ASSESSMENT OF THE SOLAR RADIATION POTENTIAL OF THE THIKA-NAIROBI AREA, PANEL SIZING AND COSTING

NAHASHON WANYONYI WASIKE

MASTERS OF SCIENCE

(Physics)

JOMO KENYATTA UNIVERSITY OF

AGRICULTURE AND TECHNOLOGY

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Nahashon Wanyonyi Wasike

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

Signature………………………………………….. Date …………………

Nahashon Wanyonyi Wasike

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

Signature: ……………………. Date………………………….

Dr. T.N.Soitah,

JKUAT, Kenya

Signature: ……………………. Date………………………….

Dr. Waweru Mugo,

JKUAT, Kenya

Signature: ……………………. Date………………………….

Dr. F. N.Kariuki,

JKUAT, Kenya

DEDICATION

I dedicate this research to my daughter Cindy Naliaka for she has been a source of inspiration in my life ever since she was born and my mother Elicah Khakasa for having been a pillar in my life.

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TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURES

LIST OF PLATES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

CIS	Copper Indium diSelenide
CR	Concentration Ratio
GoK	Government of Kenya
IR	Infra – red
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter – Tropical Convergence Zone
JKIA	Jomo Kenyatta International Airport
JKUAT	Jomo Kenyatta University of Agriculture and Technology
KIPPRA	Kenya Institute for Public Policy Research and Analysis
MPPT	Maximum Power Point Tracker
MSL	Mean Sea Level
OND	October, November and December
PVs	Photovoltaics
RETs	Renewable Energy Technologies
SEI	Stockholm Environmental Institute
SP	Sessional Paper
SREP	Scaling – up Renewable Energy Programme

SWERA Solar and Wind Energy Resource Assessment

UNEP United Nation Environmental Programme

US United States

UV Ultraviolet

LIST OF SYMBOLS

Ah	Ampere – hour
δ_s	Angle of Declination
H_d	Diffuse Solar Radiation
H_0	Extraterrestrial Solar Radiation
K_T	Clearness Index
H	Global Solar Radiation
I_{SC}	Solar Constant
ω_s	Hour Angle
T_t	The sky transmissivity
κ_H	Hargreaves Regional Coefficient
E_d	Total Daily Energy Demand
E_s	Size of Storage
G	Average Insolation
$	US Dollar
δ_v	Coefficient of Variation
σ	Standard Deviation
δ_d	Relative Mean Linear Successive Difference

$\bar{X}$	Mean/Average
W_p	Peak Watt
V_{oc}	Open Circuit Voltage

ABSTRACT

Kenya lies astride the equation and therefore receives allot of sunshine. Being a renewable energy source, its supply is abundant. The major problem in the exploitation of the resource is lack of or inadequate data on the available insolation. Several researches have earlier been conducted, but a closer scrutiny reveals that the data they used had missing values and hence empirical formulae had to be employed in filling the missing values. In the dissemination of solar technologies and most commonly solar photovoltaic systems, vendors/dealers in these fields do estimates without making reference to the available insolation. It should also be noted that there is no national data base for storage of insolation information.A detailed knowledge of solar radiation is essential for its application. Research done should rely on data that has been collected consistently for a long period of time. Estimation of photovoltaic system should rely on the findings done in those researches. So long as data collection is continuous, the analysis of the available insolation should also be continuous.This study aimed at evaluating the insolation available in the Thika-Nairobi area for purpose of solar panel sizing and costing, in consideration of increased power demand in Kenya and the increase in the cost of conventional energy resources. Data was collected at Thika agro – meteorological station, Dagoretti corner station and the JKIA station for duration of six months. The three stations lie in the same geographical location. Data was collected using the Gunn – Bellani and the pyranometer. To get more meaningful trends and validation of data, historical data for the three stations was considered. The data was analyzed in terms of the average monthly daily insolation and average annual daily insolation. Angles of declination were calculated and the extraterrestrial solar radiation values were found to be 10.14 MJ/m^2/day for Dagoretti Corner, 10.13 MJ/m^2/day for both JKIA and Thika. Average annual daily diffuse solar radiation for all the stations range between 6 – 8 MJ/m^2/day. The average monthly daily diffuse solar radiation was found to be: Dagoretti corner, 6 – 8 MJ/m^2/day; Thika, 6 – 8.5 MJ/m^2/day and JKIA station, 7 – 8.5 MJ/m^2/day. The clearness index lay between 0.4 and 0.7. Percentage contribution of the diffuse solar was also calculated. Statistical parameters were calculated using SCC stat. From the analysis, it was concluded that the average

annual daily insolation range from 4 – 6 $kWh/m^2/day$ and the average monthly daily insolation range from 3 – 7 $kWh/m^2/day$. These values have a larger range with the maximum value being 1 $kWh/m^2/day$ higher than the predicted values of which range 4 – 6 $kWh/m^2/day$ and these shows that the region is endowed with enough insolation for solar energy application. The results have been further applied in the sizing and costing of solar systems.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background information

Among the conventional energy sources, fossil fuels are currently the main sources of energy. The fossil fuel unfortunately is depleting fast to a point where it is unlikely to be able to sustain the great rate of the world energy consumption within the next 200 years. It is understood that about 80% of the world's oil reserves have been consumed by 1980 at the rate of the world energy consumption in 1975. The remaining reserves of coal in the world is estimated to last for about 25 years, while the duration through which the oil and gas reserves in the world are supposed last has not been determined (Babatunde, 2012).

It should also be noted that as the world population increases and the economic standard of third world countries improve, there is likelihood of an unprecedented rise in the global energy demands. It has also been recognized that the heavy reliance on fossil fuel has had an adverse impact on the environment. Nuclear power involves a risk from ionizing radiation in case of accidents caused due to natural events e.g earthquakes & typhoons and human error. Similarly, nuclear power generation as a source of alternative energy faces lots of social objections due to the possible radiation hazard that it may cause during production. Moreover the nuclear power material if inappropriately stored could end up in wrong hands and get turned into weapon of mass destruction that will make terrorism assume a much more dangerous dimension(Jan, 2010).

According to the *Kenya Vision 2030*blue print covering the period 2008 to 2030, the aim is to transform Kenya into an industrializing, "middle-income country providing a high quality life to all its citizens by the year 2030," (GoK, 2007). From the blue print,the energy sector will benefit in that development projects recommended under *Vision2030* will increase demand on Kenya's energy supply. Currently, Kenya's energy costs are higher than those of her competitors e.g for the period ranging from 2010 – 2014, electric power consumption (kWh per capita) in Kenya was 155 where as in Tanzania during the same period the electrical energy consumption was 92 kWh per capita. Thus Kenya must generate more energy at a lower cost and increase efficiency in energy consumption, to remain competitive. The Government is committed to continued institutional reforms in the energy sector, including a strong regulatory framework, encouraging more private generators of power, and separating generation from distribution. New sources of energy will be found through exploitation of renewable energy sources e.g. geothermal power. The other option is the exploitation of coal and connecting Kenya to energy-surplus countries in the region (GoK, 2007).

There is also the critical relationship between energy and the environment. The environment provides raw materials for the energy industry. The environment, on the other hand, is the recipient of the wastes of energy production and consumption, and fossil fuels are the largest contributors to air pollution. The emissions, especially carbon dioxide, methane, nitrogen and sulphur oxides are responsible for changes in the atmosphere that are affecting the global climate (KIPPRA, 2007, Gok, 2010, Ngaira, 2009).

According to the government of Kenya's National Climate Change Response Strategy of 2010, the evidence of climate change in Kenya is significant. Rainfalls have become irregular and unpredictable, and when it rains, downpour is more intense. Harsh weather is now a norm in Kenya. An analysis of the trends in temperature, rainfall, sea levels and extreme events points to clear evidence of climate change in Kenya. Studies indicate that temperatures have generally risen throughout the country, primarily near the large water bodies. The minimum temperature has risen by 0.7 – 2.0°C and the maximum by 0.2 – 1.3°C, depending on the season and the region. In areas near the Indian Ocean, maximum temperatures have risen much like in other areas but minimum temperatures have either not changed or become slightly lower (King'uyu *et. al*, 2000, GoK, 2010). Other projections also indicate increases in mean annual temperature of 1 to 3.5°C by 2050s (SEI 2009). The country's arid and semi – arid lands (ASALs) have also witnessed a reduction in cold temperature occurrences (Kilavi, 2008). This warming is leading to the depletion of glaciers on Mount Kenya (IPCC, 2007, UNEP, 2009) and because of the vital ecological role of mountains, this will have negative implications on biodiversity and water supply in the country and tourism, whose continued double digit growth is crucial to achieving the 10 percent economic growth rate anticipated by Vision 2030.

Climate change has also affected Kenya's energy supply. Hydropower potential has dramatically reduced during the past 20 years due to the destruction of water catchment areas. Climate change is likely to worsen the situation as it will result in prolonged droughts which will see water levels in the generating dams recede further. The country currently relies on hydropower for nearly 70% of its electricity. Further, extreme weather events such as rainstorms will destroy the energy generation and distribution systems (SREP, 2011).

Under the mitigation strategies contained in the National Climate Change Response Strategy, it was identified that the Green Energy Development Programmewill seek to take advantage of Kenya's abundant renewable energy resources. The highest geothermal steam reserves that have not been tapped are equivalent to 7000 MW (SWERA, 2008). The north-eastern parts of the country are ideal for wind power generation, with Class I wind1 turbines. The arid and semi - arid areas have long hours of sunshine throughout the year, making them conducive for solar energy capture and utilization.

From the SWERA report it was noted that some of the main challenges facing the energy sector in the country today include the diminishing biomass resources (encroachment on the water catchment areas (forest) to create land for farming), over reliance on importation of crude oil, an overstretched power transmission and distribution network and limited priority given to renewables.

The energy from the sun drives almost every known physical and biological cycle on the earth's system. Solar energy is environmental friendly (there is no production of carbon dioxide), abundant fuel and also saves on foreign exchange. User installed solar systems provide electricity to the owner and protects the owner from grid problems such as blackouts, and electricity price hikes. Also, solar equipment typically last for long, 25 – 30 years with minimal maintenance (Asplund, 2008)

For any solar energy applications, knowledge of solar radiation incident on a horizontal or inclined surface is required (i.e the knowledge is used in design and performance evaluation of both the solar thermal and photovoltaic systems) and this calls a complete study of solar radiation incident in any given locality. Many renewable energy technologies (RETs) such as solar ovens and PVs have been installed in some areas in Kenya (Hankins & Muiruri, 1991; Acker & Karmmen, 1996). However, these systems have been installed using insufficient data or no data at all apparently because there is no detailed information on the solar energy resource in the country. The result has been that many of them have not performed to the owner's expectations. For proper performance, the following need to be known beforehand:

I. The magnitude of the available resource.

II. Temporal and spatial characteristics of the available resource.

This information enables one to select or use a system that will operate well at all specific sites. This forms the basis for this research as it seeks to provide reliable information on the availability of the resource in the region (Thika – Nairobi area).

1.1.1 The solar radiation

The average solar radiation emitted by the sun is known to reach the outer atmosphere at the rate of about 1.367 kW/m^2, the value is called the *solar constant* (Duffie & Beckman, 1991). Total emission of the sun is about 3.7×10^{26} W/s. This radiation may be divided according to its spectral distribution into UV, visible and near IR, the latter two account for about 90% of the total emission (Stevovich, 1974). The atmosphere distorts the solar radiation and alters the wavelength distribution; also the solar energy actually reaching the ground varies with latitude, season, time of day and other factors such as topography, meteorological elements, atmospheric dust and contamination. The radiation available on the ground is composed of beam or direct radiation and diffuse radiation, producing half of the available energy. There is also solar reflected by the earth's surface, and long-wave re-radiation such as nocturnal radiation which is particularly significant for some cooling purposes. The direct and diffuse radiations reach some 3.14×10^7 W/m^2/day in sunny locations; it varies greatly and in any case is characterized by a low density energy (Hankins, 1995).

Total solar radiation reaching the earth's surface amounts to about 3.4×10^{24} W/year based on 62.5% transmission through the atmosphere. The present input to the world's human energy system is about 1.1×10^{20} W/year. The current utilization is 1/32000 of the energy received from the sun. Expressed in kilowatts, the average daily insolation, or primary incident on the atmosphere, amounts to 1.78×10^{14} kW for the whole globe (Karakezi &Ranja, 1997). This amounts to 1.5×10^{18} kWh/year. Of about 2.0×10^{13} kW falling on dry land, only 1×10^{9} kW has been utilized today through the use of solar thermal and photovoltaic systems (Twidell & Weir, 2005). The direct harnessing of solar energy, therefore, appears to be an alternative proposition, but still lack the complete knowledge to make effective use of solar energy. Therefore countries should invest in more on research in the field of solar energy (Duffie & Beckman, 1991).

1.1.2 Solar power applications

1.1.2.1 Solar photovoltaic technologies

Solar cells are usually classified into three main categories called generations. The first generation contains solar cells that are relatively expensive to produce, and have a low efficiency. They consist of Silicon or Germanium doped with either group III and V elements to form a pn – junction. This generation dominates the commercial market. Silicon cells have a quite low efficiency, andvery pure silicon is needed. Due to the energy-requiring process of manufacturing silicon, the price is high compared to the power output (Lasnier & Ang, 1990).

The second generation contains solar cells that have an even lower efficiency, but are much cheaper to produce, such that the cost per watt is lower than in first generation cells. These include: Amorphous Silicon Cells, Polycrystalline silicon on low cost substrate, Copper Indium diSelenide (CIS) Cells and Cadmium Telluride Cells, collectively with others called tandem solar cells(Santhanam, 2010).

The third generation cells are cells that have relatively high efficiency made from variety of new materials including nanotubes, silicon wires, and solar inks using conventional printing press technologies, organic dyes, and conductive plastics. This technology is in line with the goal to improve efficiency of solar cells already commercially available – by making solar energy more efficient over a wider band of solar energy and less expensive so it can be used by more and more people.

Solar cells are also grouped according to the materials they are made of: silicon solar cell (constructed with silicon mixed with impurities; this is called doping the silicon) (Lasnier & Ang, 1990), dye-sensitized solar cell – (low – cost solar cell belonging to the group of thin film solar cells. It is based on a semiconductor formed between a photo-sensitized anode and an electrolyte, a photo - electrochemical system) (Grätzel, 2003), polymer solar cell (flexible solar cell made with polymers, large molecules with repeating structural units, that produce electricity from sunlight by the photovoltaic effect. Polymer solar cells include organic solar cells, also called "plastic solar cells". Others include the currently more stable amorphous silicon solar cell, (Gang *et. al*, 2012) and grapheme (it is an allotrope of carbon in the structure of a plane of sp2 bonded atoms with a molecule bond length of 0.142 nanometres) based solar cells (graphene has great potential to be used for low-cost, flexible, and highly efficient photovoltaic devices due to its excellent electron-transport properties and extremely high carrier mobility) (Gu *et al.*, 2012).

1.1.2.2 Photovoltaic systems

A photovoltaic system comprisesa solar panel, storage system, charge controller, maximum power point tracker (MPPT) that is MPPT is a fully electronic system thatvaries the electrical operating point of the modules so that the modules are able to deliver maximum available power (Duffie & Beckman, 1991). However, different types of these components are made from various technologies which in effect affects the performance of a PV system. Knowledge of the performance of each component is vital in the design of the PV system. Secondly, the performance of the PV modules and other components varies from place to place depending on the weather conditions at the site. Outdoor tests performed over a period of time are the best way of evaluating the components, and hence, the system performance. Poor workmanship also affects the performance of photovoltaic systems (Akubia, 1998).

1.1.2.3 Solar thermal technologies

Solar thermal collectors are characterized by the US Energy Information Agency as low, medium, or high temperature collectors. Low temperature collectors are flat plates generally used to heat water to a temperature of not more than 100°C. Medium-temperature collectors are also usually flat plates but are used for creating hot water for residential and commercial use. High temperature collectors concentrate sunlight using mirrors or lenses and are generally used for electric power production through steam that drives the turbines. (Li jingcheng, 2010).

Solar thermo-electric technologies utilize energy from the sun in the form of heat to generate electricity (Karakezi & Ranja, 1997). The sun's rays heat a fluid from which heat transfer systems may be used to operate an engine which drives a power conversion system e.g. parabolic troughs have an operating temperature of up to 500°C and commonly drive a Rankine-cycle (steam turbine). They are commercially proven and reliable. The peak solar-to-electricity efficiency reaches 21%. Solar towers can be operated at >1000°C and are able to drive a Brayton-cycle (gas turbine) or even a combined Brayton-Rankine-cycle (Ahmed, 1994). In general, there are two types of collectors: Flat – plate solar collector and concentrating – type solar collector. Flat – plate collectors have no optical concentrator. Here, the collector area and absorber area are numerically the same, the efficiency is low, and temperature of the working fluid can be raised only up to 100° C. Concentrating or focusing collectors intercept direct radiation over a large area and focus it onto a small absorber area. Mirrors and lenses are used to concentrate sun rays on the absorber, and the fluid temperature can be raised up to 500° C. For better performance, the collector is mounted on a tracking equipment to always face the sun with its changing position (Kothari *et al.*, 2009). Flat plate collectors absorb both beam and diffuse radiation, and therefore still function when beam radiation is cut off by cloud. They do not require tracking of the sun, and require little maintenance. They are mechanically simpler than concentrating collectors (Duffie & Beckman, 1991). The simple collectors hold all the water to be heated. The more refined collectors heat only a little water at a time. The heated water is then accumulated in a separate storage tankreducing the heat lost from the whole system (Twidell & Weir, 1990).

1.1.3 Diffuse solar radiation (Hd)

The diffuse solar radiation H_d can be estimated by the empirical formula which correlates the diffuse solar radiation component H_d to the daily total radiation H. The correlation equation which is widely used was modeled by Page (1964);

$$\frac{H_d}{H} = 1.00 - 1.13K_T \tag{1.1}$$

Where H_d is the mean of the daily diffuse solar radiation and K_T is the clearness index (also referred to as the sky transmissivity).Another used correlation is due to Lui and Jordan (1960) and developed by Klein (1977), given as;

$$\frac{H_d}{H} = 1.390 - 4.027K_T + 5.53(K_T)^2 - 3.108(K_T)^3 \tag{1.2}$$

Clearness index is a measure of the degree of clearness of the sky. Clearness index is estimated by;

$$K_T = H/H_0 \tag{1.3}$$

where H is the global solar radiation and H_0 is the extraterrestrial insolation. The extraterrestrial solar radiation on a horizontal surface can be calculated using

$$H_0 = \frac{24 \times 3{,}600}{\pi} I_{sc}\left[1 + 0.033\cos\left[360\frac{dn}{365}\right]\right]\left[\left[\frac{2\pi\omega_s}{360}\right]\sin\phi\sin\delta + \cos\phi\cos\delta\sin\omega_s\right] \tag{1.4}$$

equation (Duffie & Beckman, 1991);

where I_{sc} is the solar constant equal to 1367 Wm^{-2}.

ω_s is the hour angle for horizontal surface and is estimated by;

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \qquad (1.5)$$

ϕ is the latitude and it is taken to be positive for the northern hemisphere and negative for latitude in the southern hemisphere.

δ is the declination i.e angular distance north or south from the celestial equator measured along a great circle passing through the celestial poles and is given by equation;

$$\delta = 23.45\sin\left[360\frac{284+\mathrm{dn}}{365}\right] \qquad (1.6)$$

where *dn* is the day of the year from January 1st to December 31st.

1.1.4 Theoretical modeling of solar insolation

Annandale (2002) modified the Hargreaves and Samani model (1982) of $T_t = k_{\mathcal{H}}\sqrt{\Delta T}$ to;

$$\mathrm{T_t} = \kappa_{\mathcal{H}}(1 + 2.7 \times 10^{-5}Alt)\sqrt{\Delta \mathrm{T}} \qquad (1.7)$$

where $\kappa_{\mathcal{H}}$ is an empirical constant with values of 0.16 and 0.19 for inland locations and coastal locations respectively. The coefficient 2.7×10^{-5} takes care of the reduced atmospheric height and *Alt* is the altitude and these are the two factors that were added by Annandale. T_t is the sky transmissivity which is given by;

$$\mathrm{H} = \mathrm{H_0T_t} \qquad (1.8)$$

1.1.5 Effects of the earth's revolution and rotation on insolation

The term rotation refers to the spinning of our planet on its axis. One rotation takes exactly twenty four hours and is called amean solar day**.** The earth's rotation is responsible for the daily cycles of day and night. At any one moment in time, one half of the earth is in Sunlight, while the other half is in darkness. The edge dividing the daylight from night is called the circle of illumination. The earth's rotation also increases the apparent movement of the sun across the horizon.

The equator is an imaginary line around the earth, halfway between the poles, and lies in a plane perpendicular to the axis. It is called the equatorial plane. This plane divides the earth into the northern and the southern hemispheres. The relative inclination of the axis of the earth to the sun during revolution is responsible for the annual changes in the height of the sun and causes the seasons.

The orbiting of the earth around the sun is called an earth revolution. This celestial motion takes 365.25 days to complete one cycle, which is responsible for the leap years. Further, the earth's orbit around the sun is not circular but oval or elliptical. An elliptical orbit causes the earth's distance from the sun to vary over a year. This variation in the distance from the sun causes the amount of solar radiation received by the earth to annually vary by about 6% (Muñoz,2009).

The variation in seasonal solar radiation availability at the surface of the earth can be understood from the geometry of the relative movement of the earth around the sun. The distance between the earth and the sun changes throughout the year, the minimum being 1.471×10^{11}m at winter solstice (December 21) and the maximum being 1.521×10^{11}m at summer solstice (June 21). The year round average earth sun distance is 1.496×10^{11}m. The amount of solar radiation intercepted by the earth therefore varies throughout the year, the maximum being on December 21 and the minimum on June 21 (Muñoz,2009).

The axis of the earth's daily rotation around itself is at an angle of 23.45 ° to the axis of its ecliptic orbital plane around the sun. This tilt is the major cause of the seasonal variation of the solar radiation available at any location on the earth. The angle between the earth-sun line (through their center) and the plane through the equator is called the solar declination angle; δ_s. The declination angle varies between -23.45° on December 21 to +23.45° on June 21 (Kothari, 2009). The solar declination is given by equation 6. In general, the declination is assumed to remain constant during a specific day (Padilla, 2011; Kothari, 2009; Duffie & Beckman, 1991; Hagen, 2011).

1.1.6 Factors affecting solar radiation

Solar radiation is affected by many factors such as weather conditions (e.g., cloud cover, haze, and water vapour), inclination of the surface, time of day, effects of local features (shading, topographical features, and urban landscapes), ecological and biological processes and human activities. The complex interactions of these factors affect the spatiotemporal variation in solar radiation patterns and make it difficult for it to be accurately estimated (Chow, 2008).

The distance from the sun determines the time the earth takes orbiting the sun ones and defines the length of one year as we know it (one planetary year). The distance also determines the solar energy flux density, the amount of solar energy delivered per unit time per unit area, which decreases with increasing distance from the source. Because of the large distance from the sun, the solar radiation flux density at the top of the atmosphere of the Earth is weakened. The intensity of the radiation has not been reduced but rather spread over a larger area (Hagen, 2011).

The orbit of the Earth about the sun is elliptic and the eccentricity is a measure of how much the elliptic orbit deviates from a circle. Parameters of the rotation of the Earth and their relationship to the orbit, also affect the amount of solar radiation received at the surface (Li jingcheng, 2010).

The seasonal variation of insolation at our latitudes, is mainly influenced by the angle between the axis of rotation and the normal to the plane of the orbit. This tilt is called the obliquity and is currently about 23.45° (Babatunde, 2012).

The point in the orbit of the Earth about the sun where the Sun-Earth distance is at a minimum is called perihelion and happens approximately at January 5. This is during the Southern Hemisphere summer and results in more insolation at the top of the atmosphere at Southern than in the Northern Hemisphere summer (Muñoz, 2009).

1.1.7 Energy extracted by a solar system

A solar powered system cannot convert all the energy at its absorbing surface. Depending on construction, photovoltaic panels can produce electricity from a range of frequencies of light, but usually cannot cover the entire solar range (especially, ultraviolet, infrared and low or diffused light) because of difference in their wavelength and hence the amount of energy they contain. Hence much of the incident sunlight energy is wasted by solar panels, and they can give far higher efficiencies if illuminated with monochromatic light. Therefore, another design concept is to split the light into different wavelength ranges and direct the beams onto different cells tuned to those ranges. This has been projected to be capable of raising efficiency by 50%.

Currently the best achieved sunlight conversion rate (solar panel efficiency) is around 17.4% in commercial panels typically lower than the efficiencies of their cells in isolation. The most efficient mass-produced solar panels have energy density values of up to 175 W/m^2. Solar thermal systems, (especially concentrating systems), give a maximum extractable amount of energy of 90% of that incident at the surface (Thomas *et al*., 1993).

1.2 Statement of the problem

Thika and Nairobi are among the fastest growing urban centres in both in infrastructure and population. That means that the existing electrical supply is strained because the electrical demands in the country outweigh the electrical supply. The government has also come up with regulations which stipulate that buildings should be fitted with solar conversion devices (called the green revolution). Measurement of solar radiation forms the basis in the assessment of the solar energy potential. Solar radiation data are available from Kenya meteorological station archives but there is lack of consistency (there are days with missing radiation data) in its recording and at times the equipment are not available to record the data. Most of the assessments that have been done relied on the data that had gaps and therefore empirical formulae were employed in the estimation of the missing data. The estimated sizes of solar panels and the complete systems (sold by the vendors/dealers) are done with no consideration of the available insolation in particular areas leading to the PV systems and solar thermo systems either under-performing or malfunctioning.

1.3 Justification

Kenya has been credited as being one of the forerunners in Africa in the use of solar radiation technologies with so many solar photovoltaic systems and solar thermal systems having been installed.However, most of these installations have been done without any knowledge of the insolation available. One of the major problem(s) in disseminating solar technology is the high initial capital costs and long pay-back periods. But it should also be noted that these technologies are environmental benign in terms of global warming or destruction of ozone. Solar devices have long life-spans since they have no moveable parts that can wear out. Good quality solar radiation data is important in the field of renewable energy with regard to both photovoltaic (PV) and thermal systems. Therefore it is prudent that solar radiation/insolation assessment will provide the much needed information. This will assist in doing the near exact sizing and costing of solar systems and also assist the government and architects in budgeting

1.4 Hypothesis

The solar radiation potential of the Thika – Nairobi area does not sustain the performance of solar photovoltaic systems and solar – thermo systems all the year round due to its variability.

1.5 Objectives

1.5.1 General Objectives

To assess the solar radiation potential of Thika-Nairobi area, to be used in sizing and costing of solar panels.

1.5.2 Specific Objectives

The specific objectives of this study are:

1. To collect and analyze solar radiation data from at least three locations within the Thika – Nairobi region (the Thika, JKIA and KMD stations) for a period of not less than six month.
2. To evaluate factors affecting insolation in the region.

3. To estimate collector size and cost in relation to the amount of the power they can produce.

CHAPTER TWO

2.0 LITERATURE REVIEW

According to the Sessional Paper number four of 2004 on energy, Kenya receives good all year round solar insolation estimated at 4-6 $kWh/m^2/day$ which is coupled with moderate to high temperatures. The Ministry of energy strategic plan 2008-2012, specifies that despite the fact that the country is endowed with significant amounts of renewable energy resources; few renewable energy resources in the country have been fully assessed, mapped and appraised for their technical and economic viability. If harnessed, these resources can play a significant role in the country's energy supply mix. Under the same ministry, the Scaling-up Renewable Energy Programme (SREP), Investment Plan for Kenya draft of May, 2011 also specifies that Kenya receives daily insolation of 4-6 kWh/m^2.

According to the SWERA report (2008), the maximum irradiance has never exceeded 1.356 kW/m^2 obtainable at the equator; the country is thus exposed to high radiation moderated by climatology and altitudinal differences. This was the first time detailed work on solar analysis of Kenya was undertaken using a higher resolution than the earlier available works(Thueri, 2008).

Barman (2011) outlined that Nairobi's annual irradiation is about 2,100 kWh/m^2 for a horizontal surface, which is higher compared to Gothenburg in Sweden that gets about 900 kWh/m^2. However, on a national level Nairobi receives lower level of annual solar insolation. Some places in the western part of the country receive an annual irradiation above 2,500 kWh/m^2 (Barman, 2011).

Okoola (1982) presented the spatial distribution of mean solar radiation potential in Kenya and examined the availability in relation to electrical energy demand for water heating in Nairobi and hence he deduced the sizes of solar energy conversion systems that would be required to meet this demand. In his work he observed that insolation increases from zero at sun rise and reaches its peak in the early afternoon (solar noon). The energy then reduces in intensity until it reaches zero after sunset.

The World Solar Power foundation in 1983, studied the insolation in Kenya. In their assessment, they concluded that the country's solar energy resources are, in general amongst the highest in the world at 5.5 kWh/m^2/day on average. They specified that some areas, mainly in the northern and eastern lowland regions have higher average insolation levels while the highland regions experience lengthy cloudy periods and associated lower insolation levels during rainy seasons (April to August). Nevertheless, this diffuse radiation can still be harnessed effectively (Newham *et al.*, 1983).

Ogallo and Runanu (1989) examined the seasonal power expectations at various locations in the country using daily radiation values. The study delineated the country into several homogenous solar energy zones. This forms a good basis for the planning of solar systems in the country. The practical use of any solar system however requires knowledge of the expected number of hours for operation in a given region/location.

In 1995, Hankins reviewed of the solar resources in the country. In his review, he specified that the country receives an average solar radiation of 700 W/$m^2$and mean sunshine duration of 8 hours. The sun shines all the year round except in the months of June and July (Hankins, 1995). In 1998, Mwangi evaluated the potential of the solar energy resource at the various conversion efficiencies of the solar energy conversion systems. His results show that production of electrical energy from solar power is viable so long as the electrical energy needs are below 1 kWh/m^2 daily (Mwangi, 1998).

Marigi (1999) did a site specific study of Kesses division of Uasin – Gishu district, where he carried out the measurements of global solar radiation, surface wind speeds, air temperature together with atmospheric pressure and quantities of fuel used and fuel technology devices employed. Results of the study showed that the mean solar values never exceed 972 Wh/m^2 and the values measured on the horizontal surface are greater than those on other slopes. In analysis of the countries insolation, data from collaborating station missed some values and that meant that the researcher used empirical formulae to estimate the missing values.

2.1 Study area.

The assessment was carried out in Thika-Nairobi area with the aim of establishing the insolation available, as this region has showed significant population increase, corresponding to increased demand for energy to match the required increase in production in the agricultural, industrial and domestic sectors. This has drawn a lot of attention to the use of alternative sources of energy.

2.1.1 The Thika area (Kiambu County)

The Thika agro – meteorological station is located within the Kenya Agricultural Research Institute (KARI)-Thika Branch, Central, Kenya, as shown in figure 1. Its geographical coordinates are 0°, 37° 41' East (maplandia.com).

The Thika station was taken to represent Kiambu County which is located in central Kenya. It borders Murang'a County to the north and north east, Machakos County to the east, Nairobi and Kajiado counties to the south, Nakuru County to the west, and Nyandarua County to the North West. The county has an area of 2,543.4 km^2.

The temperatures range from a minimum of 12.8°C to a maximum of 24.6°C with an average of 18.7°C. The average rainfall is 989mm per annum.

Data collection was done at the Thika agro – meteorological station which is near Thika town. Thika town is an industrial town which is 40 km north east of Nairobi. It has a population of more than 200,000 people as shown in figure 1 and is growing rapidly, as is the greater Nairobi area. Its elevation is approximately 1,631 m above sea level (GoK, 2011).

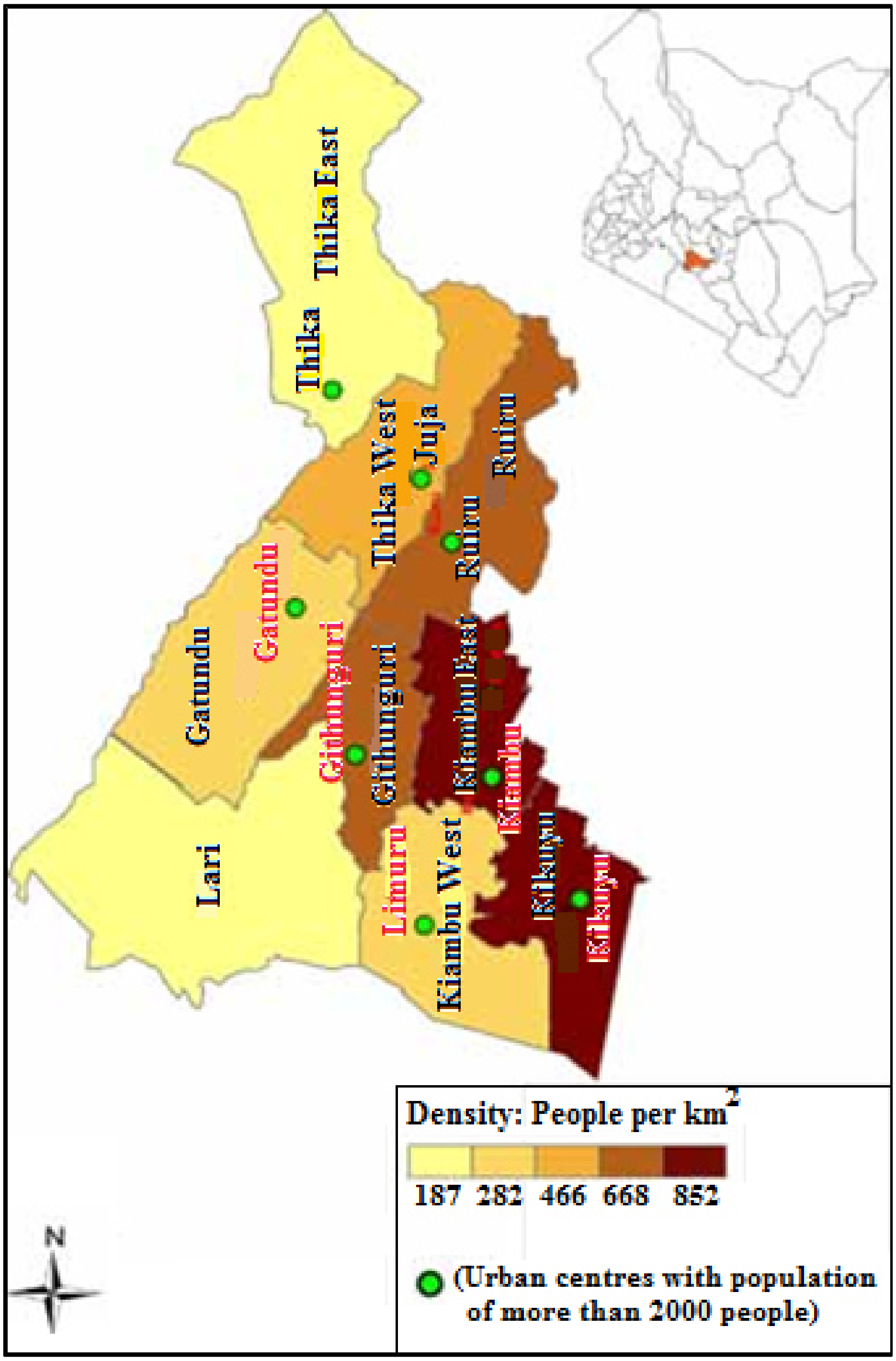

Figure 1 **A map of Kiambu County (GoK, 2011)**

2.1.2 The Nairobi area

Nairobi is located at 1°17′S, 36°49′E (1.283°S, 36.817°E) and occupies 684 km^2. Nairobi is situated between the cities of Kisumu and Mombasa. The Ngong hills, located to the west of the city, are the most prominent geographical feature of the Nairobi Area. Mount Kenya is situated north of Nairobi and Mount Kilimanjaro is towards the south-east.

At 1,795 m above sea level, Nairobi enjoys a moderate climate. Under the Koppen climate classification, Nairobi has a Subtropical Highland climate. The altitude makes for some chilly evenings, especially in the June/July season when the temperature can drop to 10 °C. The sunniest and warmest part of the year are from December to March, when temperatures average the mid-twenties during the day. The mean maximum temperature for this period is 24 °C (Opiyo, 2009).

There are two rainy seasons but rainfall can be moderate. The cloudiest part of the year is just after the first rainy season, when, until September, conditions are usually overcast with drizzle. As Nairobi is situated close to the equator, the differences between the seasons are minimal. The seasons are referred to as the wet season and dry season. Also, the timing of sunrise and sunset varies little throughout the year.

Like many other cities in developing countries, Nairobi has experienced very rapid population growth in the last 30 – 40 years. Table 1 illustrates this trend in population growth. At a population growth rate of 4.7 – 4.8% annually, the population of Nairobi grew from about 0.8 million in 1979, to 2.1 million in 1999 and 3.1 million in 2009. This is indeed a very high rate of population growth rate compared to an average of 3.4% annually for cities in developing countries and 1.8% for the world urban growth rate (Mairura, 2011)

Table 1 Table showing the population growth in Nairobi over the years

Year	1969	1979	1989	1999	2009
Kenya	10, 942,705	15,327,061	21,445,636	28,686,607	38,610,097
Nairobi	509,286	827,775	1,324,570	2,143,254	3,138,369

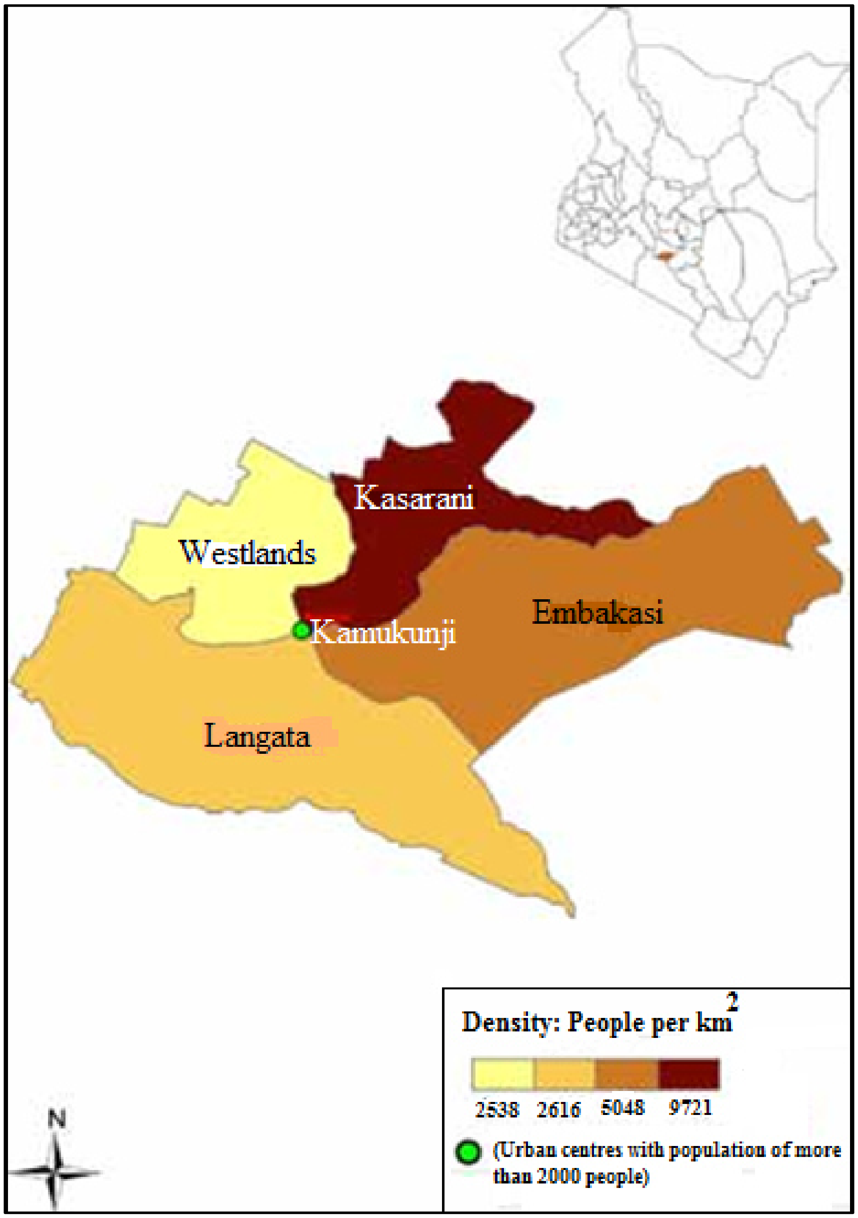

Figure 2 A map of Nairobi county (GoK, 2011)

As a desire for higher standards of living grows in a previously undeveloped society, so does its energy demand increase, per head of population. The state of development of a nation can be judged from the proportion of its people which lives in urban areas. Another telling indicator of material development is the usage of energy per head. (Brinkworth, 1972)

CHAPTER THREE

3.0 MATERIALS/ METHODOLOGY

3.1 Introduction.

In this assessment two instruments i.e. the Gunn – Bellani and the pyranometer were used in data collection. Despite the fact that their units of measurement were different (the Gunn – Bellani measures radiation in terms of the amount of liquid distilled while the pyranometer measures radiation in terms of number of counts per unit time), the data was converted and recorded in $MJ/m^2/day$. The data collection was done at Dagoretti Corner (Kenya Meteorological Department headquarters). There was also corroboration of data from JKIA and Thika Agro-meteorological station. At Dagoretti corner the collected data was for both global and diffuse solar radiation while for both JKIA and Thika agro-meteorological stations, only global solar radiation was recorded. This is because the Gunn-Bellani can only record global solar radiation while the pyranometer at the Dagoretti Corner had two sensors, one meant for global solar radiation and the second sensor was specifically meant for diffuse solar radiation.

Diffuse solar radiation for JKIA and Thika agro-meteorological stations were estimated using equation 1.1. The values for the diffuse solar radiation were useful in the calculation of the contribution of the diffuse solar in the whole spectrum of global solar radiation.

In order to achieve the research objective, the research methodology of this assessment was carried in three phases. The first phase involved data collection, which was done at the KMD and installation of a mobile station at the JKUAT. Recording of data was done for a period of six month running from beginning of May to the end of October of 2012.

The second phase involved organizing of data and analysis of the data using Microsoft excel (which included anadd in called SCC (Statistical Service Centre) stat). The software contained tools that were able to calculate measures of central tendency and plot graphs and on the graphs plotted the data limits were indicated and also some points marked as outliers from the data used could be observed. The outlier points were used to calculate errors in the calculations. Third phase involved the use of the results obtained in the sizing of panels given specific energy requirements.

3.2 Instruments

3.2.1 Gunn – Bellani radiometer

The instrument consists of a blackened hollow copper sealed to the end of a burette tube as shown in Figure 3.

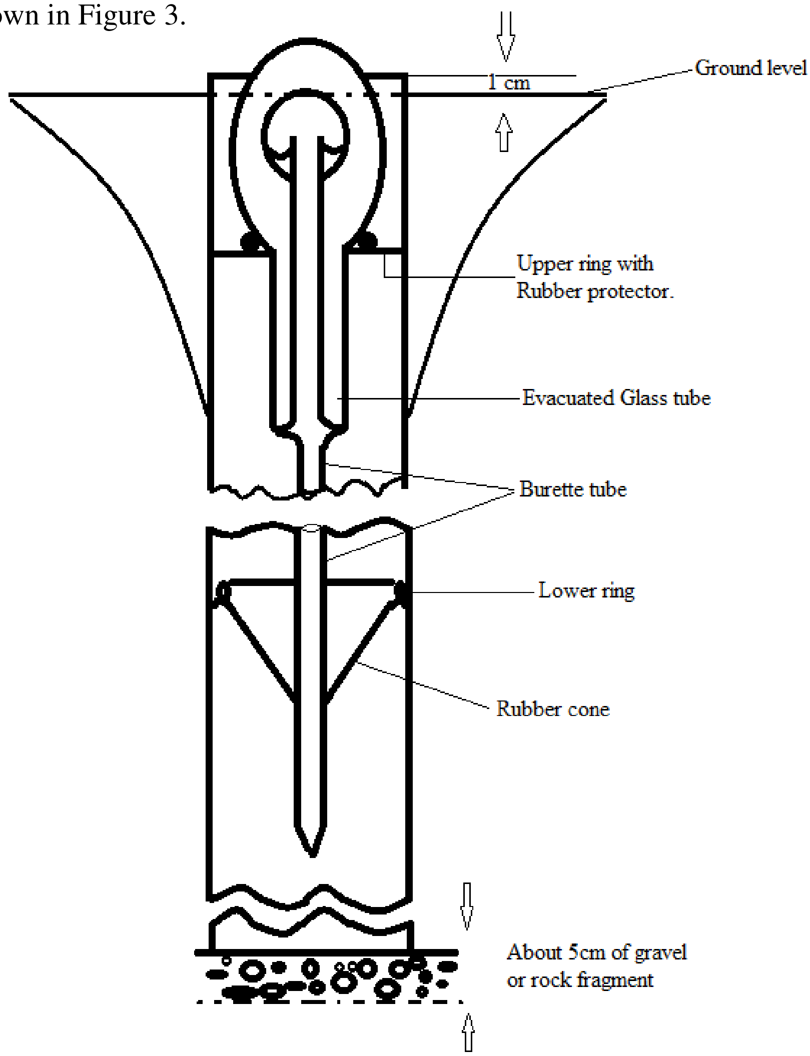

Figure 3 A sketch diagram of the setting of the Gunn – Bellani radiometer

The tube extends a considerable distance inside the copper sphere thus allowing about 40 ml of distilled water to be retained within the sphere. The sphere and burette form a sealed system in which the air pressure has been reduced to about one third the normal pressure at MSL (mean sea level). A large fraction of the incident solar radiation falling on the sphere is absorbed, and raises the temperature of the water quickly to its boiling point which is about 70°C under the reduced pressure. The vapour flows down the burette tube and condenses on the sides. The amount of water transferred by distillation in any given period of time is a measure of the amount of radiation received in that time. The sphere and top part of the burette are enclosed in an evacuated glass bulb to reduce heat transfer to or from the sphere by conduction and convection, and the whole instrument is mounted upright within a cylinder sunk in the ground to keep the lower end of the burette tube cool.

3.2.2 Exposure and Installation

The instrument was exposed in an open situation similar to that required for the sunshine recorder. It had an unobstructed "view" of the sun and sky throughout the day. Care was taken that the shadows of other instruments within the enclosure did not fall across the radiometer at any time of the day. In addition, the shadows of people moving or working within the enclosure were not allowed to fall on the instruments for any appreciable length of time. The cylindrical housing was sunk vertically in the ground with the rim 1 cm above the surface. The surrounding surface was of grass and was kept closely mown, watered in the dry season. The whole housing was made with an auger of suitable diameter and it was deep enough as to allowa 5 cm layer of coarse gravel below the cylinder to assist the free drainage of rain water.

Inside the housing, there were two metal rings, the lower which carried a rubber cone to centralize the burette. The upper ring carried a washer with a rubber protector on the inside. This supported the glass sheath at the top of the instrument at the correct level. The inside of the cylinder down the upper support was painted black so as to absorb the incident radiation falling on it.

3.2.3 Setting and Reading the Instrument

The instrument should be read and set once daily, after dusk and at times just before dawn. At agro – meteorological stationshowever, the time for reading and setting at 0900hrs local time.

The radiometer was inverted so that almost all the water runs into the copper sphere. The burette reading of the remaining water was taken, holding the instrument with the water meniscus at eye level. The reading wasalways between 0.0 and 2.0 ml. At times the readings were not in this range and therefore more water from the reservoir was allowed to flow to the burette to get the reading within this range. This was the zero reading. The instrument was then placed carefully within the mounting.

At the scheduled time, the instrument was withdrawn carefully and the burette reading was taken as before. The difference between that and the previous reading gave the amount of water distilled during the day. The radiometer was then reset and replaced.

3.2.4 Precautions

The instrument made largely of glass had to be handled carefully. It was extremely vulnerable, in its exposed position.The observer has always to be aware of this when walking within the enclosure.

3.2.5 Calculation of radiation

Each Gunn –Bellani radiometer was carefully calibrated against a standard electric radiometer before issue and each had its own calibration equation of the form:

$$R = Ad + B \tag{3.1}$$

$R =$ Radiation intensity in $\mathrm{cal/cm^2/day}$

$d =$ Amount of water distilled in ml.

A and B are calibration constants.

It was therefore of the utmost importance that records carried the NUMBER of the instrument etched on the glass sheath. Without these constants, the records would have been useless. The radiation was usually in cal/cm^2/day but the values were converted to MJ/m^2/day by multiplying by a factor of 0.042791 MJ/m^2/day per cal/cm^2/day (Mwebesa, 1980). The other instrument used in the data collection was a pyranometer.

3.3 The pyranometer

The pyranometer has a black ceramic (Al_2O_3) disk which acts as sensing element and absorbs radiant energy. One hundred thermocouples are imprinted on this disk. Only the border of the disk is in good thermal contact with the pyranometer body, which acts as a heat sink. The one hundred cold junctions are located near this border. The one hundred hot junctions are located near the centre of this disk in a rotationally symmetric arrangement. When the pyranometer is irradiated, the absorbed energy results in a heat flow from the centre to the edge of the disk. The temperature difference across the thermal resistance of the disk creates an electromotive force which is then measured by a voltmeter. The two glass domes shield the detector as shown in Figure 4. The instrument measures global solar radiation but when shielded as in Figure 5, it can be used to estimate diffuse solar radiation (Stoflel & Wilcox, 2004).

Figure 4 Unshielded pyranometer for global solar radiation (WMO, 2008).

Figure 5 Shielded Pyranometer for diffuse solar radiation (WMO, 2008)

The pyranometer voltage was converted into counts by the integrator. To convert counts to solar energy in terms of MJ/m^2, the following relation was used:

$$\text{Solar energy}(MJ/m^2) = R \times L \tag{3.2}$$

where R is the amount of radiation in terms of counts and L the instrument constant given by $L = 1.022 \times 10^{-3}$ MJ/m^2/count.

The quantities of the solar energy recorded were then converted to the power density (the solar output on the earth) by dividing by the time taken to collect the data and the Kilowatt-hour. Power density units are kWh/m^2/day.

3.4 Data processing and analysis

3.4.1 Quality control tests for the radiation records

Quality of meteorological records was tested before they were used in this study. Quality control involved detection of errors in the data to ensure that the data sets and archives were near error free, complete and had been recorded according to international standards.

The major sources of errors in the climate data were generally associated with: instrumentation; station condition; observation and recording; transmission; coding and decoding and processing of the data. The instrumentation errors were generally related to the conditions and intrinsic accuracy of the instrument. Variation in the station condition like exposure may change the microclimate of the station. Such changes induced errors in the climate data (Marigi, 1991; 1999).

Generally observation and recording errors are associated with misreading of the scales, failure in the recorders, sensors, clock devices, misinterpretation of the units. Transmission errors result from the corruption of the telemetry data, failure of the transmission and other errors connected with the transmission systems. Coding errors originated from mistakes arising from the coding and decoding of the records, while entry errors were wrong data inputs. The processing errors on the other hand associated to faults in the computer hardware, software used for data processing and use of incorrect background information during the processing of the data. In this study two methods were used namely, mass curve analysis and the box plot methods.

In the study most errors were found in the archived data. The data obtained from the archives had missing values and that is why empirical formulae were used to fill in the gaps before extrapolation of the data obtained from the assessment. The extrapolation was meant to give trends on solar radiation in the area over the years and also annual and monthly trends. Use of the box plot brought out the outliers and also the use of the equation 7 and equation, the values were corrected and thus reducing on the errors in the measurements.

It should also be noted that the three data collection points are close i.e. the JKIA has a geographical location of 1° 19’ South, 36° 55' East, Kenya Agricultural Research Institute (KARI)-Thika Branch, geographical coordinates are 0°, 37° 41' East and Dagoretti station has the location (01° 18' S, 36° 45' E) (maplandia.com)**.**The close proximity to each other was the reason the region was considered as one. There is little variation in the climatic conditions between the three stations because of the small variations in the altitude of the three stations.

3.4.1.1 Mass Curve Analysis

The method of simple mass curve analysis used cumulative values of observations plotted against time as indicated in the table 2:-

X_t – represents observed values.

Y_t – represents cumulated values of the observations.

Table 2 Table showing the tabulation of Xt and Yt

Time, t(yrs)	1990	1991	1992	1993	2020
Value, X_t	X_1	X_2	X_3	X_4	X_n
$\sum X_t = Y_t$	X_1	X_1+X_2	$X_1+X_2+X_3$	$X_1+X_2+X_3+X_4$	$X_1+\ldots+X_n$

The plot of Y_t against t gives the mass curves for the location. For homogeneity, all Y_t values clustered about a single straight line. More than one line could be fitted to the Y_t scatter diagram if the X_t values are heterogeneous. Under this study, mass curves were plotted for yearly total radiation (Marigi, 1999).

3.4.1.2 The Box Plot

In descriptive statistics, a box plot is a convenient way of graphically depicting groups of numerical data through their five – number summaries: the smallest observation (sample minimum), lower quartile (Q_1), median (Q_2), upper quartile (Q_3), and largest observation (sample maximum). A box plot may also indicate which observations, if any, might be considered outliers (Massart *et. al.*, 2005)

Box plots display differences between populations without making any assumptions of the underlying statistical distribution: they are non – parametric. The spacings between the different parts of the box help indicate the degree of dispersion (spread) and skewness in the data, and identify outliers. Boxplots can be drawn either horizontally or vertically.

The box plot is a quick way of examining one or more sets of data graphically. Box plots seem more primitive than a histogram or kernel density estimate but they have some advantages. They take up less space and are therefore particularly useful for comparing distributions between several groups or sets of data. Choice of number and width of bins techniques can easily influence the appearance of a histogram, and choice of bandwidth can easily influence the appearance of a kernel density estimate.

3.5 Prediction of diffuse solar radiation (H_d)

Diffuse solar radiation is important and its variability should also be studied. Unfortunately there is little data available for the diffuse solar radiation and hence it has to be estimated. In this analysis the correlation equation 1 was used. Using measured global radiation (H) and estimated values of extraterrestrial solar radiation (H_0) (estimated from equation1.4), the clearness index was calculated using equation 1.3. The clearness index forms an important component of equation 1.1.

3.5.1 Filling missing data through modeling

Before applying equation 1.7, the coefficient k_H, complete data sets from the three stations were used to validate the value. From the average values, it was found that the value obtained agrees with the value that was given by Hargreaves and Samani (Annadale, 2002). The missing data sets were then estimated using equation 1.7. After filling the gaps, physical scanning was done for erroneous data. Using the box plot, outliers and erroneous values were found and corrected.

3.6 Measures of dispersion

Measures of dispersion generally quantify the general spread of the observed solar energy values about the mean (normal expectations). This information is essential if the available solar energy resources were to be effectively tapped for continuous applications and planning of supplementary energy resources. The most commonly used measures of dispersion include the coefficient of variation (δ_v), relative mean linear successive difference (δ_d), skewness coefficient, kurtosis coefficient and higher order moments. In the assessment the coefficient of variation (δ_v) was considered.

3.7 Estimates of sizes of solar power interceptors and associated costs

In order to determine solar power interceptor sizes and their associated costs for the area, two assumptions have been made:

i. That the available solar energy resources may be transformed (with minimal losses) to the electrical energy used to perform the various activities.

ii. That the electrical consumptions remain constant throughout the year.

In this study, the Renewable Energy Decision Method developed by the Working Group on Development Techniques , University of Twente, Netherlands (Marigi, 1999) has been adopted. The method makes quick and simple estimations of costs of solar panel sizes.

3.7.1: Estimation of Daily Energy Demand

The total daily electrical demand (E_d) is one of the factors, which determines the size and type of the optimal energy source. This is dependent on equipment used, the energy consumption of each apparatus and how long each apparatus is used per day. If batteries are used, 40% more energy is needed. This is due to losses during charging and discharging of the batteries. Hence E_d= total in kWh/day (without batteries) or E_d= 1.4% more in total kWh/day (if batteries are used).

3.7.2: Estimation of Battery Size and Cost.

The size of the battery storage depends on the number of days required to cover the energy demand if the energy source is not available (for instance the sun was not shining). Usually a period of two or three days can be considered. In this assessment, the two days were considered.

Number of days of storage: d.

$$\text{Size of storage: } E_s = d \times E_d \quad \text{(kWh)} \tag{3.3}$$

$$\text{Investment on batteries: Inv} = 100 \times E_s \text{ (US\$)} \tag{3.4}$$

where 100 is a constant and E_s is the size of storage (capable of taking care of the electrical needs for a particular day). Lifetime of batteries N = 5 (yrs) but can different for different manufacturers.

The choice of battery is limited by what is on the market and how much you have to spend. The choice of second – hand automotive batteries should be avoided, as their capacity would have greatly reduced by age and previous cycling. Battery voltage determines the system voltage.

3.7.3: Estimation of Solar Panel Size and Cost

From the results obtained on the amount of sunshine (daily, monthly, seasonal or annual average) in this assessment, a panel of a given size can be estimated using the method below so as to fulfill the daily energy demand of a given individual or household:

Average Insolation G in $kWh/m^2/day$.

$$\text{Size of Solar System: } A = 12 \times \frac{E_d}{G}\ (m^2) \qquad (3.5)$$

Investment on solar system (Inclusive of control):

$\mathrm{Inv} = 500\$ \times A$ For $A>10m^2$

$\mathrm{Inv} = 1000\$ \times A$ For $1 \leq A < 10m^2$

$\mathrm{Inv} = 2500\$ \times A$ For $A<1m^2$

3.7.4: Investment and Running Costs

Computation of a cheaper energy option takes into consideration the investment, the running costs and the expected lifetime. To make an easy and fair comparison, the total cost per year was computed consisting of investment costs (Interest on the investment) and running costs (e.g fuel (petroleum products) and maintenance). The yearly investment costs were computed as follows:

$$\text{Investment costs} = \left[\frac{I \times \frac{d}{100}}{1-\left(1+\frac{d}{100}\right)^{-N}}\right] \text{US\$/year.} \qquad (3.5)$$

Where I is investment in (US$), N is the lifetime of investment in years and d is the discount rate as a percentage (interest less annual inflation)

For renewable energy option, the running costs are difficult to estimate. However, a certain percentage, up to a maximum of 3% of the initial investment each year is reserved for depreciation, maintenance and repair. For instance, if the initial investment is 50,000 US$, then 1,500 US$ (3%) is reserved per year. In this study, a value of 3% has been adopted.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION.

This chapter presents the results as obtained using the methodologies discussed in chapter three and the follow up discussion of the results. There were two sets of data: the data collected during the study period and the data that has already been collected and archived. The collected data was used to validate the archived data. Extrapolation of the results obtained, gave the trends in the solar radiation in the area of study (time series analysis of the solar radiation intensity).

4.1 Results from the mass curve analysis

Annual total global solar radiation values were used to come up with a cumulative frequency and together with the time, the mass curves were drawn for each station, as displayed in Figure 6.

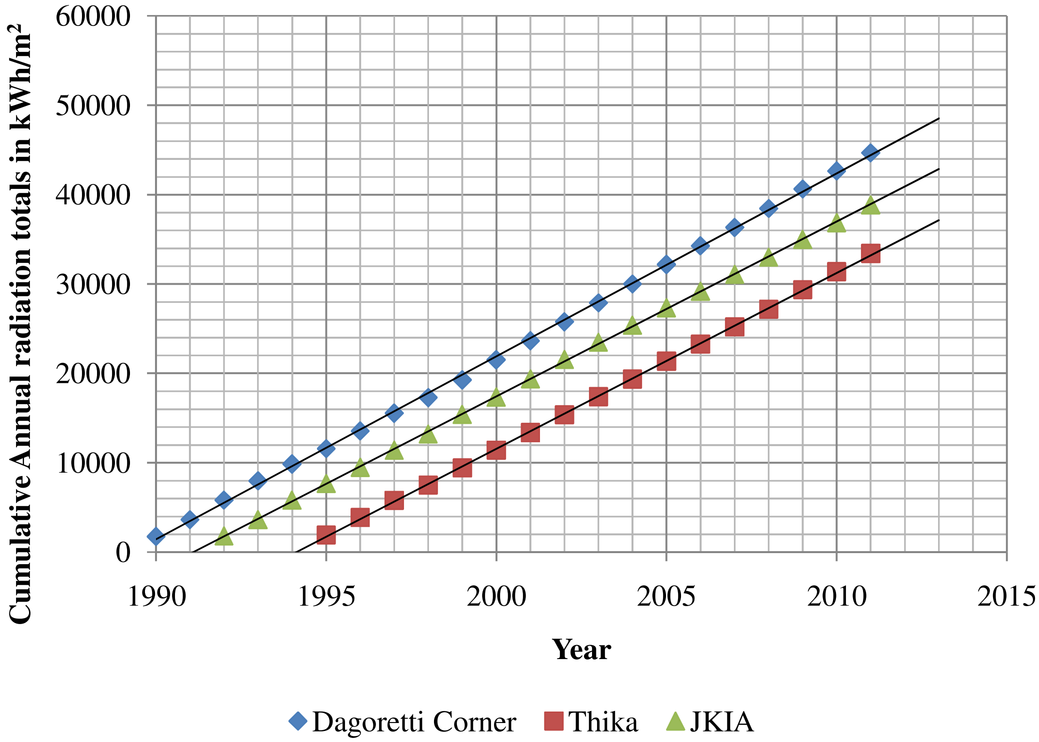

Figure 6 Mass curve analysis for Dagoretti Corner, Thika and JKIA

From figure 6 only a single straight line could be drawn for cumulative frequency of the data for each station. This indicates that the data samples were collected by the same instrument and at the same station and hence the data is homogeneous, for each station (Thika, Dagoretti Corner and JKIA). If more than one line (for each station i.e. Thika, Dagoretti Corner and JKIA) can be fitted to the Y_t scatter diagram then X_t values are heterogeneous.

4.2 Monthly global solar radiation trends

Figures 7, 8 and 9 represent the monthly trends in global solar radiation at Dagoretti corner, Thika and JKIA stations respectively. The initial plotting highlighted erroneous values which were corrected using the modified Hargreaves and Samani model represented by equations 7 and 8. The values of the extraterrestrial solar radiation used are presented in appendices 1,2 and 3.

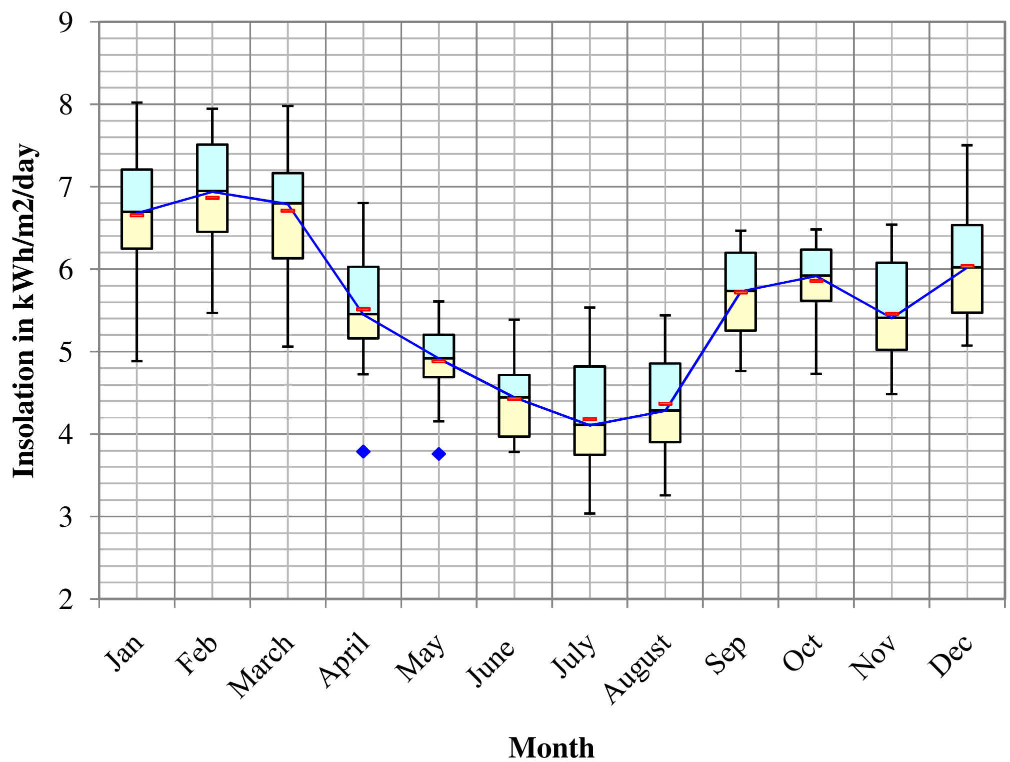

Figure 7 Monthly insolation trend for Dagoretti Corner station

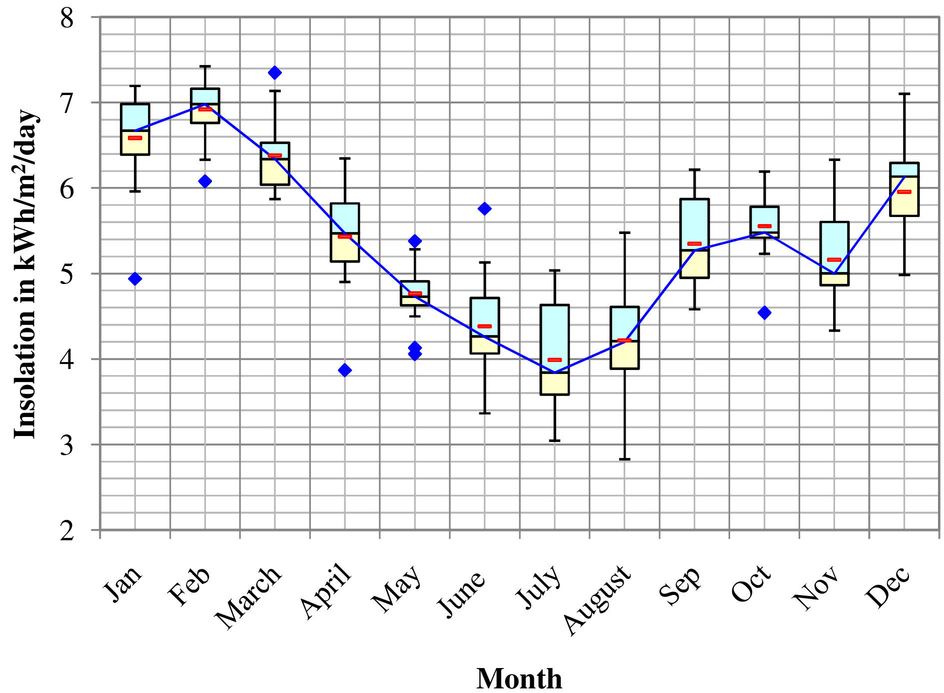

Figure 8 Monthly insolation trend for Thika agro-meteorological station

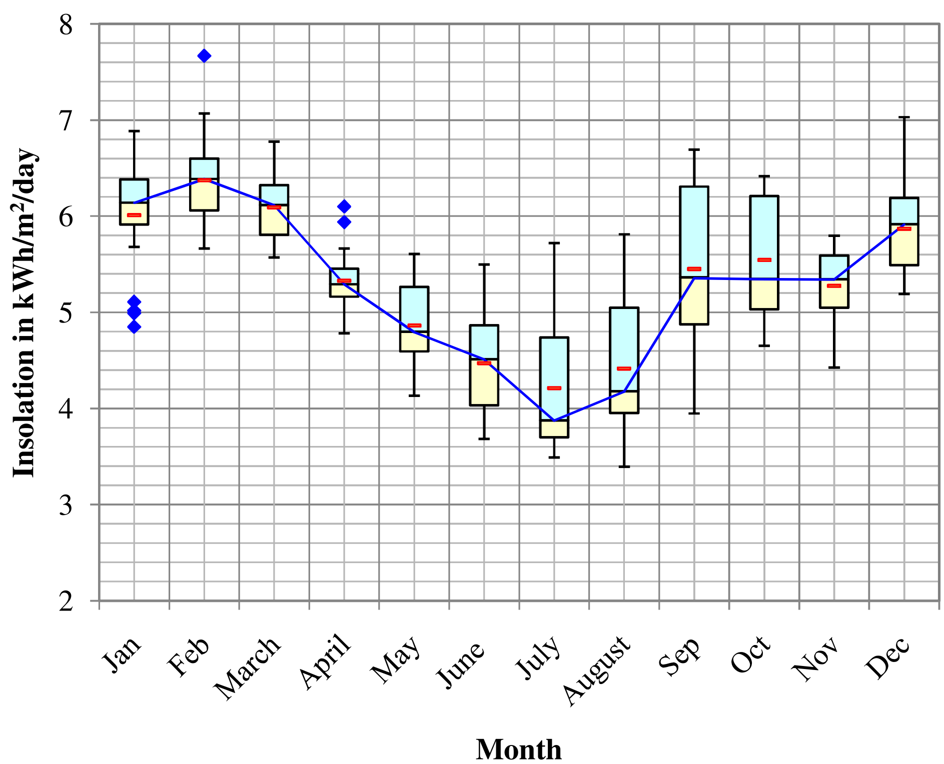

Figure 9 Monthly insolation trend for JKIA station

From the figures 7, 8 and 9, it can be seen that global solar radiation reaching these regions increased in intensity in January and reachedits highest peak value in February.Despite the intensity being high in March, it startedto decrease, a process that continued in the follow up months reaching the lowest intensity in July. The radiation intensity then started increasing again in August through September and reached another peak in October. This peak was lower than the one in February. It was also observed that the intensity slightly reduced in November and then increased during the month of December.

The lozenge signs (blue in colour) in figures 7, 8 and 9, represented the outliers. Figure 7 showed that there were only two outliers found in the data set which represented an error of 0.76%. In figure 8, there were nine outliers which represent 4.41% error in the data set whereas figure 9 had six outliers which represented 2.5% error in the measurement.

Peak radiation registered in the month of February as shown in figures 7, 8 and 9, was attributed to the fact that the month fell in the December to February season which usually is generally dry and less windy. The month of March marks the onset of the long rains season as well as the downward trend in the insolation. The rains begin in the mid of March and runs through to May. April therefore is the climax of the long rains with much of the rains falling in this month. The long rains season is characterized by the heavy clouds which adversely affect the amount of radiation received during this season. This was consistent with the work done by Hille in 2011. He observed that the amount of incident radiation was affected by the amount of cloud cover, (Hille *et. al*, 2011).

The cold season starting in June, runs through to August. The month of June experiences lower radiation expectations because it is in this month that the sun is farthest from the earth especially at the summer solstice (June 21^{st}). The lowest insolation level for all the three stations was registered in this season. The season normally characterized by lower tropospheric clouds (stratiform type) that are convectively stable coupled with low level temperature inversions especially over the highlands. The clouds obstruct the beam radiation with much of the radiation either absorbed by the water droplets or reflected back into the sky. In effect this causes July to have the least insolation.

September to November is the short rains period. The season is associated with abundant moisture, cloudiness and rainfall. Most of the short rains fall in the month of October, November and December (OND). From the figures 10, 11 and 12, lower insolation is experienced in October and November. This insolation is higher than the insolation in July which shows that the amount of obstruction to the radiation is lower than in July. The ministry of energy in 2002 specified that the solar energy received in most parts of the country averaged $350\ Wm^{-2}$ with the flux rising to $1000\ Wm^{-2}$ around noon. The ministry went further and noted that the intensity also varies throughout the year. It is highest in December to February when skies are clear and is lowest in June to August when skies are overcast (MoE, 2002). The results in this study agrees with these findings.

4.3 Time series analysis of the global solar radiation

The time series was meant to bring out the exact picture of how the global solar radiation has been varying over the years. In this case, archived data was used. The main purpose of the time series analysis was for projection purposes in terms of planning for the solar radiation technology installation. The average annual daily global solar radiation values were calculated and used in this analysis. The graphs below represent variability of the global solar radiation for the Dagoretti corner, Thika and the JKIA stations respectively.

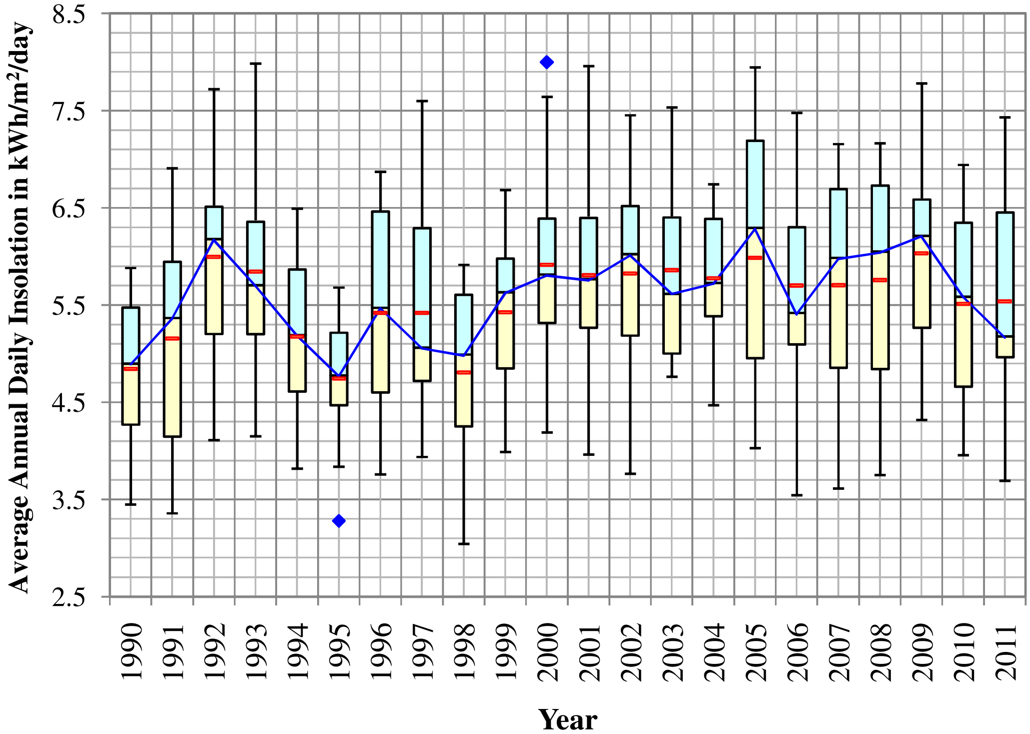

Figure 10 Annual global solar radiation trend at the KMD station

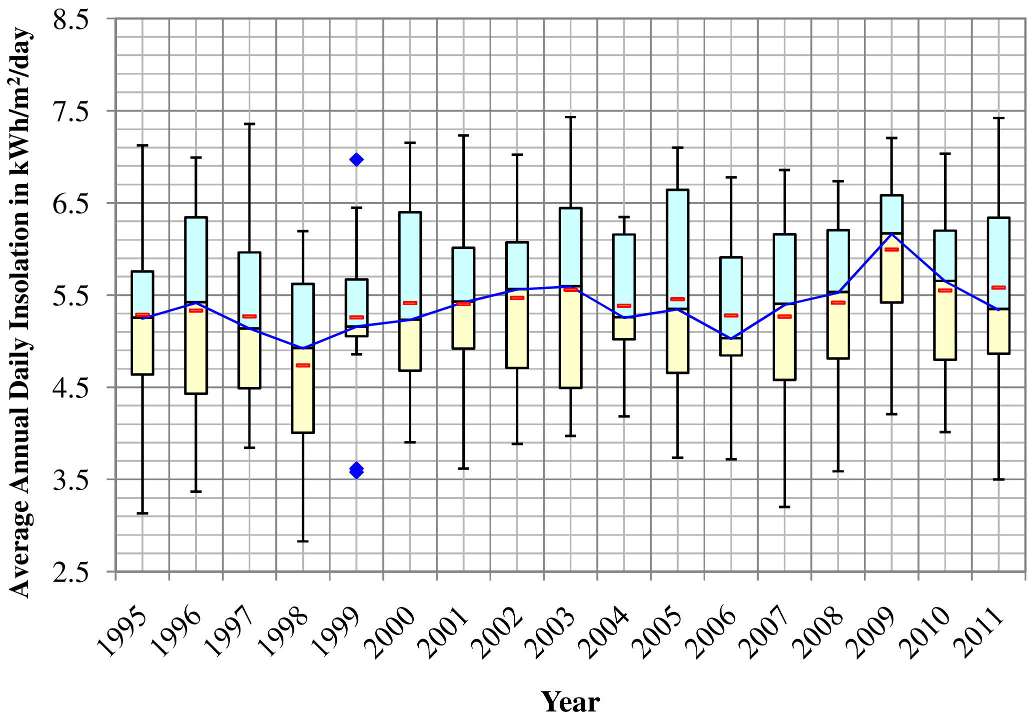

Figure 11 Annual global solar radiation trend at the Thika station

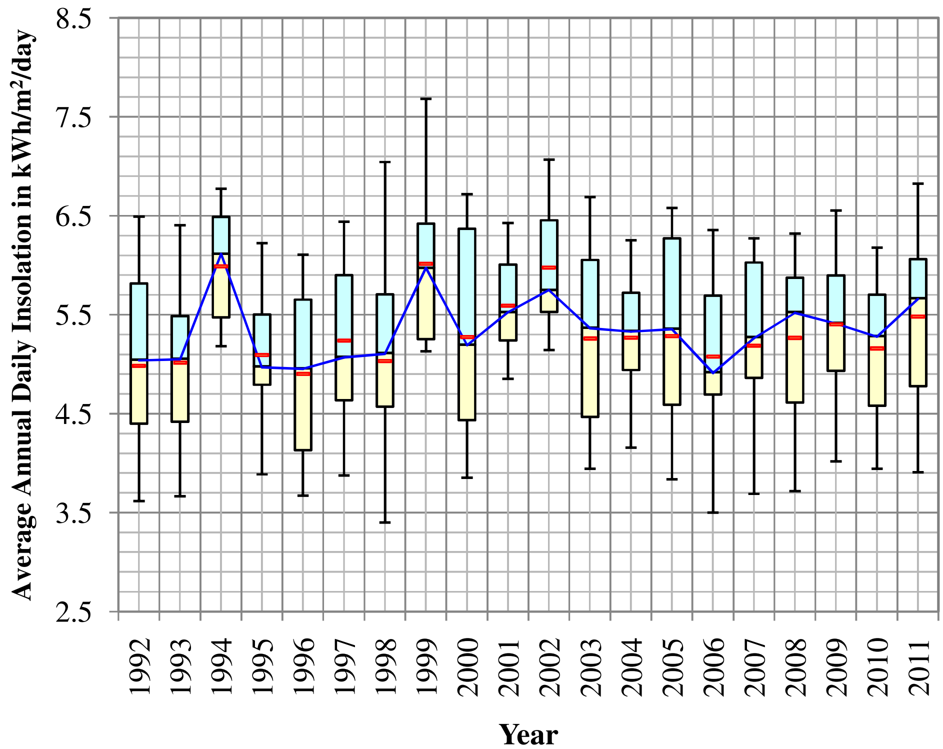

Figure 12 Annual global solar radiation trend at the JKIA station

From figure 10, peaks can be noted in the following years: 1992, 1996, 2000, 2002, 2005 and 2009. In figure 11, peaks can be noted in the years: 1996, 2003, 2005 and 2009 while in figure 12, the peaks can be seen in the following years: 1994, 1999, 2002, 2005 and 2008. From the three figures, it can be noted that the average annual daily insolation ranges from 4 $kWh/m^2/day$ to 7 $kWh/m^2/day$. From figure 10, there were only outliers represented by two blue lozenges. This represented a 0.76% error in the calculation of the values of average annual daily insolation values. In figure 11, two outliers were found (represented by the two blue lozenges). They represented a 0.98% error in the calculation of the values of the average annual daily insolation values. Figure 12 had no outliers and hence there were minimal errors in the calculation of the average annual daily insolation values.

The peaks in the average annual daily insolation were recorded in the years the country experienced drought. From figure 10, it can be noted that the highest peaks were in the years 1992, 2005 and 2009. Other notable peaks were in the years 1996, 2000 and 2002. Figure 11, has the highest peak in the 2009. There are other peaks in the years 1996 and 2003. Figure 12 has peaks in the years 1994, 1999, 2002, 2005 and 2008. It is documented that these are years drought was experienced in Kenya (Huho *et.al*, 2011; GoK, 2012). Some of the droughts were mild while others were severe. The most notable droughts in the country were the droughts of the years 1999/2000, 2004/2005 and 2008/2009. There is a direct relation between the amount of radiation received and the increase in temperature. This can be attributed to the fact that with the existence of droughts, the skies are clear with no cloud cover allowing much of the beam radiation to reach the ground. The amount of moisture in the sky is normally reduced and therefore reducing the effect of moisture on the incoming solar radiation.

Dust particles normally scatter the radiation and are usually carried by the winds and once blown off the ground, these particles get suspended in the atmosphere. Less dust particles sent in the sky reduces the amount of scattering. This in effect allows more radiation to reach the surface.

Temperatures have increased significantly due to global warming as shown in the increase in the amount of insolation received and should be noted from figures 10, 11 and 12 that from the year 2000 the radiation intensity remained high due to the high temperatures. Generally from the graphs, the average annual daily insolation levels range between 4 kWh/m^2/day to 7 kWh/m^2/day. This value agrees with national average highlighted in the National Energy Policy, Sessional Paper No. 4 of 2004 on energy and also specified by Hille (2011). Newham (1983) found 5.5 kWh/m^2/day as the national average and therefore his value is within the range found in this study. Karakezi *et al.* (2006) also found Kenya's average annual daily insolation is 6.0 kWh/m^2/day. This average falls within the average arrived at in this study. Gichungi (2012) also found the national average as 4.5 kWh/m^2/day. The average given by Gichugi was lower than the averages from other researches despite the fact that it falls within the results obtained in this analysis. Solar and Wind Energy ResourceAssessment (SWERA) report of 2008, shows that the average annual daily insolation in the study area ranges from 4.5 – 4.75 kWh/m^2/day which falls within the range arrived at in this analysis.

Baanabe *et.al.*(2008) specify that all the countries in the East and Horn of Africa region enjoylong sunshine hours and have a daily average solar insolation of about 4.5–6.5 kWh/m^2. This result agrees with the finding in this analysis.

4.4 Monthly trend in diffuse solar radiation

Diffuse solar radiation forms part of the global solar radiation and that meant it was important that its variability needed to be studied. The diffuse solar radiation values were computed using equation 4. Figures 13, 14 and 15 represent how the diffuse solar radiation varies over the year.

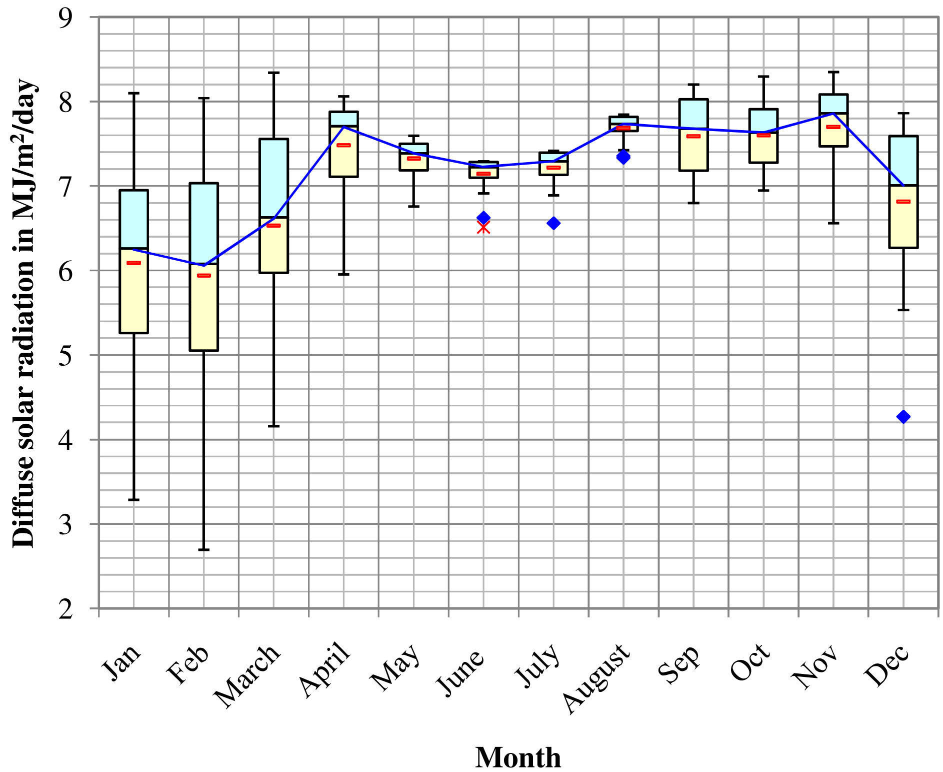

Figure 13 Average monthly daily diffuse radiation at the KMD station

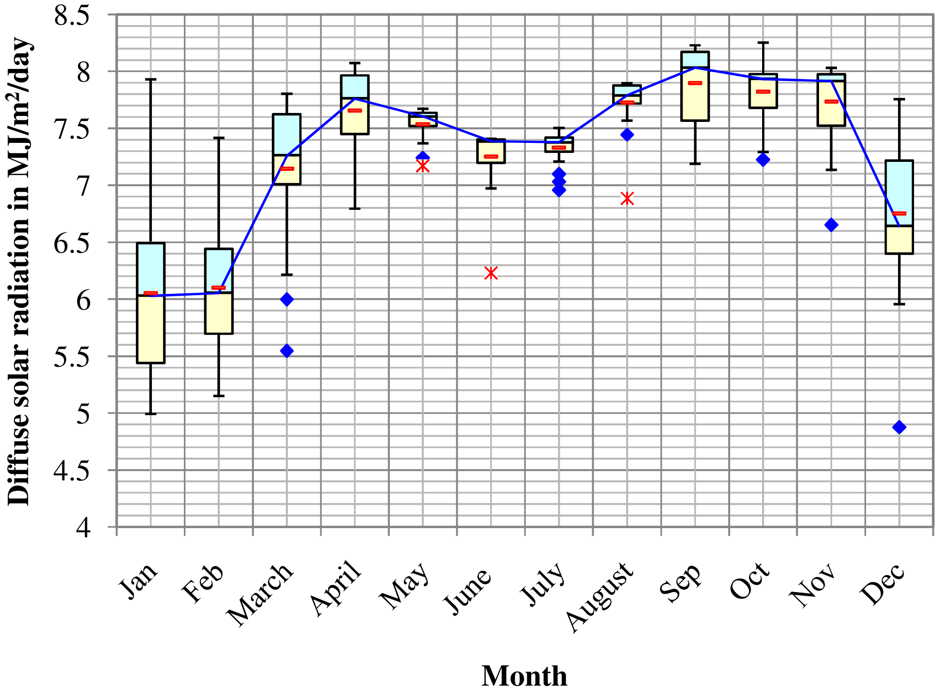

Figure 14 Average monthly daily diffuse radiation for the Thika station

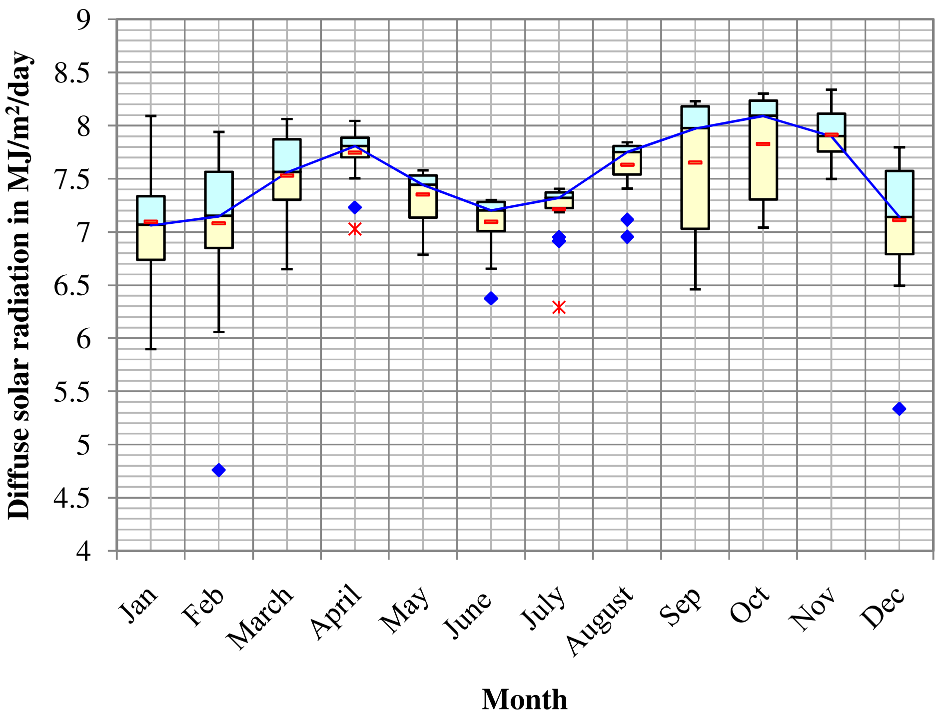

Figure 15 Average monthly daily diffuse solar radiation for the JKIA station

From the figures, the first peak diffuse solar radiation received was in April for all the stations. Dagoretti corner's other peaks were seen in August and November. Thika station had peaks in September and November while JKIA had only one other peak inOctober though the radiationin November wasstill high.

Using the outliers (represented by the blue lozenge signs and the red asterisk signs), the error in the estimation of diffuse solar radiation values for Dagoretti Corner station (figure 13) was 3.79%. Thika station (figure 14) had a 6.37% error in the estimation while JKIA station (figure 15) had 4.17% error in the estimation.

For diffuse radiation, highest intensity was recorded in April. This observation can be understood from the fact that this month falls in the long rains season and the season is characterized by heavy cloud cover. The clouds reflect the beam radiation. The moisture absorbs part of the radiation and much of what is received is diffuse solar radiation after scattering has taken place. One other reason that could be leading to the high diffuse solar radiation is the closeness of the sun to the equator. The sun is normally overhead at the equator on March 21st. The expected radiation i.e. the extraterrestrial solar radiation is higher in the month of March and April. Therefore as much as we have the obstruction of the beam radiation more radiation will find its way down in the form of diffuse solar radiation.

The sun is overheard the tropical of cancer on June 22nd and this is the onset of the cold season in the country. At this point, the radiation coming in is spread over a larger area and therefore this affects both the beam and diffuse solar radiation due to the cosine angle of the solar radiation. The cold season is normally characterized by lower tropospheric clouds (stratiform type) that are convectively stable coupled with low level temperature inversions especially over the highlands. The low clouds causes depletion of the radiation reducing the amount of diffuse solar radiation received.

The sun is overhead the equator again on the September 21st and from the figures 13, 14 and 15, it can be noted that the amount of diffuse solar radiation increases. This is because, the angle at which the rays strike the surface close to the equator reduces and that means that in the area of study, solar radiation is more concentrated than before. The last peak intensity appears in October and November. The two months fall in the short rains period with the rains falling mostly in the month of October, November and December (OND). The short rains season is associated with abundant moisture, cloudiness and rainfall. The clouds obstruct much of the beam radiation and the moisture absorbs the beam radiation. The diffuse solar radiation is received after much of the scattering taking place in the sky.

4.5 Time series analysis of the variability in diffuse solar radiation

The average annual daily diffuse solar radiation values were computed and used to come with the graphs in the figures 16, 17 and 18.

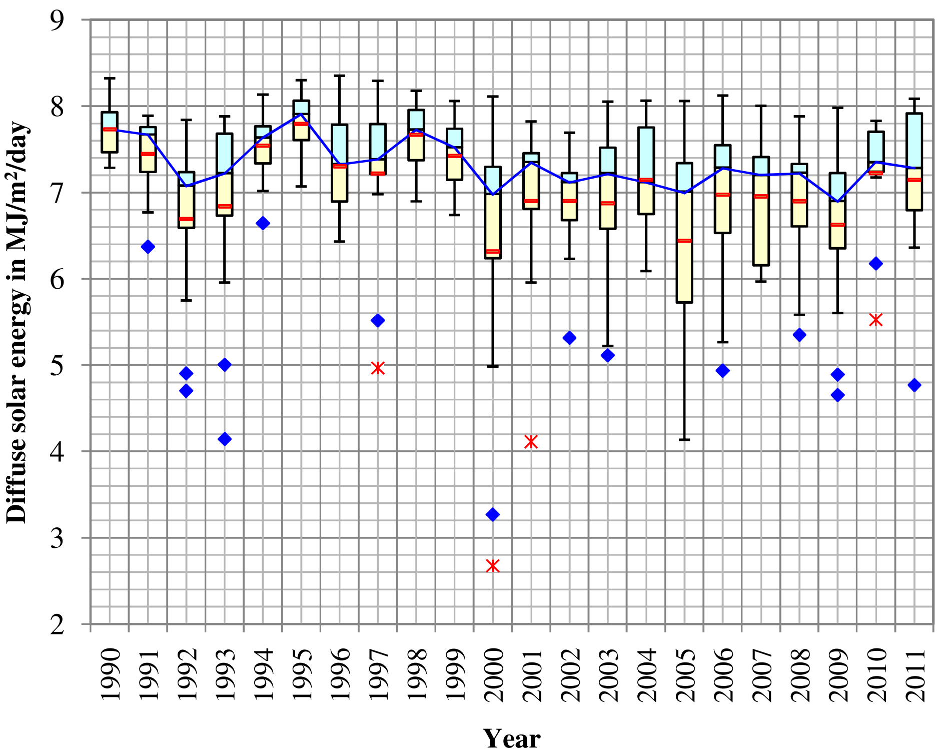

Figure 16 Variability in the diffuse solar at the KMD station

From the graph it was noted that the lowest diffuse solar radiation was recorded in the following years: 1992, 2000, 2005 and 2009. Peaks were noted in years 1995 and 1998. It was also noted that generally, the diffuse solar radiation reduced with higher values in the 90s but lower values after the year 2000. Erroneous values were noted on the figure (shown by the blue lozenges and red crosses). In total there were

17outliers which represented a 7.58% error in the estimation of the diffuse solar radiation values.

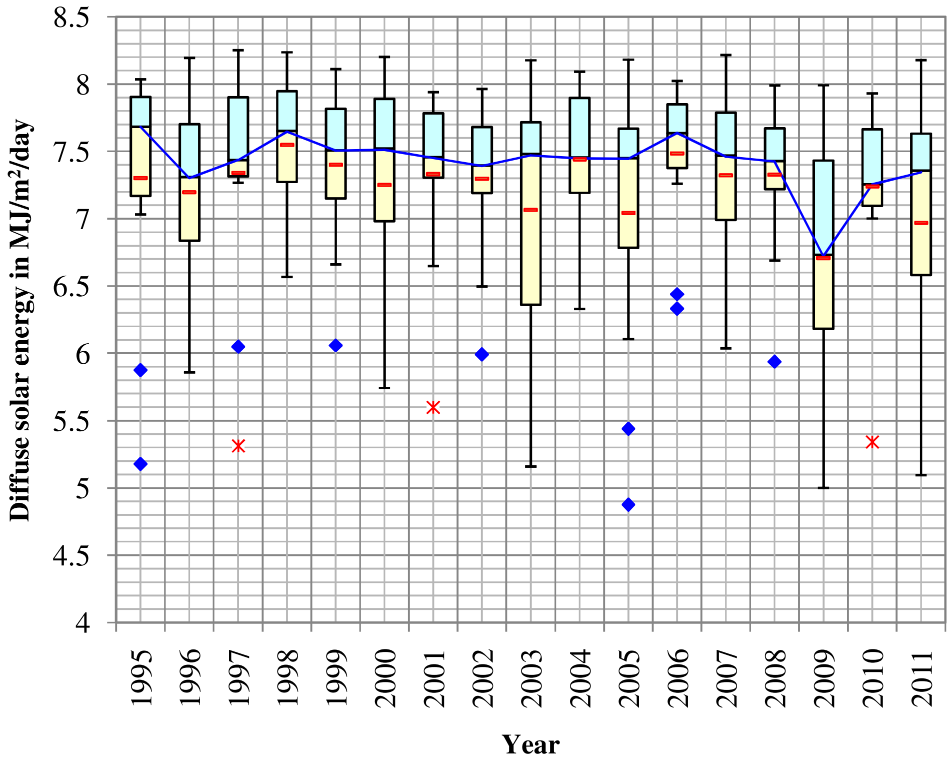

Figure 17 Variability in the diffuse radiation at the Thika station

From figure 17, the lowest diffuse solar were recorded in the year 2009, with peaks noted in the years 1998 and 2006. Figure 18 had the lowest diffuse solar radiation noted in the years 1994, 1999 and 2002. The peaks in the figure were noted in the years 1998, 2004 and 2010. Figure 17 had 13 outliers, three of which are extreme outliers i.e. they fall outside the data limits. All the outliers represented a 6.37% error in the estimation of the diffuse solar radiation values for the Thika station.

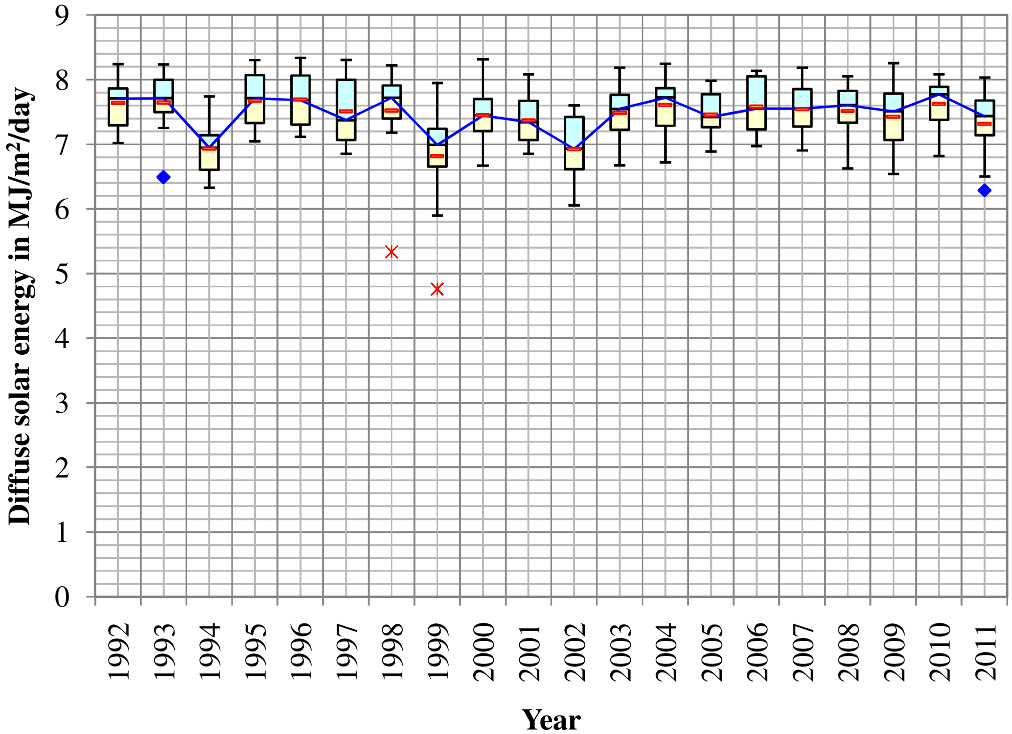

Figure 18 Variability in the diffuse radiation at the JKIA station

Figure 18 had 4 outliers, two of which were extreme outliers. The outliers represented a 1.67% error in the estimation of the diffuse solar radiation values for the JKIA station. From figures 16, 17 and 18, it was noted that average annual daily diffuse solar radiation ranges from 6 – 8 MJ/m^2/day.

The average annual daily diffuse solar radiation for all the station remain fairly constant. It ranges from 6 MJ/m^2/day to 8 MJ/m^2/day. The lowest average annual daily diffuse solar radiation values were recorded in the years the country experienced drought and as discussed earlier. Clear skies allow more of the beam radiation to be received because of the reduced amount of depletion. The figures 16, 17 and 18 show that after the year 2000, the amount of diffuse solar radiation show a downward trend. This can be explained to the effect that the dry conditions occasioned by increasing temperatures due global warming are affecting the amount of diffuse solar radiation received.

4.6 Percentage contribution of the diffuse solar radiation.

This subsection presented the percentage contribution of the diffuse solar radiation. This was mainly on a monthly basis. It gave an overview of when expected contribution of diffuse solar radiation was the highest. The information was vital in the dissemination of the solar radiation technologies, because some use both the diffuse and the beam radiation and can still function when the beam radiation has been cut off and there are those that depend solely on beam radiation.

The percentage contribution was calculated as follows:

The percentage contribution $= \frac{H_d}{H} \times 100\%$

where H_d was the diffuse solar radiation and H the global solar radiation.

The values for the monthly contribution of diffuse solar radiation for the three stations were graphically presented in the figures 19, 20 and 21.

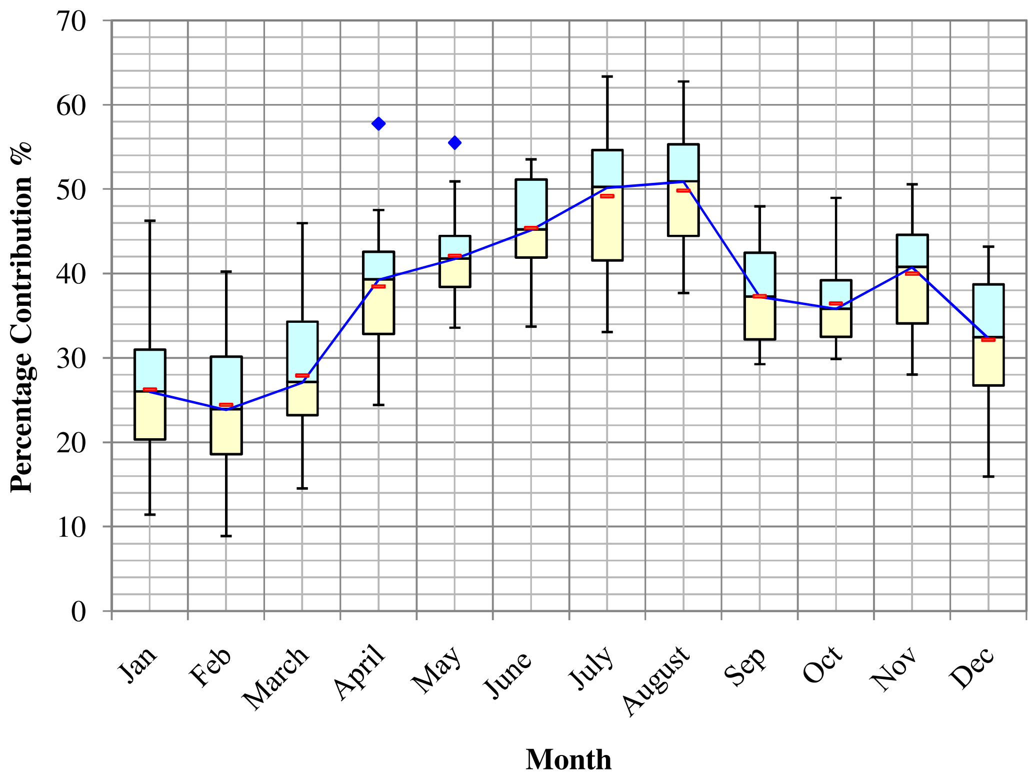

Figure 19 The percentage contribution of diffuse radiation at KMD station

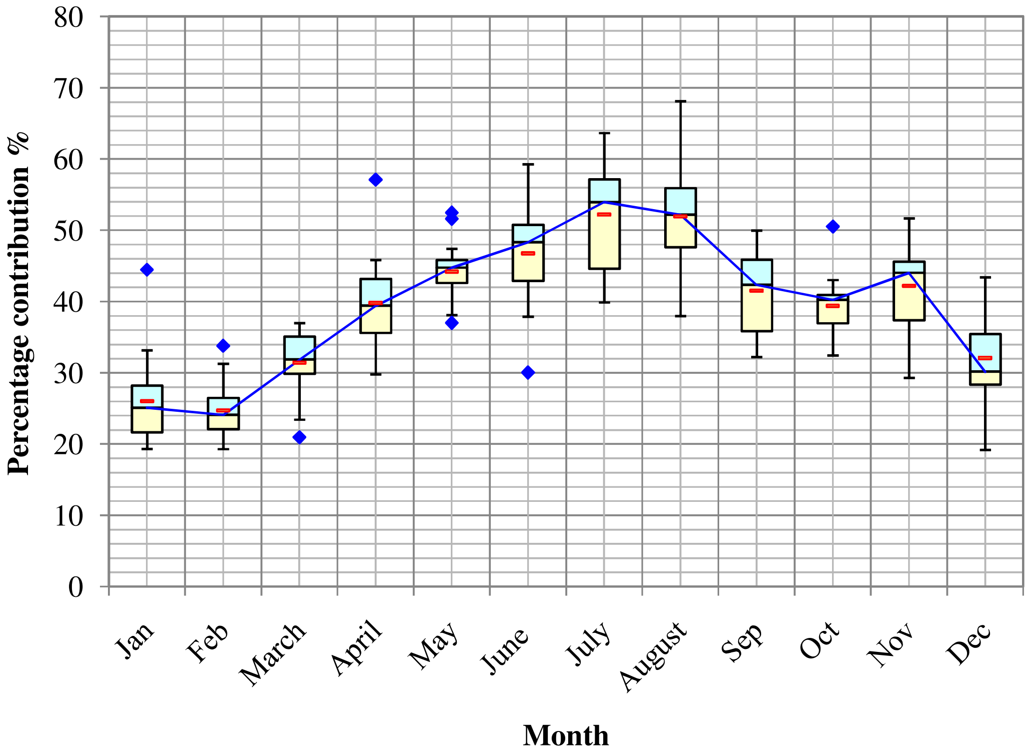

Figure 20 Percentage contribution of diffuse radiation at the Thika station

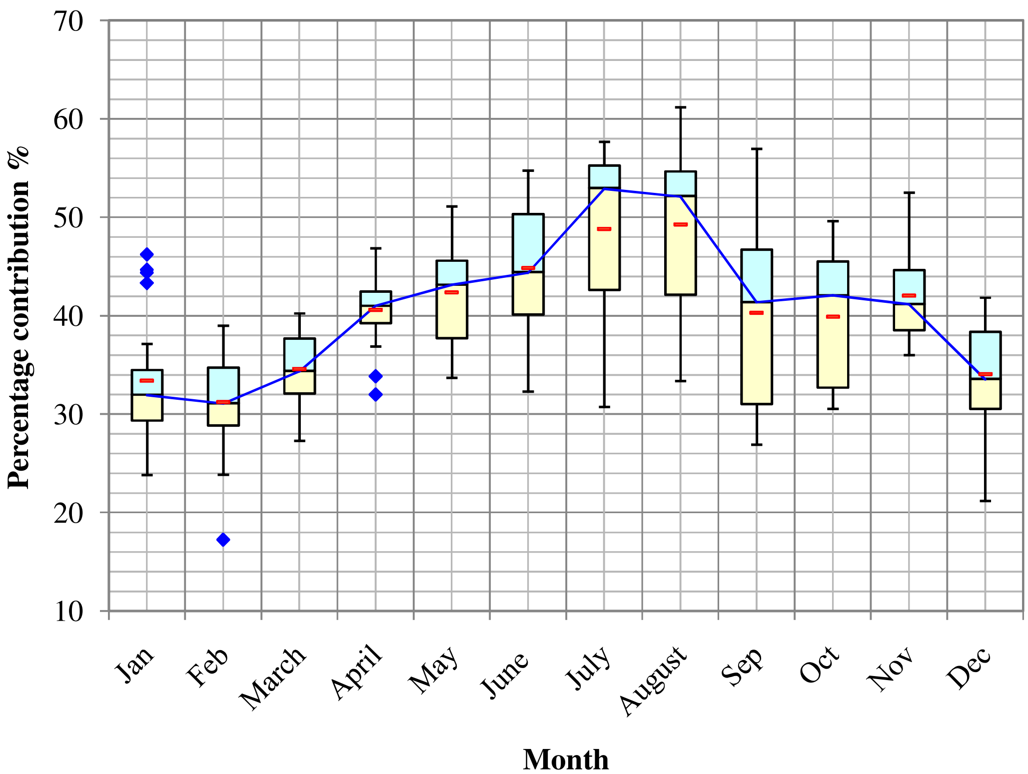

Figure 21 Percentage contribution of the diffuse radiation – JKIA station

Generally, the diffuse solar radiation increased in intensity from a minimum in February to a maximum in either July or August. The intensity then reduced through October. It increased slightly in November and then decreased through January.

From the graphs in figures 19, 20 and 21 it should be noted that the maximum contribution of diffuse solar radiation was received between June and September. Dagoretti corner had the maximum contribution falling in the month of August; Thika and JKIA have their maximum contribution in July.

From figure 19, there are only two outliers which represent a percentage error of 0.76%. Figure 20 shows that there are nine outliers which represent a percentage error of 4.41% in the calculation of the values. Figure 21 shows that there were six outliers which represent an error of 2.5% in the calculation of the values.

The highest contribution of the diffuse solar radiation was noted in the month of July and August. The cold season normally starts in the mid of June but most of the effect of the season are felt in the month of July and august. These results are consistent with the results obtained by The World Solar Power foundation, 1983. They specified that some areas, mainly in the northern and eastern lowland regions have higher average insolation levels while the highland areas experience lengthy cloudy periods and associated lower insolation levels during rainy seasons (April to August). Nevertheless, diffuse radiation can still be harnessed effectively (Newham *et al.*, 1983).

From appendix 3, it can be noted that as the months progress away from June, the amount of extraterrestrial solar radiation increases. This is because the angle of the sun's rays is reducing as it moves towards the equator. More beam radiation is therefore expected but due to the cloud cover during this month only a small fraction of the extraterrestrial solar radiation actually reaches the ground with most of it coming in as diffuse solar radiation.

There is less contribution of the diffuse solar radiation in the month of December, January, February and March. These months are generally dry and therefore more beam is received with only a small fraction of the diffuse solar radiation. November shows a notable increase in the diffuse solar radiation. As explained earlier, the abundant moisture serves to absorb part of the beam radiation and the clouds obstruct the beam radiation and therefore more of the diffuse is received.

4.7 Monthly variation in the clearness index

Then monthly average clearness index $\overline{K}_T$ is the ratio of the monthly averaged daily radiation on a horizontal surface to the monthly average daily extraterrestrial radiation i.e. the values were calculated using equation 3. The clearness index is also called the sky transmissivity. The results were presented in the figures 22, 23 and 24

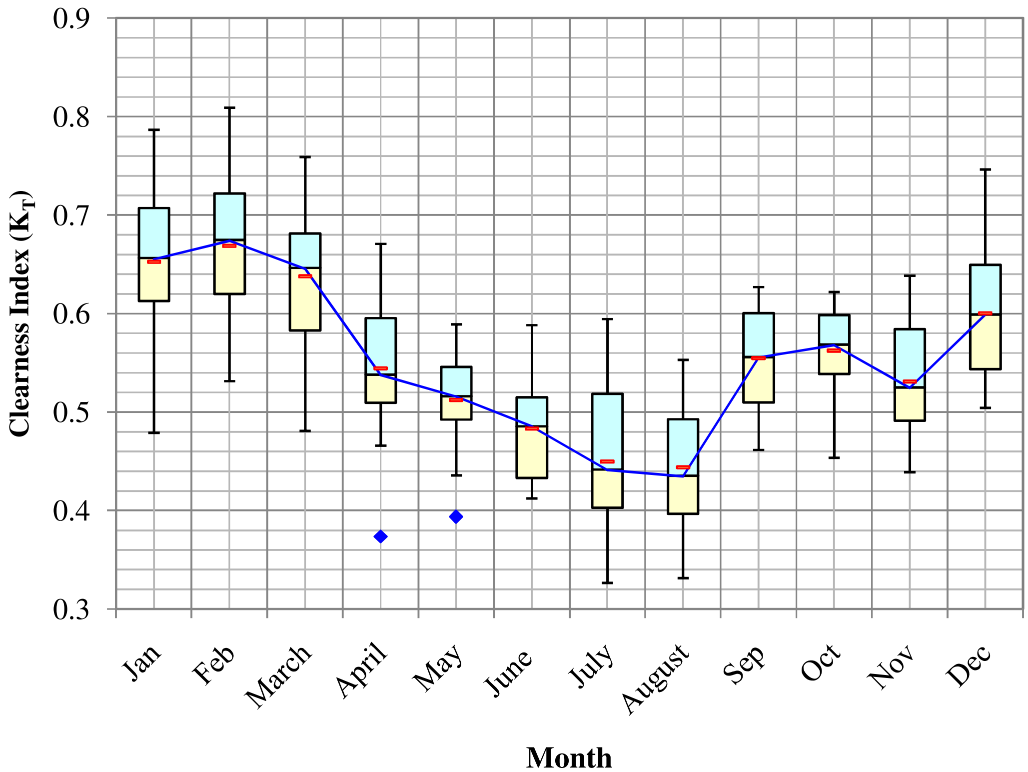

Figure 22 Average monthly clearness index – KMD station

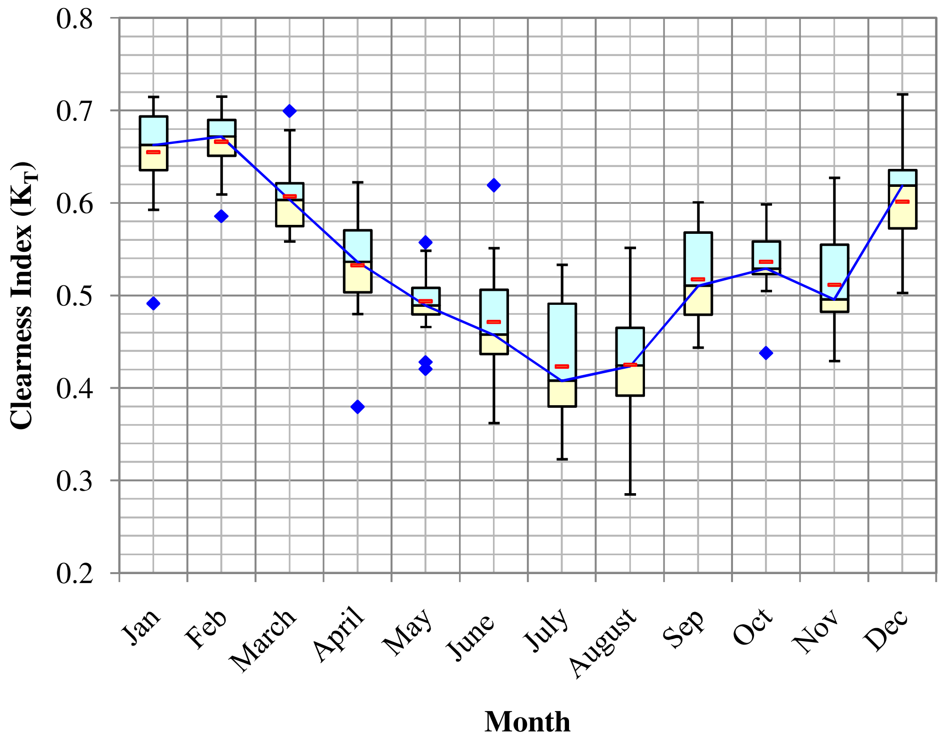

Figure 23 Average monthly clearness index – Thika station

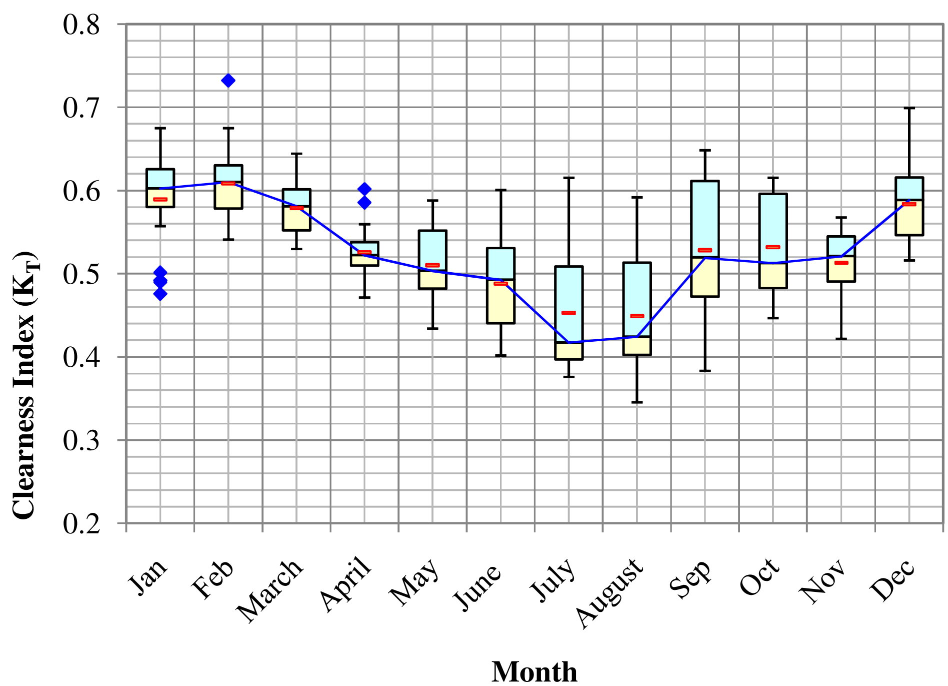

Figure 24 Average monthly clearness index for JKIA station.

From figures 22, 23 and 24, the clearness index peaked in February; it then reduced to its minimum in July and August. August lied in the cold season while February fell in the dry season. From August, the clearness index increased as the amount of obstruction to the incoming solar radiation reduced but with the short rains, it shouldbe seen that in November, the index reduced slightly before increasing again in December.

The clearness index serves to show the transparency of the sky/atmosphere to the incoming solar radiation. From figures 22, 23 and 24, it can be noted that January, February and March have a transparency index falling between 0.6 and 0.7 which is the highest, clearly indicating that these are the month when more beam radiation is received. June, July and August have a transparency index of less than 0.5 which shows that these are the month when more of the diffuse solar radiation is received. The rest of the months (April, May, September, October, November and December) have transparency index that fall between 0.5 and 0.6. In these month there seem to be an equal distribution of the number of days with overcast conditions and the number of clear sky conditions.

Based on the archived data annual insolation totals were calculated. The mean annual total radiation for Dagoretti Corner station was 2030.75 kWh/m^2. The respective maximum and minimum values recorded between 1990 – 2011 years were 2253.48 kWh/m^2 and 1728.01 kWh/m^2. Barman 2011 considered data for the year 2000 and concluded that Nairobi has an annual total of 2100 kWh/m^2. For Thika station, the mean value for 17 years (1995 – 2011) was 1966.19 kWh/m^2. The maximum annual total recorded during this period was 2183.42 kWh/m^2 and the minimum was 1726.48 kWh/m^2. For JKIA station had data averaged for 20 years (1992 – 2011). The mean value for this period was 1942.86 kWh/m^2. The maximum annual total between 1992 – 2011 was 2190.38 kWh/m^2 and the minimum 1793.43 kWh/m^2.

For diffuse solar radiation, the annual total diffuse solar radiation, Dagoretti Corner had an annual total diffuse solar radiation of 720.11 kWh/m^2, maximum annual total diffuse solar radiation of 790.1 kWh/m^2 and minimum annual total diffuse solar radiation of 643.17 kWh/m^2. The Thika station had a mean annual total diffuse solar radiation of 736.11 kWh/m^2, a maximum annual total diffuse solar radiation of 764.99 kWh/m^2 and minimum annual total diffuse solar radiation of 680.75 kWh/m^2. JKIA had the mean annual total diffuse solar radiation of 754.72 kWh/m^2. The maximum and minimum annual total diffuse solar radiation were 781.99 kWh/m^2 and 692.45 kWh/m^2 respectively. The minimum annual total diffuse solar radiation were recorded in the year 2000 (Dagoretti), 2009 (Thika) and 1999 (JKIA). These are the years during which the country experienced drought (Huho *et. al*., (2011).

The maximum annual total diffuse solar radiation values were recorded in 1995 (Dagoretti), 1998 for both Thika and JKIA. These are among the years the country experience high levels of precipitation with the high cloud cover shielding off the beam radiation (Jennifer, 2011).

On an annual basis the contribution of the diffuse solar to global solar radiation was calculated. At Dagoretti Corner the annual contribution ranges from 24 – 52 % with a mean value of 35.8% (figure 19). At Thika the contribution ranges from 24 – 54% with a mean value of 37.55% (figure 20). JKIA has a contribution ranging from 31 – 54% with a mean value for JKIA being 39.05% (figure 21). Therefore, generally the contribution ranges from 30 – 50%. Extraterrestrial solar radiation that reaches the surface as diffuse solar radiation falls between 15 – 25%.

With global and diffuse solar radiation values, the beam solar radiation was calculated as the difference between global solar radiation and the diffuse solar radiation. Dagoretti Corner station had a mean of 1310.6 kWh/m^2. Maximum and minimum annual totals were recorded in the years 2000 and 1995 with values of 1610.3 kWh/m^2 and 937.91 kWh/m^2 respectively. Thika had a mean of 1230.08 kWh/m^2 a maximum of 1502.67 and a minimum value of 961.48 kWh/m^2. These maximum and minimum values were recorded in the years 2009 and 1998 respectively. JKIA had a mean of 1188.14 kWh/m^2, a maximum of 1497.93 kWh/m^2 (1999) and a minimum of 1011.43 kWh/m^2 (1996).

Beam radiation falls between 50 – 75 % of the total/global solar radiation. The beam radiation received annually forms between 25 – 45% of the extraterrestrial solar radiation.

Measures of central tendency and measures of dispersion were calculated. The most important for this analysis was coefficient of variation. Values of coefficient of variation (δ_v) which are less than one reflect cases where the standard deviation is greater than the mean expectation. The larger the δ_v values reflects higher degree of variability in the available solar power potential. Higher variability degrees quantify the higher degree of unreliability of the available solar power (Marigi, 1999).

From this analysis, all the values of δ_v are less than 1 as shown in appendix 6, 7 and 8, which shows that there is a low degree of variability and hence a high degree of reliability. The highest variability is experienced from June to October. The annual variability ranges from 0.15 to 0.25. Variability of 0.2 and above were noted in the years 1991, 1996, 1997, 1998 and 2000 – 2008 for the Dagoretti corner station, 1995 – 1998, 2005, 2007 and 2011 for the Thika agro –meteorological station and 1998 and 2000 for the JKIA station. The annual variability is higher than the monthly variation but both the annual and the monthly variations are less than one and hence they both show that the resource is highly reliable.

4.8 Factors affecting solar radiation in the region

From this study it was clearly shown that there exists large diurnal and seasonal variations which affect the available solar power resource. Climatic factors have a greater influence on the amount of solar radiation received. It was noted that the onset of the long rains reduces the amount of radiation received. The cold season also significantly affects the amount of beam radiation received. The short rains season, due to the abundant moisture and cloudiness, most of the beam radiation is normally shielded. The rain season is controlled by the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ). It is a relatively narrow belt of very low pressure and heavy precipitation that forms near the earth's equator. The ITCZ migrates southwards through Kenya in October to December, and returns Northwards in March (Marigi, 1999). This causes Kenya to experience the two distinct wet periods – the 'short' rains in October to December and the 'long' rains in March to May.

Insolation in this region is also affected by the earth's rotation and revolution. This causes the path of the sun's rays to vary with the time of the day, season of the year and position of the site on the earth's surface. The 23.5^0 tilt of the earth's axis affects the angle of incidence of solar radiation on the earth's surface and causes seasonal and latitudinal variations in day length. This tilt is the one responsible for the sun to be seen to be overhead the equator, tropical of cancer or tropical of Capricorn.

4.9 Energy extractable by a solar energy system

The maximum amount of energy that can be extracted/converted to useful energy is simply the product of the available energy per unit area and interceptor efficiency. An efficiency of 17.4% (this is the conversion efficiency of silicon solar cells which are the most common on the market and specifically the Kenyan market) was used to calculate the extractable energy for photovoltaic and 90% for the solar thermal systems especially the concentrating systems. The results are presented in the tables 3 and 4.

Table 3, shows solar energy received in kWh/m^2/day for the three stations (Thika, Dagoretti Corner and JKIA). These values were obtained by calculating the mean monthly daily solar radiation values for the three stations. It also shows the amount of useful solar energy that can be converted to electrical energy at a conversion efficiency of 17.4%. Table 4 shows Solar energy received kWh/m^2/day and the amount is converted into thermal energy by solar thermal converter at an efficiency of 90%.

Table 3 Received and extractable energy at a 17.4% efficiency for PV system

Month	Solar energy received kWh/m²/day									Extractable solar energy by the photovoltaic system kWh/m²/day								
	Dagoretti Corner			Thika station			JKIA station			Dagoretti Corner			Thika station			JKIA station		
	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN
Jan	6.65	8	4.87	6.59	7.19	4.94	6.01	6.88	4.85	1.16	1.39	0.85	1.15	1.25	0.86	1.05	1.2	0.84
Feb	6.87	7.93	5.46	6.92	7.42	6.08	6.37	7.67	5.66	1.19	1.38	0.95	1.2	1.29	1.06	1.11	1.33	0.98
March	6.71	7.96	5.05	6.38	7.35	5.87	6.09	6.77	5.57	1.17	1.39	0.88	1.11	1.28	1.02	1.06	1.18	0.97
April	5.52	6.79	3.79	5.43	6.34	3.87	5.33	6.1	4.78	0.96	1.18	0.66	0.95	1.1	0.67	0.93	1.06	0.83
May	4.88	5.6	3.76	4.77	5.38	4.06	4.86	5.6	4.13	0.85	0.97	0.65	0.83	0.94	0.71	0.85	0.97	0.72
June	4.43	5.38	3.78	4.38	5.76	3.36	4.47	5.49	3.68	0.77	0.94	0.66	0.76	1	0.58	0.78	0.96	0.64
July	4.18	5.52	3.03	3.99	5.03	3.04	4.21	5.71	3.49	0.73	0.96	0.53	0.69	0.88	0.53	0.73	0.99	0.61
August	4.37	5.43	3.25	4.22	5.46	2.82	4.41	5.8	3.39	0.76	0.94	0.57	0.73	0.95	0.49	0.77	1.01	0.59
Sep	5.72	6.46	4.76	5.35	6.21	4.58	5.45	6.68	3.94	1	1.12	0.83	0.93	1.08	0.8	0.95	1.16	0.69
Oct	5.86	6.47	4.72	5.56	6.19	4.54	5.54	6.41	4.65	1.02	1.13	0.82	0.97	1.08	0.79	0.96	1.12	0.81
Nov	5.46	6.53	4.48	5.16	6.32	4.33	5.28	5.79	4.42	0.95	1.14	0.78	0.9	1.1	0.75	0.92	1.01	0.77
Dec	6.04	7.49	5.07	5.96	7.09	4.98	5.87	7.02	5.19	1.05	1.3	0.88	1.04	1.23	0.87	1.02	1.22	0.9

Received and extractable energy at a 90% efficiency - thermal system

	Solar energy received kWh/m²/day									Extractable solar energy by the photovoltaic system kWh/m²/day								
	Dagoretti Corner			Thika station			JKIA station			Dagoretti Corner			Thika station			JKIA station		
Month	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN
Jan	6.65	8	4.87	6.59	7.19	4.94	6.01	6.88	4.85	5.99	7.2	4.38	5.93	6.47	4.45	5.41	6.19	4.37
Feb	6.87	7.93	5.46	6.92	7.42	6.08	6.37	7.67	5.66	6.18	7.14	4.91	6.23	6.68	5.47	5.74	6.9	5.09
March	6.71	7.96	5.05	6.38	7.35	5.87	6.09	6.77	5.57	6.04	7.16	4.55	5.74	6.62	5.28	5.48	6.09	5.01
April	5.52	6.79	3.79	5.43	6.34	3.87	5.33	6.1	4.78	4.96	6.11	3.41	4.89	5.71	3.48	4.8	5.49	4.3
May	4.88	5.6	3.76	4.77	5.38	4.06	4.86	5.6	4.13	4.39	5.04	3.38	4.29	4.84	3.65	4.37	5.04	3.72
June	4.43	5.38	3.78	4.38	5.76	3.36	4.47	5.49	3.68	3.98	4.84	3.4	3.95	5.18	3.02	4.02	4.94	3.31
July	4.18	5.52	3.03	3.99	5.03	3.04	4.21	5.71	3.49	3.76	4.97	2.73	3.59	4.53	2.74	3.79	5.14	3.14
August	4.37	5.43	3.25	4.22	5.46	2.82	4.41	5.8	3.39	3.93	4.89	2.93	3.8	4.91	2.54	3.97	5.22	3.05
Sep	5.72	6.46	4.76	5.35	6.21	4.58	5.45	6.68	3.94	5.15	5.81	4.28	4.81	5.59	4.12	4.91	6.01	3.55
Oct	5.86	6.47	4.72	5.56	6.19	4.54	5.54	6.41	4.65	5.27	5.82	4.25	5	5.57	4.09	4.99	5.77	4.19
Nov	5.46	6.53	4.48	5.16	6.32	4.33	5.28	5.79	4.42	4.91	5.88	4.03	4.65	5.69	3.9	4.75	5.21	3.98
Dec	6.04	7.49	5.07	5.96	7.09	4.98	5.87	7.02	5.19	5.43	6.74	4.56	5.36	6.38	4.48	5.28	6.32	4.67

4.10 Applications of the measured solar radiation for photovoltaic systems

The main purpose of the project was to assess the solar radiation potential of the Thika – Nairobi area. The results that were obtained were to be used in coming up with solar photovoltaic system that would either operate independently or be used as back up systems in case of power blackouts. These systems were to also be used to substitute paraffin in homes where the families depend on kerosene lamps.

A visit was conducted to systems already installedwithin the study area and the following was observed:

4.10.1 Case one: The solar energy demonstration centre – Jamhuri show grounds – Nairobi

The renewable energy demonstration centre has a solar radiation display unit with the energy stored being used to light up the rooms and security lights. The solar system consists of 19, 80W solar panels installed on the roof. The panels support the charging of 10, 200 Ah batteries, which store the solar energy before it is used.

There was a charge controller that protects the batteries from damage. When fully charged, it cut off the current supply from the panels and also back flow of current to the panel. Two Magnum inverters were installed; one which supported the lighting system and the other one supported the power unit. Two fuses were fitted in the circuit. There was a power distribution unit and the control unit with the circuit breakers.

The solar PV system supported the operation of:

i. Six computers which were operated for varied number of hours during the day.

ii. There are six security lamps which operate for 12 hours in a day (they were lit at 7:00 p.m and switched off at 7.00 a.m) .

iii. There are six lamps in the corridor which operator for 8 hours in a day.

iv. Then 18 lamps, the time they were used was dependent on the user. There were some which were operated for 8 hours and some which were not lit the whole day.

v. There was a solar operated refrigerator. It was operated on 12V direct current. The refrigerator was not used often.

vi. Other than the fore mentioned appliances, the occupants of the offices charged their mobile phones using the same system.

The average cost of the solar photovoltaic system is given in table 5.

Table 5 The cost of installation of a solar PV system - Renewable Energy Centre

Appliance	**Number of units**	**Price per unit KSh.**	**Total KSh.**
Solar panels	19	12,000	228,000
Maintenance free solar batteries	10	45,000	450,000
Magnum inverter	2	150,000	300,000
Solar lamps (18W)	30	350	10,500
Distribution unit	1	7,000	7,000
Charge controller	2	25,700	51,400
Fuse	2	2,160	4,320
Total			**1,051,220**

The total for the accessories was KShs. 1,046,900. The price excluded the wiring in the house. At the same solar demonstration centre, there was a solar operated pump. This pump is operated by 6, 120W, solar panels and controlled by a sensor. The cost of the sensor and the solar panels is KShs. **206,000.**

4.10.2 Case two: Photovoltaic System installed on a house in Ruiru

In the second case, a solar pv system installed in Ruiru, consisted of 2, 120W solar panels, a 200 Ah maintenance free solar battery, a charge controller (15A, 12V), a distribution unit and a 600W inverter. The system supports 11 lighting points with each lamp rated 8W, a television set and home theatre system.

The lamps were normally lit for 3 hours in a day. Other than the appliances, the system also supported the charging of 8 mobile phones every day. The average cost of the system is shown in the table 6.

Table 6 The cost of a Photovoltaic System installed on a house in Ruiru

Appliance	**Number of units**	**Price per unit KSh.**	**Total KSh.**
Solar battery	1	40,000	40,000
Solar panel	2	18,000	38,000
Charge controller	1	6,450	6,450
Inverter	1	7,500	7,500
Distribution unit	1	7,000	7,000
Lamps	11	150	1,150
Fuse	1	1,000	1,000
Total			**101,100**

The solar photovoltaic systems were able to run all the appliances they were meant to support. This was a clear indication that the solar energy available was enough and can be tapped for home systems. This was most notable during days when the sky was clear. When the energy was stored continuously it could still support the running of the appliance on cloudy days when the sun was obstructed. It was also noted that the panels tapped diffuse solar radiation although the efficiency of charging was lowered.

4.10.3 Home solar power kits

The powerpoint systems (E.A) limited had home solar power kit. The standard solar lighting kits consisted a solar module, charge controller, battery, fluorescent lights and electrical accessories. The kits were calculated to provide a daily average of 2 hours of light per day if all lights were left on simultaneously and the panel had received about 4.5 hours of peak sunshine.

Table 7 Solar Energy kits for smaller energy needs

Type of kit	Items	Price Ksh.
Starter	1, 15 W solar panel; 1, 50Ah solar battery; 2,10 W fluorescent lights and 1,5A charge controller. (can also operate a radio)	12,000
Typical	1,20Wsolar panel; 1,50Ah solar battery; 2,10W fluorescent lights; 2, 15W fluorescent lights and 1,5A charge controller. The arrangement can also support a radio and TV	32,000
Medium	1,43W solar panel; 1,70Ah solar battery; 4,10W fluorescent lights; 1,15W fluorescent light; 1,18W fluorescent lights and 1,10A charge controller. A radio and TV can also run on the same PV system.	42,570
Big	1,75W solar panel; 1,100Ah solar battery; 5,10W fluorescent lights; 2,15W fluorescent lights; 1,18W fluorescent lights and 1,20A charge controller. The PV system can also be used to operate a radio and TV.	87,234

4.11 Sizing and Costing of the Solar Photovoltaic System

For an individual with a daily energy demand of 3742 W, his/her energy demand can be taken to be 3.742 kWh (without batteries) or 5.2388 kWh (without the batteries). This follows from equation. In this region, there can be two days without sunshine and therefore the days of autonomy (days of overcast conditions) are two. The size of storage that is required has to have a capacity capable of supplying the power for the two days without running out of charge. Using equation 3.3, the storage required therefore has to be 10.4776 kWh solar battery. The battery will cost 1047.6$.

The insolation for Nairobi's Dagoretti corner station was taken as the benchmark result in the calculation. This was the lowest insolation and therefore the system sized was to work throughout the year. The problem with using a higher insolation value makes one come up with a smaller system that can only function with higher insolation. Using equation 3.5, the panel required has to be 15.04m^2. Since A> 10 m^2 then investment on this panel will be 7519.81$.

Using equation 3.6, the yearly investment costs in the study area was 578.78$. The figure was arrived at after considering a total investment of 7519.81$, a lifetime of investment of 25 years and a discount rate (d) 5.83% (d =% (interest rate – annual inflation) the current inflation rate in Kenya is 9.5 % and the annual inflation rate is 3.67%). The running cost tabulated at 3% of the initial investment each year for maintenance and repair was found to be 17.36$.

The above method was developed by the Renewable Energy Decision Method developed by the Working Group on Development Techniques (WOT), University of Twente, Netherlands (Marigi, 1999).

Alternatively the models below can also be used. In the first model, the electric energy that a PV panel needs to produce each day is given by:

$$E_{PV\ Produced} = E_{Daily\ Energy\ demand}/(\text{Electronic Efficiency} \times \text{Battery charge/Discharge Efficiency}) \quad (4.1)$$

Considering an electronic efficiency of 80% and energy losses during charging and discharging to be 40% (therefore the useful energy will be 60%), the energy the PV needs to produce was found to be 7795.83 Wh/day. Therefore the amount of solar radiation/insolation that the PV panel needs to collect is 45857.84 Wh/day given that:

$$E_{Solar\ Radiation\ Needed} = E_{PV\ Produced} / (\text{PV panel conversion efficiency}) \quad (4.2)$$

This will therefore require solar panels which will cover an area of 10.97 m^2 i.e.

$$\text{Size of PV Panels} = E_{\text{Solar Radiation Needed}}/\text{Daily Solar Radiation} \qquad (4.3)$$

This model did not include how the prices can be calculated. In the second alternative model, the total watt – hours per day which must be provided by the panels, was 5238.8 Wh given by:

$$\text{Total watt – hours} = 1.4 \times 3742 \qquad (4.4)$$

To calculate the panel generation factor the following corrections should be included:

i. 15% for temperature above 25^0C.
ii. 5% for losses due sunlight not striking the panel straight on (caused by glass have increasing reflectance at lower angles of incidence)
iii. 10% losses due to not receiving energy at the maximum power point tracker (not present if there is a MPPT controller).
iv. 5% allowance for dirt.
v. 10% allowance for the panel being below specifications and for ageing.

Total power = $0.85\times 0.95 \times 0.90 \times .95 \times 0.90 = 0.62$ of the original W_p rating. Therefore the panel generation factor for the study area considering the month of July as the design month and the July for Nairobi as the benchmark for the other two stations is given below.

$$\text{Panel generation factor} = 0.62 \times 4.18$$

$$= \mathbf{2.592}$$

The panel generation factor for this location was 2.592, and when used in determining the total Watt – Peak Rating Needed for PV Modules, it gives 2021.142 W_p. This amount of power required 7 modules which each module rated 320W.

The system of seven solar panels will required an 800W inverter, a 12V 1300Ah battery and 60A at 12V solar Charge Controller. The 1300 Ah solar batteries were not available. The batteries are bulky and also very costly. The batteries available on the market are 12V, 200 Ah batteries. Therefore in this case, the system will required 7, 12V,200 Ah batteries. The best batteries on the market were the maintenance free batteries. They are expensive to purchase but given that they don't require much attention to maintain, they offered more service than the batteries that require to be maintained.

The approximate cost of the system is put in the table below:

Table 8 Solar Energy kits for smaller energy needs

Item	Number of unit	Cost per unit	Total cost
Solar panel – 320W	7	48,000	336,000
60A, 12V Charge controller	1	22,000	22,000
12V, 1,300 Ah Deep Cycle battery	7 units of 12V, 200Ah	24,000	168,000
800W inverter	1	32,000	32,000
TOTAL			**558,000**

From the table it can be noted that the cost of installing a solar system for the case scenario used in this study is **Kshs. 558,000**.

The three models all use the results from the assessment. They all give a price of between KShs. 400,000 to KShs. 600,000 to be the price for the installation of a solar photovoltaic system which will cater for the electrical needs of an individual with a daily energy requirement of 3742 W.

4.12 The Kenya Power billing.

Kenya power requires that on new installation, an individual should pay KShs. 35,000. Following the above requirement the energy demand (112.26kWh/month) considered in this assessment will be billed as follows using the table in appendix 4:

Table 9 The Kenya Power Billing concept

BILLING CONCEPT	AMOUNT IN KShs.
Fixed charge	120
Consumption	224.52
Fuel cost charge @ 538.00 cents/ kWh	603.9588
Forex adjustment @ KShs. 104.00 cents/ kWh	116.7504
Inflation adjustment @ 30.00 cents/ kWh	33.678
ERC levy @ 3.00 cents/ kWh	3.3678
REP levy 5.00% of the consumption	11.226
Value added tax (VAT) 16.00%	178.1602
TOTAL	**1291.661**

Therefore the customer will be required to pay a monthly bill of KShs. 1291.661 and KShs. 15499.93 every year. These levies are subject to adjustments and therefore the monthly bill is bound to increase. If the price remains constant, the individual is supposed to pay a total of KShs. 422498.35 for a duration of 25 years. This cost is for the consumption of the electrical energy and the connection fee only. The price for other accessories has not been included. The cost of electricity is subject to changes and therefore this figure might be higher than the cost of solar.

Installation of solar has a high initial cost but the running cost is cheaper. The running cost for solar is 17.36$ dollar per year (3% of the total investiment). This source electrical energy is clean and is more reliable. There will be no power cuts due to low level of water in the dams. There will no power blackouts due to the rains and other causes. The power supply from the grid system is so erratic and therefore there are so many risks of loss off appliances due to the power surges. With solar, the power is regulated at one point and there all these risks are alleviated. Therefore considering all these, other than the installation cost solar is a better option over the grid connection.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

This chapter provides conclusions and recommendations which were derived from this study.

5.1 CONCLUSION

Results from the study show that the Thika – Nairobi area has abundant solar energy resources, with average annual daily insolation ranging 4 $kWh/m^2/day$ to 7 $kWh/m^2/day$. Although there exists diurnal and seasonal variability, results from the coefficient of variation show that the coefficient is less than 1 and hence there is less variability in the solar energy resource. The available insolation is able to sustain the running of both solar photovoltaic and solar thermal systems all the year round.

The clearness index show that the region receives allot of beam radiation save for the month of June, July and August, because the annual clearness index is greater than 0.4 for all the years. This calls for the installation of both the solar photovoltaic and solar thermal systems. In the absence of direct solar radiation, the solar PV and solar thermal non – concentrating type can still function when only diffuse solar radiation is received.

The contribution of the diffuse solar radiation to the global solar radiation ranges from 30 – 50% and therefore can't be ignored. This shows that in the absence of the direct/beam radiation, most of the devices depend on the diffuse solar radiation. It is prudent that the manufacturer of the solar technologies should consider coming up with devices that utilize more of the diffuse solar radiation.

The solar photovoltaic system sizes depend majorly on the available insolation which the study reveals is abundant and secondly on the daily electrical energy demands of a particular individual. The higher the daily energy demand, the larger photovoltaic system and hence the higher the investment cost. Calculation of the estimated costs of installations show that solar technologies are still very expensive despite the government effort to reduce the prices.

5.2 RECOMMENDATION

When sizing the solar system, it good to consider the month with the least insolation. This month is referred to as the design month. From figures 7, 8, and 9, it should be observed that the month with the least insolation is July and the maximum is insolation is in the month of February. Insolation in the month of July falls between 3 – 5 $kWh/m^2/day$ while the insolation in February falls between 6 – 7 $kWh/m^2/day$, therefore in this study the insolation in July was considered in the calculation of the estimated sizes of the solar panel and the subsequent investment in a solar photovoltaic system. The use of the insolation of the design month will allow one to come up with a system that will function the whole year.

The changing positions of the overhead sun pose a challenge to the amount of the available solar radiation that can be tapped. It is advisable that the panels be fitted with trackers and as the position of the overhead sun changes, the orientation of the panel can be changed so as to generate more electrical energy when facing the sun directly. If the physical tracking is difficult, one can invest in a maximum power point tracker. The MPPT varies the ratio between the voltage and current delivered to the battery, in order to deliver maximum power. If there is excess voltage available from the PV, then it converts that to additional current to the battery. As the V_{pp} of the PV array veries with temperature and other conditions, it “tracks” this variance and adjusts the ratio accordingly.

Proper planning is required when sizing a solar photovoltaic system. It is advisable to consult experts in the field in order to get proper direction on what is required and the impending cost of installation and maintenance.

It should be noted that different companies offer different prices for the panels and the other accessories. Once in the hands of the dealers, they have to make profit. Therefore when planning for a solar radiation technology installation, it is advisable that one should shop around before making the final estimate. When one gets the best price, then it can be considered in the planning. The government should try to control the pricing of the solar technologies devices. Some of the companies dealing in selling these devices are still way beyond the prices offered by their competitors.

More ground stations need to be put up to capture more data on solar energy resource. The equipment to be installed should be able to capture data for global, diffuse and beam solar radiation. They should also be fitted onto devices that store data directly for easier retrieval. This will enable further research on solar radiation resource especially on an inclined surface and therefore the element of the altitude will be factored inn and the estimates/values obtained will give a clearer picture of the available insolation.

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APPENDICES

Appendix 1 A summary of the basic solar energy parameters

Year	Annual Total Insolation (H) in kWh/M^2			Annual Total Extraterrestrial Solar Radiation (H_0) in kWh/m^2			Annual Total Diffuse Solar Insolation (H_d) in kWh/m^2			Annual Total Beam Radiation (H_b) in kWh/m^2		
	KMD	THIKA	JKIA	KMD	THIKA	JKIA	KMD	THIKA	JKIA	KMD	THIKA	JKIA
1990	1766.34			3653.92	3653.82	3653.66	783.68			982.66		
1991	1876.43			3653.92	3653.82	3653.66	755.67			1120.8		
1992	2191.9		1821.77	3672.39	3663.71	3672.14	680.95		777.29	1511		1044.48
1993	2129.42		1829.26	3653.92	3653.82	3653.66	694.64		775.48	1434.8		1053.78
1994	1885.98		2184.65	3653.92	3653.82	3653.66	764.86		702.75	1121.1		1481.9
1995	1728.01	1925.48	1855.74	3653.92	3653.82	3653.66	790.1	740.91	778.21	937.91	1184.57	1077.53
1996	1982.52	1950.27	1793.43	3672.39	3663.71	3672.14	742.43	731.88	781.99	1240.1	1218.39	1011.43
1997	1973.51	1919.29	1909.6	3653.92	3653.82	3653.66	733.5	745.61	761.99	1240	1173.68	1147.61
1998	1753.37	1726.48	1834.79	3653.92	3653.82	3653.66	777	764.99	762.24	976.37	961.483	1072.55
1999	1977.67	1914.29	2190.38	3653.92	3653.82	3653.66	753.12	751.17	692.45	1224.5	1163.12	1497.93
2000	2253.48	1980.09	1928.7	3672.39	3663.71	3672.14	643.17	737.5	757.42	1610.3	1242.6	1171.28
2001	2114.77	1968.22	2039.65	3653.92	3653.82	3653.66	701.68	744.37	747.18	1413.1	1223.85	1292.47
2002	2122.09	1991.7	2179.91	3653.92	3653.82	3653.66	700.84	740.89	702.68	1421.3	1250.81	1477.24
2003	2135.34	2024.34	1916.75	3653.92	3653.82	3653.66	697.92	717.25	759.45	1437.4	1307.09	1157.3
2004	2114.28	1971.08	1928.15	3672.39	3663.71	3672.14	726.26	756.3	773.32	1388	1214.78	1154.82
2005	2181.24	1989.29	1925.95	3653.92	3653.82	3653.66	654.21	714.07	756.5	1527	1275.22	1169.45
2006	2077.47	1924.1	1852.36	3653.92	3653.82	3653.66	707.8	759.35	769	1369.7	1164.75	1083.36
2007	2078.64	1919.2	1890.92	3653.92	3653.82	3653.66	705.24	742.8	764.61	1373.4	1176.4	1126.3
2008	2104.54	1980.69	1925.46	3672.39	3663.71	3672.14	701.35	745.08	763.98	1403.2	1235.61	1161.47
2009	2198.75	2183.42	1968.93	3653.92	3653.82	3653.66	672.38	680.75	753.34	1526.4	1502.67	1215.59
2010	2010.46	2024.15	1882.94	3653.92	3653.82	3653.66	731.91	733.81	772.38	1278.6	1290.34	1110.56
2011	2020.39	2033.18	1997.96	3653.92	3653.82	3653.66	723.71	707.21	742.15	1296.7	1325.97	1255.81
MEAN	**2030.75**	**1966.19**	**1942.86**	**3658.12**	**3656.15**	**3658.28**	**720.11**	**736.11**	**754.72**	**1310.6**	**1230.08**	**1188.14**
MAX	**2253.48**	**2183.42**	**2190.38**	**3672.39**	**3663.71**	**3672.14**	**790.1**	**764.99**	**781.99**	**1610.3**	**1502.67**	**1497.93**
MIN	**1728.01**	**1726.48**	**1793.43**	**3653.92**	**3653.82**	**3653.66**	**643.17**	**680.75**	**692.45**	**937.91**	**961.483**	**1011.43**

Appendix 2 A summary of the basic solar energy parameters

Year	H_d/H			H/H_0 (clearness index K_T)			H_d/H_0			H_b/H			H_b/H_0		
	KMD	THIKA	JKIA	KMD	THIKA	JKIA	KMD	THIKA	JKIA	KMD	THIKA	JKIA	KMD	THIKA	JKIA
1990	44.37			0.48			21.45			55.63			26.89		
1991	40.27			0.51			20.68			59.73			30.67		
1992	31.07		42.67	0.6		0.5	18.54		21.17	68.93		57.33	41.14		28.44
1993	32.62		42.39	0.58		0.5	19.01		21.22	67.38		57.61	39.27		28.84
1994	40.55		32.17	0.52		0.6	20.93		19.23	59.45		67.83	30.68		40.56
1995	45.72	38.48	41.94	0.47	0.53	0.51	21.62	20.28	21.3	54.28	61.52	58.06	25.67	32.42	29.49
1996	37.45	37.53	43.6	0.54	0.53	0.49	20.22	19.98	21.3	62.55	62.47	56.4	33.77	33.26	27.54
1997	37.17	38.85	39.9	0.54	0.53	0.52	20.07	20.41	20.86	62.83	61.15	60.1	33.94	32.12	31.41
1998	44.31	44.31	41.54	0.48	0.47	0.5	21.26	20.94	20.86	55.69	55.69	58.46	26.72	26.31	29.36
1999	38.08	39.24	31.61	0.54	0.52	0.6	20.61	20.56	18.95	61.92	60.76	68.39	33.51	31.83	41
2000	28.54	37.25	39.27	0.61	0.54	0.53	17.51	20.13	20.63	71.46	62.75	60.73	43.85	33.92	31.9
2001	33.18	37.82	36.63	0.58	0.54	0.56	19.2	20.37	20.45	66.82	62.18	63.37	38.67	33.5	35.37
2002	33.03	37.2	32.23	0.58	0.55	0.6	19.18	20.28	19.23	66.97	62.8	67.77	38.9	34.23	40.43
2003	32.68	35.43	39.62	0.58	0.55	0.52	19.1	19.63	20.79	67.32	64.57	60.38	39.34	35.77	31.68
2004	34.35	38.37	40.11	0.58	0.54	0.53	19.78	20.64	21.06	65.65	61.63	59.89	37.8	33.16	31.45
2005	29.99	35.9	39.28	0.6	0.54	0.53	17.9	19.54	20.71	70.01	64.1	60.72	41.79	34.9	32.01
2006	34.07	39.47	41.51	0.57	0.53	0.51	19.37	20.78	21.05	65.93	60.53	58.49	37.48	31.88	29.65
2007	33.93	38.7	40.44	0.57	0.53	0.52	19.3	20.33	20.93	66.07	61.3	59.56	37.59	32.2	30.83
2008	33.33	37.62	39.68	0.57	0.54	0.52	19.1	20.34	20.8	66.67	62.38	60.32	38.21	33.73	31.63
2009	30.58	31.18	38.26	0.6	0.60	0.54	18.4	18.63	20.62	69.42	68.82	61.74	41.77	41.13	33.27
2010	36.4	36.25	41.02	0.55	0.55	0.52	20.03	20.08	21.14	63.6	63.75	58.98	34.99	35.31	30.4
2011	35.82	34.78	37.15	0.55	0.56	0.55	19.81	19.36	20.31	64.18	65.22	62.85	35.49	36.29	34.37
MEAN	**35.8**	**37.55**	**39.05**	**0.56**	**0.54**	**0.53**	**19.69**	**20.13**	**20.63**	**64.2**	**62.45**	**60.95**	**35.82**	**33.64**	**32.48**
MAX	**45.72**	**44.31**	**43.6**	**0.61**	**0.6**	**0.6**	**21.62**	**20.94**	**21.3**	**71.46**	**68.82**	**68.39**	**43.85**	**41.13**	**41**
MIN	**28.54**	**31.18**	**31.61**	**0.47**	**0.47**	**0.49**	**17.51**	**18.63**	**18.95**	**54.28**	**55.69**	**56.4**	**25.67**	**26.31**	**27.54**

Appendix 3 Extraterrestrial solar radiation values.

EXTRATERRESTRIAL RADIATION IN MJ/m²/day													
MONTH	Station	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
NORMAL YEAR	THIKA	36.22	37.39	37.83	36.73	34.77	33.5	33.95	35.7	37.19	37.29	36.33	35.67
	JKIA	36.71	37.7	37.87	36.5	34.32	32.98	33.47	35.38	37.13	37.52	36.78	36.21
	KMD	36.71	37.7	37.87	36.5	34.33	32.98	33.48	35.41	37.13	37.51	36.77	36.21
LEAP YEAR	THIKA	36.22	37.4	37.82	36.67	34.71	33.48	34	35.75	37.22	37.27	36.3	35.67
	JKIA	36.71	37.71	37.85	36.43	34.26	32.96	33.52	35.45	37.17	37.51	37.75	36.21
	KMD	36.71	37.71	37.85	36.44	34.26	32.97	33.53	35.48	37.17	37.5	37.74	36.2

Appendix 4 The billing concept from Kenya Power

Item	Cost
Fixed charge of KShs. 120.00	
Consumption @ KShs. 2.00/ kWh.	
Fuel cost charge @ 538.00 cents/ kWh.	
Forex adjustment @ KShs. 104.00 cents/ kWh.	
Inflation adjustment @ 30.00 cents/ kWh	
Energy Regulatory commission (ERC) levy @ 3.00 cents/ kWh.	
REP levy 5.00% of the consumption.	
Value added tax (VAT) 16.00%.	

Appendix 5 Equation for measures of central tendency and dispersion

Average/ mean = $\frac{\sum fx}{\sum f}$

$$\text{Standard deviation } (\sigma) = \sqrt{\frac{\sum f x^2}{N} - (\bar{x})^2}$$

$$\text{Skewness (S)} = \frac{\sum_{i=1}^{N}(X_i - \bar{X})^3}{(N-1)\sigma^3}$$

$$\text{Kurtosis (K)} = \frac{\sum_{i=1}^{N}(X_i - \bar{X})^4}{(N-1)\sigma^4}$$

Cofficient of variation (δ_v) = $\frac{\sigma}{\bar{X}} \times 100$

Lower Quartile (Q_1) = $L + \left[\frac{\frac{N}{4} - c.f}{f}\right] \times C$

Upper Quartile (Q_3)= $L + \left[\frac{3.\frac{N}{4} - c.f}{f}\right] \times C$

Appendix 6 Descriptive statistics for Dagoretti corner station.

Descriptive statistics	Month											
	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Number of numeric values	22	22	22	22	22	22	22	22	22	22	22	22
Mean ($\bar{X}$)	6.65	6.87	6.71	5.52	4.88	4.43	4.18	4.37	5.72	5.86	5.46	6.04
Standard Deviation(σ)	0.73	0.77	0.76	0.65	0.44	0.46	0.67	0.62	0.52	0.47	0.65	0.67
Range	3.13	2.47	2.91	3	1.84	1.6	2.49	2.18	1.7	1.75	2.05	2.42
Minimum	4.87	5.46	5.05	3.79	3.76	3.78	3.03	3.25	4.76	4.72	4.48	5.07
Lower Quartile(Q_1)	6.24	6.44	6.12	5.12	4.69	3.97	3.74	3.9	5.25	5.61	5.02	5.47
Median(Q_2)	6.68	6.94	6.79	5.45	4.92	4.45	4.11	4.28	5.73	5.92	5.41	6.02
Upper Quartile(Q_3)	7.195	7.5	7.155	6.03	5.2	4.72	4.81	4.85	6.195	6.23	6.07	6.53
Maximum	8	7.93	7.96	6.79	5.6	5.38	5.52	5.43	6.46	6.47	6.53	7.49
Skewness(S)	-0.47	-0.49	-0.26	-0.51	-0.76	0.46	0.27	0.12	-0.31	-0.91	0.27	0.25
Kurtosis(K)	0.28	-0.83	-0.49	1.3	0.79	-0.56	-0.71	-0.8	-1.19	0.58	-1.11	-0.62
Coefficient of Variation(δ_v)	0.11	0.11	0.11	0.12	0.09	0.1	0.16	0.14	0.09	0.08	0.12	0.11

Appendix7 Descriptive statistics for Thika station

	Month											
Descriptive Statistics	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Number of numeric values	17	17	17	17	17	17	17	17	17	17	17	17
Mean ($\bar{X}$)	6.59	6.92	6.38	5.43	4.77	4.38	3.99	4.22	5.35	5.56	5.16	5.96
Standard Deviation(σ)	0.55	0.39	0.43	0.58	0.35	0.56	0.65	0.65	0.5	0.39	0.53	0.56
Range	2.25	1.34	1.48	2.47	1.32	2.4	1.99	2.64	1.63	1.65	1.99	2.11
Minimum	4.94	6.08	5.87	3.87	4.06	3.36	3.04	2.82	4.58	4.54	4.33	4.98
Lower Quartile(Q_1)	6.39	6.76	6.04	5.14	4.63	4.06	3.58	3.88	4.95	5.42	4.86	5.67
Median(Q_2)	6.67	6.98	6.34	5.47	4.73	4.26	3.84	4.2	5.27	5.48	5	6.13
Upper Quartile(Q_3)	6.98	7.16	6.53	5.82	4.91	4.71	4.63	4.6	5.87	5.78	5.6	6.29
Maximum	7.19	7.42	7.35	6.34	5.38	5.76	5.03	5.46	6.21	6.19	6.32	7.09
Skewness(S)	-1.7	-0.79	0.98	-0.9	-0.3	0.72	0.19	-0	0.41	-0.7	0.66	-0.2
Kurtosis(K)	4.16	-0.01	0.32	2.09	0.2	1.24	-1.29	0.29	-1.2	2.02	0	0
Coefficient of Variation(δ_v)	0.08	0.06	0.07	0.11	0.07	0.13	0.16	0.15	0.09	0.07	0.1	0.09

Appendix 8 Descriptive statistics for JKIA.

Descriptive Statistics	Month											
	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Number of numeric values	20	20	20	20	20	20	20	20	20	20	20	20
Mean($\bar{X}$)	6.01	6.37	6.091	5.33	4.86	4.47	4.21	4.41	5.45	5.54	5.28	5.87
Standard Deviation(σ)	0.59	0.47	0.366	0.32	0.39	0.54	0.67	0.71	0.83	0.6	0.42	0.47
Range	2.03	2.01	1.2	1.32	1.47	1.81	2.22	2.41	2.74	1.76	1.37	1.83
Minimum	4.85	5.66	5.57	4.78	4.13	3.68	3.49	3.39	3.94	4.65	4.42	5.19
Lower Quartile(Q_1)	5.91	6.06	5.805	5.16	4.59	4.03	3.7	3.95	4.87	5.03	5.04	5.49
Median(Q_2)	6.14	6.39	6.115	5.29	4.8	4.51	3.88	4.18	5.36	5.35	5.34	5.92
Upper Quartile(Q_3)	6.38	6.6	6.323	5.45	5.26	4.86	4.74	5.04	6.3	6.21	5.59	6.19
Maximum	6.88	7.67	6.77	6.1	5.6	5.49	5.71	5.8	6.68	6.41	5.79	7.02
Skewness(S)	-0.8	0.97	0.297	0.8	0.22	0.19	0.89	0.71	0.11	0.27	-0.7	0.54
Kurtosis(K)	-0.2	1.66	-0.622	1.01	-0.62	-1.1	-0.5	-0.68	-1.1	-1.4	-0.5	0.23
Coefficient of Variation(δ_v)	0.1	0.07	0.06	0.06	0.08	0.12	0.16	0.16	0.15	0.11	0.08	0.08

CASE EXAMPLE I. THE SOLAR PHOTOVOLTAIC SYSTEM.

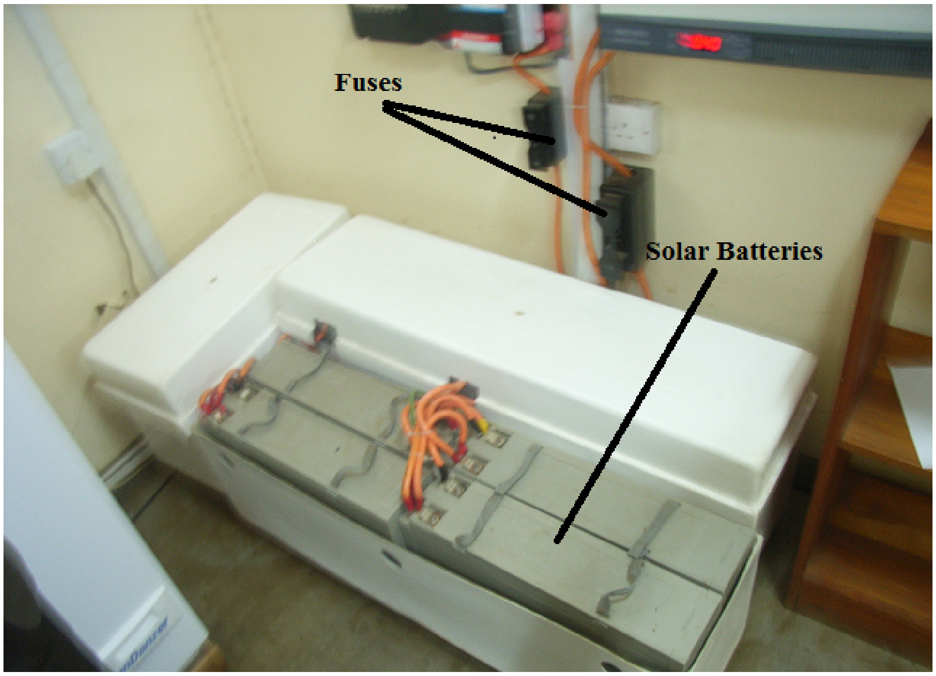

Plate 1 **Maintenance free batteries and the fuses at the renewable energy centre**

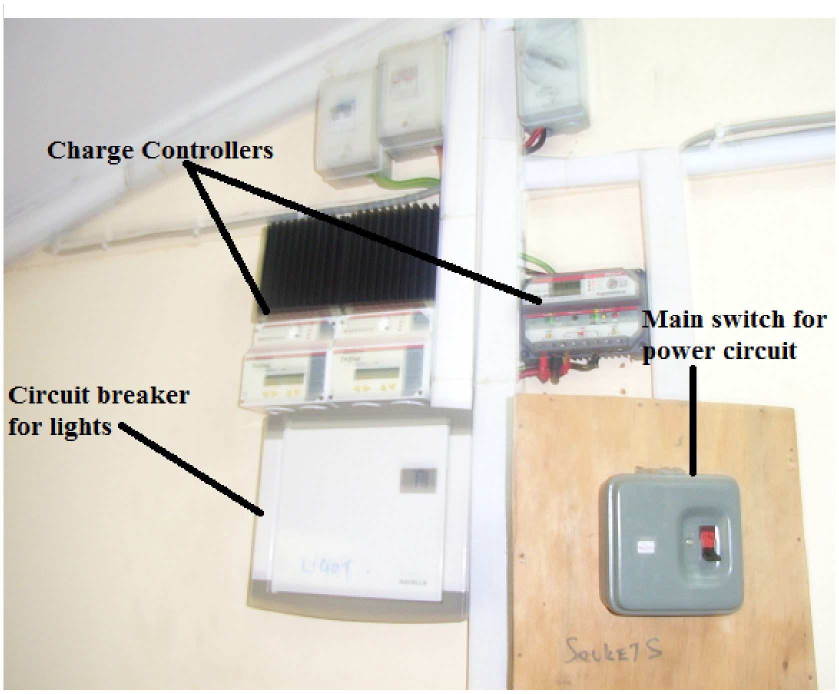

Plate 2 **Charge controllers and distribution unit renewable energy centre**

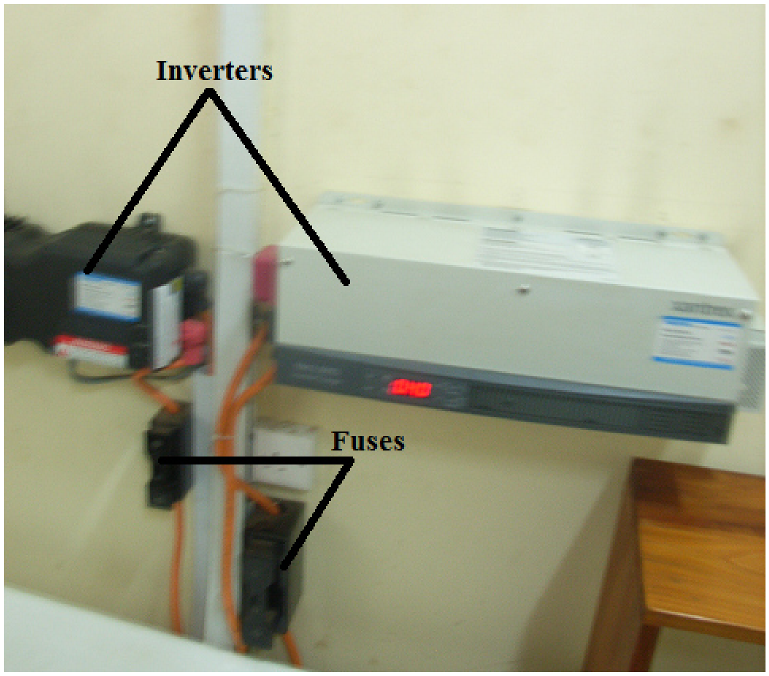

Plate 3 **Fuses and the inverters at the renewable energy centre**

Plate 4 **19 solar panel array at the renewable energy centre**

CASE EXAMPLE II: SOLAR PHOTOVOLTAIC SYSTEM IN RUIRU

Plate 5 The 2 solar panels installed in a house in Ruiru.

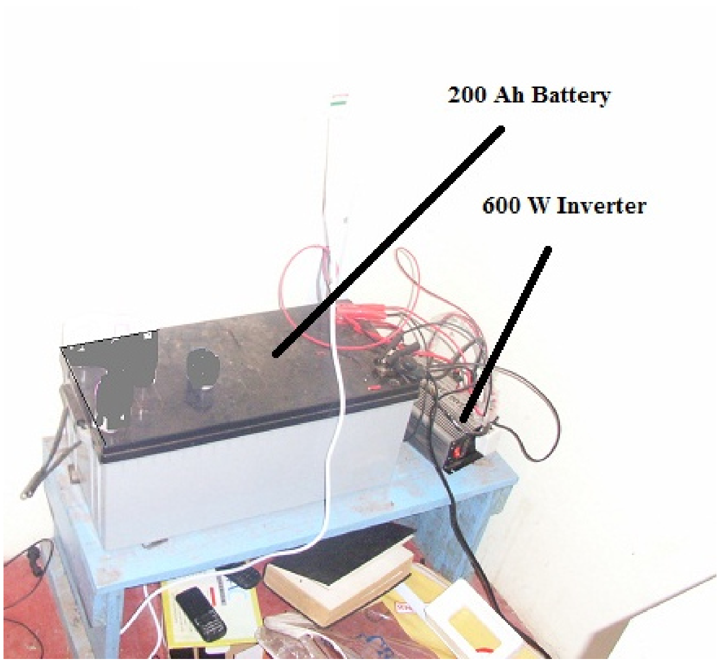

Plate 6 The Solar battery and the inverter, supported by the two solar panels

Plate 7 The distribution unit for a PV system for the house in Ruiru

Plate 8 Charge controller for a house in Ruiru