basic components of the system are the PV modules, charge controller, battery bank, an inverter, loads (appliances), and the switch over control system.

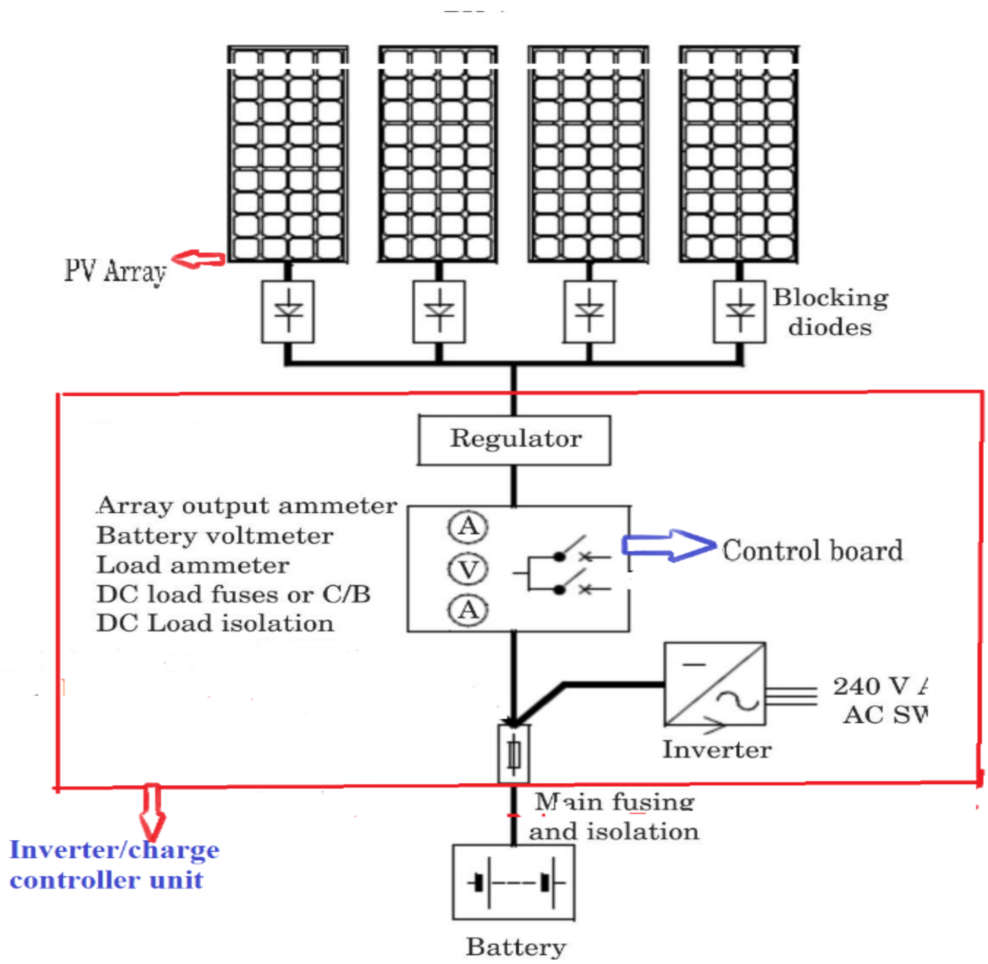


Figure 3.2: Schematic diagram of the studied PV backup system

3.3.1 The PV modules

The PV module is the back-born of any PV power plant system because it is the generator of the electrical energy. Four identical polycrystalline PV modules each with a power rating of 195 W are used in the system and are mounted on the roof of the social/ dining hall of the institution as depicted in Figure 3.3. Thus, the tilt angle and orientation (azimuthal) of the PV array is dictated by the pitch angle and the orientation of the roof of the building. The roof of the social/ dining hall has a pitch angle of 15^o and oriented in the NE-SW direction, which are respectively the tilt and azimuthal of the PV modules. As it can be observed from Figure 3.3, the PV modules were mounted on a metallic frame for securing them to the roof and an air gap of about 18 cm was provided at the rear of the arrays to provide cooling during dry seasons by allowing natural (buoyancy) air circulation. The natural cooling is necessary because the electrical conversion efficiencies of the PV modules degrade with increasing temperatures of the solar panels.

Figure 3.3: Photograph of roof-mounted PV Array at the Institute's Social/ dining hall.

Table 3.1 presents the technical specifications of the modules used. In the present system, the PV array consists of two pairs of series connected modules, which are in turn connected in parallel. Therefore, the resulting bus voltage of the array is 24 V. From Table 3.1, the rated output peak Watt (W_P) of each module is 195 W, hence, the nominal output power is 780 W. In addition, the nominal efficiency of each module is specified by manufacturer as 15.6%.

Table 3.1: Technical specification of PV module

Parameter	A (m^2)	V_{oc} (V)	I_{sc} (A)	P_o (W)	$NOCT$ (^oC)	V_{mp} (V)	I_{mp} (A)	η_{ref} (%)	β ($^oC^{-1}$)
Value	0.4	44.5	5.70	195	45±2	36	5.56	15.6	0.0041

3.3.2 Inverter/Controller unit

The charge controller and the inverter are usually separate components, but in the present system, they are integrated together as one unit, and their functions are respectively to monitor charging/ discharging processes of the battery and conversion of dc power from PV modules to ac power for integration into the ac network of the social/ dining hall. The switch over control system is also integrated in this inverter/ controller unit, and is a logic switch which triggers automatically the switching from either grid to solar and vice-versa. Whenever a blackout occurs, the control switch automatically connects the PV system to power the social /dining hall appliances, and when grid power is restored, it disconnects the PV system. In addition, this unit has an integrated data acquisition system which records electrical quantities such as current, voltage and energy generated by the PV system when operating.

Figure 3.4 shows the picture of the inverter/ controller unit. The inverter in the studied PV system has maximum output ac voltage of 230 ± 0.05 V and 50 Hz line frequency (i.e., ac grid frequency in Kenya). The charge controller monitor the state of charge of the battery during charging and discharging cycles by disconnecting the batteries automatically from the PV array to prevent overcharging during charging or loads during discharging to prevent deep discharge. The output DC voltage and current of the PV array were measured and recorded in an internal data storage card integrated in the inverter/ charge controller unit. The electrical data were measured using a digital multimeter integrated in the inverter that measures the voltage and amperes being generated by the PV array. To measure the DC voltage the “DC V” was selected and to measure the DC current the “DC I’’ was selected manually and time duration and interval set for the period that data will be recorded automatically after turning on the multimeter. The technical characteristics of the inverter and charge controller are given in Appendices II and III respectively.

Figure 3.4: Picture of Integrated Inverter/Controller Unit.

3.3.3 Battery Storage System

The studied system uses a battery bank consisting of six (6) lead-oxide batteries mounted on a wooden cage to ensure electrical safety in its handling and use. Spacing is provided between the batteries to provide air channels for natural convective air cooling. Each battery has a power rating of 200 Ah and nominal output voltage of 24 V. The batteries are connected in parallel to match the PV module bus voltage of 24 V and to increase output current, hence output power to match the load demand. Figure 3.5 shows the picture of battery bank, and the specifications of the batteries are presented in Appendix IV.

Figure 3.5: Picture of Battery Bank System.

3.3.4 Loads

The PV system is adopted as a backup system; hence it will power the existing loads in the social/dining hall building during grid power outages. The power rating of each load/appliance in the building was assessed and the findings are listed in Appendix V. A worst-case scenario of two hours blackout per day was assumed and used to estimate the daily power that the PV system must supply to meet the demand. The total power rating excluding all the losses was approximately 2.076 kWh/day. Fridge was operated as base load and since the location is part of the tropical region, fans are operated mainly during midday hours in the months that experience relatively high insolation and ambient temperatures.

3.4 Instrumentation and data collection

Outdoor measurements of the PV operating conditions and electrical parameters of the PV system were done at the site and recorded. The operating conditions measured were the solar radiation, ambient temperature, and wind speed, while the electrical parameters were the output voltage and current of the PV array. The data were measured at intervals of five minutes and logged by data acquisition cards incorporated in a radiometer for solar radiation and inverter/controller unit for electrical parameters. The data were collected for a period of one year in 2020.

Figure 3.6shows the pyranometer readout meter (model SPM-1116SD) that was used to measure solar irradiance intercepted by the PV modules. It has an extension probe connected to the digital recorder with an internal data acquisition and storage card integrated in the meter system where data were measured and recorded. The solar sensor was mounted on the surface of the PV array. Technical specifications of the meter are given in Appendix VI. The data were downloaded from the card as an Excel file and stored in the computer for analysis.

Figure 3.6: A picture of a digital recorder and the pyranometer (model SPM-1116SD)

The ambient temperature and wind speed data were obtained from a nearby meteorological station. Ambient temperature was measured using type-K thermocouple, which consists of alloy compositions NiCr (+) and NiAlSi (-)mounted on a secure shaded region to prevent direct heating from the solar radiation while wind speed was measured in m/s using a rotating cup anemometer mounted in an open at 10 m from the ground level.

3.5 Performance functions of PV modules

The parameters recommended in IEC61724-1 (2021) standard to qualify the performance of a PV system include conversion efficiency, the fill factor (FF), yield ratios (reference yield, Y_r, final yield, Y_f and system losses, L_S), performance ratio

(PR), and capacity factor (CF). These parameters were evaluated and used to characterize the performance of the studied PV system.

3.5.1 Efficiency, fill factor and output energy

The energy conversion efficiency of a PV array, (η_{array}) is the ratio between the maximum electrical power that the array can produce to the amount of solar irradiance received at the surface of PV array (Ayompea *et al.*, 2011; Rakhi and Tiwari, 2012):

$$\eta_{array} = \frac{P_{max}}{A \times G_t} \times 100\% \tag{3.1}$$

where A is the PV array surface area, G_t is the POA solar irradiance and P_{max} is the PV array output power generated. The P_{max} is given as (Al-Addous *et al.*, 2017):

$$P_{max} = V_{oc} I_{sc} FF = V_{max} \times I_{max} \tag{3.2}$$

where V_{oc} is the open circuit voltage, I_{sc} is the short circuit current, V_{max} is the maximum voltage and I_{max} is the maximum current values both determined at the MPP on the I-V characteristic curve of the PV module, and FF is the fill factor. Fill factor is the ratio of the actual maximum obtainable power (represented by the area of the largest rectangle which will fit in the I-V curve) to the product of short I_{sc} and V_{oc}. It gives an idea of the quality of the array, and the closer it is to unity (1), the more power the array can produce. Typical values are between 0.7 and 0.8 (Ayompea *et al.*, 2011; Jain, 2004).

The energy output from the PV array is an integral factor of the measured solar irradiance and the array efficiency as determined in equation (3.1) and is given as (Abawi *et al.*, 2016; Jain, 2004; Al-Addous *et al.*, 2017; Kim *et al.*, 2021):

$$E_{PV} = \int_{t=1}^{n} \frac{1}{6000} G_t A \eta_{array} \quad (3.3)$$

3.5.2 Yield factors, performance ratio and losses

The Y_r and Y_f ratios are defined by IEC 61724 standard (Usman *et al.*, 2020; Aguilera and Espinoza, 2019; AlYahya and Irfan, 2016; Satsangi *et al.*, 2018; Almarshoud, 2017) respectively as:

$$Y_r = \frac{G_t}{G_o} \quad (3.4)$$

And

$$Y_f = \frac{E_{PV}}{P_o} \quad (3.5)$$

where G_o is reference irradiance (i.e., irradiance at STC or 1000 W/m^2), E_{PV} is the net dc output energy generated by the PV systems over a specified period (e.g., a day, month, or year) and P_O is the nominal DC output power of the PV array. The Y_r is a measure of the number of hours when the solar irradiance is above 1000 W/m^2 and hence has units of kWm^{-2}, and is normally referred to also as solar peak hours (PSH) in PV literature. Also, Y_r is a function of the location, orientation of the PV array and seasons of the year (Ketjoy *et al.*, 2013; Malvoni *et al.*, 2017; Aguilera and Espinoza, 2019, Pearsall, 2016; Almarshoud, 2017; Skoczek *et al.*, 2011). The Y_f, on the other hand, represents the number of hours that the PV array would need to operate at its rated power to provide the same energy and is useful when estimating the return on investment (ROI) of a PV system. The unit for Y_f is hours or kWh/kW and it is also used as a convenient parameter to compare the energy produced by PV systems of differing sizes (Ferrada *et al.*, 2015; Muñoz *et al.*, 2016; Aguilera and Espinoza, 2019; Sreenath *et al.*, 2020).

Performance ratio (PR) also known as quality factor, gives a measure for the degree of utilization of an entire PV system (Sidi *et al.*, 2016). It indicates the overall effect of losses on the overall performance of the PV system, and includes effects of PV array temperature, incomplete utilization of irradiation; system component limited efficiencies, and failures (Reich *et al.*, 2012). It is defined in the standard IEC 61724-1 (2021) as the ratio of final PV system yield (Y_f) to the reference yield (Y_r) expressed as (Trillo-Monteroet *et al.*, 2014; Almarshoud, 2017; Chioncel *et al.*, 2010; Reich, 2012):

$$PR = \frac{Y_f}{Y_r} \qquad (3.6)$$

The relation indicates whether the system is operating optimally and quantifies the overall effect of losses on the rated output power. These losses are caused by many factors including the inverter losses, wiring and mismatch, module temperature, incomplete use of irradiance by reflection from the module front surface, soiling or snow, system down-time and component failures (Usman *et al.*, 2020; Louwen *et al.*, 2017). For the studied system, PR values are reported on monthly basis.

The system losses (L_s) were obtained through evaluation of the difference between PV array productivity and the overall productivity which in essence represents the inverter conversion losses expressed as (Cherfa *et al.*, 2015; Ayompea *et al.*, 2011; Sidi *et al.*, 2016; Bajpai and Yadav, 2018; Martinez *et al.*, 2019; Žnidarec *et al.*, 2019):

$$L_s = Y_r - Y_f \qquad (3.7)$$

3.5.3 Capacity factor

Capacity factor (CF) is a dimensionless ratio of an actual electrical power output from a PV system (P_O) over a given period of time to the energy generated by the PV system when it operates at its full rated power $P_{\max}$ over similar period. It indicates the extent of use of the power generating PV system in percentage and is expressed as (Usman *et al.*, 2020, Kumar *et al.*, 2014; Pundir *et al.*, 2017; Emziane and Al Ali, 2015):

$$CF = \frac{P_O}{P_{\max}} \times 100 \qquad (3.8)$$

In addition, the CF measures PV actual generation compared to the rated maximum generation over a given period of time and is bound by the number of sunshine hours (Ayompea *et al.*, 2011). The average monthly capacity factor was considered for performance analysis in this study.

3.6 Economic performance indicators

The study compares the economic performance of the PV system with that of an equivalent diesel power generator where a life cycle cost (LCC) analysis technique is used to evaluate their costs. The LCC of a system is the sum of all the costs incurred during the respective system life time (Allouhi *et al.*, 2019; Abd El-Shafy, 2009). It takes into account the applicable inflation and interest rates. Inflation rate measures the degree to which the value of money has declined. Interest rate provides the information about the amount of profit that is obtainable from saving a sum of money (Akinyele and Rayudu, 2016). The inflation and interest rates world over change with time, which is why all costs and evaluation are usually reviewed and updated. The LCC analysis starting year was set to be 2016 which is the year the PV system was installed and in order to reflect the PV module and DG market status. The analysis period was set to be 25 years, which is the service life of the PV modules (Rodrigues *et al.*, 2016; Kaplanis and Kaplani, 2011). The current reflecting average annual value of 2.6% is taken for inflation rate and 6.0% for interest rate respectively (Economic survey, 2021).

3.6.1 Life cycle cost analysis

The PV system and the DG costs were determined by application of the *LCC* technique. The LCC technique entails determination of all costs from component acquisition, operating, maintenance to replacement expressed as the present worth given as (Assad, 2010; Allouhi *et al.*, 2019; Pacca *et al.*, 2007; Braker *et al.*, 2011; Branker *et al.*, 2011; Dally, 2013; Gulaliyev *et al.*, 2020; Pillai and Naser, 2018):

$$LCC = \sum_{r=1}^{6} C_r \tag{3.9}$$

where C_r is the individual component present worth expressed as:

$$r \in \langle 1,2,3,4,5,6 \rangle \equiv [C_{PV}, C_B, C_{CON}, C_{INV}, C_{INST}, C_{O\&M}] \tag{3.10}$$

where C_{PV} is the PV array cost, C_B is the battery cost, C_{CON} represent charge controller cost, C_{INV} represent the inverter cost, C_{INST} represent installation cost and $C_{O\&M}$ represent operation and maintenance costs.

To determine the present worth of the battery we use the equation as expressed below (Assad, 2010):

$$C_B = C_{BO} + \sum_{k=1}^{j} C_{BO} \left(\frac{1+d}{1+i} \right)^n \tag{3.11}$$

where i (%) is the interest rate, d (%) is the inflation rate, C_{BO} is the initial cost of the battery, j is the number of replacements and n is the battery life span.

For the operation and maintenance costs $C_{O\&M}$, the present worth is expressed as (Oliver and Jackson, 2001):

$$C_{O\&M} = C_{O\&M/y}\left(\frac{1+i}{1+d}\right)\frac{1-\left(\frac{1+d}{1+i}\right)^{N}}{1-\left(\frac{1+d}{1+i}\right)} \tag{3.12}$$

where $C_{O\&M/y}$ is the operation and maintenance cost per year and N is the life span of the PV module

The number of years it takes to recover the initial investment cost (i.e. the number of years needed to balance cumulative discounted cash flows and the initial investment), the payback time (*PBT*) is calculated using the following equation (Lai and McCulloch, 2017; Rodrigues *et al.*, 2017; Alsema, 2000):

$$\mathrm{PBT} = \frac{\mathrm{LCC}}{\mathrm{Q_{AP}} \times \mathrm{UEC_{KE}}} \tag{3.13}$$

where UEC_{KE} is the cost of electricity supply in Kenya and Q_{AP} is the annual energy production from either the PV system or the DG expressed as:

$$Q_{AP} = 8760E_{dc} \tag{3.14}$$

The PBT variation is dependent on factors such as the type of solar cell, irradiation at the location, capacity of the system and degrading factor of the PV module.

3.6.2 Levelized cost of energy

This is a widely used technique that gives a more accurate energy cost calculation and is defined as the ratio between the LCC of the PV system to the whole life cycle produced energy (LCE). Furthermore, it ascribes all future costs to the present value, resulting in a present price per unit energy value expressed as (Rehman *et al.,* 2007; Kost *et al.,* 2013; Mulligan *et al.,* 2015; Rodrigues *et al.,* 2017; Muslim *et al.,* 2018; Mohammed *et al.*, 2012 and Darling *et al.,* 2011):

$$LCOE = \frac{LCC}{LCE} \tag{3.15}$$

The *LCE* is calculated using Equation (3.16) (Bhakta and Mukherjee, 2017):

$$LCE = \sum_{i=0}^{n} \frac{AEP \times (1 - f_{PV})}{(1+r)^{r}} \tag{3.16}$$

where *AEP* is the expected annual energy produced during the PV system life span and *r* is the discount rate where a value of 7.0% is considered in this study (Economic survey, 2021). Generally the lower the discount rate the smaller the range of LCOE and in extension the PV technology has greatly improved leading to much lower capital costs across all discount rates. As the system time goes by, the output power yield will be degraded with a factor f_{PV} (maximum value is one) that was used here to get a better energy cost forecast.

3.7 Environmental analysis

The environmental impact of the PV system installed on a given site can be defined as the amount of the produced or mitigated CO_2 emissions. In this study, almost entire life cycle of the PV system is considered (except the disposal), where non-renewable energy sources are used in the manufacturing process of the semiconducting materials (Peng *et al.,* 2013). According to Jungbluth, (2005) the environmental analysis is a method that helps quantify and determine the price of CO_2 emissions into the environment for a given system and CO_2 emissions rate is useful index to know to what extent the PV is effective to the global warming. The environmental cost analysis is based on CO_2emission price and emitted carbon quantity. The amount of CO_2 emitted per month/ annum for a PV system is expressed as (Tiwari *et al.*, 2015; Alsema, 2000):

$$\Phi_{CO_2} = \frac{\Psi_{CO_2} \times E_{overall}}{1000} \tag{3.17}$$

where Φ_{CO_2} is CO_2 emission reduction (tCO_2/annum), Ψ_{CO_2} is the average CO_2 equivalent intensity for electricity generation from coal (2.0 $kgCO_2$/kWh) and $E_{overall}$ is the annual overall energy generated from the PV system. The environmental cost is given as (Tiwari *et al.*, 2015):

$$C_{CO_2} = c_{CO_2} \times \Phi_{CO_2} \tag{3.18}$$

where c_{CO_2} is the carbon price. From the international carbon price, the average value is 14.5\$/tCO_2 (Den *et al.*, 2011).

3.8 Diesel generator fuel consumption model

Diesel generators in many occasions in Kenya are used as primary power source for electrifying a particular location or as backup to the main grid supply in certain periods when there are power outages. The generator's fuel consumption rate F_c is given by Equation 3.19 as (Akinyele *et al.*, 2014):

$$F_c = XP_{out} + YP_{rated} \tag{3.19}$$

where P_{out} is the operating output power (kW), X is the generator fuel gradient (typically 0.246 litre/kWh), P_{rated} is the rated generator power (kW) and Y is the fuel curve intercept coefficient (typically 0.08415 L/kWh) (Oparaku, 2003; Idika, 1995).

3.9 PVSyst Simulation tool

Theoretical investigation of the PV backup system was performed using a freely available PVSyst 6.7.0 software tool to determine the various PV backup system performance parameters e.g. the system energy yield, system performance ratio (PR), fill factor (FF), capacity utilization factor (CUF) etc. (Belmahdi and Bouardi, 2020; Satish *et al.*, 2020; Shukla *et al.*, 2016). The operating system that the tool runs on must be windows 7 and above (32-bit or 64-bit). It is widely used simulation software for optimization of a PV system under outdoor conditions of a given location and in estimating their performance parameters (Odeh and Nguyen, 2021). Furthermore, the tool enables one to assess the main performance attributes including technical, economic and environmental parameters of the PV systems. Economic evaluation was performed using respective present worth of individual component prices. In addition, a performance comparison is subsequently made between the PV system and diesel generator when each is used as an independent backup system. Figure 3.7 shows a modified schematic of the PV system together with a diesel generator.

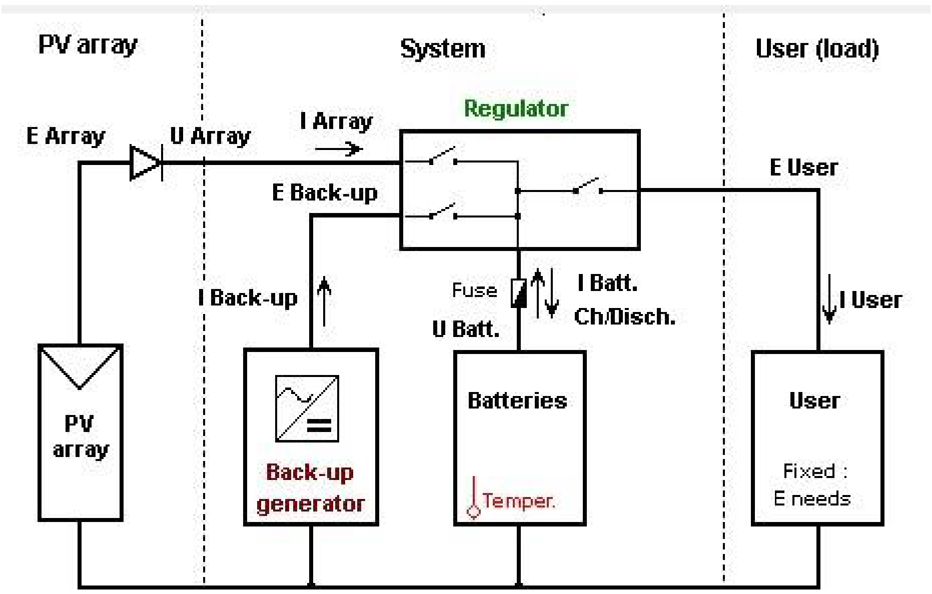


Figure 3.7: Modified schematic backup system layout in PVSyst software.

The tool has wide options and built-in features that enable one to input in-situ measured data or use the already existing PVSyst databases (built in Meteo database) e.g. the solar irradiance and ambient temperature (Meteonorm, 2010). The weather dataset used for evaluation is extracted from PVSyst database and has the attributes; solar radiation and ambient temperature. The array was designed based on the architecture design of the house and upon the roof (Figure 3.3). The data input include the characteristic details of the PV modules (type and manufacturer), orientation and the site details which include latitude, longitude, altitude and time zone were entered. Also the load demand per day where power consumed by each electronic device is estimated as hourly load and daily load were keyed in. Hence inverter selection is based on hourly load whereas battery selection is done on daily load (Rekhashree *et al.,* 2018). Output results can be obtained on weekly, daily, or hourly basis depending on the user's needs in form of project details, tables and graphs for performance characterization of the PV system.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents technical, economic and environmental performance results and discussions of the installed PV backup system obtained through experimental measurements and simulation using PVSyst software tool. Typical measured data include the solar irradiance, ambient temperature and wind speed which constitute the outdoor operating conditions of the PV system. The measured solar irradiance data were used in the assessment of existing irradiance models that best fit the experimental data for the site and were also used in the characterization of the PV backup system's performance. The technical performance indicators evaluated include the electrical conversion efficiency, fill factor and system energy production of the PV system. The economic and environmental performance comparison results between PV system and DG, when utilized individually as backup power system, are reported in terms of LCC, LCEO and amount of CO_2 avoided respectively.

4.2 Operating conditions

Data were collected daily for one year in 2020, hence enormous data were recorded, and as such representative results have been presented for each month based on clear sky conditions. The monthly selected days were 21st January, 18th February, 11th March, 16th April, 20th May, 10th June, 14th July, 9th August, 11th September, 16th October, 23rd November and 18th December of the year 2020.

Figure 4.1 shows the monthly representative raw results of the measured solar irradiance.

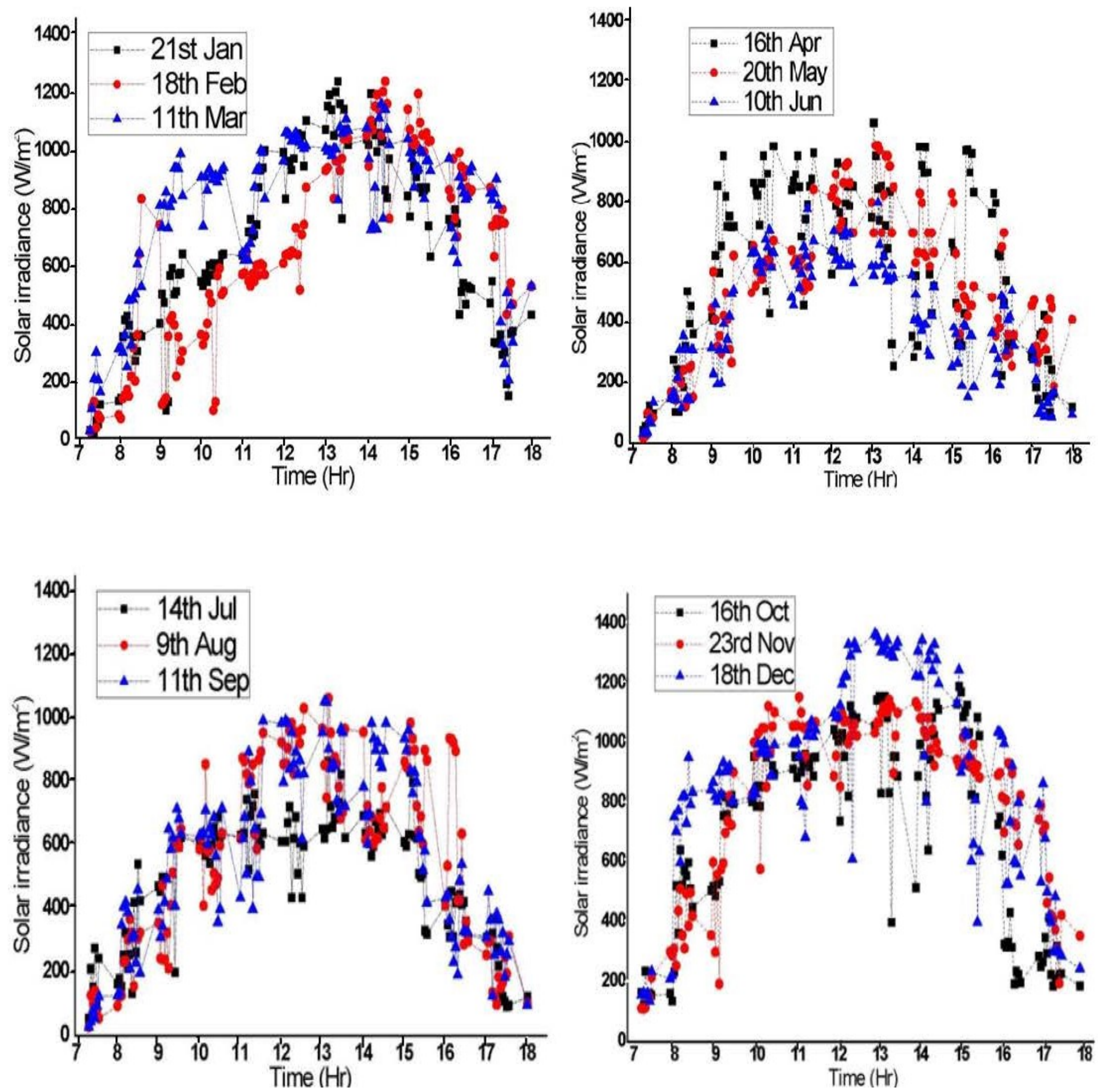


Figure 4.1: Measured solar irradiance representative results

The graph is a plot of solar irradiance against time (5-minute interval) and the corresponding data are given in Appendix IX. These results show that the solar radiation at the site can be as high as 1200 W/m^2 with a value of over 800 W/m^2 being realized as early as from 9 am in the morning up to about 5 pm in the evening throughout the year. In addition, the Y_r value or in other words the peak solar hour (PSH) obtained from these results is between 4 to 5 hours and is realised between 10:30 am to 3:30 pm, mainly in the dry season in the months of January to March and August to December as indicated in Figure 4.2, which presents clearness index (K_T) of the site.

Figure 4.2 shows the monthly clearness index (K_T) for the site and the corresponding data are given in Appendix X.

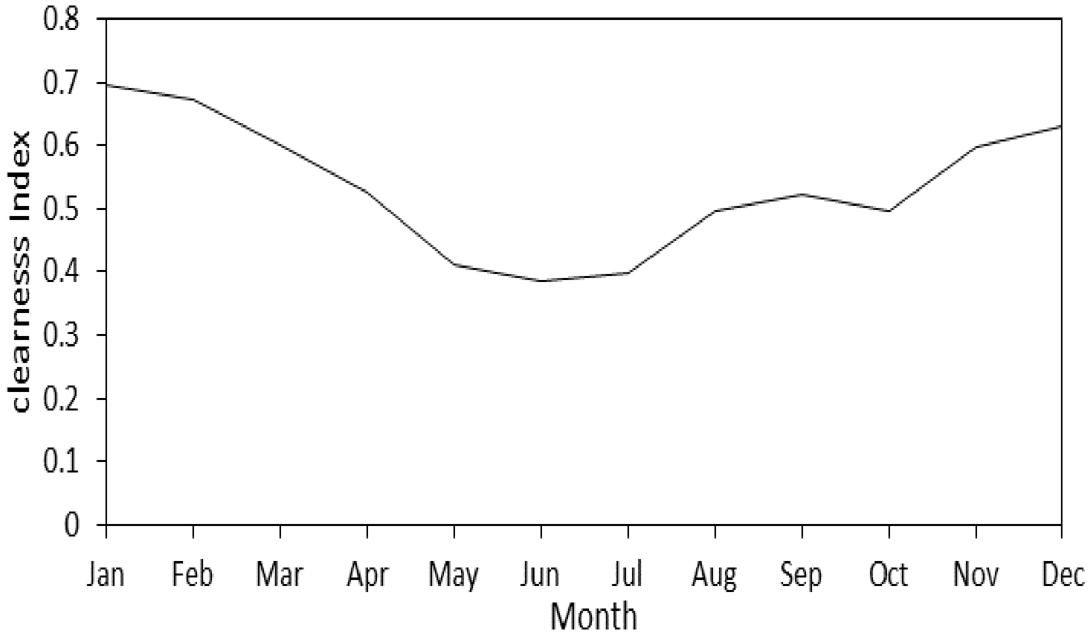


Figure 4.2: Monthly clearness index

These results show that the dry season has $KT > 0.5$ (sunny) and occurs in the months of January to March and August to December while the wet season has $0.3 \leq KT \leq 0.5$ (partly cloudy) in the months of April to July. These results demonstrate that the site is sunny most of the year, eight months to be specific and partly cloudy for three months only, implying optimum operation of the installed PV system. The region, therefore, being in the tropics, has abundant solar radiation throughout the year, and can be harnessed for energy production (electricity and thermal) affordably and reliably in all the seasons.

Figure 4.3 shows the monthly average of ambient temperature and wind speed measured at the site and the corresponding data is given in Appendix XI. From these results, the monthly average ambient temperature varies from 16.3 ^{0}C to 19.0 ^{0}C. However, the daily ambient temperature at the site can be as low as 8.8 ^{0}C in the wet season and can be as high as 28.4 ^{0}C in the dry season. The monthly average wind speed at the region varies from 1.07 m/s to 3.78 m/s. Low and high wind speeds occur during the wet and dry seasons respectively. Therefore, these wind speeds can be sufficient to provide a natural air cooling of the PV array through the air gap provided for as shown in Figure 3.3.

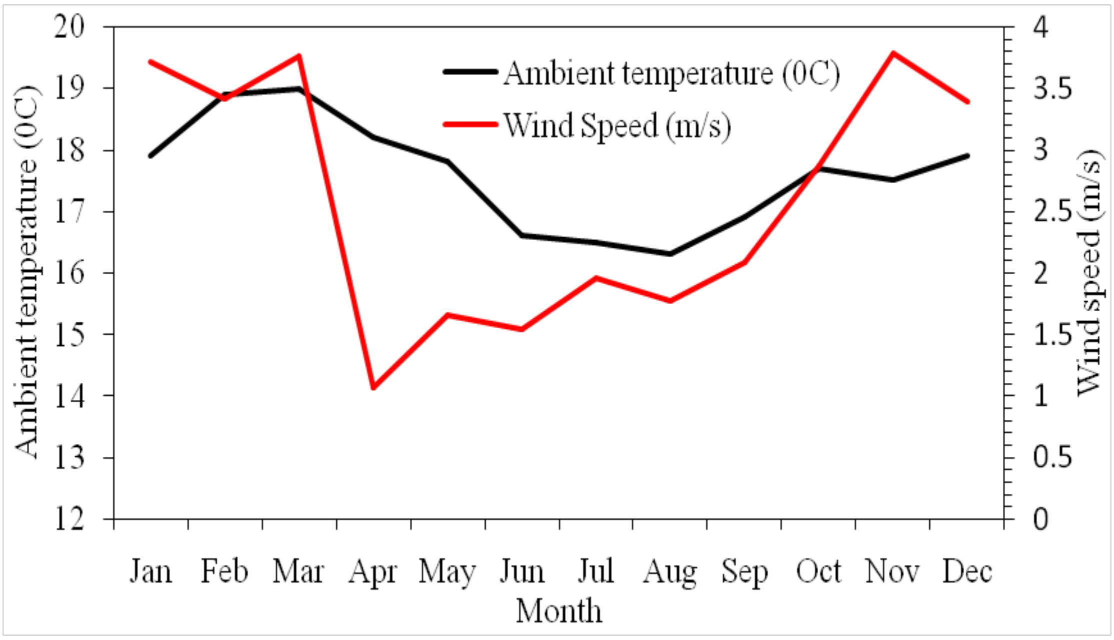


Figure 4.3: Monthly average ambient temperatures and wind speeds at the site.

The measured solar irradiance data was utilized in the selection of the models that best fit the solar radiation collected at the site. Figure 4.4 present comparison of monthly average solar radiation for the estimated data from the four selected models (based on input parameters that are easily available or determined at the site) and the measured data. These results show that all the models slightly underestimate the amount of solar radiation at the site, hence will present acceptable results when used to estimate solar radiation. For instance, using the estimated data to size any solar conversion device at the site will result to slightly oversized system, which is acceptable with regard to energy production, but then will lead to a higher initial cost of the system, and hence a longer payback period of the system.

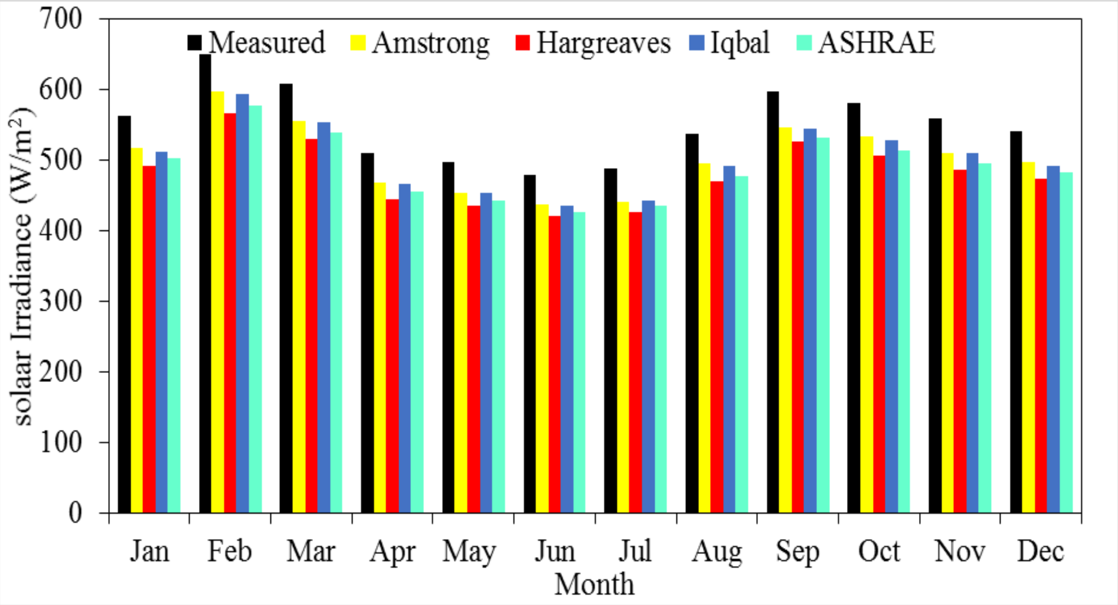


Figure 4.4: Comparison between estimated (by the four models) and measured values of monthly average Daily global solar irradiance at the site.

The sensitivity analysis of how the models predict the solar irradiance at the site was carried out to determine the most accurate model(s) under the local climate of the site. Table 4.1 presents statistical tests of the models based on MAPE and RMSE indicators. From these results, the MAPE test gives average monthly relative uncertainties of 8.5%, 11.0%, 12.6% and 8.9% respectively for Angstrom-Prescott, ASHRAE, Hargreaves-Samanni, and Iqbal models. From the literature, a MAPE value of less than 10% is regarded as having a very good fit and hence provides a very good forecast (Doorga *et al.*, 2019). Based on this criterion, therefore, Angstrom-Prescott is the best model for the site at 8.5%, followed very closely by Iqbal at 8.9%. The other two, however, are outside the good limit and in descending order of uncertainties are ASHRAE and Hargreaves-Samanni models.

Table 4.1: Comparison performance of the four selected models on predicting solar irradiance at the site.

Month	Angstrom		ASHRAE		Hargreaves		Iqbal	
	MAPE	RMSE	MAPE	RMSE	MAPE	RMSE	MAPE	RMSE
Jan	8.1	0.217	10.8	0.365	12.7	0.325	9.1	0.187
Feb	8.1	0.521	11.1	0.119	12.9	0.356	8.7	0.822
Mar	8.8	0.317	11.5	1.023	12.8	0.723	8.9	0.124
Apr	8.4	0.117	10.9	1.823	12.9	0.117	8.6	0.562
May	8.6	0.214	10.8	0.256	12.5	0.692	8.9	0.098
Jun	8.9	0.154	11.0	0.113	12.3	0.127	9.2	0.156
Jul	9.6	0.111	10.9	0.21	12.7	0.114	9.1	0.165
Aug	7.9	0.231	11.2	0.112	12.6	0.123	8.6	0.462
Sep	8.6	0.562	11.0	0.145	11.8	1.035	8.8	0.165
Oct	8.2	0.321	11.5	0.732	12.7	0.601	9.1	0.633
Nov	8.8	0.145	11.4	0.561	12.9	0.532	8.7	0.126
Dec	8.0	0.124	10.7	0.085	12.5	0.096	9.0	0.125
Average	**8.5**	**0.252**	**11.0**	**0.462**	**12.6**	**0.403**	**8.9**	**0.302**

On the other hand, the RMSE test gives standard deviation between estimated and measured valuesof 0.252, 0.403, 0.462, and 0.302 respectively for Angstrom-Prescott, Hargreaves-Samanni, ASHRAE and Iqbal models. These test results again show that Angstrom-Prescott and Iqbal are the most accurate models for the site because of their lowest standard deviations. However, unlike MAPE test, Hargreaves-Samanni model performs better than ASHRAE model. From these results, the Angstrom-Prescott and Iqbal models give closer prediction, followed respectively by ASHRAE and Hargreaves-Samanni. This means that Angstrom-Prescott and Iqbal models are again more accurate for estimating the solar radiation for the site. Therefore, from the two tests, the Angstrom-Prescott and Iqbal models are the models that can be used for estimation of solar radiation in the region.

4.3 Electrical performance of the PV system

4.3.1 I-V characteristic of PV modules

Figure 4.5 shows typical representative I-V characteristic curves for the selected days for the twelve months of the year 2020 where the corresponding data is given in Appendix XXI. Their respective solar irradiance values are presented for each day in the graph and are instantaneous values recorded at 12.24 pm. From these curves, the V_{max} and I_{max} points were determined and used to evaluate the PV array efficiency (η_{array}) and fill factor (*FF*) as presented in equations (3.1) and (3.2) respectively. In addition, the MPP points for the respective days are 122.80 W on22nd January, 78.83 W on 13th February, 105.99 W on 7th March, 104.80 W on 5th April, 108.82 W on 22nd May, 79.54 W on 8th June, 138.10 W on 12th July, 146.76 W on 6th August, 119.73 W on 2nd September, 138.83 W on 16th October, 150.08 W on 3rd November and 112.78 W on 18th December.

Table 4.2 gives a summary of the experimental representative results obtained from Figure 4.5. The representative values of η_{array} varied from 7.26% on 8th February, 2020 to 11.29% on 11th March, 2020 while the FF varies from 0.39 on 10th June, 2020 to 0.61 on 23rd November, 2020. The efficiency results are lower than the STC value, and are expected for outdoor test. In addition, the conversion efficiency fluctuates with the season of the year because of changing operating conditions. On the other hand, the values of the FF are almost one-half of the expected value of one (1), meaning that the POA solar radiation is not optimized. The possible reason for these low values of FF is that the studied PV system was not installed optimally with regard to tilt angle (should be equal to latitude of the site) and azimuthal angle or orientation.

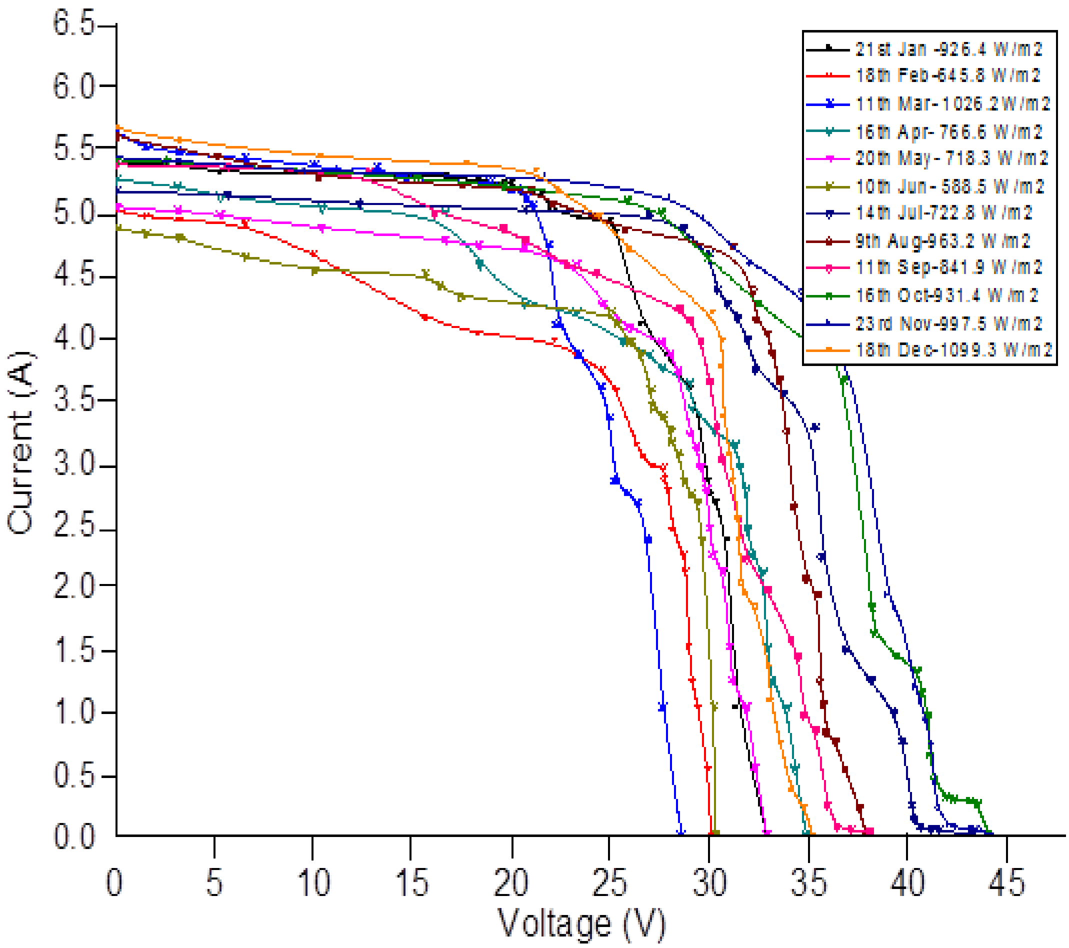


Figure 4.5: PV module I-V characteristics.

Table 4.2: Electrical PV module performance parameters.

Day (2020)	Solar irradiance (W/m^2)	V_{max} (V)	I_{max} (A)	FF	η_{array}(%)
21st Jan.	926.4	25.07	4.89	0.48	9.22
18th Feb	645.8	23.25	4.01	0.46	7.26
11th Mar	1026.2	22.36	4.99	0.48	11.29
16th Apr	766.6	29.41	4.12	0.44	9.25
20th May	718.3	28.41	4.25	0.47	9.21
10th Jun	588.5	20.49	3.99	0.39	8.55
14th Jul	722.8	29.47	4.56	0.56	8.11
9th Aug	963.2	30.95	4.85	0.59	9.22
11th Sep	841.9	27.56	4.30	0.44	9.15
16th Oct	931.4	37.12	3.86	0.56	9.45
23rd Nov	997.5	34.92	4.41	0.61	10.54
18th Dec	1099.3	22.51	5.67	0.49	11.02

4.3.2 Energy Production Performance parameters

Energy production performance indicators include E_{DC}, Y_r, Y_A, L_A, *PR* and *CF* as defined and discussed in Section 3.5. Table 4.3 gives tabulation of the calculated monthly average values of these quantities.

The experimental results in Table 4.3 show that the E_{DC} varied from 206.86 kWh to 328.91 kWh and were recorded in the months of June and February respectively with an annual average value of 266.90 kWh while the theoretical results varied from 285.5 kWh in the month of January and 345.2 kWh in the month of October with an annual average value of 312.19 kWh. This shows that the theoretical results are higher than the experimental results, which is attributed to the fact that the former assumes optimized system. However, the deviation between the average values of the experimental and theoretical calculations is ~14.5% which, though slightly high, is acceptable. Form these results, it can be seen that the daily E_{DC} for the experimental results is 8.89 kWh and that for theoretical results is 10.41 kWh as compared to daily energy load demand of 2.076 kWh as given in Appendix IV during times of blackouts. Therefore, it can be inferred that the produced E_{DC} is sufficient to serve the facility loads and in addition the PV system can be used not only as a backup system but also to alleviate part of the grid demand for the facility in the institution.

Table 4.3: Monthly average values of energy performance parameters.

Month	E_{DC} (kWh)		Y_r(kWh/kW)		Y_A (kWh/kWp)		L_A (kWh/kW)		PR (%)		FF		CF (%)		Efficiency (%)	
	Exp.	Theo.	Exp.	Theo.	Exp.	Theo.	Exp.	Theo.	Exp.	Theo.	Exp.	Theo.	Exp.	Theo.	Exp.	Theo.
Jan	284.64	285.50	5.64	5.99	4.80	3.60	0.81	0.76	0.769	0.689	0.70	0.68	19.53	18.45	11.95	14.92
Feb	328.91	296.51	6.50	5.95	5.46	3.26	1.04	0.85	0.805	0.659	0.68	0.71	19.45	19.96	13.96	14.56
Mar	310.41	305.72	6.09	5.69	5.10	4.15	0.99	0.72	0.796	0.745	0.70	0.75	19.56	20.95	12.93	14.68
Apr	240.25	300.51	5.11	5.72	4.43	4.15	0.68	0.65	0.728	0.76	0.65	0.65	19.56	21.95	11.64	13.35
May	221.87	345.22	4.97	5.12	4.76	4.22	0.21	0.46	0.730	0.749	0.65	0.68	20.83	21.66	10.95	12.54
Jun	206.86	325.62	4.80	4.98	4.78	5.21	0.12	0.49	0.745	0.75	0.61	0.67	20.55	25.66	10.52	12.85
Jul	217.04	318.60	4.88	4.95	4.72	5.38	0.16	0.38	0.730	0.792	0.62	0.65	18.97	24.99	10.75	12.45
Aug	253.12	302.40	5.38	5.52	5.20	5.02	0.18	0.40	0.720	0.785	0.62	0.64	19.56	24.95	11.04	12.03
Sep	304.25	336.34	5.97	5.68	5.40	4.10	0.57	0.66	0.798	0.745	0.67	0.69	20.33	23.95	12.53	12.17
Oct	295.81	324.50	5.81	5.62	4.09	3.94	0.62	0.72	0.776	0.736	0.65	0.66	18.98	21.65	11.78	12.28
Nov	274.98	309.10	5.59	5.52	5.00	3.64	0.59	0.61	0.784	0.695	0.70	0.69	19.58	18.62	11.22	12.56
Dec	264.76	296.46	5.41	5.84	4.92	3.51	0.47	0.69	0.779	0.730	0.69	0.67	20.67	11.99	11.45	13.95
Yearly	**266.90**	**312.20**	**5.51**	**5.55**	**4.89**	**4.18**	**0.54**	**0.61**	**0.76**	**0.736**	**0.66**	**0.68**	**19.80**	**21.23**	**11.70**	**13.19**

The experimental values of Y_A varied from a minimum value of 4.09 kWh/kWp in April to a maximum value of 5.46 kWh/kWp in February with an annual average of 4.89 kWh/kWp. On the other hand, the theoretical values varied from 3.26 kWh/kWp to 5.38 kWh/kWp with an annual average of 4.182 kWh/kWp. From these results, the number of hours per year at which the system effectively operates at its rated power was ~4 hours.

The experimental and theoretical annual average values of L_A were 0.52 kWh/kW and 0.61 kWh/kW respectively. These results take into account all the system losses which include the PV loses due to irradiance level and ambient temperature, mismatch losses, ohmic wiring losses, unused energy losses, converter losses, battery efficiency losses and charging/discharging losses. They range from the characteristics of the modules themselves (e.g., tilt and orientation angles) which can be rectified and environmental factors (e.g., shading and soiling). All these losses have an impact on efficiency and output energy of a PV system. To minimize or avoid the system energy losses, the institution should carry out preventive maintenance periodically to detect and avoid energy losses due to failures from components such as the inverter and the batteries. The theoretical losses (source and quantities) are given in a loss diagram presented in Appendix XVI.

The experimental values of Y_r vary from 4.8 kWh/kW to 6.5 kWh/kW which were realized in the months of February and June respectively with an average annual value of 5.513 kWh/kW. On the other hand, the theoretical values of Y_r varied between 4.95 kWh/kW to 5.99 kWh/kW with annual average value of 5.548 kWh/kW. Thus, the average annual values for both experimental and theoretical results are relatively close and agree with similar studies carried out in Kenya that gave a value of 5.5 kWh/kW (Oloo *et al.*, 2015 and Kiplagat *et al.*, 2011). In other words, these results imply that the daily site peak sun hours were slightly over 5 hours and can be improved with optimal orientation of the PV array.

The experimental values of PR varied from 72% in the month of August to 80.5% in the month of February with an average annual value of 76.3% while the theoretical values varied from 65.9% in the month of February to 79.2% in the month of July with an average annual value of 73.6%. This means that ~25% of the incident solar energy is not converted into usable energy which indicates a possible fault in components, conduction losses and thermal losses. The obtained PR value acts as an indicator and can prompt more detailed inspection of the PV plant so that, for example, soiling of the PV modules is removed or defective BOS components can be repaired or replaced. Both values are within the agreed range in literature (e.g., Rekhashree *et al.,* 2018; Seme *et al.,* 2019 and Znidarec *et al.,* 2019). The corresponding theoretical PR data are given in Appendix XIV.

The solar PV backup system has a CF of 19.80% whereas PVsyst modeled a CF of 21.23%. Fixed-tilt PV systems (the case for the studied system) are expected to have CF values between 20.8% and 26% in high solar radiation regions according to literature (e.g., Gottschalg *et al.*, 2005; Dena *et al.*, 2019 and Ding *et al.*, 2019), hence the obtained results compare well with the reported range. From these results, generally location has got an impact on CF; the site has very good solar energy potential sufficient for exploitation for electricity generation.

4.4 Economic performance

The economic performance methods that were implemented were the LCC, PBT and LCOE for PV system and the diesel generator. The PV system and the DG cost parameters that were considered in this study are given in Appendices VI and VII respectively. Assessment period was based on the long-lasting component, which is the PV module in this case. The expected life span of the PV systems is reported in literature and also by manufacturers to be between 25 to 30 years, but in this study, a period of 25 years was used.

Figure 4.6 presents LCC comparison between the PV backup system and DG over the PV modules lifetime of 25 years.

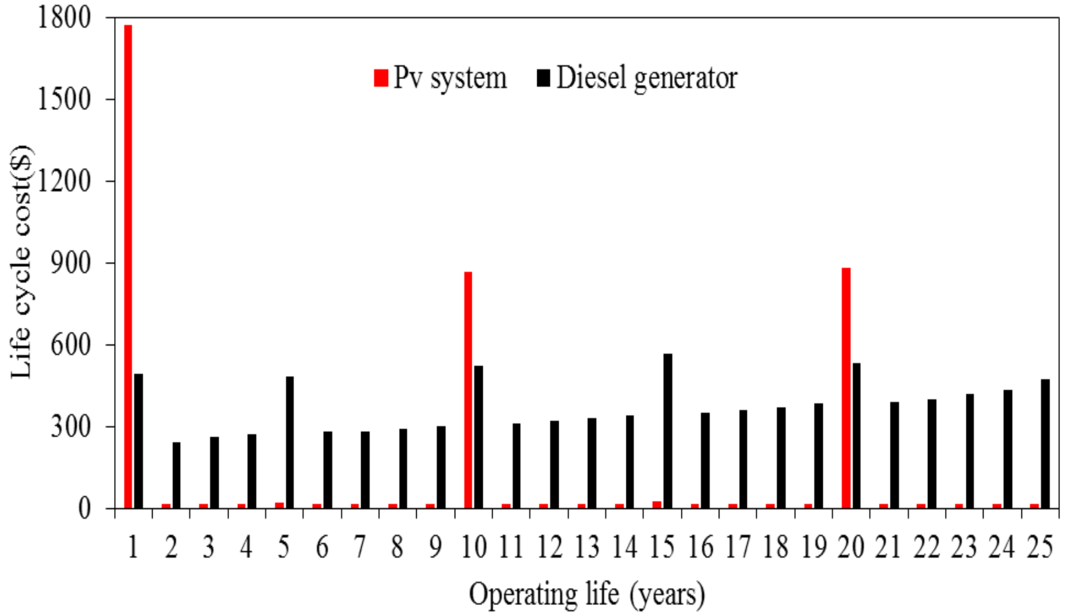


Figure 4.6: PV backup system versus diesel generator life cycle costs

From these results, the DG has low initial capital cost as shown in year one (2016) and is as low as ~ 27% of the value obtained for the PV system. The PV system high initial costs are constituted in a large percentage by the PV modules, inverter/charge controller unit and battery bank costs. These costs can be reduced by lowering the battery capacity since many loads are not classified as critical loads and can be reduced during times they are not necessarily in use. The relatively higher LCC of the DG which is more than twice that of the PV backup system is attributed to the cost of fuel and routine maintenance while the PV system is characterized by low operation and maintenance cost over the 25 years project life. It can be seen from Figure 4.6 that there is gradual increase in LCC of the DG with time. This is attributed to yearly rise in the cost of fuel as a result of inflation and routine maintenance of the diesel generator.

Table 4.5 gives the economic comparative performance results based on LCC, PBT and LCOE analysis of the PV backup system and that of an equivalent diesel generator. The PV arrays normally do not require any maintenance over their lifetime apart from module surface cleaning. For the studied PV system natural cleaning through rain is sufficient to remove any accumulated dust and other particles that may fall on the PV array surface. However, the batteries, inverter/charge controller unit require replacement and maintenance regularly. According to literature, the total operation and maintenance (O & M) cost for a PV system is 2% of PV array cost per year (e.g., Shah *et al.*, 2018 and Shaw-Williams *et al.*, 2018). Therefore, the O & M costs for the PV system under study with a lifespan of 25 years was $433.00or $17.32 yearly. On the other hand, the O & M cost for the diesel generator with lifespan of 5 years was $5220.25 or $26250.35over the PV array lifespan assuming that it operates 2 hours per day of blackouts.

The total replacement cost for the PV system was $5240, and out of these costs, the batteries' replacement cost was 91.4% of the total costs because they are replaced four times over the system lifespan and the remaining 8.6% is the replacement cost for inverter/charge controller unit. The diesel generator replacement costs over 25 years of the PV system life span with four times replacements was $6482.60 or $259.30 annually.

Table 4.4: Summary of PV system versus diesel generator economic performance

Parameter	PV system	Diesel generator
Initial cost	$1774.02	$494.55
Power rating of the facility	63.145 kWh/year	63.145 kWh/year
O & M cost	$433	$26250.35
Replacements	$5240	$6482.60
Price of fuel	-	1.0 $/L
Annual fuel consumption	-	$253.20
Total electrical units produced in one Month	266.90 kWh,	318.21 kWh,
LCC	$3057.93	$7792.75
PBT	6.38 years	4.25 years
LCOE	0.045 $/kWh	0.325 $/kWh

It can be seen from the Table 4.4 that the cost of energy (determined using equation (3.15) for the PV system was 0.045 $/kWh which was far much cheaper compared to that of the diesel generator which was 0.325 $/kWh. These results represent the average revenue per unit of electricity generated where the PV backup system LCOE value was 12.2% lower than that of the diesel generator which makes PV backup power a competitive alternative as a primary source of energy during power outages in comparison with other technologies.

The PBT for the PV backup system was determined using equation (3.13) and results give 6.38 years with a lifetime of 25 years compared to that of the diesel generator with a lifetime of 5 years and a PBT of 4.25 years. Improvements on individual component conversion efficiencies will reduce the PBT of PV systems which will eventually improve the LCOE value.

The LCOE values for the PV system and diesel generator were 0.045 $/kWh and 0.325 $/kWh respectively. This is a clear indication that the cost of solar power as a backup system is cheaper by a factor of seven than that of the diesel generator when used as a backup system.

From these economic performance results, as evident from all the considered parameters, the PV backup system is more cost effective as a long-term backup power supply system. The economic benefits of the PV system assume that the price of electricity remains constant (except for inflation) throughout the analysis period. In the long term, deployment of PV backup systems will lead to decrease in price of electricity, which in turn will spur economic growth and completely replace deployment of expensive diesel generators as power backup option.

4.5 Environmental performance of the PV system

Figure 4.7 presents the experimental and theoretical (corresponding data is given in Appendix XII) monthly variation of CO_2 avoided by use of PV system as a backup system and the environmental cost parameter of the PV system. The amount of CO_2 emission avoided and their costs were determined using equations (3.17) and (3.18) respectively. These results only consider the emissions avoided during PV array operation stage and exclude production, transportation and end-of-life process.

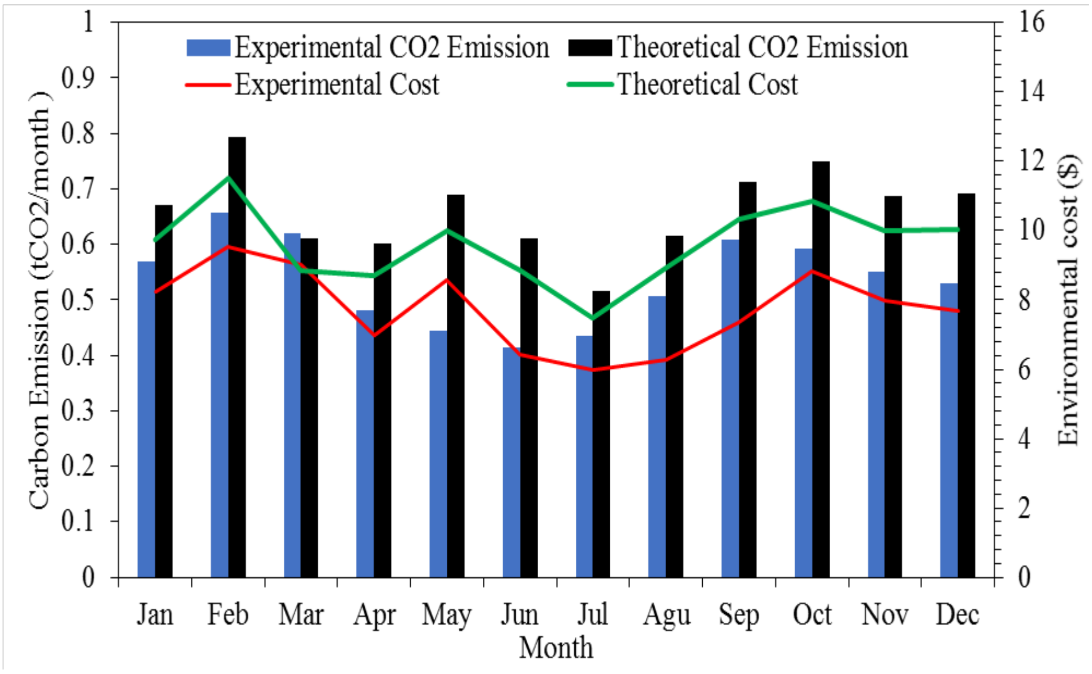


Figure 4.7: Monthly carbon reduction and environmental cost

It is seen from Figure 4.7 that mitigation of CO_2 emission rate varies from the minimum of 0.48 tCO_2/month in the month of June to a maximum of 0.67 tCO_2/month in the month of February. Generally, high insolation months (i.e., January to March and then September to December) give the highest amount of CO_2 avoided while low insolation months (i.e., April to August) give the lowest amount of CO_2 mitigated. On the other hand, theoretical results show that the amount of CO_2 emission avoided varies from 0.517 tCO_2/month in the month of July to 0.79 tCO_2/month in the month of February. The total annual amount of CO_2 emission avoided when PV is used instead of DG power backup system are 5.84 tCO_2/year and 7.95 tCO_2/year for experimental and theoretical results respectively. The experimental result value is lower than the theoretical value because emissions avoided is a factor of the annual energy generated by the system. These results show that use PV backup systems have considerable potential for reduction of GHGs emissions which may lead to saving on fossil fuel use and its importation. In addition, the amount of CO_2avoided is a factor of solar radiation received at a given location hence, reduction in the emissions of CO_2 signifies an environmental improvement when a PV backup system is used as a substitute to diesel backup generators.

The experimental cost parameter of the avoided CO_2 emissions (i.e., the cost of avoided CO_2 emissions) varies from a minimum of \$6.95 in the month of June to a maximum of \$9.72 in the month of February with average annual value of \$9.61 as shown in Figure 4.7. The theoretical cost parameter varied from \$8.27 to \$11.46 with an average annual value of \$116.18. This is the amount of money that one should be paid as compensation for using a PV system instead of a DG as a backup system. In addition, these findings can provide policymakers with useful information for both evaluating and planning the PV power plant-related policies and to deal with the environmental damage that is caused by use of DGs as backup systems.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The results show that the site is in a sun-belt region with high solar irradiance throughout the year and therefore ideal for PV applications. The region registers as high as 800 W/m^2 as early as 9:00 am and can be as high as 1200 W/m^2 on clear sky days. The site has high solar irradiance during the months of January to March and August to December and relatively low during the months of April to July with average Y_r or PSH of ~ 4 -5 hours.The MAPE test on the performance of the four models selected gave absolute uncertainties of 8.5%, 11.0%, 12.6% and 8.9% while RMSE test gave standard deviations of 0.252, 0.463, 0.403 and 0.302 respectively for the Angstrom-Prescott, ASHRAE, Hargreaves-Samanni and Iqbal models. These results show that the models are suitable for the site and have relatively good estimation of the monthly average of daily global solar radiation, but Angstrom-Prescott and Iqbal models predict the monthly average solar radiation with higher accuracy than the other two models for this site.

The electrical performance of the PV system showed that the PV system annual experimental efficiency was 11.71% with monthly range of 10.52% to 13.96% while the simulation results annual efficiency was 13.19% with monthly range of 12.03% to 14.92%. The PV backup system is not operating optimally since the experimental and the simulation FF values are << 1 with annual values of 0.66 and 0.68 respectively. Theselow efficiencyand FF values are attributed to non-optimized installation of the PV array with regard to tilt angle (should be equal to latitude of the site) and orientation and losses from BOS components and degradation. The annual effective energy output of the PV backup system was 3412.94 kWh where the month of February gave the highest value of 328.91 kWh and the month of June produced the lowest value of 206.63 kWh. The annual average array yield was 4.92 kWh/kW whereas the array losses average annual value was 0.54 kWh/kW. The average yearly reference yield was 5.51 kWh/kW, annual average PR was 76.0% and annual capacity factor of 19.80% was attained. On the other hand, simulation results showed that annual PV system PR was 73.33% and the total produced energy was 4615 kWh/year. These results indicate that the system performance is adequate with regard to yield and PR values. All the electrical performance parameters considered, PV system has showed potential and proved its reliability to meet the energy demands of the KTTC social hall during periods of power outages.

The results show that the DG has low initial capital cost and is as low as ~ 27 % of the value obtained for the PV system. The O & M cost for the PV system was $433.00 or $17.32 yearly over its lifetime while that of the DG with lifespan of 5 years was $5220.25 or $26250.35 over the PV array lifespan assuming that it operates 2 hours per day of blackouts. Total replacement costs are $5240 with batteries' value taking 91.4% of the total PV system replacement costs. It is further shown that the investment will be recovered in 6.38 years for the PV system and 4.25 years for the DG. The LCC value of the DG is $7792.75 and that of the PV system is $3057.93hence, the DG value is more than twice that of the PV system due to the cost of fuel and routine maintenance. The experimental and simulation results showed that LCOE values are 0.045 $/kWh and 0.059 $/kWh respectively for the PV system which indicates that the cost of solar power is far much below the cost of electricity from the DG with annual LCOE value of 0.325 $/kWh. These economic indicators show that the PV backup system is worthy of investment compared to diesel backup generators which have for long been the traditional way to backup grid electricity sources.

Mitigation of CO_2 emission rate varied from minimum of 0.48 tCO_2/month to a maximum of 0.67 tCO_2/month. The emissions are taken as the quantity of CO_2 that can be saved by use of PV system where cost parameters vary from minimum of $6.95 to a maximum of $9.72. This shows that the PV system can contribute significantly to the mitigation of CO_2 emission. In addition, the total amount of carbon dioxide emissions that are directly saved is 5.3 tCO_2 equivalent to 0.44 tCO_2/month with LCE value of 334 $KgCO_2$/module and a subtotal of 1336 $KgCO_2$ for the four modules. The PV power presents net benefits over diesel power in all economic performance indices evaluated, and hence can be used as a reliable and affordable replacement for DG backup systems.

5.2 Recommendations

1. The site is adequate for harnessing PV power as the primary source of energy since the region has abundant solar radiation throughout the year. For optimal performance realization, the PV modules should be installed properly for optimum operation through orientation and tilt angles adjustments. The PV backup systems should be used as an alternative to DGs because PV powered system have economic advantage after 6.38 years of installation compared to the DG. By taking PV systems as backup systems instead of DG will contribute to increased use of renewable energy.
2. Angstrom-Prescott and Iqbal models are recommended for the site because they estimate the solar radiation data which are closer to the measured values than the ASHRAE and Hargreaves-Samanni models.
3. There is need to set a national degradation test facility for further research to investigate the effect of degradation on PV system performance. In addition, a test bed of a PV backup system can be set up to have the test for various PV technologies under uniform climatic conditions.

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APPENDICES

APPENDIX I: INSTALLED CAPACITY OF ELECTRICITY BY SOURCE, 2016-2020

Year	INSTALLED CAPACITY						Total	EFFECTIVE CAPACITY						Total
	Hydro	Thermal Oil	Geo-thermal	Wind	Co-gene-ration	Solar	MW	Hydro	Thermal Oil	Geo-thermal	Wind	Co-gene-ration	Solar	MW
2016	818.7	801.6	652	26.1	28	0.6	2327	797.5	762.9	644	26	23.5	0.2	2254.1
2017	826.2	806.9	652	26.1	28	0.7	2339.9	805	765.8	644	25.5	23.5	0.6	2264.4
2018	826.2	807.7	663	336.1	28	50.7	2711.7	805	768.2	655	335.5	23.5	50.6	2637.8
2019	826.2	749.3	828.4	336.1	28	51	2818.9	805	716	816	325.5	23.5	50.4	2736.4
2020	834	749.1	863.1	336.1	2	52.5	2836.7	805	715.5	805.1	325.5	2	52.2	2705.3
Notes:														
1. Megawatt = 1,000 kilowatts = 1,000,000 watts														
2. Installed capacity refers to the maximum theoretical electric output a power station could produce when operating at 100 percent														
3. Effective capacity refers to the maximum electric output a power station is expected to achieve given current operating constraint														

Source: Kenya Power & Lighting Company Ltd and Kenya Electricity Generation Company Ltd (2020).

APPENDIX II: INVERTER TECHNICAL CHARACTERISTICS

Parameter	**Value**
Power requirement (kW)	0.08
Rated AC output voltage(V)	230±5
Maximum DC Input Voltage (V)	1000
Input voltage (V)	750
Maximum output current (A)	22
Maximum input current (A)	15
Efficiency (%)	96
AC line frequency (Hz)	50
Power factor	0.9
Power Control	MPPT
Operating Temperature (^{0}C)	0~60

APPENDIX III: CHARGE CONTROLLER SPECIFICATIONS

Parameter	**Magnitude**
Nominal system voltage (V)	12-24
Maximum input voltage (V)	24
Max. PV input power (W)	1040
Rated battery current (A)	20
Rate load current (A)	15
Self-consumption	≤16mA
Working temperature	$-25^0C \sim +60^0C$
Power conversion efficiency (%)	95%
Safety factor	1.25

APPENDIX IV: BATTERY TECHNICAL PARAMETERS

Parameter	**Magnitude**
Battery capacity (Ah)	200
Nominal voltage (V)	25.4
Energy (WH)	5120
Depth of discharge (DOD)	0.8
Efficiency (%)	96
Discharge temperature (^0C)	-20~60
Charge temperature (^0C)	0~45
Self-discharge	<1% per month
Peak discharge current (A)	200
Discharge cut-off voltage (V)	4.2±0.05

APPENDIX V: LOAD POWER RATINGS

Appliance	Quantity	Power rating (W)	Operation time (h/day)	Daily power load (kWh/day)
Light bulbs	4	8.5	2	0.068
Fluorescent tube	12	35	2	0.840
Desktop computer	1	30	2	0.060
PC (Laptop)	2	18.5	2	0.074
Television	1	60	2	0.120
Fridge	1	150	2	0.300
Phone/ mobile	6	6	2	0.072
Fan	6	30	2	0.360
Printer	1	21	2	0.022
Sound system	4	20	2	0.160
Total				**2.076**

APPENDIX VI: PYRANOMETER (SOLAR METER) SPECIFICATIONS

Parameter	**Value**
Timer	Sampling from 1 second to 3600 seconds
Spectral response	400 to 1100 nm
Solar power range	0~2000 W/m^2 or 634 $Btu/ft^2 \times h$
Solar power accuracy	$\pm$ 10 W/m^2 or 5 % reading
Angular accuracy	Cosine corrected <5% for angles < 60^0
Operating temperature	0~50 ^0C
Operating humidity	Less than 85% R.H

APPENDIX VII: PV SYSTEM COST PARAMETERS

Item	Value
Module cost ($)	1.11/W
Battery cost ($)	@114.28
Charge controller/inverter ($)	165.24
4 x 16mm^2 cable ($/m)	1.0
Length of cable (m)	235
Installation cost ($)	5% of component cost
O&M/year ($)	2% of PV array cost
No. of replacement for PV	0
Battery lifespan (years)	10
No. of replacement for battery	2
Charge-cum-inverter lifespan (years)	10
No. of replacement for charge-cum-inverter	2
PV derating factor (%)	80
Interest rate (%)	6.5
Inflation rate (%)	2.0
Average hours of operation	9
Continuous cloudy days	4
Temperature correction factor	0.95
Cost of electricity ($) (grid)	0.21/kWh
Inverter replacement periodic cost ($)	220

APPENDIX VIII: DIESEL GENERATOR COST PARAMETERS

Parameter	Value
Interest rate (%)	7.5
Inflation rate (%)	6.0
Generator cost ($)	240
Installation cost ($)	5% of components cost
O and M cost ($ per op. Hr)	0.03
Generator lifespan (years)	5
Number of generators	1
Number of replacements	4
Fuel cost- average ($)	1.0 /L
Length of cable (m)	235
Cost of cable ($/m)	1.0

APPENDIX IX: REPRESENTATIVE MONTHLY SOLAR IRRADIANCE

Time	Time	21st Jan	18th Feb	11th Mar	16th Apr	20th May	10th Jun	14th Jul	9th Aug	11th Sep	16th Oct	23rd Nov	18th Dec
7.34	07:34:00 AM	25.3	21.6	24.3	42.3	18.6	32.1	54	28.6	29	65.2	12.3	56.3
7.39	07:39:00 AM	11.2	106.5	101	56	25.3	31	212	128.3	45	24.1	11.2	62.9
7.44	07:44:00 AM	15.2	125.2	204	95	100.2	35	154	100.5	81	135.9	15.2	54.9
7.49	07:49:00 AM	58.7	35	296	124	95.6	78.5	276	142.6	56	56.3	58.7	61
7.54	07:54:00 AM	46.9	78.5	201	96.3	85	66.7	103	81	95	62.9	46.9	36.6
7.59	07:59:00 AM	115.8	66.7	158	99.2	84	135.6	245	56	124	54.9	115.8	135
8.04	08:04:00 AM	127.6	78.5	308	154	168	147.4	165	95	127.6	61	202	111.2
8.09	08:09:00 AM	137.7	66.7	312	276	166.1	166.1	179	124	137.7	36.6	189	122.3
8.14	08:14:00 AM	350.2	135.6	296	103	144.1	144.1	157	127.6	350.2	135	212	653.1
8.19	08:19:00 AM	407.4	147.4	356	245	212	218.6	254	235.1	407.4	422.3	155	604.9
8.24	08:24:00 AM	421.6	166.1	245	102.3	215.6	312.1	325	235.6	421.6	262.8	339	674.2
8.29	08:29:00 AM	389.7	144.1	476	205.6	196	118.5	214	304.2	389.7	541.6	413	500.9
8.34	08:34:00 AM	212.6	212	321	185.7	243.4	356.1	256.3	369	212.6	425.9	256.3	720
8.39	08:39:00 AM	349	312.1	478.2	323.2	122.1	312.1	135	325	310.1	471.8	213	724.5
8.44	08:44:00 AM	266.7	196	498.2	504.7	142.3	148	422.3	157	319	455.6	395.7	632.4
8.49	08:49:00 AM	299.3	356.1	600.4	398.1	249.9	144.1	262.8	315.6	230.1	500.7	287.6	852.9
8.54	08:54:00 AM	356.9	635.1	639.5	456.4	256.3	312	541.6	308	461.1	412.3	400.8	694.2
8.59	08:59:00 AM	351.1	826.4	522	363.9	152.7	310.1	425.9	325	199.1	350.2	321.6	736.8
9.04	09:04:00 AM	395.3	736.4	803.4	421.5	448	319	471.8	356	397.1	407.4	256.9	745.2
9.09	09:09:00 AM	496.8	115.8	728.5	407.4	569	230.1	455.6	245	312	421.6	501.2	769.8
9.14	09:14:00 AM	468.1	127.6	805	625.1	412	461.1	500.7	476	345	389.7	200.1	722.6
9.19	09:19:00 AM	95.5	137.7	849	856.1	322	196	241	241	423	426.1	459.7	705.7
9.24	09:24:00 AM	123.8	350.2	725	566.5	356	311.1	326	326	496	437.3	93.3	803.4
9.29	09:29:00 AM	560.9	407.4	800	656.3	296	199.1	214	214	653	726.8	478.2	728.5
9.34	09:34:00 AM	586.2	421.6	823	956.3	425	397.1	412	412	589	657.1	498.2	835.6
9.39	09:39:00 AM	495.7	389.7	931.9	822.1	500	312	514	514	625	720.6	600.4	806.6
9.44	09:44:00 AM	505.8	212.6	932.1	722.6	412	345	200	615.8	411	658.7	639.5	812.4
9.49	09:49:00 AM	564.9	349	930.8	755.8	312	423	612	612	716	703	722.6	822.7
9.54	09:54:00 AM	569.1	266.7	981.9	721.3	267	496	596	596	685	725.6	625.9	704.5
9.59	09:59:00 AM	635.9	299.3	836	722.6	625	509	625	653	635.4	698.3	803.4	704.6
10.04	10:04:00 AM	541.1	356.9	901	658.2	500	632.6	611	589	631.3	705.4	728.5	722.6
10.09	10:09:00 AM	524.3	322.1	732	865.6	656	633.6	612	625	635.6	856.3	903.5	748.1
10.14	10:14:00 AM	567.4	351.1	901.9	845.7	523	635	589	411	639.4	689.5	859.6	729.7
10.19	10:19:00 AM	541.1	395.3	856	826.4	574	590.6	569	856.5	712	756.4	933.5	897.3

10.24	10:24:00 AM	596.1	496.8	928.5	726.5	584	605.6	584	584	603	689.9	478.5	869.3
10.29	10:29:00 AM	562.3	468.1	912.1	864.1	546	567.6	546	587.9	656	754.1	951.7	877.6
10.34	10:34:00 AM	601.9	95.5	894.2	956.4	603	598	603	459.7	632	896.5	951.3	901.5
10.39	10:39:00 AM	596.2	123.8	905.7	505.8	589	677.6	656	512.4	689	854.3	754.3	867.2
10.44	10:44:00 AM	564.2	560.9	884.8	896.5	611	653.6	632	478.2	568	876.2	1024.5	865.3
10.49	10:49:00 AM	603.5	586.2	903.5	433.2	612.3	710.6	689	498.2	359	867.2	869.2	789.6
10.54	10:54:00 AM	631.8	495.7	924.4	635.9	589	584	623	600.4	400	825.6	956.5	789.6
10.59	10:59:00 AM	635.4	505.8	933.5	989.5	672.7	633.6	635.4	639.5	718	796.3	1004.5	894.5
11.04	11:04:00 AM	631.3	564.9	639	844	641.4	485	631.3	623	436	814.1	957.6	901
11.09	11:09:00 AM	635.6	569.1	613	872.1	598.6	459	635.6	876.2	623	856.4	959	898.4
11.14	11:14:00 AM	639.4	635.9	653.2	896.2	611.8	587.6	639.4	867.2	690	786.3	958.8	910.3
11.19	11:19:00 AM	712	541.1	613	956.1	611.4	603.2	745	825.6	512	856.2	1054.3	856.2
11.24	11:24:00 AM	755	524.3	672	854.2	578.5	518	525	796.3	895.3	804.1	1002.5	705.2
11.29	11:29:00 AM	698	567.4	718	689.5	614.8	564	695	814.1	803.5	829.7	953.3	689.5
11.34	11:34:00 AM	702.6	541.1	865.9	458.6	505.6	652.8	725	856.4	400.8	863.1	856.3	585.2
11.39	11:39:00 AM	736.9	596.1	924.6	745.8	534.9	625	763	635.2	653.2	845.9	758.6	925.6
11.44	11:44:00 AM	865.9	562.3	932.7	796.5	586.2	778.7	654	589.7	502.1	821.1	960.7	945
11.49	11:49:00 AM	924.6	601.9	994.1	854.6	523.3	589	612	872.1	501.2	852.6	965.3	973.1
11.54	11:54:00 AM	932.7	596.2	986.4	877.3	621.3	554	603	896.2	700.2	789.6	967.8	922.8
11.59	11:59:00 AM	994.1	564.2	826.7	965.4	845.3	672.7	639	956.1	994.1	854.2	970.3	945.6
12.04	12:04:00 PM	986.4	603.5	956.8	562.1	823.1	641.4	613	925.6	986.4	946.5	789.5	1000.7
12.09	12:09:00 PM	826.7	631.8	1055	639.4	846.3	705.6	613	857.4	800.3	926.6	857.6	986.5
12.14	12:14:00 PM	956.8	635.4	1054	789.6	895.3	611.8	613	859.6	994.1	906.7	984.6	989.9
12.19	12:19:00 PM	956.4	631.3	1046	933.6	803.5	611.4	672	907.7	986.4	639.1	754.8	1026.8
12.24	12:24:00 PM	926.4	645.5	1026.2	766.6	718.3	588.5	722.8	963.2	841.9	931.4	997.5	1099.3
12.29	12:29:00 PM	965.8	639.4	1043	702.6	736.9	612	436	986.4	956.8	856.2	973	1122.5
12.34	12:34:00 PM	1032.9	725.6	1055	736.9	865.9	687.9	623	826.7	857.3	911.7	975.3	1126.3
12.39	12:39:00 PM	1051.1	632.5	1033	798.4	924.6	706.1	690	956.8	895.6	722.8	900.5	1230.5
12.44	12:44:00 PM	1033.7	511.6	1022	854.6	932.7	589	512	956.4	825.6	1026	923.3	1194.3
12.49	12:49:00 PM	1045.2	702.6	1010	789.5	865.2	696	610	923.5	869.5	994.1	954.4	512.3
12.54	12:54:00 PM	939.5	736.9	1001	857.3	700.5	594.5	436	965.8	621.3	965.3	964.8	1235
12.59	12:59:00 PM	1096.3	865.9	1008	854.6	700.25	535	600	1032.9	826.7	985.6	925.3	1215.7
13.04	01:04:00 PM	1065.2	924.6	1002	752.1	800.25	588	653	968.7	956.8	956.8	935.6	1266.2
13.09	01:09:00 PM	1145.9	932.7	990.4	1065.2	700.25	558	623	854.6	1055	1045.2	967.8	1258.6
13.14	01:14:00 PM	1186.3	994.1	990.9	956.4	990.4	588	653	752.1	1054	1056.8	970.3	1239.8
13.19	01:19:00 PM	1134.2	986.4	976.7	847.1	990.9	800	865	1065.2	905.2	732.5	1000.2	1206.4
13.24	01:24:00	1045.6	826.7	1000	741.6	976.7	660	725	956.4	845.6	1032.9	1023.3	1214.2

	PM												
13.29	01:29:00 PM	1196.5	956.8	997.8	854.7	700.25	594	659	847.1	856.3	1056.3	1024.5	1228.1
13.34	01:34:00 PM	1231.9	956.4	822.2	624.3	826.7	624	689	879.2	852.4	986.2	1005.2	1245.5
13.39	01:39:00 PM	1154.6	923.5	1073	725.1	956.8	561	685	859.1	741.5	733.8	1045.2	1196.9
13.44	01:44:00 PM	758.2	965.8	1052	648.5	956.4	540	735	785.4	706.1	300.2	1022.3	1205.9
13.49	01:49:00 PM	1135.9	1032.9	1059	837.7	923.5	547	825	687.9	968.35	856.2	800.1	1189.3
13.54	01:54:00 PM	1066.3	1051.1	1102	330.5	700.25	590	725	706.1	958.41	856.3	924.6	1223.1
13.59	01:59:00 PM	1012.9	1033.7	1063	256.1	852.3	551	625	968.35	725	789.5	1002.3	1238.6
14.04	02:04:00 PM	1033.5	1045.2	1072	355.7	700.25	560	695	958.41	785.6	415.7	1038.1	1125.4
14.09	02:09:00 PM	1012.9	939.5	965.2	287.1	700.25	408	639	618.2	692	789.5	1023.4	1209.5
14.14	02:14:00 PM	1189.6	1096.3	718.6	556.9	600	494	695.6	725	605	896.5	984.2	1123.5
14.19	02:19:00 PM	1089.7	1065.2	736.9	324.4	635	414	605.6	645	700.2	985.4	985.9	1245.9
14.24	02:24:00 PM	1046.8	1145.9	865.9	986.4	831.6	396	567.6	692	986.5	859.1	942.4	856.2
14.29	02:29:00 PM	989.5	1186.3	721.5	925.6	800	374	598	605	937.4	722.5	923.2	704.1
14.34	02:34:00 PM	1053.6	1134.2	1106	899.9	632	392	677.6	623	901.1	542.6	985.6	1178.6
14.39	02:39:00 PM	1024.9	1045.6	1154.6	985.6	623	395.6	653.6	623	926.4	845.5	880.1	1208.3
14.44	02:44:00 PM	1027.3	1196.5	758.2	900.6	700.25	304.2	702.1	687.3	865.1	986.5	946.3	1144.7
14.49	02:49:00 PM	856.9	1231.9	1135.9	561.9	589	290	636.3	784.1	847.7	926.7	824.6	1232.3
14.54	02:54:00 PM	829.4	1154.6	1066.3	432.5	700.25	425	656	656	900.5	1033.5	901.3	1178.9
14.59	02:59:00 PM	964.3	758.2	1012.9	524.1	635	521.6	721	721	986.5	1012.9	869.8	1100.2
15.04	03:04:00 PM	836	1135.9	1033.5	665.4	831.6	254	612	865.1	937.4	1032.4	845.2	1034.4
15.09	03:09:00 PM	765	1066.3	985	638.8	800	385	600	847.7	901.1	1089.7	824.9	1145.2
15.14	03:14:00 PM	986.5	1012.9	965	465.2	632	365	635	900.5	964.3	1072.6	833.4	803.5
15.19	03:19:00 PM	937.4	1033.5	865.9	327.9	451	265.9	831.6	986.5	836	989.5	920.3	824.9
15.24	03:24:00 PM	901.1	1012.9	924.6	336.1	362	324.6	800	937.4	765	1006.7	936.4	935.6
15.29	03:29:00 PM	926.4	1189.6	932.7	325.4	525	189	632	901.1	831.6	1028.3	845.3	926.2
15.34	03:34:00 PM	865.1	1089.7	994.1	432.1	489	394.1	623	725	800	935.6	823.1	856.4
15.39	03:39:00 PM	847.7	1046.8	986.4	973	478	386.4	512	645	632	726.3	846.3	505.4
15.44	03:44:00 PM	856.9	989.5	826.7	975.3	425	154	502	692	623	829.4	895.3	562.3
15.49	03:49:00 PM	865.2	1053.6	956.8	901.1	458	356.8	514.5	605	523.6	719.4	803.5	710.1
15.54	03:54:00 PM	732.6	1024.9	956.4	964.3	458	356.4	332	901.3	583.6	986.1	824.9	300.6
15.59	03:59:00 PM	625.9	1027.3	923.5	836	522.3	186	322	869.8	421	925.4	785.6	536.8
16.04	04:04:00 PM	754.8	856.9	965.8	765	485	365.8	412	412	436	628.3	793.5	938.2
16.09	04:09:00 PM	735.9	829.4	725	831.6	368	313	352	536.8	445	652.9	800.3	935.3
16.14	04:14:00 PM	752.1	964.3	645	800	356	233	312	938.2	365.8	523.4	720.4	924.7
16.19	04:19:00 PM	789.5	758.6	692	632	415	280	456	935.3	313	226.1	601.3	899.1
16.24	04:24:00 PM	741.6	695.3	605	623	385	193	312	924.7	233	217	710.1	426.9

16.29	04:29:00 PM	426.7	986.5	901.3	225.1	653	489.3	421	899.1	280	234.6	833.4	428.6
16.34	04:34:00 PM	505.6	937.4	869.8	465.1	700.5	457.8	436	426.9	193	331.8	831.6	637.1
16.39	04:39:00 PM	534.9	901.1	845.2	541.6	289	305	445	428.6	489.3	216.7	800	824.6
16.44	04:44:00 PM	461.5	926.4	824.9	330.3	360	412.9	415	637.1	541.6	94.5	632	505.4
16.49	04:49:00 PM	523.3	865.1	833.4	326.1	298	421.4	423	289	330.3	137.1	623	496.2
16.54	04:54:00 PM	517.6	847.7	920.3	330.1	256	508.3	362	360	326.1	126.2	560.25	702.3
16.59	04:59:00 PM	514.8	856.9	936.4	356.7	359	325	312	298	325	98.7	725	455.6
17.04	05:04:00 PM	465.1	865.2	845.3	286.7	458	312	310	256	312	186.2	645	696.1
17.09	05:09:00 PM	541.6	732.6	823.1	295.7	475	276	316	296	456.2	152.3	692	435.8
17.14	05:14:00 PM	330.3	625.9	846.3	186.3	322	212	300	300	365.2	168.1	605	765.9
17.19	05:19:00 PM	326.1	754.8	895.3	145.9	269	96	324	137.1	126	249.3	623	582.2
17.24	05:24:00 PM	330.1	735.9	803.5	359.4	299	101	369	126.2	254	196.5	365.3	402.6
17.29	05:29:00 PM	356.7	752.1	400.8	368.1	351	124	278	98.7	385	314.6	450.2	321.9
17.34	05:34:00 PM	286.7	789.5	321.6	425.6	362	86	221	186.2	365	125.9	325	300.7
17.39	05:39:00 PM	295.7	741.6	256.9	154	311	89	145	152.3	265.9	86.4	312	201.9
17.44	05:44:00 PM	186.3	426.7	501.2	276	412	135	125	168.1	324.6	109.1	276	385.6
17.49	05:49:00 PM	145.9	505.6	200.1	103	478	154	110	249.3	185	219.3	212	206.4
17.54	05:54:00 PM	359.4	534.9	459.7	245	452	85	92	196.5	256	126.2	96	198.6
17.59	05:59:00 PM	368.1	461.5	330	165	189	169	96	314.6	300	128.7	325	188.5
18.04	06:04:00 PM	425.6	523.3	524		412	95	123	102.3	98	87	255	145.5

APPENDIX X: MONTHLY CLEARNESS INDEX

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Clearness index	0.694	0.672	0.599	0.524	0.412	0.386	0.397	0.496	0.522	0.497	0.596	0.631

APPENDIX XI: MONTHLY AVERAGE WIND SPEED AND AMBIENT TEMPERATURE

Month	**Wind Speed (m/s)**	**Ambient temperature (^{0}C)**
Jan	3.71	17.9
Feb	3.41	18.9
Mar	3.76	19
Apr	1.07	18.2
May	1.66	17.8
Jun	1.54	16.6
Jul	1.96	16.5
Aug	1.77	16.3
Sep	2.08	16.9
Oct	2.87	17.7
Nov	3.78	17.5
Dec	3.39	17.9

APPENDIX XII: MONTHLY CO_2 EMISSION AND ENVIRONMENTAL COST

Month	Experimental		Theoretical	
	Experimental CO_2 Emission	Experimental Cost ($)	Theoretical CO_2 Emission	Theoretical Cost ($)
Jan	0.56928	8.25456	0.671	9.7295
Feb	0.65782	9.53839	0.793	11.4985
Mar	0.62082	9.00189	0.6114	8.8653
Apr	0.4805	6.96725	0.601	8.7145
May	0.44374	8.57849	0.6904	10.0108
Jun	0.41372	6.43423	0.6112	8.8624
Jul	0.43408	5.99894	0.5172	7.4994
Aug	0.50624	6.29416	0.6148	8.9146
Sep	0.6085	7.34048	0.7126	10.3327
Oct	0.59162	8.82325	0.749	10.8605
Nov	0.54996	7.97442	0.6882	9.9789
Dec	0.52952	7.67804	0.6928	10.0456

APPENDIX XIII: INPUT AND OUTPUT SIMULATION PARAMETERS

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Stand Alone System: Main results

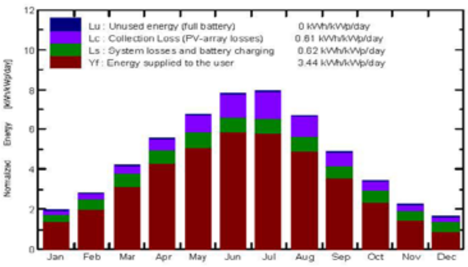
Project : **KAIBOI**

Simulation variant : **New simulation variant**
Simulation for the first year of operation

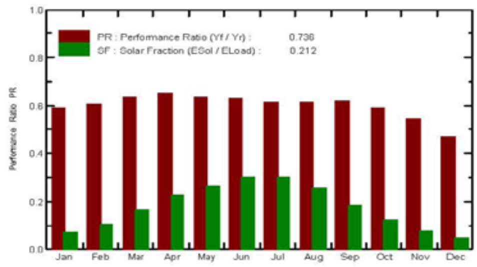
Main system parameters	System type	**Stand alone with back-up generator**		
PV Field Orientation	**tilt**	15°	azimuth	180°
PV modules	Model	LX-195M/125-72+	Pnom	195 Wp
PV Array	Nb. of modules	4	Pnom total	**780 Wp**
Battery	Battery module	Li-Ion, 26V 180 Ah	Technology	Lithium-ion, LFP
Battery Pack	Nb. of units	4	Voltage / Capacity	**26 V / 800 Ah**
User's needs	Daily household consumers	Constant over the year	Global	4614 kWh/year

Main simulation results				
System Production	**Available Energy**	**1092 kWh/year**	Specific prod.	1401 kWh/kWp/year
	Used Energy	4615 kWh/year	Excess (unused)	0 kWh/year
	Performance Ratio PR	73.63 %	Solar Fraction SF	21.23 %
Back-Up energy from generator	Back-Up energy	3636 kWh/year	Fuel Consumption	2181/year
Investment	Global incl. taxes	3568 US$	Specific	4.57 US$/Wp
Yearly cost	Annuities (Loan 5.0%, 20 years)	286 US$/yr	Running Costs	2447 US$/yr
Energy cost		**0.59 US$/kWh**		

Normalized productions (per installed kWp): Nominal power 780 Wp



Performance Ratio PR and Solar Fraction SF



New simulation variant
Balances and main results

	GlobHor kWh/m²	GlobEff kWh/m²	E Avail kWh	EUnused kWh	E User kWh	E Load kWh	SolFrac
January	95.7	55.2	40.7	0.000	392.0	391.9	0.097
February	106.2	72.4	53.0	0.005	354.0	354.0	0.126
March	158.5	123.1	87.5	0.000	392.0	391.9	0.197
April	185.0	160.3	111.1	0.000	379.3	379.3	0.268
May	220.2	202.4	135.1	0.005	392.0	391.9	0.317
June	238.3	226.5	146.0	0.000	379.4	379.3	0.363
July	254.4	238.3	150.7	0.000	392.0	391.9	0.360
August	227.7	200.6	129.3	0.005	392.0	391.9	0.304
September	171.4	138.3	93.4	0.000	379.3	379.3	0.223
October	139.9	98.2	68.7	0.000	392.0	391.9	0.149
November	101.5	60.7	44.2	0.000	379.3	379.3	0.091
December	83.3	44.9	32.9	0.005	392.0	391.9	0.057
Year	1981.8	1620.9	1092.5	0.019	4615.4	4614.5	0.212

Legends:
- GlobHor — Horizontal global irradiation
- GlobEff — Effective Global, corr. for IAM and shadings
- E Avail — Available Solar Energy
- EUnused — Unused energy (full battery) loss
- E User — Energy supplied to the user
- E Load — Energy need of the user (Load)
- SolFrac — Solar fraction (EUsed / ELoad)

APPENDIX XIV: MAIN RESULT OF PV SYSTEM PRODUCTION

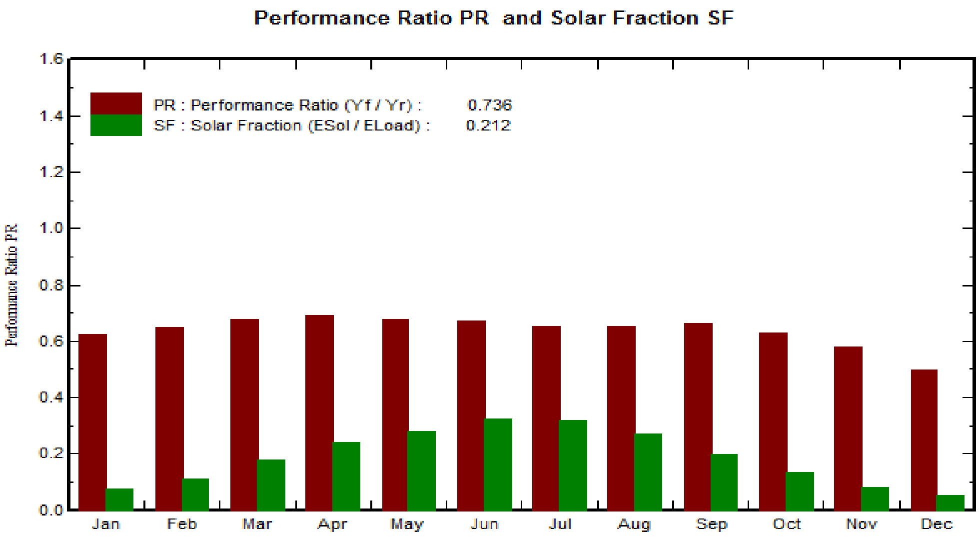
Stand Alone System: Main results

Project : **KAIBOI**

Simulation variant : **New simulation variant**
Simulation for the first year of operation

Main system parameters	System type	**Stand alone with back-up generator**		
PV Field Orientation	**tilt**	15°	azimuth	180°
PV modules	Model	LX-195M/125-72+	Pnom	195 Wp
PV Array	Nb. of modules	4	Pnom total	**780 Wp**
Battery	Battery module	Li-Ion, 26V 180 Ah	Technology	Lithium-ion, LFP
Battery Pack	Nb. of units	4	Voltage / Capacity	**26 V / 800 Ah**
User's needs	Daily household consumers	Constant over the year	Global	4614 kWh/year
Main simulation results				
System Production	**Available Energy**	**1092 kWh/year**	Specific prod.	1401 kWh/kWp/year
	Used Energy	4615 kWh/year	Excess (unused)	0 kWh/year
	Performance Ratio PR	73.63 %	Solar Fraction SF	21.23 %
Back-Up energy from generator	Back-Up energy	3636 kWh/year	Fuel Consumption	2181/year
Investment	Global incl. taxes	3568 US$	Specific	4.57 US$/Wp
Yearly cost	Annuities (Loan 5.0%, 20 years)	286 US$/yr	Running Costs	2447 US$/yr
Energy cost		**0.059US$/kWh**		

APPENDIX XV: PERFORMANCE RATIO AND ANNUAL SOLAR FRACTION



APPENDIX XVI: PV SYSTEM LOSS DIAGRAM

Stand Alone System: Loss diagram

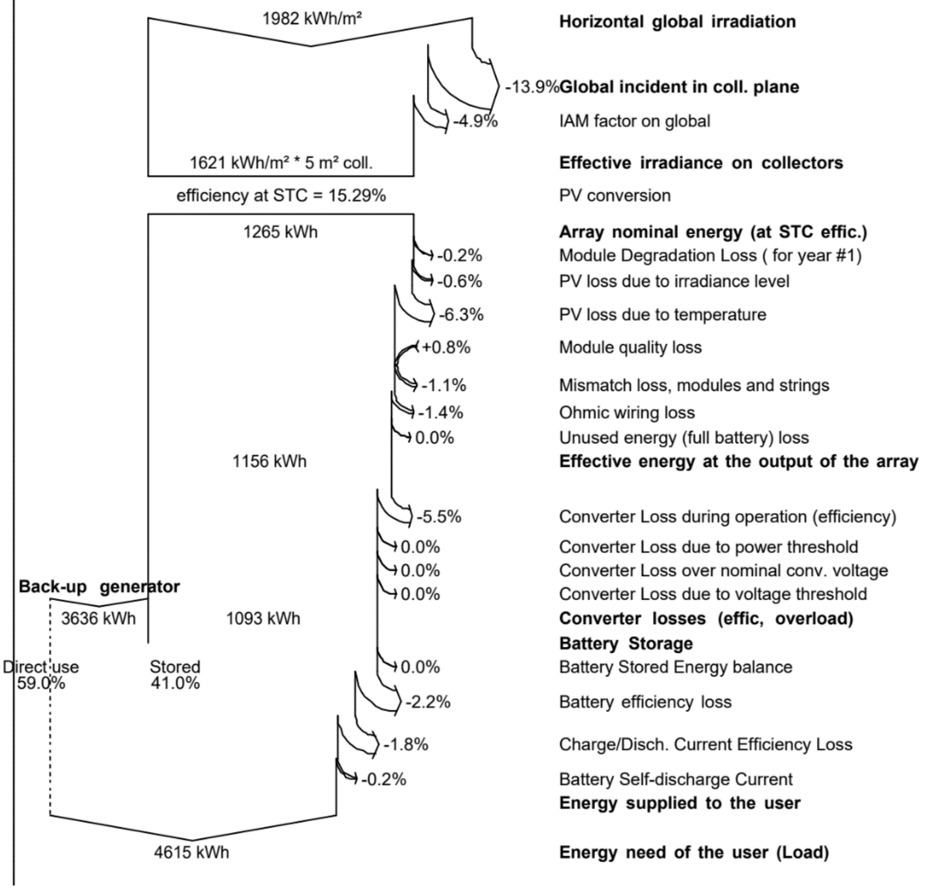
Project : **KAIBOI**

Simulation variant : **New simulation variant**

Simulation for the first year of operation

Main system parameters	System type	**Stand alone with back-up generator**		
PV Field Orientation	tilt	15°	azimuth	180°
PV modules	Model	LX-195M/125-72+	Pnom	195 Wp
PV Array	Nb. of modules	4	Pnom total	**780 Wp**
Battery	Battery module	Li-Ion, 26V 180 Ah	Technology	Lithium-ion, LFP
Battery Pack	Nb. of units	4	Voltage / Capacity	**26 V / 800 Ah**
User's needs	Daily household consumers	Constant over the year	Global	4614 kWh/year

Loss diagram over the whole year



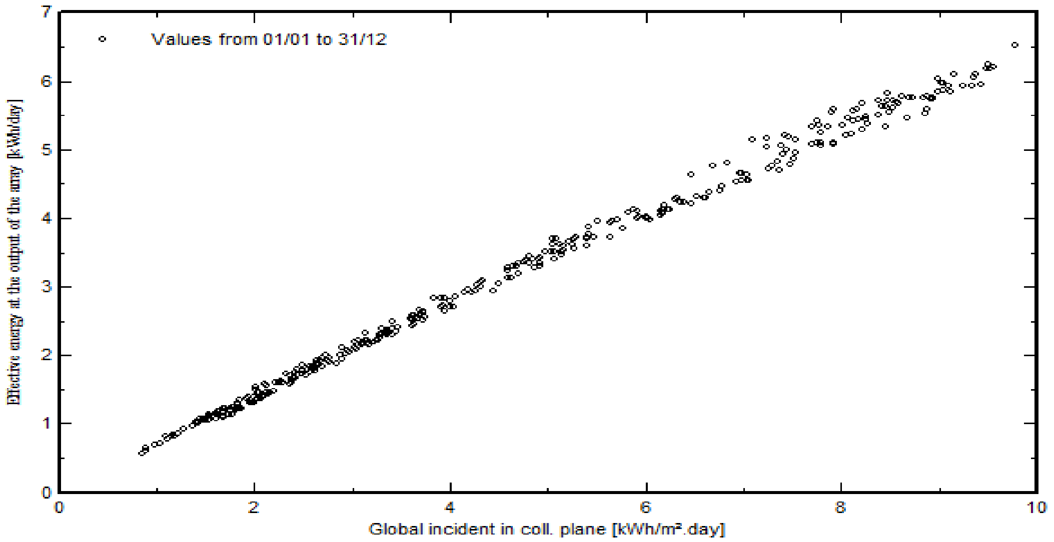
APPENDIX XVII: PV SYSTEM PERFORMANCE COEFFICIENTS

Normalized Performance Coefficients

	Yr kWh/m².day	Lu	Yu kWh/kWp/d	Lc	Ya kWh/kWp/d	Ls	Yf kWh/kWp/d	PR
January	2.00	0.000	2.00	0.215	1.78	0.377	1.40	0.703
February	2.81	0.000	2.80	0.243	2.56	0.523	2.04	0.727
March	4.20	0.000	4.20	0.377	3.83	0.627	3.20	0.761
April	5.57	0.000	5.57	0.547	5.03	0.680	4.35	0.780
May	6.75	0.000	6.75	0.832	5.92	0.789	5.13	0.760
June	7.80	0.000	7.80	1.188	6.61	0.726	5.88	0.755
July	7.94	0.000	7.94	1.332	6.60	0.763	5.84	0.736
August	6.71	0.000	6.71	1.054	5.66	0.727	4.93	0.735
September	4.86	0.000	4.86	0.639	4.22	0.611	3.61	0.743
October	3.41	0.000	3.41	0.416	3.00	0.580	2.42	0.708
November	2.25	0.000	2.25	0.260	1.99	0.519	1.47	0.654
December	1.65	0.000	1.65	0.212	1.44	0.513	0.93	0.562
Year	4.67	0.000	4.67	0.612	4.06	0.620	3.44	0.736

APPENDIX XVIII: DAILY ENERGY OUTPUT OF THE PV ARRAY

Daily Input/Output diagram



APPENDIX XIX: SIMULATION ECONOMIC PERFORMANCE RESULTS

Stand Alone System: Economic evaluation

Project: **KAIBOI**

Simulation variant: **New simulation variant**

Simulation for the first year of operation

Main system parameters	System type	**Stand alone with back-up generator**		
PV Field Orientation	**tilt**	15°	azimuth	180°
PV modules	Model	LX-195M/125-72+	Pnom	195 Wp
PV Array	Nb. of modules	4	Pnom total	**780 Wp**
Battery	Battery module	Li-Ion, 26V 180 Ah	Technology	Lithium-ion, LFP
Battery Pack	Nb. of units	4	Voltage / Capacity	**26 V / 800 Ah**
User's needs	Daily household consumers	Constant over the year	Global	4614 kWh/year

Investment

PV modules (Pnom = 195 Wp)	4 units	215 US$ / unit	858 US$
Supports/Integration		0 US$ / module	0 US$
Batteries (26 V / 3 Ah)	4 units	450 **US$ / unit**	1800 US$
controller			210 US$
Settings, wiring, .			235 US$
Substitution underworth			0 US$
Gross investment (without taxes)			**3103 US$**

Financing

Gross investment (without taxes)		3103 US$
Taxes on investment (VAT)	Rate 15.0 %	465 US$
Gross investment (including VAT)		3568 US$
Subsidies		0 US$
Net investment (all taxes included)		**3568 US$**
Annuities	(Loan 5.0 % over 20 years)	286 US$/year
Maintenance		17 US$/year
insurance, annual taxes		0 US$/year
Provision for battery replacement	(lifetime 6.9 years)	20 US$/year
Fuel for Back-Up generator	(Back-Up energy 3636 kWh/year)	2410 US$/year
Total yearly cost		**2734 US$/year**

Energy cost

Used solar energy	4615 kWh / year
Excess energy (battery full)	0.0 kWh / year
Used energy cost	0.059 US$ / kWh

APPENDIX XX: CO_2 EMISSION BALANCE.

Stand Alone System: CO2 Balance

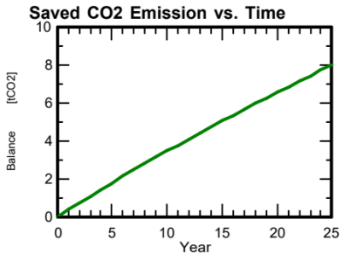
Project : **KAIBOI**

Simulation variant : **New simulation variant**

Simulation for the first year of operation

Main system parameters	System type	**Stand alone with back-up generator**		
PV Field Orientation	tilt	15°	azimuth	180°
PV modules	Model	LX-195M/125-72+	Pnom	195 Wp
PV Array	Nb. of modules	4	Pnom total	**780 Wp**
Battery	Battery module	Li-Ion, 26V 180 Ah	Technology	Lithium-ion, LFP
Battery Pack	Nb. of units	4	Voltage / Capacity	**26 V / 800 Ah**
User's needs	Daily household consumers	Constant over the year	Global	4614 kWh/year

Produced Emissions	**Total:**	**0.00 tCO2**		
	Source:	Custom value supplied by User		
Replaced Emissions	**Total:**	**9.0 tCO2**		
	System production:	1092.41 kWh/yr	Lifetime:	25 years
			Annual Degradation:	1.0 %
	Grid Lifecycle Emissions:	331 gCO2/kWh		
	Source:	IEA List	Country:	Kenya
CO2 Emission Balance	**Total:**	**8.0 tCO2**		



APPENDIX XXI: I-V CHARACTERISTIC DATA

21st Jan		18th Feb		11th Mar		16th Apr		20th May		10th Jun		14th Jul		9th Aug		11th Sep		16th Oct		23rd Nov		18th Dec	
Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)
0.00	5.38	29.99	0.00	0.01	5.62	0.00	5.24	0.00	5.02	0.01	4.85	0.01	5.15	37.8	0.01	0.00	5.36	0.00	5.4	0.00	5.42	0.00	5.65
3.12	5.36	29.86	0.53	1.52	5.49	3.12	5.19	3.12	4.99	1.52	4.81	5.62	5.12	37.51	0.22	5.62	5.34	2.56	5.39	3.21	5.39	3.25	5.55
5.26	5.3	29.35	1.02	3.21	5.46	5.26	5.11	5.26	4.96	3.21	4.78	12.3	5.05	36.77	0.52	12.75	5.31	15.2	5.26	9.56	5.3	10.32	5.42
10.36	5.29	29.05	1.23	6.52	5.41	10.36	5.01	10.36	4.85	6.52	4.62	20.66	5	36.29	0.75	16.06	4.96	19.56	5.19	21.71	5.28	17.72	5.37
16.62	5.28	28.89	1.5	10	5.36	16.62	4.98	16.62	4.76	10	4.51	26.92	4.96	35.84	0.82	19.54	4.85	25.82	5.08	27.97	5.11	21.2	5.32
18.35	5.23	28.75	2.11	11.11	5.31	18.35	4.56	18.35	4.71	15.62	4.49	28.65	4.85	35.69	1.05	20.65	4.76	27.55	4.98	29.7	4.93	22.31	5.15
19.63	5.22	28.65	2.24	13.2	5.34	20.63	4.24	20.63	4.69	16.35	4.39	29.93	4.64	35.52	1.23	22.74	4.56	29.83	4.62	31.98	4.56	24.4	4.95
20.03	5.21	28.05	2.44	14.7	5.24	23.23	4.19	23.23	4.56	17.35	4.29	30.33	4.35	35.46	1.92	24.24	4.49	32.43	4.25	34.58	4.34	25.9	4.68
20.55	5.13	27.85	2.76	18.9	5.22	25.55	3.95	24.55	4.25	24.95	4.18	30.85	4.25	34.8	2.05	28.44	4.21	34.75	3.95	35.9	3.92	30.1	4.18
21.06	5.14	27.65	2.85	19.4	5.19	26.86	3.85	25.86	4.05	25.24	4.1	31.36	4.14	34.18	2.62	28.94	4.11	36.06	3.85	37.21	3.76	30.6	3.95
21.55	5.12	27.65	2.94	19.95	5.15	27.55	3.73	27.55	3.95	25.89	3.95	31.85	3.96	33.83	3.23	29.49	3.95	36.75	3.64	38.9	1.92	30.55	3.75
21.95	5.01	27.02	2.95	20.44	5.16	28.95	3.62	27.95	3.84	26.02	3.94	32.25	3.72	33.48	3.64	29.98	3.62	38.15	1.82	39.3	1.81	30.64	3.35
23.36	4.93	26.58	3.02	20.75	5.09	29.06	3.41	28.36	3.71	26.45	3.85	33.66	3.53	33.1	3.85	30.29	3.26	38.26	1.61	39.71	1.68	30.95	3.05
24.96	4.92	26.25	3.12	21.03	5.04	30.16	3.23	28.96	3.21	26.98	3.56	35.26	3.26	32.89	4.01	30.57	3.00	39.36	1.43	40.31	1.18	31.13	2.84
25.26	4.82	25.23	3.56	21.88	4.72	31.26	3.12	29.26	3.1	27.04	3.42	35.56	2.22	32.3	4.12	31.42	2.53	40.46	1.32	40.61	1.07	31.38	2.54
26.49	4.08	24.56	3.72	22.23	4.08	31.49	2.94	29.49	2.94	27.56	3.35	36.79	1.48	32.14	4.35	31.77	2.21	40.69	1.14	40.84	0.91	31.43	2.36
27.79	3.84	23.25	3.84	23.35	3.84	31.79	2.76	29.79	2.76	27.95	3.25	38.09	1.24	31.16	4.71	32.89	1.96	40.99	0.96	41.14	0.73	31.55	2.01
28.95	3.58	22.15	3.95	24.51	3.58	31.85	2.44	29.95	2.44	28.01	3.15	39.25	0.98	25.66	4.84	34.05	1.56	41.05	0.64	41.3	0.41	31.71	1.92
29.39	3.34	18.26	4.01	24.87	3.34	32.09	2.24	30.09	2.24	28.36	3.05	39.69	0.74	24.15	4.95	34.41	1.42	41.29	0.44	41.44	0.21	32.27	1.82
29.85	2.83	15.63	4.12	25.14	2.83	32.65	2.11	30.65	2.11	28.65	2.83	40.15	0.23	22.06	5.05	34.68	0.95	41.85	0.31	42	0.08	32.94	1.35
29.96	2.73	10	4.65	25.79	2.73	32.86	1.5	30.96	1.5	29.01	2.73	40.26	0.13	20.95	5.16	35.33	0.84	42.06	0.3	42.31	0.07	32.99	1.08
30.26	2.66	6.52	4.89	26.34	2.66	33.06	1.23	31.06	1.23	29.36	2.66	40.56	0.06	17.47	5.2	35.88	0.23	42.26	0.29	42.41	0.06	33.54	0.74
30.85	2.36	3.21	4.92	26.82	2.36	33.85	1.02	31.85	1.02	29.56	2.36	41.15	0.05	10.25	5.26	36.36	0.06	43.05	0.28	43.2	0.05	34.02	0.36
31.25	1.02	1.52	4.95	27.56	1.02	34.25	0.53	32.25	0.53	30.14	1.02	41.55	0.04	5.12	5.42	37.1	0.04	43.45	0.25	43.6	0.04	34.76	0.22
32.83	0.01	0.01	4.99	28.5	0.01	34.83	0.00	32.83	0.00	30.25	0.01	43.13	0.01	0.00	5.59	38.04	0.03	44.03	0.01	44.18	0.00	35.13	0.00

APPENDIX XXII: SIMILARITY REPORT

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IN SITU TECHNO-ENVIROECONOMIC ANALYSIS OF A ROOFTOP PHOTOVOLTAIC (PV) BACKUP SYSTEM IN THE TROPICAL CLIMATE by Wilkins Cheruiyot

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6 < 1% match (Internet from 16-Mar-2020)
https://www.mdpi.com/2227-9717/7/10/708/html

7 < 1% match (Internet from 07-Feb-2022)
https://www.mdpi.com/1996-1073/14/9/2344/html

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