Design of a Grid Connected Photovoltaic System for Enhancement of Electrical Power Supply in Kenya: A Case Study of Nairobi Embakasi Suburb

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DECLARATION

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

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DEDICATION

This work is dedicated to my family wife Margaret Njeghe, my children Samuel Guyo, Gabriel Pelu and Olive Machocho for their patience and understanding during the entire research period. May all Glory be to God.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AGM	Absorbent Glass Matt
BIPV	Building Integrated Photovoltaic
BP	British Petroleum
CC	Charge Controller
DOA	Days of Autonomy
DOD	Depth of Discharge
DSM	Demand Side Management
ENS	Embakasi Nyayo Suburb
FIT	Feed in Tariff
FLA	Flooded Lead Acid
GDC	Geothermal Development Cooperation
GMT	Greenwich Mean Time
GTI	Grid Tied Inverter
GW	Giga Watts
GWh	Giga Watt Hours
HVD	High Voltage Disconnect
HVR	High Voltage Reconnect

IPP	Independent Power Producers
IRR	Internal Rate of Return
IV	I-Current and V- Voltage
JKIA	Jomo Kenyatta International Airport
JKUAT	Jomo Kenyatta University of Agriculture and Technology
KESI	Kenya Electricity Supply Industry
KenGen	Kenya Electricity Generating Company
KPLC	Kenya Power and Lighting Company
kW/m^2	Kilo Watts Per Meter Square
kWh	Kilo Watt Hours
kWh/m^2	Kilo Watt hours Per Meter Square
kWp	Kilo Watts Peak
LPG	Liquefied Petroleum Gas
LVD	Low Voltage Disconnect
LVR	Low Voltage Reconnect
MET (JKA)	Meteorological Department (Jomo Kenyatta Airport)
MJ	Mega Joules
MOE	Ministry of Energy
MPPT	Maximum Power Point Tracking
MW	Mega Watts
MWh	Mega Watt Hours

NASA	National Aeronautics Space and Administration
NEMA	National Environmental Management Authority
NEC	National Electric Code
NGO	Non Governmental Organization
NOCT	Nominal Operating Cell Temperature
NM	Net Metering
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NSSF	National Social Security Fund
PV	Photovoltaic
PWM	Pulse Width Modulation
RE	Renewable Energy
RER	Renewable Energy Resources
SHS	Solar Home Systems
SOC	State of Charge
SOS	Save Our Souls
STC	Standard Testing Conditions
TUM	Technical University of Mombasa
UNEP	United Nations Environmental Program
USA	United Sates of America
UTCE	Union for Coordination of Electricity Transmission

VDC	Direct Current Voltage
VAC	Alternating Current Voltage

ABSTRACT

The demand for electrical energy in Kenya has been on the increase since the country got its independence that brought freedom in 1963. This increase in power consumption has been due to population increase and national economic growth. The increase in demand without a matching increase in generation has resulted in perennial electrical power shortfall necessitating the Kenyan Electricity Supply Industry (ESI) to resort to expensive fossil fuels for electrical power generation. This electricity shortfall has affected industrial growth and envisaged markets expansion in the country. If the problem is not addressed, in good time, future national growth projections may not be met.

Power generation in Kenya is mainly from hydro, geothermal, diesel, gas and to a lesser extent, wind.

Kenya has a geographical advantage by virtue of being located at the equator and between the tropics where the solar cycles can be accurately predicted. This research therefore, sought to explore available methods so as to develop a renewable method to mitigate electrical power generation shortage in the country using grid-connected solar photovoltaic (PV) electricity generation in urban areas.

Data for solar insolation and domestic load from the case study suburb (Embakasi Nyayo Estate) was collected and then matched so as to design a typical solar

photovoltaic system. Data collected show that the case study suburb receives a monthly average solar insolation of 5.2 kWh/m^2/day for most part of the year. In this area and time solar irradiance of 1.25kW/m^2 is a common occurrence between 11.00 AM and 1 PM. The same data also reveal that one three bed roomed master en-suite apartment building at the case study, requires about 6.13 kWh per day with a morning peak of 1.5 kW and an evening peak of 2.5 kW, while a block of eight apartments has a daily energy demand of 48.8 kWh.

Both statistical and solar PV system design software were used to develop the plant. The design was done with a block peak power demand consideration of 12.5 kW so there is surplus solar PV electricity generation during off peak that could be injected into the grid. A battery storage capacity of 3600 Ah was provided that could supply the evening peak and also provide 1 days of autonomy. The researcher has produced a complete typical solar PV electricity generation system design suitable for the case study suburb.

Further the solar photovoltaic electricity generation potential for the entire case study suburb was aggregated so as to quantify the amount of enhancement resulting from the solar PV systems implementation. The case study suburb aggregated peak solar photovoltaic electricity generation is estimated at 3.12 MW. Design results show that one block of eight apartments will be capable of generating 19,402 kWh annually making the total energy generated in the 480 block suburb to be 9,312,960 kWh annually.

A financial analysis of the designed system was done and the system was found to be viable only when the cost of the project is subsidized. The financial analysis obtained a best net present value of 27,129 for the solar PV system with a 27% subsidy.

This system will be capable of injecting power to the grid so there will be need for the suburb to spearhead the development of a National Electric Code (NEC) which will introduce favorable tariffs like the net metering one that will cover small grid-interactive power systems. Further, there will be need to develop trained human capacity to support the solar PV systems.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Highlights

Like most countries in the world Kenya uses electrical energy to meet domestic, commercial and industrial energy requirements. Electrical energy comprises almost 10% of the total energy used in the country annually [1]. Lately there has been increased demand for more electricity generation due to population growth and economic development. This chapter presents the current electricity generation position and introduces the methods that could be used to enhance electricity generation in the country.

1.2 Background of the Study

The electricity generation mix of Kenyan Electricity Supply Industry (KESI) consists of: hydro, geothermal, thermal and wind. The generation commitment is guided by economic merit order. This means that most of the base load is supplied by the cheaper hydro and geothermal power generating plants while the peak power is supplied by the more expensive generators like diesel, thermal and gas plants [1]. Most of this electrical energy is consumed by industries in the urban centers. A considerable amount of this energy is also consumed by the urban domestic consumers during the evening and the morning peak energy demands. Nairobi city suburbs alone consume about 15% of the total electrical power generated in the country during the peak hours [2].

The Kenyan Electricity Supply Industry (KESI) relies on hydro power generation for up to 48% when the reservoirs are full of water. The effective hydro electrical power generation in the country totals 759 MW supplied by the plants along the Tana, Sondu and Turkwel rivers as shown in Table 1.1.

Table 1.1 Power Generating Stations

Interconnected Hydro Power Stations					
Power Station	**Installed Capacity (MW)**	**Effective Capacity (MW)**	**Power Station**	**Installed Capacity (MW)**	**Effective Capacity (MW)**
Gitaru	225	216	Tana	20	20
Kiambere	144	144	Wanji	7.5	7.4
Turkwel	106	106	Ndula	2.5	1.8
Kamburu	95	92	Gogo	2.25	1.4
Masinga	40	36	Sagana	1.5	1.5
Kindaruma	72	72	Mesco	0.38	0.36
Sondu Miriu	60	60	Sossiani	0.4	0.2
Total Hydro	**777**	**759**			
Geothermal Power Stations					
KenGen Olkaria 1	45	20	Or Power Olkaria III	13	12
KenGen Olkaria II	70	50	Or Power Olkaria IV	35	
KenGen Olkaria III	35	35			
Total Geothermal	**198**	**152**			
Diesel and Gas Power Plants					
Embakasi Gas	60	30	Eldoret Aggreko	40	40
Kipevu Diesel	120	120	Iberafrica	109	109
Kipevu Tsavo Diesel	74	74	Rabai	89	89
Embakasi Aggreko	50	50			
Total Diesel and Gas	**542**	**463**			
Off-Grid Diesel Power Plants					
Lodwar	2.4	2	Garissa	3.4	3.0
Lamu	2.4	2.2	Moyale	2	2
Marsabit	5.2	5.0	Mandera	1.2	1.2
Total Off-Grid	**16.6**	**15.4**			
National Total	**1533**	**1374**			

Source: [3]

The effective geothermal energy resource contributes 152 MW of electrical power which is generated at Olkaria in the southern part of the Rift Valley in Kenya. The geothermal plants are very important to the KESI because they supply most of the base load during the dry seasons. The KESI has plans to further develop Olkaria 4 geothermal plant expected to generate some 280 MW when completed by 2014 [4].

The other major generating plants are: Gas turbine at Embakasi, diesel plants of KenGen and Tsavo both located at Kipevu, Aggreko diesel plants at Embakasi and Eldoret. The newly completed Rabai diesel plant now adds 89 MW into the national grid. These power generation plants are shown on Table 1.1. The KESI is currently developing a 150 MW coal plant at Rabai [5].

Isolated electricity generation plants are located in: Lodwar, Garissa, Lamu Moyale and Marsabit. Most of these plants are small diesel stations of up to 2000 kW. The wind turbines plants at Ngong and Marsabit generate a total of 5.4 MW, out of which 5.1 MW is connected to the national grid. Currently, the KESI is seeking funds to develop a 300 MW wind farm in Turkana district. Besides the Turkana project, there are plans to increase wind power generation capacity at Ngong by 20.4 MW in 2013 [6].

By end of 2011, the peak electrical power demand in the country was estimated at 1289 MW which was larger than the effective total hydro and geothermal generation combined of 911 MW. This implied that the KESI had to top up generation by about 378 MW using diesel and gas generators to supply the peak demand. Unlike the standard practice world over, where electricity supply industries (ESI) use hydro generation for peak demand, Kenya relies heavily on hydro generation for its base load. Hence electricity generation shortfall is worse during the dry seasons when the water reservoir levels are very low and the ESI is forced to rely more on the geothermal plants to supply the base load. During such harsh weather conditions, like the 2008 dry spell, the ESI had a shortfall of 160 MW, out of its 715 MW effective hydro generation. During this period, the ESI totally relied on diesel and gas generating plants to supplement the geothermal plants to supply the demand. When available generation was not adequate, the KESI resorted to a nationwide power rationing program which lasted for two months [7].

With the current global climatic changes, the Kenyan electricity supply industry has to review its electrical generation mix with a view to develop and exploit other energy resources like solar photovoltaic, wind, biogas and geothermal. The world-wide trend is to shift from over reliance on fossil fuels to renewable energy resources. Kenya has to make the same shift if the ESI is to continue serving the consumer effectively. Further, if Kenya is to realize the objectives of vision 2030, the electricity supply industry must be enhanced to withstand the energy demand pressure that comes with rapid economic and population growth.

Renewable energy has been used in many countries. Countries like the United States of America (USA) have instituted a policy that in every state, 6% of the total electricity generation must come from renewable sources to cut down on pollution caused by fossil fuel plants [8]. In Germany, the introduction of the Renewable Sources Act of 2000, of granting priority to renewable energy sources, encouraged growth of the installed solar PV capacity level from 113 MWp in 2000 to 794 MWp in 2004 and 7.5 GWp by 2011 [9]. In Ghana, government support schemes, particularly the national electrification scheme backed by donor funding increased solar PV growth from 160 kWp in 2000 to 1 MWp in 2004 and 1.8 MWp by 2009 [10]. Locally Kenya had 3.6 MWp installed solar PV by the end of 2009 that was mostly concentrated in the rural areas [11].

1.3 Problem Statement

From the overview done on the Kenyan electricity supply industry, it is evident that there is insufficient electricity supply and overreliance on fossil fuels and hydro in electricity generation. The installed effective electricity generation capacity in Kenya stood at 1374 MW as of June 2011 while the peak power demand was 1289 MW [3]. The difference of 85 MW or 6 % of generation comprised spinning reserve which was below recommended best practice of 12 to 15% [12]. With a 6% spinning reserve capacity, the industry encountered difficulties in handling the sharp evening peak power demand. Furthermore, the effective electricity generation capacity was made up of 448 MW or 33% fossil fuel based generation whose unit cost relied on the ever increasing price of petroleum products. This amount of fuel based generation contributed a large percentage to electrical energy price in the country. Thus, there is a need to reduce fuel base electricity generation by exploiting and increasing renewable methods of generation.

1.4 Justification of the Study

In view of the present electrical energy shortfall in the Kenyan electricity supply industry as highlighted in section 1.3, it is evident that the industry needs to take urgent measures to make supply more reliable. Information in Nairobi Embakasi suburb indicates that there have been frequent scheduled and unscheduled electrical power outages some lasting up to 12 hours. In August 2009, the Kenya Power and Lighting Company (KPLC) issued a power management program, due to sporadic non-availability of electricity generation plants, to avoid customer inconvenience due to electrical power interruption without notice [13].

Grid connected solar PV systems have the following benefits:

- Solar PV electricity generation supplement a large amounts of grid power presently used by urban domestic consumers. This power offload would reduce demand of grid electricity generation.
- Solar PV electricity generation would improve the voltage profile in the distribution lines, thereby reducing transmission and distribution losses.
- Solar PV development would encourage the introduction of Building Integrated Photovoltaic (BIPV) legislation that would accelerate solar PV penetration.
- Solar PV electricity generation would reduce reliance on fossil fuel generators.

1.5 Objectives of Study

1.5.1 Main Objective

The main objective of this study is to design and size a grid connected solar photovoltaic system for use by domestic consumers and investigate the impact of such systems on the Kenyan Electricity Supply Industry.

1.5.2 Specific Objectives

The study had the following specific objectives:

i. To identify and select a suburb for the case study based on electrical energy demand and available solar radiation.

ii. To collect and analyze domestic load and solar insolation data from the suburb for case study.

iii. To design and size a typical grid connected solar PV electricity generation system for the case study.

iv. To perform a financial analysis of the solar PV electricity generation system of the case study.

v. To aggregate the available solar PV generation potential by tallying the individual plants generation in the case study to assess its impact to the grid.

1.6 Scope of the Study

The scope of this study is limited to collection and analysis of solar insolation and domestic load demand data so as to analyze the trends and enable the sizing of a typical grid connected solar photovoltaic electricity generation system. The scope does not cover energy management at the selected case study. This study also compares other benefits of using solar PV electricity generation with respect to using fossil fuel based grid electricity generation. Within the confines of the study, a workable solar PV and grid hybrid system is developed.

Finally a financial analysis is carried out to evaluate implementation cost and financial benefits to the consumer.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Highlights

Solar photovoltaic generation is one of the most environmentally friendly methods of generating electricity and a lot of work has been done in this field since the solar PV cell was invented. This chapter reviews literature on studies and work done in data acquisition, designing and sizing of solar photovoltaic generating systems and other similar previous studies done on solar photovoltaic harnessing and development. The chapter concludes by summarizing the achievements made in the solar PV field and their future opportunities.

2.2 Solar Photovoltaic's in Kenya

Studies done in Kenya show that a United Nations Environmental Program (UNEP) funded conference on renewable energy and environment held in Nairobi in 1981 marked the beginning of solar photovoltaic electricity generation [14]. This conference attracted a lot of renewable energy experts from all over the world to discuss the global progress of renewable energy and aroused a lot of interest among Kenyans and donor organizations in the country. The interest resulted in importation of solar modules and accessories to set up solar home systems especially in the rural areas of the country. By 1986, hundreds of rural solar home systems (SHS) had been installed in the coffee and tea farms in Meru, Chuka and Embu [15].

A preliminary survey carried out by the Kenya Investment Authority in 2005 established that the annual market for solar PV modules in Kenya was 500 kWp and this was projected to grow by 15% annually. A government program initiated in 2005 to provide basic electricity to boarding schools and health centers in remote rural areas increased the annual installation demand for solar PV modules by 100 kWp by 2006 [16]. Another survey carried out between 2003 and 2004 for monitoring SHS data in the country revealed that in contrast to the developed countries, Kenya has installed most of her solar PV generation systems in the rural areas as stand-alone off grid systems.

So far no urban or rural domestic grid connected solar PV electricity generation system has been done in the country despite the fact that domestic consumers in the urban areas consume an estimated 30% of the electricity generated. The revelation that no such studies have been done make the current study very necessary so as to reveal the unknown potential of solar PV in urban areas and the benefits of developing urban solar PV generation systems in the country.

2.3 The Solar Resource Assessment

The sun commonly referred to as “a ball of fire in the sky” is the source of solar and all energy on the earth’s surface. It is composed of a mixture of gases with a predominance of hydrogen gas. As it converts hydrogen to helium in a massive thermonuclear fusion reaction, mass is converted to energy according to Albert Einstein’s formula; $E = mc^2$. As a result of this reaction, the surface of the sun is maintained at a temperature of approximately 5800 degrees Kelvin or 5526.85 ^{0}C. This energy is radiated away uniformly in all directions in close agreement with Planks blackbody radiation formula [17]. The energy density per unit area, W_{λ}, as a function of wavelength, λ, is given by (2.1)

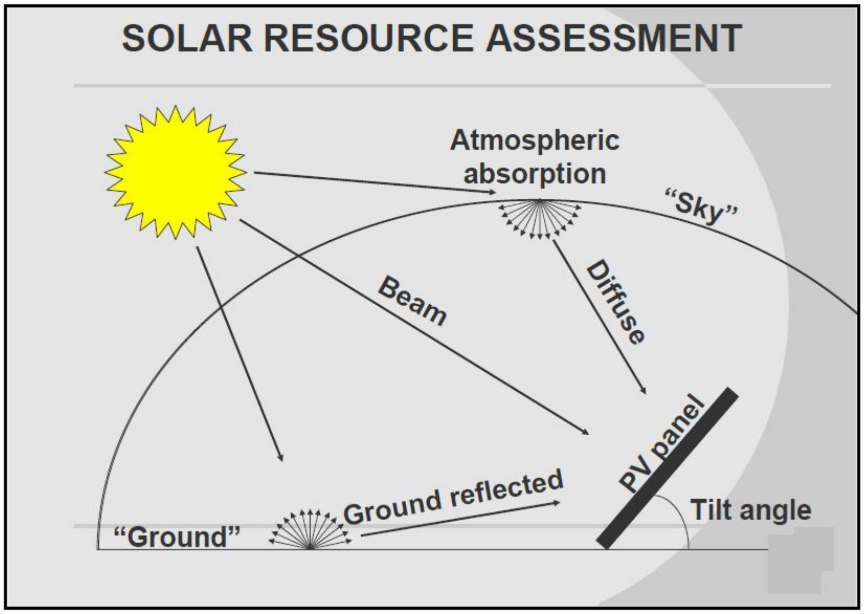
$$W_{\lambda} = \frac{2\pi h C^2 \lambda^{-5}}{e^{\frac{hc}{\lambda KT}} - 1} \tag{2.1}$$

Where h is Planks constant (6.63 x 10^{-34} W s^2), c is speed of light in vacuum (3.00 x 10^8 m/s), k is Boltzmann's constant (1.38 x 10^{-23} J/K), t is temperature of blackbody in degrees Kelvin,

λ is Wavelength

In one hour, the earth receives enough energy from the sun to meet its energy needs for a whole year [17]. For a long time, man depended on the sun for drying and heating until the petroleum discovery in mid nineteenth century diverted the global energy demand source to overreliance on fossil fuels. The sun radiates solar energy on the earth surface as the earth moves on its own axis and revolves round the sun on an elliptical orbit. This phenomenon makes the suns radiation reaching the earth's surface to vary as the earth moves around the sun. Due to this phenomenon, the parts of the earth nearest to the equator receive more solar energy than parts far from the equator. This phenomenon also supports the reason why there are longer days and nights depending on one's location on the earth and time of the year.

The solar energy reaching a solar PV array on the earth surface consists of the main beam which is direct radiation, the diffused beam which is direct radiation affected by atmospheric absorption and the ground reflected beam which is as a result of reflection of the direct beam from the earth surface as shown in the Figure 2.1.



Source: [18]

Figure 2.1: The Solar Insolation on an Array on the Earth Surface

Figure 2.1 shows that not all the radiation that is released by the sun will reach the solar PV array surface placed on the earth. This makes the orientation of the solar PV array very important for energy absorption. The orientation of the Solar PV array has two major parameters; the slope and the azimuth. The slope is the angle of tilt with reference to the ground horizontal surface and the azimuth is the direction towards which the array surface face. When a solar PV array is installed south of the equator, azimuth is due north and when installed north of the equator, azimuth is due south. The azimuth can be due south or due north depending on the latitude of the site or location on the earth's surface.

At noon every day, the sun rays are perpendicular to the earth surface on the equator and give maximum radiation. Any other time of the day, the position of the sun is affected by the latitude, longitude, time of the day and day of the year. The angle formed between the plane of the equator and a line drawn from the center of the earth is called the solar declination angle denoted by δ. The angle of declination is expressed in equation (2.2) as;

$$\delta = \frac{23.45^0(360^0\, x\, 284 + n)}{365} \qquad (2.2)$$

Where n is the day of the year and January 1st is day one of the year.

Holding the earth stationary, the time of the day affects the location of the sun in the sky, and this effect is described by an hour angle. The hour angle is calculated as;

$$\omega = (T_s - 12)15^0/hr \qquad (2.3)$$

Where T_s is the solar time in hours

The value of T_s is 12 hours at solar noon.

Equation 2.3 is obtained from the fact that the sun moves across the sky at a speed of 15 degrees per hour. Most solar PV system designers assume that all time dependent data; such as solar radiation and electric load, are specified in civil time, which is also referred to as local standard time of the location.

The relationship between solar time and standard time is given in (2.4);

$$T_s = T_c + \frac{\lambda}{15^0/hr} - Z_c + E \qquad (2.4)$$

Where T_c is the local standard time corresponding to the midpoint of the time step in hour,

λ is the longitude in degrees, Z_c is the time zone in hours east of Greenwich Mean Time (GMT), E is the eccentric anomaly of the sun due to earths obliquity, currently the earth's tilt is 23.44^0.

The Equations 2.3 and 2.4 mean that the sun covers 15^0 every one hour so when a solar PV array is tilted 15^0 after every hour, the array will remain almost perpendicular to the sun and a near maximum power output can be achieved.

2.4 Solar Photovoltaic Array Output

Solar photovoltaic array output is the power output of the solar PV array that will be delivered to the designed solar PV system. Normally the power that is delivered by the solar PV array is lower than its rated capacity because of the effect of the derating factors mainly due to temperature and irradiance. The power output of a solar PV array can be expressed as;

$$P_{pv} = Y_{pv}\, f_{pv} \left(\frac{G_t}{G_{t,STC}}\right)\left[1 + \alpha_p \left(T_c - T_{c,STC}\right)\right] \tag{2.5}$$

Where

P_{pv} - Power output of solar PV array

Y_{pv} - Rated capacity of the PV array under STC [kW]

f_{pv} - PV derating factor [%]

Gt - Solar radiation incident on the PV array [kW/m^2]

$Gt,_{STC}$ - Incident radiation at STC [1 kW/m^2]

α_p - Temperature coefficient of power [%/^{0}C]

Tc - PV cell temperature [^{0}C]

$Tc,_{STC}$ - PV cell temperature under STC [25^{0}C].

2.5 Design and Sizing of a Grid Solar Photovoltaic System

From work done in solar photovoltaic systems previously, it is noted that the components and their sizes are very important in design and sizing because they determine the type and capacity of the system. Figure 2.2 shows a general schematic representing a grid connected solar PV system.

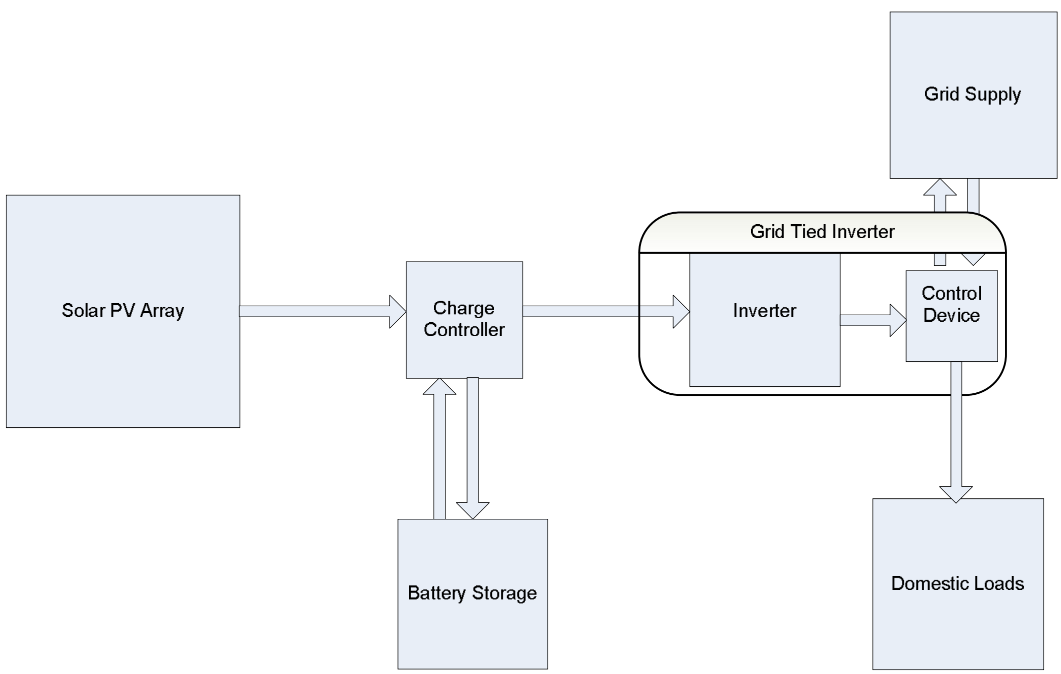


Figure 2.2: Schematic Diagram of a Grid Connected Solar Photovoltaic System

Most studies have shown that in order to determine the sizes of the components forming the solar photovoltaic system, consideration has to be made of the daily energy demand

and daily peak power including the standby power consumed by idle equipment. The demand can then be matched with the solar radiation available on site. Some, designers have had to develop their own algorithms to size solar PV systems for residential consumers where the load is matched with the available radiation; Zakaria Anwar et al developed such an algorithm in Sudan and achieved good results [19]. In their work Zakaria et al used 30 year average solar insolation design data as shown in Table 2.1. The Table 2.1 shows the design data that was used by Zakaria for their study.

Table 2.1: Design Parameters for South Sudan

Parameter	Value	Units
System voltage	48	V
Number of days of autonomy	1	Days
Battery ampere hour rating	70	Ah
Battery voltage	12	V
Battery depth of discharge	50	%
Battery efficiency	83	%
Inverter efficiency	83	%
Solar module maximum current	3.15	A
Solar module voltage	12	V
Average solar insolation	6.2	$kWh/m^2/day$

Source: [19]

Some designers mostly in Europe use the month with the lowest insolation as the reference month to avoid loss of power during winter/cloudy months. However for situations in most parts of Africa and especially within the tropics, where annual average solar insolation is between 4 to 6.4 $kWh/m^2/day$, and solar irradiance of 1.25 kW/m^2 is a common occurrence, a designer could easily end up with an over design of a solar PV system if the month with lowest insolation is used as the reference month. It is therefore important to consider prevailing weather conditions and obtain accurate load data when designing a solar photovoltaic system. It is even better when a designer uses an average monthly insolation data instead of a single annual value as some researcher do. Fan Jiang et al used average solar insolation data from the Singapore National Environmental Agency for an array comprising of 256 x 75 Watts modules divided into four sets of strings of 8 x 8 that fed power into four inverters of 4 kWp each making a total of 19.2 kWp [20]. The research work took 8 years and results showed success.

2.5.1 Daily Electrical Energy Demand

The daily electrical energy demand is the amount of electrical energy that is required by the consumer to be supplied by the solar PV electricity generation system. Studies show that daily energy demand has been estimated differently by many researchers mostly by taking the ratings of electrical appliances that are used in a day and the time that they are used during the day or night time. The information then forms a load list which when multiplied by the duty cycle of each appliance provide the kWh consumed in a day. A tally of the individual appliance energy demands gave the estimated energy demand of the site under consideration [19],[21]. A study by Zakaria Anwar used controllable domestic load data to design for a case study in Sudan as shown in Table 2.2 [19]. Elsewhere Atel El-Zeftawy used a model of summation of hourly power consumed to achieve diurnal load demand for a case study in Egypt and also used solar insolation data from the meteorological Authority in the country [22].

Table 2.2: Controllable Residential Input Load Data (Sudan)

Appliances Name	Units	Watts	Hourly Night	Hourly Day
1200mm fluorescent lamps	9	360	5	-
600mm fluorescent lamps	1	20	5	-
75watts bulbs	2	150	12	-
60watts bulbs	1	60	12	3
Refrigerator	1	200	10	10
Washing Machine	1	400	-	1
Electric oven	1	1300	-	1
Water pump	1	370	-	2
Fans	3	300	2	6
Air water cooling	2	500	2	6
Electric Iron	1	1000	-	1
Mixers	1	125	0.25	0.25
Television & Receiver	1	150	6	2

Source: [19]

Elsewhere in Bangi Malaysia, Musse M. et al used a load list with duty cycle for each load to design a daily power and energy demand data. In the study at Bangi a 5% extra power was allowed to account for power loss for each domestic appliance. Musse used 30 panels of 75 W each and 24 L-16 type batteries to run a daily load of 6931 kWh as shown in Table 2.3 [23].

Table 2.3: Average Power Consumption of Appliances (Bangi-Malaysia)

Appliance	Watts	Hours/Wk	Watts hours/wk
Blender	300	0.5	150
CD Player	35	5	175
Clock Radio	1	168	168
Coffee Maker	1000	10	10000
Computer	125	14	1750
Furnace Blower	700	21	14700
Garage door opener	350	1	350
Hair dryer	1200	1	1200
Iron	1000	0.5	500
Microwave	1500	1	1500
Laser Printer	400	1	400
Refrigerator (20cf)	150	70	10500
18” satellite dish	30	10	300
Bread toaster	1200	1	1200
25” color television	150	14	2100
Vacuum cleaner	1000	0.5	500
VCR	40	4	160
Washing machine	500	1	500
42 W halogen lamp	42	7	294
25W compact fluorescent lamps	28	49	1372
Gas dryer	350	2	700
			48519

Source: [23]

Musse M. obtained a daily energy consumption of 48519/7 = 6931 Wh

The methods used by Zakaria and Musse et al have some level of accuracy but more accurate data could still be obtained using other methods, for example, when the load data is collected using a power data logger.

When using a power data logger, the period for data logging should be able to capture both the daily energy demand and electrical peak power. This method is more accurate compared to the method of tallying the individual appliance demand because it gives actual values of energy consumed per day. To obtain monthly or annual energy demand, synthetic load data can be created by introducing random variability of 5% to 10% to the accurately logged daily energy demand data. This random variability will create annual realistic load profiles because the daily energy demand is never the same for different days. This is done because it would otherwise be very expensive and time consuming to collect actual annual daily energy demand data which would still not exactly replicate in the subsequent years. Using monthly average solar insolation data also achieves more accurate results compared to using a single annual data.

2.5.2 Solar PV Array Sizing

The solar PV array is the energy gateway into the entire solar photovoltaic system so its good performance is important for the reliability of the system. The output of the solar PV array is affected by many factors like irradiance and temperature so when designing a solar photovoltaic array, these factors require consideration so that the designer can achieve acceptable and accurate results. In these factors, there are tradeoffs which also define the best achievable accuracy in the design. These derating factors must be considered because they adversely affect the performance of the solar PV array, battery storage and the power conversion components.

(a) Types and Performance of Modules

There are mainly three types of solar PV module cells; those made from silicon semiconductors, chemical compounds and organic materials. The silicon cells are produced from either crystalline silicon or amorphous silicon. The Crystalline silicon cells are cut from silicon ingots and can be of monocrystalline or polycrystalline form, whereas the amorphous silicon cells are produced from a non crystalline structure material. The other types of solar cells are the dye sensitized cells that are currently under investigation but have very low efficiencies and degrade very first. Research is under way to improve their efficiencies and reduce the effects of degradation.

The silicon crystalline and amorphous silicon modules are the most common because they are the earliest technologies, first generation of PV cells and also have the best cell efficiencies so far. Further, in the silicon types of modules, the monocrystalline type has the highest cell efficiency followed by the polycrystalline and lastly the thin film amorphous silicon. Table 2.4 shows the efficiencies, cost of production and physical dimensions of the different silicon cells.

Table 2.4: Module Cell Efficiency

Module Cell Type	Efficiency (%)	Production cost USD/W	Physical Dimensions
Monocrystalline Silicon	18 -22	2	150mm x 150mm
Polycrystalline Silicon	15 -20	1.76	150mm x 150mm
Amorphous silicon	10 -12	1.25	150mm x 150mm

Source: [17]

When selecting solar PV modules, their cell efficiency is not a major factor because modules of the same rating will produce the same rated power output but will only differ in their physical sizes [17]. Therefore the main factors to be considered are cost, physical size and manufacturing standards for durability and reliability. This is done by making sure that the modules to be used have detailed technical data sheets.

Crystalline silicon solar modules are normally a series connection of silicon cells. A 12 V DC solar module has 36 series connected cells split into two circuits of 18 cells each. Across each of the 18 cells there is a bypass diode that allows current to flow when the cells are shaded. Figure 2.3 shows how the current flows in a 12 V module of 36 cells.

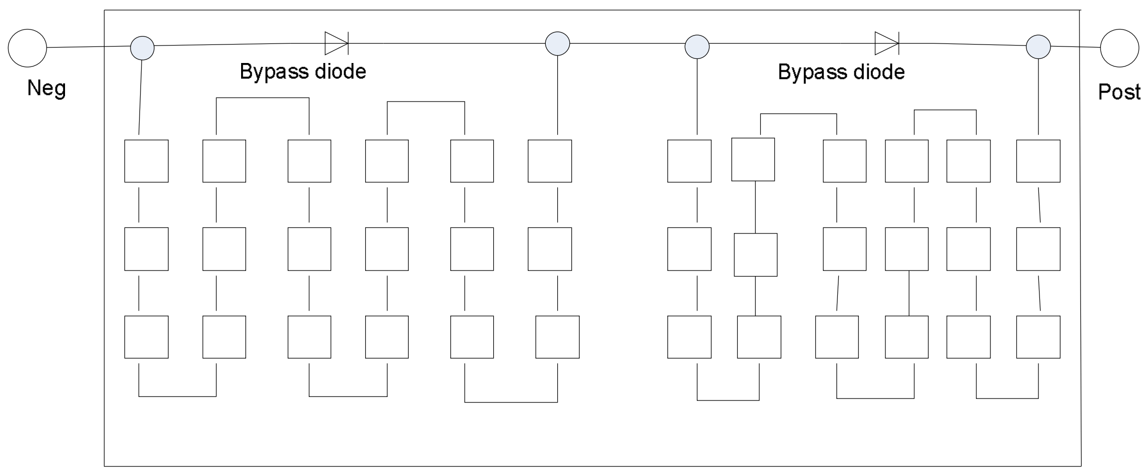


Figure 2.3: A 36 Cell Solar PV Module with Two Bypass diodes

Solar arrays are made of modules connected in a series-parallel formation depending on the power and voltage requirements. When an array is exposed to the sun, the same current flows through all series connected cells and the save voltage is across all the parallel connected cells. The resultant I-V curve of the array is an integration of the I-V curves of all the cells in series and parallel.

(b) Orientation of the Solar PV Array and the Tilt Angle

The solar PV array slope or angle of tilt is the angle formed by the array with reference to the horizontal earth surface when mounted. The slope will vary depending on the location of mounting the array. Studies show that common practice of mounting solar modules is to have them at a fixed angle with reference to the ground because it is the simplest and cheapest option. Such fixed orientations normally adopt the latitude of the location as the angle of tilt with the right azimuth. An angle of tilt equal to the latitude of the location and the right azimuth will enable the solar array to extract maximum radiation when irradiance is high between 10 AM and 4.30 PM in most locations. In schemes where the angle of tilt is made equal to the latitude, the systems achieve better annual solar PV energy production compared to other arbitrarily fixed angles schemes [24]. Therefore, the designer must select the best method of tilting the array considering the available conditions of installation. Seth Blumsack et al 2010 designed a system in Pennsylvania USA to have a split array of modules whose orientation was fixed to the East, West and South all at a tilt angle of 25^0. The system was grid tied with no battery storage particularly intended to sell power to the grid during the peak demand. Seth Blumsack et al used surface solar radiation data from the meteorological department at the Pennsylvania state University. In this study fixed angle orientation was used that managed to create a bimodal distribution of power output from the solar modules. Blumsack concluded that by splitting the orientation of the array panels to East and West azimuth rather than a predominantly Southern azimuth, significant power gains could be realized during the morning and evening demand peaks. It was further noted that the study was more advantageous to residential customer generators since the East –West orientation was more closely matched to the residential customers' load demand [25].

Fan Jiang et al at the Singapore Polytechnic, whose location is 1.32^0 north of the equator, used a fixed tilt angle of 15^0 with a southern azimuth and obtained good results [26].

Figure 2.7 shows a graph of current, voltage and power curves for a 60 watts (Chloride Exide -UBINK) solar photovoltaic Polycrystalline module. The measurements carried out at the JKUAT obtained a maximum power output of 56 watts as shown on the current, voltage and power curves in Figure 2.4. During the measurements, the tilt angle was fixed at 15^0 facing north because the test site was 1.5^0 south of the equator.

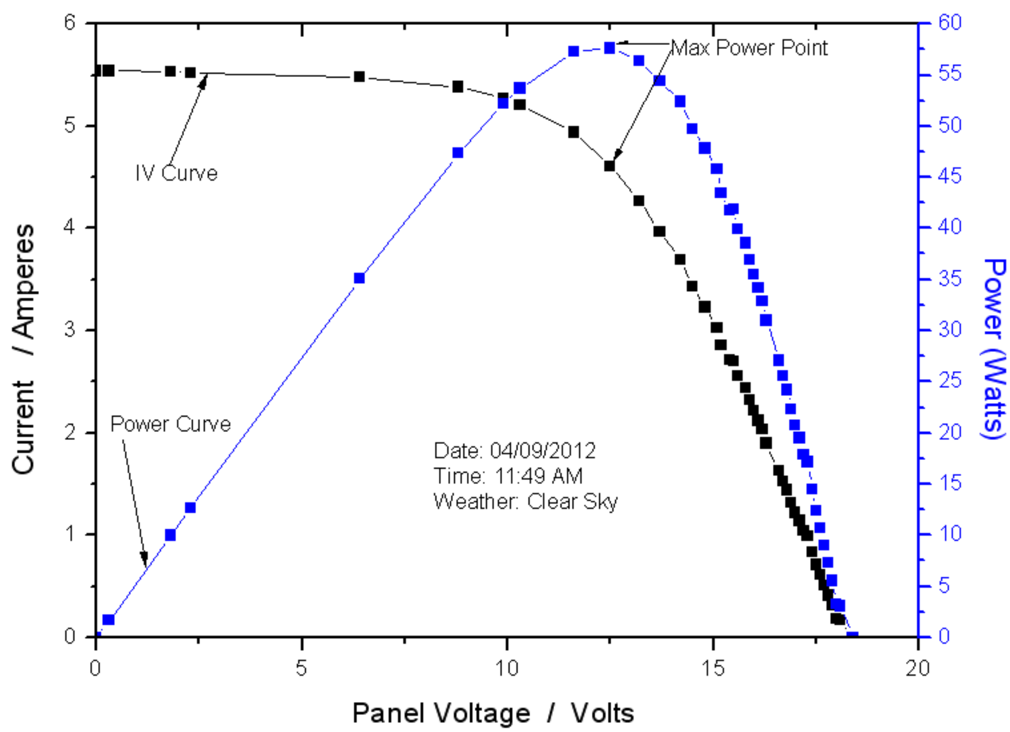


Figure 2.4: Current, Voltage and Power Curves of a Solar PV Module

In the USA, the National Renewable Energy Laboratories (NREL) did a study of solar PV module fixed tilt angles output with comparison to the output from Maximum Power Point Tracking (MPPT) angles output and realized that the fixed angles could give 80% of the MPPT output when maintained at certain values. The researchers recommended the angle values shown in Table 2.5 for fixed tilt angles schemes. The studies by the NREL also showed that fixed angles for different latitudes can achieve very good results. However, for locations very near to the equator, the purpose of tilting the array is to enable its natural cleaning during rainy seasons to avoid dust accumulation. Further, tilting the array also provides free air space under the array which enhances the cooling of the array.

Table 2.5: Recommended Fixed Angles for Solar Modules

Latitude Angle	**Recommended angle**
Latitude < 15 degrees	15 degrees
15 degrees < Latitude < 20 degrees	Latitude
20 degrees < Latitude < 35 degrees	Latitude + 10 degrees
35 degrees < Latitude	Latitude +15 degrees

Source: [26]

(c) Effects of Shading on Arrays

A solar PV array performs by generating electricity well when it receives direct radiation from the sun. When the sun is obstructed or shaded to the array, the output of the array is reduced proportional to the amount of shading. As shown in Figure 2.3, the cells are in series in a module so when a cell is shaded, the bypass diode conduct but the output current is greatly reduced.

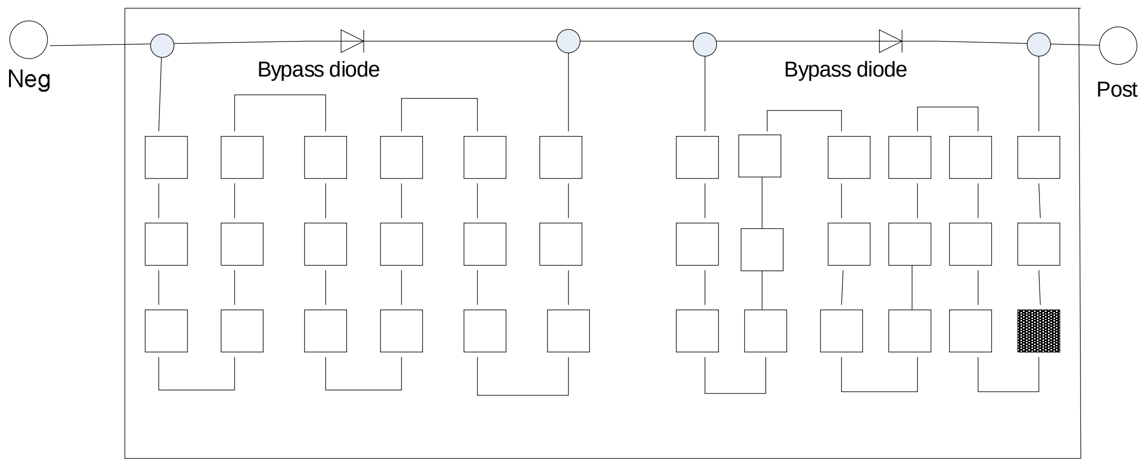
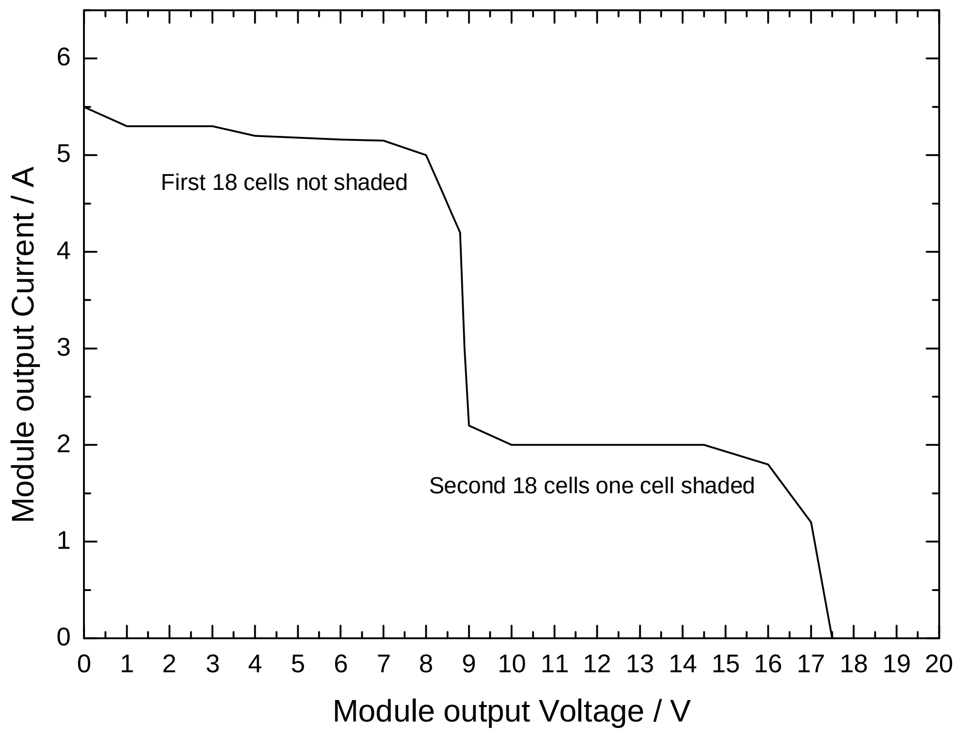


Figure 2.5: A 36 Cell Module with One Cell Shaded

Figure 2.5 shows a 36 cell module whose one cell is shaded. The effects can be well observed using the I_V curves of the two sets of 18 cells. The power output of the second 18 cells of the module is adversely affected by the shading of one cell.

Figure 2.6 shows the I-V curves of the 36 cell module when the second set of 18 cells has one cell shaded. The output current of the second 18 cells of the module is greatly affected. Note that at low voltages, the module will perform well with a current of up to 5.5 A, but at voltages above 9 V, the total output current is reduced to 2 A.



Source: [17]

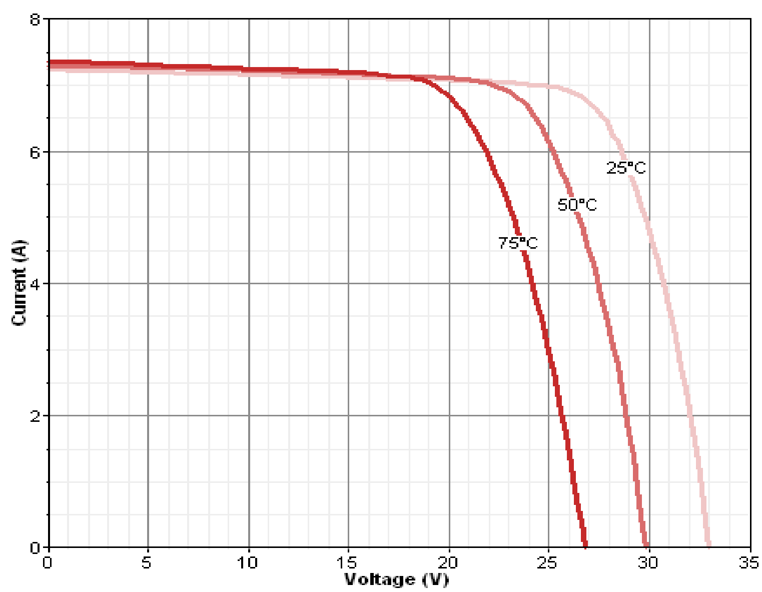
Figure 2.6: 36 cell I-V Curve with Two Bypass Diodes Module One Cell Shaded

Module cell shading can be caused by trees, flying objects and even clouds. Short lasting shading does not affect the daily charging current but persistent shading caused by trees and clouds reduces the daily output current of the modules a lot.

(d) Effects of Temperature and Irradiance

The performance of the solar PV array normally depends on the amount of irradiance reaching the array surface. Unfortunately, this also causes heating on the solar cells of the array as the day progresses and affects the output voltage of the module as shown in Figure 2.6. When irradiance reaching the module is reduced, the output current and hence the power is reduced. The effects of reduced irradiance are shown in Figure 2.9, where current is greatly affected while the voltage is affected slightly. Extreme high temperatures also reduce the lifespan of the modules by fast weathering.

When effects of temperature are not clearly accommodated in the design of a solar PV array then a temperature derating factor is also applied. In Singapore Fan Jiang et al observed high cell temperatures at noonday when temperature on the solar PV array rose up to 60^0 C and reduced the array cell output voltage down to 83.94% of the rated 21.1 volts open circuit value. Necessary temperature adjustments were made to the design and the project was observed for 8 years and good results were obtained [26]. Figure 2.7 show the effects of temperature on a solar cells IV characteristics.



Source: [17]

Figure 2.7: Effects of Temperature on the Solar Cell IV Characteristics

As shown on the cell temperature characteristics in Figure 2.7, temperature adversely affects the power output of the solar cell by reducing the output voltage of the array. At lower temperatures, more power can be extracted from the solar cell with the same solar insolation. But as the temperature increases from 25^0C to 75^0C, the power output is reduced for the same solar insolation. Therefore, this trend makes the cell temperature a major factor to be considered when designing a Solar PV system.

(e) Other Minor Derating Factors

Minor derating factors are factors whose effects also reduce the output of the array but the effects could be controlled or eradicated during design and sizing. These are factor like; aging, which can be controlled by timely replacement of modules, dust, which can be minimized by tilting the modules, wiring, which can be reduced by using the right size of conductors and mismatch, which can be eradicated by using modules from the same manufacturing standards. Though these factors are controllable, they still affect many solar PV systems because of lack of proper consideration during design and sizing. Table 2.6 shows most of the derating factors that are used in design and sizing

Table 2.6: Derating Factors for Solar PV Modules Sizing

Derating Due to	Factor Percentage
Mismatch	0.98
Efficiency	0.95
Dust	0.97
Shading	0.99
Wiring	0.98
Temperature	0.96
Aging	0.98

Source: [17]

2.5.3 The Solar Photovoltaic System Bus Voltage

The solar PV system voltage is the Direct Current (DC) bus voltage at which the solar array, the battery bank and the system power inverter are operated. Depending on the power output of the system, the system voltage could be in the range 12 V up to 500 V DC [14 17]. The battery bank is normally formed by individual batteries at 2 V, 6 V or 12 VDC depending on the preference of the designer and the allowable voltage drops in the DC circuit. So the total number of individual batteries that a designer will need to complete the battery bank will be determined by the system voltage and the total ampere hour capacity required by the system. Most of the time, the battery bank ampere hour capacity is held at safe levels so that the system voltage increases as the power increases. For instance, it is much safer to have a 15 kW power system at 360 V DC than to have the same system at 24 V DC system voltages.

2.5.4 Battery Storage System

The battery storage system is so far the most efficient and readily available method of storing electrical energy in Renewable Energy (RE) systems. Batteries are used to store electrical energy in renewable solar PV energy schemes because the source of energy is only available for part of the day. There are three major types of batteries popularly used in RE systems studies namely; the flooded lead acid (FLA) battery, Sealed Absorbent Glass Mat (AGM) battery and the sealed Gel cell battery. All the three types of batteries can be manufactured as deep cycled or duty cycled battery types for use in RE schemes. Such duty cycled batteries are capable of holding charge for long periods and also withstanding deeper discharge cycles of up to 80% of their charge capacity as compared to the shallow discharge types. They are also able to withstand harsh weather conditions like high and low ambient temperatures. Among the three types, the AGM and Gel cell batteries are more expensive on initial capital cost but are almost maintenance free compared to the FLA types of batteries. The advantages of the AGM and Gel batteries outweigh their initial capital cost and so they are preferred to the FLA for use in RE systems. Among the last two types, the Absorbent Glass Mat type is the most popular type in renewable systems because of its performance, long life and reliability [17]. Studies have shown that the GEL-type batteries can sustain from 400 to 500 deep discharges of up to 80% in their lifetime [23].

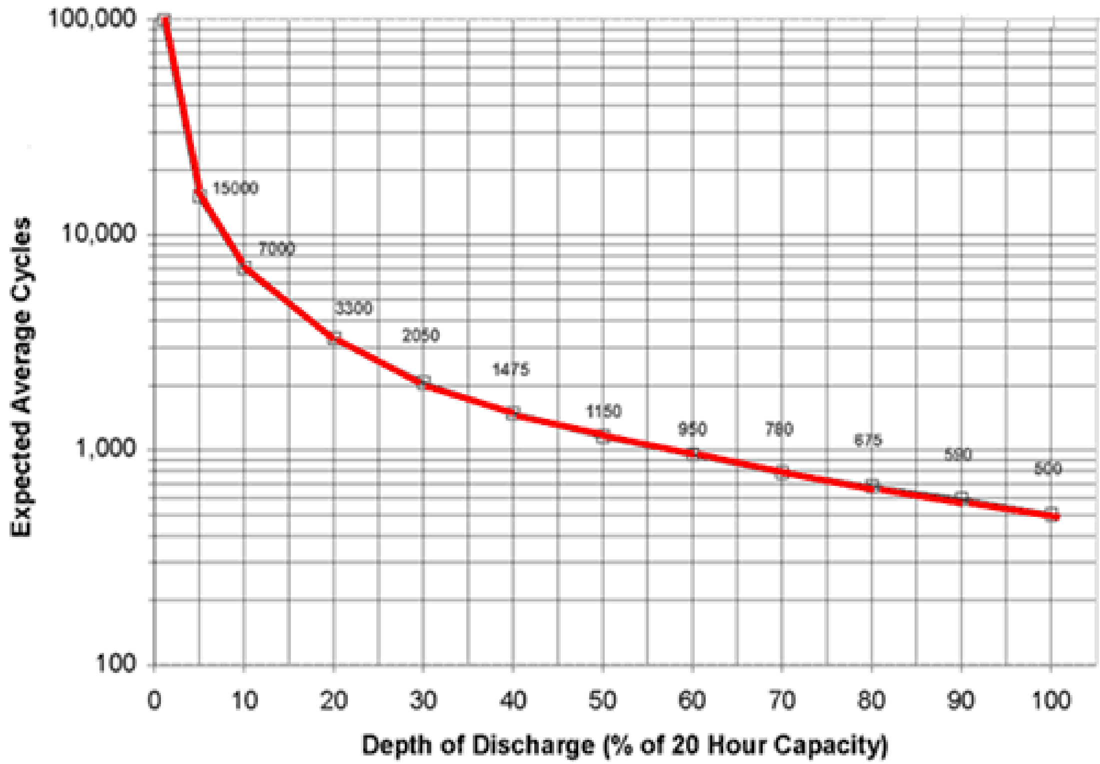
Studies done previously show that before determining the size of the battery bank, there are factors that must be considered so as to get the right size of battery bank. These factors are; the daily energy demand, number of days of autonomy, depth of discharge (DOD), ambient temperature of the location and system bus voltage [26],[28],[29],[30].

The daily electrical energy demand of a consumer, as stated previously, is the amount of energy that will be required by the consumer for the whole day and must be supplied by the solar PV system every day. This demand can be estimated by taking the ratings of electrical appliances that are used and the period that they are used in a day as it was done for the solar PV array sizing. Then daily ampere hour capacity rating of the battery is obtained by dividing the daily energy demand by the system voltage.

The number of days of autonomy is the number of days in a row when the user of the solar PV energy will need to draw energy from the battery bank without recharging the bank. In other words these are the number of consecutive “cloudy” days when the sky is not clear and the output of the solar PV array is very low. The accurate number of the days of autonomy is difficult to predict but an estimate could be obtained from a weather website /station or local weather station.

The battery depth of discharge is the limit of electrical energy capacity in ampere hours at the rated bus voltage that can be withdrawn from the battery in one full cycle. A cycle starts when the battery is in a fully charged state to the state when it is fully discharged and back to a fully charged state. The depth of discharge is normally expressed as a percentage of the total charge capacity. A battery is fully charged when it attains its rated ampere-hour capacity and the cell voltage is 2.3 volts DC. The same battery is fully discharged when the cell voltage reduces to 1.85 volts and has 20% its rated ampere hour capacity.

Battery discharge states can either be shallow or deep. A shallow discharge state is when the depth of discharge does not exceed 20% of the battery rated capacity after discharge. Where as a deep discharge state is when the DOD does not exceed 80% of battery rated capacity after discharge. Deep battery discharges normally shorten the life of the batteries because they reduce the charging cycles. This is the main reason why battery manufactures recommend that batteries should never be discharged below 50% of their rated ampere hour capacity rating. The shallower the level of the cycle DOD the longer will be the battery life. A safe DOD for a battery is 20% of its full capacity rating every day [28 , 29]. Figure 2.8 shows how the DOD affects the charging cycles of a battery. Sustained deep discharges will subsequently shorten the life of the battery.



Source: [27]

Figure 2.8: Effect of Depth of Discharge to Charging Cycles

The temperature of the surrounding affects the performance of most batteries especially when the temperature is on the low or high extreme. Normally batteries operate well under moderate ambient temperature conditions ranging from 27^{0} C to 40^{0} C. Extremely cold temperatures tend to reduce the battery capacity while the extreme high temperatures above 70^{0}C shorten the battery's life. In reality the FLA batteries will get destroyed when exposed to freezing temperatures for more than a month without charge

[17]. Although the sealed batteries can operate under sub freezing temperatures, their reserve capacities are normally substantially reduced in the process. It is for this reason that manufacturers of batteries indicate the safe ambient temperatures under which the batteries can be operated and even stored.

When designing a solar PV battery system, the designer must take into consideration the ambient temperature because the effects of ambient temperature will reduce the output of the battery bank. Table 2.7 shows the derating factors recommended for different temperatures. Low temperatures reduce battery capacity so derating factors are recommended to cushion the battery bank against the adverse effects.

On the other hand, high temperatures above 70^0 C tend to shorten the lifetime of the battery by wearing off the battery plates (electrodes) due to grid corrosion [17]. When high temperatures persist, the plates wear out completely causing permanent damage to the battery.

Table 2.7: Derating Factors on Ambient Temperature

Temperature in degrees C	**Derating factor**
26.6	1.0
22	1.04
21.1	1.11
15.5	1.19
10	1.30
4.4	1.4
1	1.59
-6.7	1.7

Source: [17]

For temperatures between 80 and 20 degrees Fahrenheit or 26.6 and -6.7 degrees centigrade, the derating factor D_t can be calculated using the empirical equation 2.6.

$$D_t = \frac{C}{C_0} = \frac{1}{0.00575T + 0.54} \qquad (2.6)$$

Where

D_t = Derating factor due to temperature, C = Battery capacity at temperature T (in ^{0}F)

C_0 = Rated battery capacity at 80 degrees Fahrenheit or 26.6 ^{0}C

The battery storage capacity can be calculated using equation 2.7

$$\beta_c = \frac{P \ X \ D}{V \ X \ DOD \ X \ \eta} \qquad (2.7)$$

Where β_c is Battery capacity, P is daily energy demand, D is days of autonomy, V is bus voltage, DOD is depth of discharge and η is battery efficiency

2.5.5 Battery Charge controller

A battery charge controller (CC) is a component that is used between the solar PV module and the battery to switch ON and OFF the battery charging process. Charge controllers keep the batteries fully charged so as to protect them from exceeding charge and discharge levels. Most charge controllers like the pulse width modulated (PWM) types, have capabilities of controlling the discharge process of the battery by disconnecting the load when a preset discharge level is attained. On the other hand, the Maximum Power Point Tracking (MPPT) charge controller has capabilities of shifting the charging point of the battery from the battery voltage to the MPPT voltage thereby increasing the charging power. However this charge controller is not suitable where temperatures are very high like in arid areas. Consequently, the choice of a CC is made considering ambient temperature and irradiance of the particular site.

Charge controllers are rated in system DC voltage and the maximum charging current of the solar PV array. Most charge controllers have two modes of charging; the boost charging mode and the trickle charge mode. The boost charge is used to charge the battery to full charge and the trickle charge mode is used to maintain the battery at full charge without getting over charged. The PWM type of CC works very well to maintain the trickle charge of batteries. However in PV systems, the charging current is totally dependent on the amount of solar irradiance so the controllers alternate from full rate to trickle charge mode during daily charging.

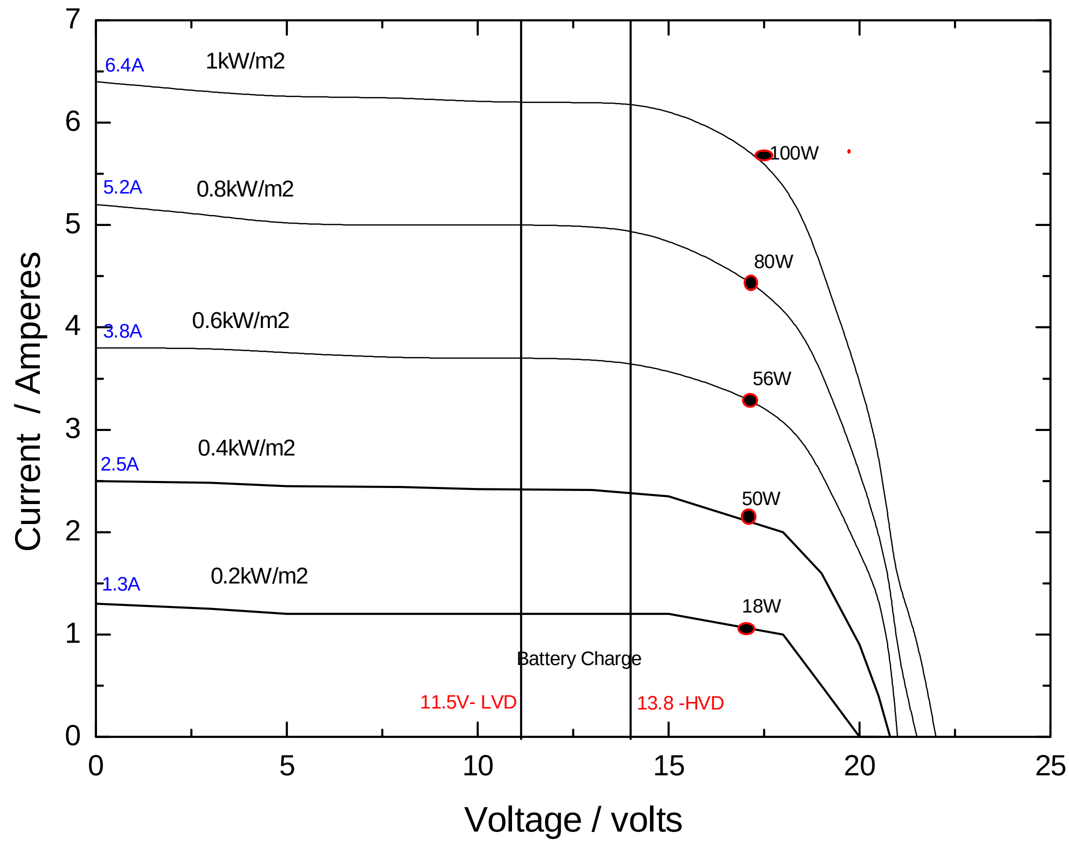


Figure 2.9: Charging Voltage of a Solar Module

Figure 2.9 shows the battery charging voltages and currents as the irradiance changes. These results were obtained from a 100 watts UBBINK solar PV module. A charger controller has two major voltage set points the low voltage disconnect (LVD) and the high voltage disconnect (HVD) as shown on Figure 2.9. Apart from the LVD and HVD set points, some charge controllers have other two intermediate points namely the high voltage reconnect (HVR) and the low voltage reconnect (LVR). These set points maintain the battery voltage between the two safe limits LVD and HVD. From the IV curves it can be seen that batteries do not charge at the maximum power point (MPP) of the array. The MPPT type of charge controller is the only CC that is capable of shifting and matching the charging point of the battery to the MPP of the solar PV array.

2.5.6 Solar Photovoltaic Inverter

An inverter is an electrical appliance that converts direct current electrical power to Alternating Current (AC) power. All power generating plants that generate direct current power normally need inverters to convert the power generated to alternating current power for use by alternating current rated appliances.

Solar PV inverters can be either stand alone or grid tied. Stand alone inverters rely on both the battery storage system and the solar PV array for their power supply. Therefore, these inverters are less complicated because they have less control and monitoring features. On the other hand, the grid tied inverters (GTI) are used in solar PV and other RE hybrid systems that rely on both the solar PV and the grid for their power supply. Grid tied inverters are very sophisticated because apart from the power conversion features, they also incorporate control and monitoring features. Grid tied inverters usually monitor both the solar PV system and the grid so as to respond to the consumers' load demand. The GTI also protect the system from grid or utility power outages by isolating the grid during outages and sometimes incorporate a metering facility to enable flexible import and export of power from and to the grid [17]. Grid tied inverters have intelligent control devices which safely isolate or shut down the solar PV system inverter in case of extreme adverse conditions like power outages and overvoltage. Fan Jiang etal used such grid tied inverters at the Singapore Polytechnic that was fed from a 4.8 kWp solar array. The inverter converted the power to alternating current power output at 230 VAC that was fed directly into the grid. Inverters are conversion devices and have efficiencies depending on the manufacturing technology. Table 2.8 shows some conversion efficiencies for solar PV conversion devises.

Table 2.8: Approximate Efficiencies for Different Conversions

Operation	Conversion from X to Y	Efficiency
1	DC to DC	95%
2	Electrical to Electrochemical	86%
3	Electrochemical to Electrical	86%
4	DC to AC and then AC to DC	95%

Source [27]

2.5.7 Power Rating of Solar PV Inverters

Solar PV inverters are rated in the AC voltage and power they can supply and the input DC voltage and current. The choice of an inverter is normally dictated by the features the designer of the solar PV system would want to have. Inverters can be manufactured of different power ratings for both single phase and three phase power output. The input DC voltages can range from 12 V DC to 1000 V DC depending on the power output of the inverter.

The GTIs are the most superior in the market and operate at high efficiencies of up to 95% and at a near unity power factor. The frequency of these inverters is synchronized by a monitoring circuit to that of the grid. During operation, the monitoring circuit sees the GTI as a slave with reference to the grid and so makes the frequency of the GTI synchronized to that of the grid. When the grid frequency falls by 2% or rises by 2% above the pre-set frequency, the GTI is automatically isolated because the condition is similar to a grid power outage [28]. The inverters also incorporate maximum power point tracking (MPPT) features which enable them to extract maximum power from the solar PV array. The maximum power point tracking feature enables the inverter to adjust the output power operation point in real time according to the instantaneous variation of the sun's irradiance received on the solar PV array during the day. The inverter monitors the solar array output so as to regulate its operating power point. This feature is useful when the inverter is supplied directly from the array mostly in systems without storage. During the night, the inverter operates depending on the bus voltage thus overriding the array output which is zero at night. The grid interactive features of the GTI also enable the inverters to deliver power to the grid whenever the solar PV system has excess power from the solar PV array during the day.

The rating of the inverter is determined by the peak power demand of the consumer under consideration. This peak demand can be obtained using a power data logger at the site as in the battery sizing design. The designer must make sure that the inverter peak power rating will accommodate the surge power required by starting motors of all domestic rotating machines. The input voltage to the inverter sometimes rises above the expected bus voltage during peak sun hours when the solar irradiance is very high. Therefore the input voltage rating of the inverter should be able to accommodate the voltage variations during the charging hours.

In Lisbon, Portugal, Antonio Roque et al did an economic analysis of a solar and wind hybrid system for an implementation to a domestic micro generation and obtained the results tabulated in Table 2.9. The hybrid system had only 12 solar modules due to space restriction. The methods used to develop the system were based on site solar radiation data, module configuration, the house load power demand, the Portuguese feed –in tariff and the days of autonomy. The study was able to produce a domestic micro-generation system that was capable of producing some 2825 kWh annually from the solar PV system alone using a standalone inverter [29].

Table 2.9: Site Solar Radiation and Capacity Data in Lisbon Portugal

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Nominal Voltage -Vdc	24	24	24	24	24	24	24	24	24	24	24	24
Radiation -kWh/m^2	3.39	3.72	5.39	5.43	6.04	6.48	6.75	6.71	5.99	4.84	3.4	3.07
Peak sun hours	3.4	3.7	5.4	5.4	6.1	6.5	6.7	6.7	6.0	4.8	3.4	3.1
Module Ah/day	195	303	439	442	492	528	549	546	488	394	277	250
Days of Autonomy	4	4	4	4	4	4	4	4	4	4	4	4
Number of batteries	8	8	8	8	8	8	8	8	8	8	8	8
Battery Capacity Ah	988	988	988	988	988	988	988	988	988	988	988	988
Discharge rate	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Number of PV odules	12	12	12	12	12	12	12	12	12	12	12	12

Source [29]

The economic analysis performed considered a 7% annual growth and 1% of the investment for maintenance expenses. The system had an optimistic 6 year payback period which corresponded to an internal rate of return (IRR) of 21.74% over a period of 20 years with a net present value (NPV) of 32299 Euros.

2.6 Summary

In summary, the main features of the solar resource design and sizing methods of solar photovoltaic systems have been reviewed. In the review many observations have been made concerning design and sizing methods of solar PV systems in different parts of the world. It has also been observed that many researchers have done work in the area of solar photovoltaic generation using different approaches and obtained very reliable results. It was also noted that as technology progresses new design and sizing methods are being developed to make solar PV designs and subsequent results as accurate as possible. Lately, solar photovoltaic electricity generation has emerged as a major alternative to conventional hydro, coal, diesel, wind and geothermal methods for electricity generation. Solar PV electricity generation is gaining popularity and the prices of solar PV materials are reducing so that in future solar photovoltaic generation will play a major role in electricity generation using clean methods.

CHAPTER THREE

3.0 SOLAR PV SYSTEM DESIGN

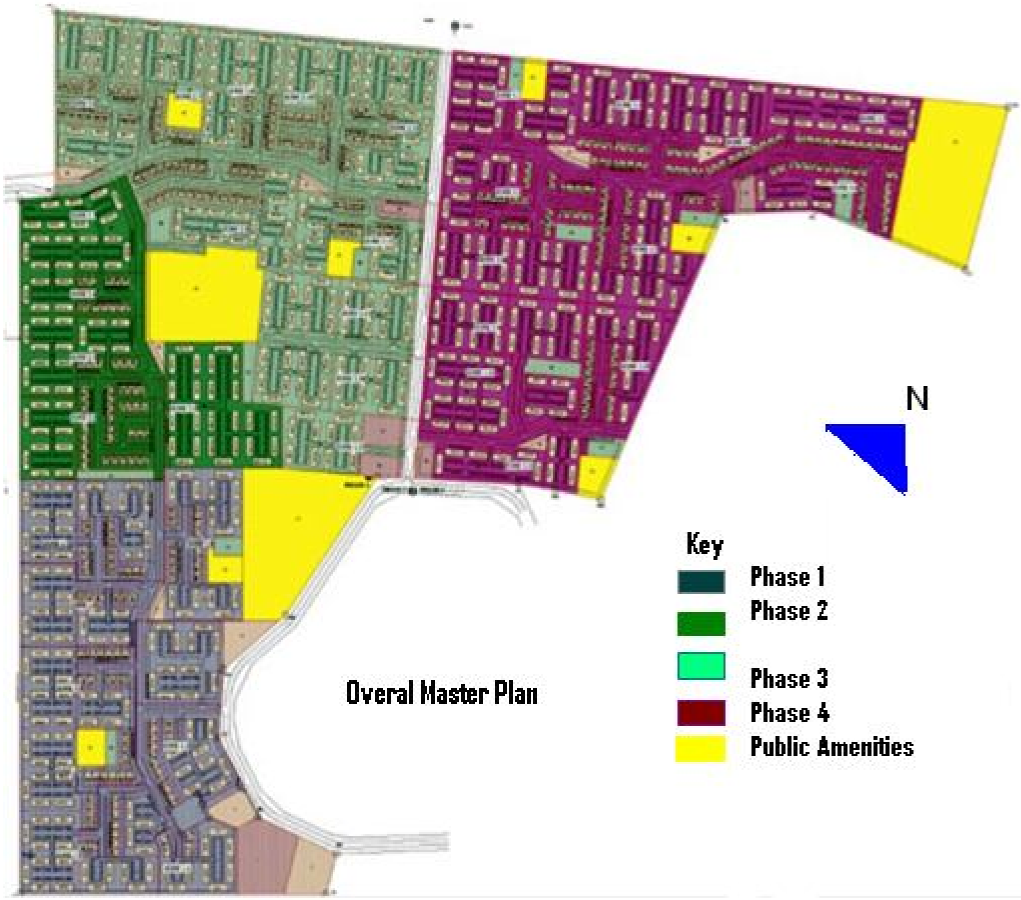
3.1 Highlights

This chapter presents the methods used to collect load and solar insolation data. The methods of data analysis and those used to size the different solar photovoltaic system components are also presented. Sizing methods, flow diagrams and orientation of the modules are also discussed and presented. Finally the system financial and cost analysis methods are presented and discussed

3.2 Case Study Selection

The Embakasi Nyayo Suburb (ENS) was selected as the case study because it is currently one of the largest middle class suburbs in Nairobi and by extension the country [30]. Embakasi Nyayo Suburb is situated 18 km from the Nairobi city centre. The buildings at the suburb have large bare roofs and are occupied by people who are able and capable of embracing renewable energy initiatives for electricity generation.

The suburb is built on approximately 200 acres of land and the infrastructure include paved tarmac roads with street lighting, an 11 MW utility power sub-station and 100 million liters of water storage reservoirs. The ENS consists of 4774, 3 bed-roomed housing units in 480 apartment blocks each with 8 apartments and 934 masionettes. The apartments constitute 80% of the total housing unit population whereas the masionettes constitute 20%.



Source: [31]

Figure 3.1: Site Plan for the Embakasi Nyayo Suburb

Figure 3.1 shows a site plan of the Embakasi Nyayo Suburb. Phase 1 consists of 114 blocks, phase 2 has 78 blocks, phase 3 has 122 blocks and phase 4 has 166 blocks. The suburb accommodates an estimated population of 15,000 residents. Most of the residents are middle class who have home internet connectivity and rely a lot on daily media news and can afford a domestic solar PV electricity generation system to avoid loss of power during utility power outages which sometimes deny them their comfort not to mention the ever rising price of grid electricity. The financial status of the residents is evident from the properties they own; for example, the type of domestic appliances and vehicles. This financial ability was important for the study because it confirmed that the residents could afford the solar PV electricity generating systems that the study was undertaking.

On account of the above review of Embakasi Nyayo Suburb, it was concluded that the suburb is a suitable case study. Figure 3.2 shows a section of the Embakasi Nyayo Suburb phase one. The blocks on the right hand side of the figure are facing south.

Figure 3.2: View of a Court of Apartment Blocks at the Embakasi Nyayo Suburb

3.3 Data Collection

To carry out the study, some specific data was required, that is solar insolation, site geographical position, and electrical load and case study site details. Solar insolation data were obtained from three sources: meteorological department headquarters (Dagoreti), Embakasi Nyayo Suburb as shown in (Appendix A) and the National Aeronautics Space and Administration (NASA) website. The information on the number of blocks, the development phases in the suburb and the roof type and orientation were acquired from the National Social Security Fund (NSSF), the developer of the ENS.

3.3.1 Electrical Load Data Collection

Domestic electrical load data were acquired from residents of ENS by means of questionnaires and oral interviews. Other electrical load data were collected using a data logger hooked to selected blocks for a week. A sample of the questionnaire is given in Appendix B.

During the electrical load data collection, three hundred questionnaires were administered to the ENS residents. The completed questionnaires were analyzed for details and completeness after which the best were selected for direct interview. Due to the unavailability of the residents and their willingness to have the interviews, only thirty residents were visited. The direct interviews were done to confirm the accuracy of the filled data by physically checking the appliances.

During the load data logging exercise, the data logger was connected to some two blocks in the suburb for a continuous six days to collect real time data and monitor the load behavior. The blocks used for data logging were picked in accordance with those residents who gave consent for the exercise. The data logger was connected at the blocks main electricity incoming three phase power point so that the logging could capture the total power of the block. The data logger was set to record the total power consumed by the block at the set data collection rate and the total energy consumed by the block per day. During the design of the solar PV system, the data from the questionnaires was not used because of the low response instead, only the logged data was used.

3.3.2 Solar Insolation Data Collection

The solar insolation data was collected from the Embakasi Nyayo Suburb site, National Aeronautics Space and Administration (NASA) website and the Meteorological department data center at (Dagoreti). After analysis the solar insolation data obtained from the Kenya Meteorological (MET) Department was selected for sizing the solar PV system. The Meteorological department collects and stores environmental data that is used to carry out environmental and any other related studies. Such data are like solar insolation and ambient temperatures which were necessary for the study. The solar insolation data were in form of raw data as collected by the Meteorological department in Mega Joules per square meter (MJ/m^2), thus they were converted to kWh/m^2 before being used in the design and sizing of the solar PV system.

The historical data used from the Meteorological Department, covered a period of twenty (20) years. This data period is a typical meteorological year (TMY) data period for the location (Embakasi Nyayo suburb). Further, since the lifespan of the solar modules is 25 years, the 20 years data would capture almost the entire lifetime of the system. Other researchers, like Fan Jiang et al used 2 year monthly average data from the Singapore National Environmental Agency. The study by Fan Jiang was addressing the availability of solar PV resource in a typical tropical country and its unique weather conditions [20]. While Xiao Jian Ye et al used 8 year temperature data for a study at Wuhan in the province of Hubei China where the effects of using air conditioning loads during the day were investigated [32]. Zakaria Anwar et al used 30 year solar insolation data for a study in Sudan to investigate the total energy requirements met by a solar PV system. From the periods used by other researchers, it is clear that the data periods were based on specifics like lifetime of the study, type of study and whether standalone or grid connected systems where long time data ranging to 30 years was necessary.

3.4 Solar Photovoltaic Electricity Generation System

The main components that constitute a solar PV electricity generation system are; the solar PV array, charge controller, battery storage and the inverter. In design and sizing, the process starts with sizing the solar PV array using the load demand and available insolation. After the array is sized, the size of the battery storage capacity is determined using the array output, the load demand and the system voltage. Later, the size of the charge controller is determined using the output from the array and the charging current of the battery system. The last component to be determined is the DC to AC inverter whose size normally depends on the peak power of the consumer.

3.4.1 Solar Photovoltaic Array Sizing

In array sizing, the designer will consider many factors that affect the design and sizing. The major ones being the module type, mode of connection, angle of tilt, effects of shading and effects of temperature and irradiance. Apart from the major factors mentioned above, other minor design factors are derating due to dust, aging, mismatch and wiring. The derating factors have minor effects on the performance of the array. These derating factors have been addressed extensively in Chapter 2.

3.4.1.1 Model Calculation of the Array size

To design and size the solar PV array, the designer must know the total daily energy demand for the system. This is useful in providing adequate charging capacity from the array to the batteries. The array capacity is directly linked to the charging capacity of the battery storage. In this research work, the array is sized to meet the full batteries charging load and also supply the load that occurs during sunshine hours.

The solar PV array generates electricity and then it is transmitted through other devices (charge controller, battery and inverter) to run the electrical appliances. Thus in sizing, the power generated by the array is subjected to the efficiencies of all these devices. Besides these efficiencies, the output performance of the modules must be taken into consideration together with the insolation and irradiance of the site for the sizing of the array. Table 3.1 shows the efficiencies of some of the components used in this study.

Table 3.1: Efficiencies of Solar PV Components

Component	Efficiency (%)
Modules output Performance [1]	83
Battery efficiency	86
Inverter efficiency	95

Source: [17]

The total energy that will be supplied by the solar PV array is calculated by dividing the load energy demand with the product of the efficiencies of the components. To calculate the peak power rating of the array, the energy demand obtained in the previous step is divided with the peak sun hours for the site.

The peak sun hours are calculated by dividing the annual insolation of the area with the STC power rating of 1 kW/m^2.

For locations near the equator like Nairobi (ENS), peak irradiance values of 1.25 kW/m^2 are attainable so the peak power obtained in the previous step must be multiplied with the peak irradiance (1.25kW/m^2) because it was initially calculated at STC. Other researchers obtained values of up to 1.1kW/ m^2 in Nairobi [33]. The result obtained is then divided by the product of the derating factors for the solar PV modules (array) that are shown on Table 2.6, so as to achieve the peak power value of the array.

Eventually, the system designer has to recommend a module type from available module types in the market that is suitable for use at the site. Mostly designers consider modules on the basis of available physical space and cost. Table 2.4 in Chapter 2 shows the cell efficiencies of the common modules in the market.

1 Module output with changing irradiance.

When the designer settles on a module type, sample calculations are done using the system voltage, STC rating of the modules and irradiance of the area to ascertain the array output. Most of the time module specifications are given as a data sheet or are stuck on the module back side for ease of reference. Table 3.2 shows typical sample specifications for a 140 watt polycrystalline module that was used in the design and sizing.

Table 3.2: Specifications of a 140 Watt Polycrystalline Module

Characteristic	**Value**
Cell Efficiency	15.7%
Maximum Power	150 Wp
Rated power at STC	140 W
Maximum Voltage	18.1 V DC
Maximum Current	11.058 A
Open Circuit Voltage	22.6 V DC
Short Circuit Current	11.8 A
Dimensions	162mm x 97mm x 4mm

Source [34]

Temperature rise on the module reduces the output voltage of the module as shown in the I-V curves in Figure 2.7 of Chapter 2. Therefore the temperature coefficient of the module type has to be used to achieve the array size. The temperature coefficient of power for the polycrystalline silicon module is – 0.48 %/ ^{0}C and this is the value that is used for the ENS sizing to allow for the effects of temperature changes/ deviations on the solar modules when in use.

Finally, the array size is determined using Equation (2.5).

When selecting among the crystalline silicon modules, the polycrystalline silicon module was preferred over the other two types considering the magnitude of the project and the available roof space. The polycrystalline type of module was used in the design.

3.4.1.2 Embakasi Nyayo Suburb Array Size Calculation

Using the model calculation in section 3.4.1.1 the total energy from the solar PV array for the Embakasi Nyayo Suburb was calculated as total energy demand divided by the efficiencies of the devices (array, batteries and inverter) as 71.96 kWh.

$$P_p = \frac{E}{\eta} x \frac{F_{pv}}{Pv_{STC}} x \frac{1}{1.25} \qquad (3.1)$$

Where P_p the Peak power output of the PV array, E is is the daily energy demand, η is the total efficiency of the components, F_{pv} is the product of the derating factors and Pv_{STC} is the module output at STC.

The peak sun hours for the site are calculated by dividing the average annual daily insolation 5.12 kWh/m^2 by 1kW/m^2 of STC so for ENS the value is 5.12h

The rating of the array at STC is then calculated by dividing the energy from the array with the peak value of irradiance at the area/site which in ENS was 1.25 kW/m^2 and peak sun hours for the site (ENS) is 5.12 h.

The peak value of irradiance for Kenya is 1.25kW/m^2 **(**as measured on site)

The peak power output obtained by calculating the previous step was 11.24 kWp.

Using the derating factors mentioned in Table 2.4, the total derating factor which is a product of the factors for dust, aging, wiring and shading, is obtained as $F_{pv} = 0.92$.

The peak power demand from the array was calculated by dividing the peak power obtained previously by the total derating factor 11.24/0.92 is 12.22 kWp.

During the data logging process, the highest peak power obtained was 11.44 kWp so the figure of 12.22 kWp obtained in the calculation is used so as to accommodate any unforeseen power surges. The value of the array peak power obtained had to match with available module ratings so the solar PV array size was determined as 12.5 kWp and this shall be able to supply the load for most of the year with the grid supplementing the deficiency. From the recommendations on Table 2.5 the fixed tilt angle for the Embakasi Nyayo Suburb was set at 15^0 facing north, because the suburb is at 1.19 degrees south [26].

When the array output is not exactly matched to the load, the grid will supplement the power supply shortfall. After the design, modeling and simulation of the system it was observed that the solar PV system shall require a maximum power of 2.5 kW from utility electricity to supplement the solar PV shortfall throughout the year. When the solar PV electrical power generation exceeds the consumers' power demand, the surplus power is released or sold to the grid. The power deficit and surplus will be varying throughout the year so it is impossible to state the instantaneous values. Annual power demand surplus and deficiency are presented in the aggregated form in section 4.6 of Chapter 4.

3.4.1.3 System Design Software

Considering that factors like solar irradiance, ambient temperature, shading and other derating factors are never constant, it implies that the output of the solar PV array will be varying as frequently as the parameters changes. This means that long hand calculation cannot adequately give an accurate design where all conditions are matched. There are solar PV design software's to simplify the solar PV systems model design process like HOMER which was developed by the National Renewable Energy Laboratories (NREL) of USA. This software was used in the design of the solar PV system for the case study. The software matches all possible conditions according to the data provided and gives the most suitable size of the array. The conditions used by the software are; the solar insolation, ground reflectance, the hourly load and the load random variability.

3.4.2 Sizing of the Battery Storage Capacity

After the array is sized, the size of the battery storage capacity is determined using the array output, the load demand and the system voltage. The array output is used because it is required to supply the load during sun shine and at the same time charge the batteries. When the battery is feeding the inverter at night, the demand from the batteries is subjected to the efficiency of the inverter so the losses at the battery and inverter must be taken care of in the sizing battery storage. For good design practice, the storage system should be sized to handle the entire load when the array is not generating and also be capable of supplying the deficiency during cloudy weather.

On the other hand the system voltage should be able to handle the voltage drop that occurs when discharging to the load as the current drawn by the load varies. The battery system design parameters are; daily energy demand, days of autonomy, battery safe depth of discharge, battery efficiency, inverter efficiency and the system voltage.

Battery storage capacity is calculated using

$$\beta_c = \frac{P\ X\ D}{V\ X\ DOD\ X\ \eta}$$

Where P was 48.8 kWh/d, D is days of autonomy used, V is the system voltage, DOD is 0.2 and the battery efficiency of 86%.

(a) Daily Energy Demand

The daily energy demand is the amount of energy that will be supplied by the battery system when the array is not generating electricity. This amount of energy is normally a fraction of the total capacity of the battery system. For domestic consumers, most of the energy is consumed early in the morning and late in the evening.

(b) Days of Autonomy

When sizing a battery storage system, the amount of time that the battery system will supply the load has to be predicted during design. This is because the time the battery system will supply the load will determine the size of the bank in Ampere hours. The continuous number of days that the battery system supplies the load without any charging supply from the array is known as the days of autonomy. Due to cost, the most economical number of days of autonomy is 1 day but the system designer could use up to three days beyond which the storage system becomes uneconomical [34]. During the days of autonomy, the battery system should be capable of discharging 80 % of its capacity, which is why the deep cycle batteries are preferred for use in solar PV systems. The battery safe depth of discharge, efficiency and inverter efficiency were discussed in the array design section.

In this study, three scenarios 1, 2, and 3 were considered with 1, 2, and 3 days of autonomy, respectively.

(c) System Voltage

The system voltage is the nominal DC voltage at which the solar array, the battery storage, the charge controller and the inverter operate. When designing the battery storage, the system voltage guides the connection of the battery bank. When choosing the system voltage the designer must consider the possible series and parallel connections of both the array and the battery storage system.

When sizing the daily battery ampere hour capacity required by the consumer, the daily energy demand of the consumer is used. In the ENS scenario, the data obtained using the load data logging method at the consumers' premises that was done for six consecutive days was used.

The ampere hour capacity required by the consumer for the acceptable DOA will provide adequate battery depth of discharge capacity. When the designer has decided on the system voltage, DOD, DOA, type of battery and its efficiency, inverter efficiency and the daily energy demand, the battery storage capacity is calculated using Equation 2.7 given in Chapter 2.

3.4.3 Sizing of the Battery Charge Controller

The charge controller maintains the state of charge of the battery bank and it operates at the voltage of the solar PV array. Charge controllers are essentially switching devices so the only difference between one CC and another is the mode of switching either series or shunt and additional features like PWM, MPPT and boost charge. A charge controller operates at the system voltage so the current through it depends on the irradiance on the array. Among the types of CC, the MPPT type is preferred over the others for use in the tropical areas because of its MPPT features. The size of the CC is calculated by using the array I-V curve charging current from the PV array and the charging voltage of the battery system. Normally a 12 V DC battery charges at between 11.5 and 13.8 V DC so the designer has to identify the charging current on the I-V curves of the array as shown in Figure 2.6. The HVD and LVD values of the CC are determined by the selected system voltage. The voltage rating of the charge controller will also depend on the string nominal voltage of the battery bank. In the three scenarios, the system voltages are different so the system voltage settings of the charge controller will also differ. In the three scenarios, the smaller battery bank will charge faster during the day due to the high current from the PV array but also discharge faster in case of unavailability of solar irradiance.

For areas on or near the equator, the designer will allow for high irradiance values of STC (1.25kW/m^2) so that the CC is not subjected to over current conditions. Also for safety reasons, the charge controller size obtained must be able to accommodate the maximum and short circuit currents of the solar PV array and the MPPT voltage of the array which could be far above the system voltage. The Charge controller voltage rating is the maximum voltage of the solar PV array because it will be operating at maximum power point.

To calculate the charging current of the CC, multiply the resultant maximum currents of the parallel connected modules by a figure of 1.25 that is obtained by dividing the maximum tropical irradiance of 1.25kW/m^2 by the irradiance at STC of 1 kW/m^2. Lastly, the value of current is multiplied with 1.3 which is the ripple factor for the MPPT charge controller. The value of current obtained and the arrays maximum voltage are the current and voltage ratings of the charge controller.

$$A_{cc} = \frac{[(P_p|1.3)]}{V} \qquad (3.2)$$

Where A_{cc} is the charge controller maximum current rating, P_p is the peak power of the array, V is the system voltage and 1.3 is the charge controller ripple factor

$$A_{cc} = \frac{(12.5\ x\ 1000|1.3)}{180} \quad \text{Amperes}$$

3.4.4 Sizing of the Solar PV Inverter

The solar PV Inverter receives power directly from the array during the day and from the battery storage during the night. The voltage from the batteries is normally the system voltage level but the voltage from the array changes with irradiance and temperature.

Inverter Peak power is Wp

$$W_p = \frac{P_p}{\langle \eta_{cc} | \eta_{inv} | \eta_{bat} \rangle} \tag{3.3}$$

$$W_p = \frac{11.44_p}{\langle 0.9_{cc} | 0.95_{inv} | 0.86_{bat} \rangle}$$

To calculate the maximum DC input power to the inverter a designer must use the maximum power of the array at STC then multiply the values with a factor of 1.25 which is obtained by dividing the tropical maximum irradiance by the STC irradiance. The maximum AC power output of the inverter must be equal to the peak power demand by the consumer. For the ENS the logged value of peak power was 11.44 kW. Further, installations like the Nyayo Embakasi suburb, where the inverter is grid tied, the inverter should have features of importing and exporting power to the grid so that the size of the solar system does not become uneconomically too large.

3.5 Solar PV System Design flow Diagrams

The design of a grid connected solar PV or any other equally intermittent resource type of system has many variables which change in real time so the calculations consist of much iteration that are too intensive to be done long hand and still remain accurate. The solar irradiance and cell temperature are never constant and the domestic load also changes every second as observed in the power data logging process. The calculations involve matching the load with the solar PV resource following a time series format so as to accurately size the array. The next calculation involves the sizing of the inverter that will supply the AC loads through power conversion from DC to AC. Then the charge controller is sized to accommodate the maximum charging voltage and current that will be supplied by the solar PV array.

During the design and sizing of the solar PV system, the researcher developed a flow diagram for sizing each component of the solar PV system as shown in Figures 3.3 to 3.6. The flow diagram final output is obtained after the matching has been done for the 365 days of the year.

Output (A) is the solar PV array size calculation where initially the daily energy demand and insolation are entered. The energy demand for each day is compared with the insolation available during that day. When the two are completely matched or when the insolation is adequate, an array size is given as an output. When the daily demand is not matched to the insolation, the deficiency is sourced from the grid and an array size output is given. When comparing the solar PV cost to the grid cost, the cost of grid energy unit is used. On the other hand when there is surplus from the array, the surplus is exported to the grid. This is done for all the 365 days of the year and in the end the largest and cost effective array size is given as the ultimate array size. The costs of the system compared to the cost of grid power are the last determining factors when insolation and load do not match. The days of autonomy are a worst case scenario that rarely occurs. When it occurs, the battery storage will discharge to 80 % DOD and take up to a week to charge to 100 % full capacity again.

Likewise the battery storage is processed and an output (B) is given as the battery storage size. The battery storage capacity is matched with the load demand when the solar PV irradiance is not available. The largest battery bank must be able to accommodate the 3 days of autonomy (DOA) and also supply the peak demand. The output (B) is the largest cost effective battery bank at the system voltage. The strings are eventually determined by the individual battery voltage, system voltage and ampere hour capacity of the selected battery and the total battery capacity. The overriding factor in the design of the battery storage is the cost of extending its size as compared to the cost of grid power. The software design and simulation results are presented in Chapter 4 showing graphs of sampled periods of the year.

Output (C) is the charge controller output size. The charger controller is only a switching device so it is matched with the array size and the maximum possible charging current of the array. In the tropics (Kenya), the irradiance could rise to 1.25kW/m^2 so the charging current calculations must take into account this irradiance and not the STC value of 1 kW/m^2. The choice of other features is made after the voltage and current ratings have been obtained.

Output (D) is the system inverter size which is matched with the system DC input voltage and the peak power demanded by the consumer. The sizes obtained during the matching exercise are analyzed and the most recurrent size is used as the component size for the system. The final design and sizing exercise was done by simulation using a solar design and sizing software whose results are presented in chapter 4.

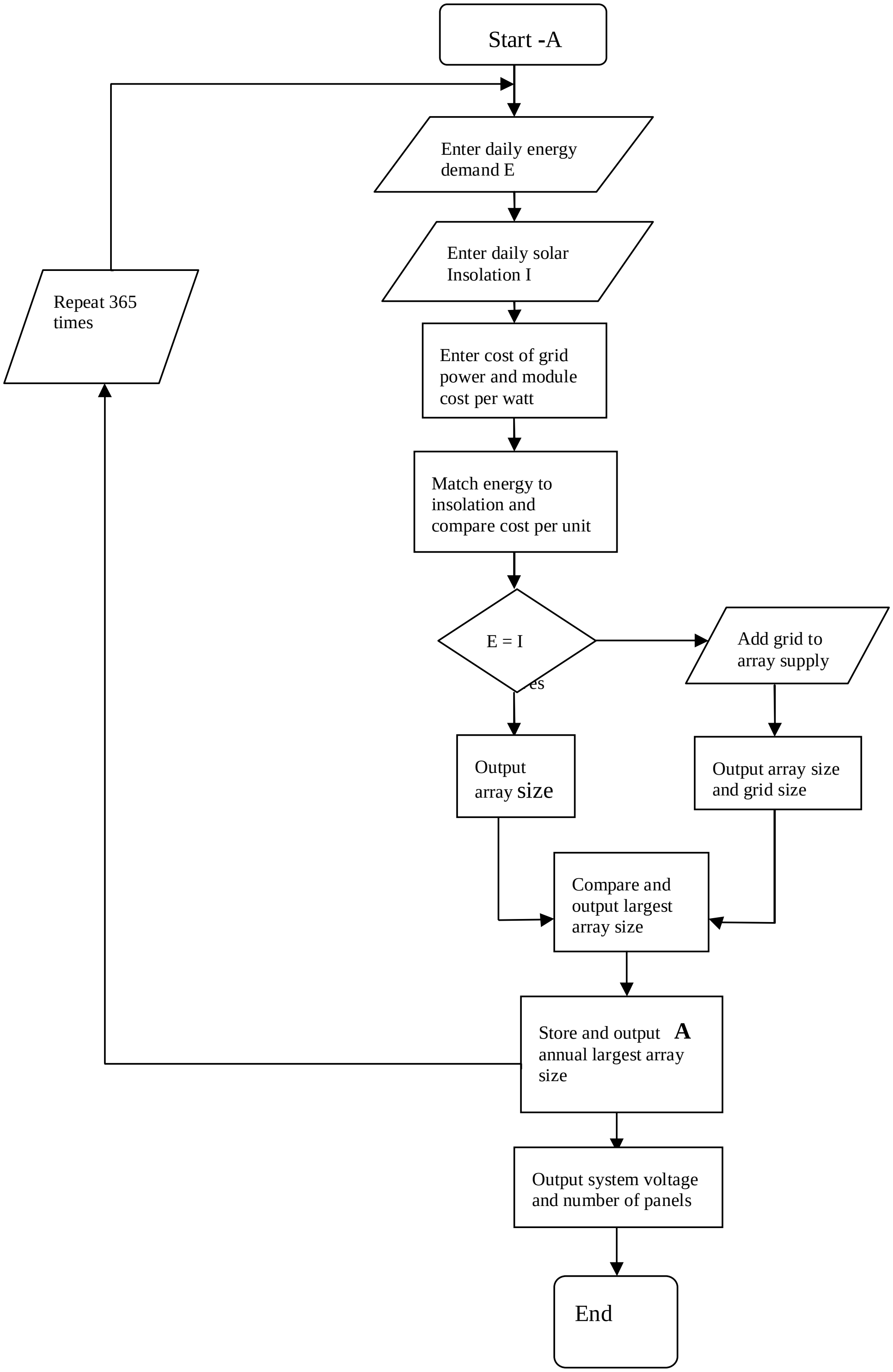


Figure 3.3: Solar PV System Sizing Flow Diagrams

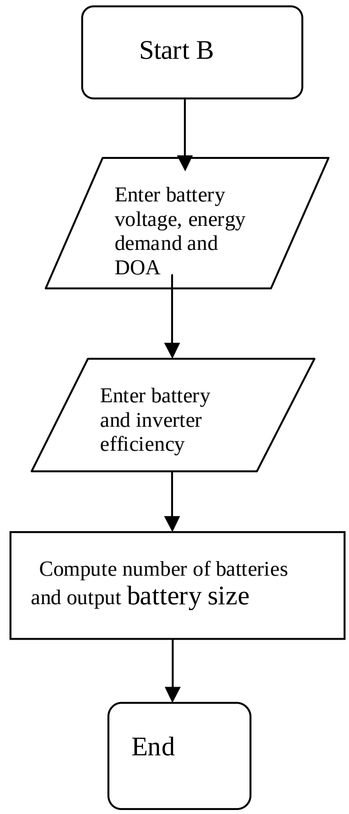


Figure 3.4: Battery Sizing Flow Diagrams

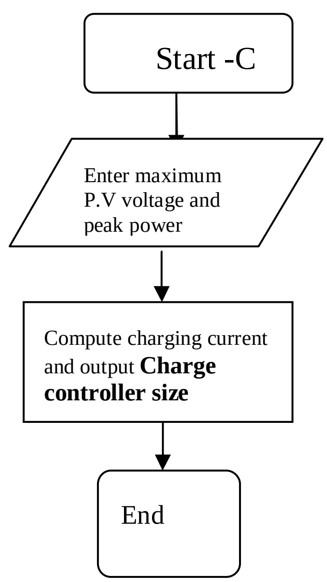


Figure 3.5: Solar PV System Charge Controller Sizing Flow Diagram

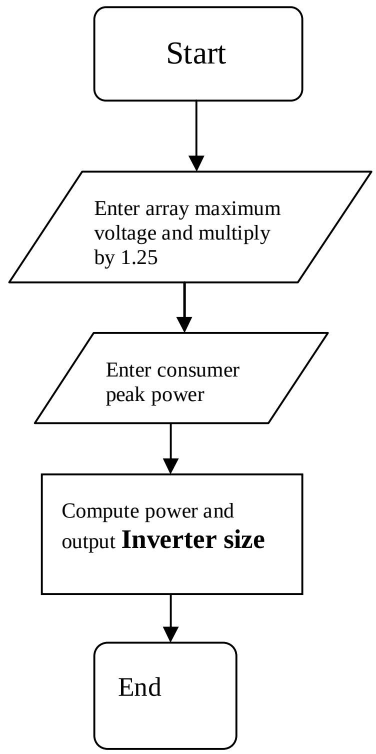


Figure 3.6: Solar PV System Inverter Sizing Flow Diagram

3.6 System Financial and Cost analysis

Every project needs a financial feasibility analysis and economic analysis to confirm its viability. The financial feasibility of a project is the tangible output able to service the project loan, pay operation and maintenance costs and meet other financial requirements of the project. Economic feasibility involves the analysis of both tangible and intangible benefits and cost of the project depending on how it will impact on the society. An investment can be both financially and economically feasible or either, but for it to sustain itself, it must be financially feasible.

In the study the financial analysis of the solar PV system is used because it is more important for telling the self sustenance of the project.

Currently solar PV systems require a high initial capital investment but have very low operating cost. This makes solar PV projects sensitive to financial interest rates. In this project, batteries are replaced over the lifetime of the project and this makes the project to be affected by effects of inflation.

3.6.1 The Net Present Value of the Solar Photovoltaic System

The Net Present Value (NPV) of a system is a time series of cash flows both incoming and outgoing (positive and negative). It is also defined as the sum of all the discounted benefits minus the sum of all the discounted costs of the project. NPV was therefore calculated as;

$$\text{NPV} = \sum_{t=1}^{n} \frac{B}{(1+i)^t} - \sum_{t=1}^{n} \frac{C}{(1+i)^t} \qquad (3.4)$$

Where; i - the discounting rate where each cash flow is discounted to its present value, B – are the benefits, C – are the cost of running the entity, n – Life span of the project and t is the period.

The NPV of a project is an indicator of the worthiness of the project. When a project returns a positive NPV it shows that the project is viable and will have a financial benefit. When a project returns a zero NPV, it shows that the benefits and cost will break even and there will be no tangible returns. On the other hand, when a project returns a negative NPV, it shows that the cost of running the project will be more that the benefits. Projects that yield zero and negative NPV are usually not implemented.

The parameters used to carry out the financial analysis were;

a) Cost per unit of grid/ utility electricity, GPUC
b) Operation and maintenance cost of the solar PV system
c) Discount rate for the value of money
d) Life span of the system or useful life of the system
e) Total energy generated by the solar PV system
f) Annuity of the project
g) Interest rate of borrowing money

The life span of the project was taken to be 20 years.

The cost of generating a kWh of solar PV (PUS) electricity is computed using both the variable and fixed costs of running the system. Fixed costs alone consist of loan repayment premiums including interest on capital and insurance while the variable costs comprise of cost of component replacement, maintenance and operation cost. The calculation of the unit cost of solar energy (PUS) was done in an excel format and is provided in Appendix E 1.

The unit cost of grid electricity (GPUC) was calculated using the electricity consolidated bill for the period of 2008 and 2009. This consolidated cost of energy was obtained from the electricity bills sampled in the questionnaires and during the interviews at the suburb. The calculation process of the unit cost is also provided in Appendix E 2

The net present value (NPV) method was used to carry out the financial feasibility of the solar PV project because it has more advantages compared to other methods like the life cycle cost (LCC) and internal rate of return (IRR) methods. The advantages of NPV are;

(i) Monetary indication of the project feasibility

(ii) Recognition of the time value of money

(iii) NPV method makes use of opportunity cost of capital

Operation and maintenance (O&M) cost of solar PV projects with storage of sizes above 10 kWp range between 2 - 3 % of the capital cost of the system [37].

The procedure followed to determine the NPV of the project was;

(i) Calculation of Annuity

$$A = \frac{C \ x \ i}{1-(1+i)^{-n}} \tag{3.5}$$

Where A is annuity, C is the capital cost, i interest rate and n is the loan repayment period.

(ii) Calculation of annual operation and maintenance cost

$$O\&M = C \ x \ 0.02 \tag{3.6}$$

(iii) Calculation of the annual benefits from energy used or supplied to the domestic load

$$B = \sum_{i}^{n} (\mathrm{DED} - \mathrm{GEP} + \mathrm{GES})\mathrm{PGUC} \tag{3.7}$$

DED is the domestic energy demand, GEP is the grid energy purchase, GES is the grid energy sales from the solar system, GPUC is the consolidated grid energy unit cost, i is the beginning period and n is the useful life of the project.

(iv) Total cost is calculated as;

$$C = O\&M + A \qquad (3.8)$$

The solar PV output is expected to reduce by 0.07% annually over the lifetime of the system so the domestic energy demand, grid sales and grid purchases are adjusted proportionally. The cost of grid energy cost is also estimated to rise by 50% so a 2.5% increase is added to the GPUC annually.

3.7 Summary

This chapter has dealt with the methods used to collect data that were necessary for the sizing of the different solar PV system components. The methods selected were an improvement of what had been done previously by other researchers. Methods of sizing all solar PV components were done and sample calculations were also done. The financial analysis of the system has been discussed and the results are presented in Chapter 4. Flow diagrams were designed to size the solar PV array, charge controller, battery capacity and the inverter of the solar PV system. Finally the collected data was used to do the system simulation using a solar PV design and sizing software (HOMER) whose results are also presented in Chapter 4. The data was used as input load and solar insolation resource data required by the soft ware for simulation and optimization. The student had also to select types of solar PV modules, batteries, and inverter among the ones in the software data to be used for simulation. For the software to simulate, the student had to specify the latitude and the longitude of the location so as the software to recommend the most accurate angle of tilt for the solar PV modules.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Highlights

This chapter presents the results obtained during the data analysis, design and sizing of the solar PV system for the Embakasi Nyayo Suburb. The results also include system simulation results using a renewable energy design and sizing software. Using the load data collected and solar insolation data, the researcher was able to size the system that would adequately supply electricity to a whole block of 8 apartments at the Embakasi Nyayo Suburb for most of the year. The designed system will require additional power supply from the grid to supplement the solar PV during the months of July, August and September when solar insolation is not enough to supply the entire domestic load demand.

The typical solar PV electricity generation design for an apartment block at the Embakasi Nyayo Suburb could later be emulated in any other suburb in the country. A financial analysis has been done so as to compare the solar PV system to the utility grid supply in terms of unit cost. The net present value has also been determined so as to evaluate the financial viability of the system. Further an estimated total of the domestic electrical power generation of the case study is done and the amount of enhancement that would result from the solar PV systems implementation in the suburb is quantified.

4.2 Data Analysis

In this section load data was analyzed in readiness for the design. The data analysis involved conversion of insolation data and unloading one minute high rate sampled load data and its subsequent conversion to hourly data for use in the design and sizing.

4.2.1 Load Data

The load data was collected using three methods as explained in the previous chapter. Among the three methods used, the data logging method was found to be the most suitable for collecting design data because the data was real-time and continuous. The other two methods of using questionnaires and direct interview were only suitable for detailed appliance information. Data logging was done for 24 hours a day over a period of six days and the highest instantaneous peak power observed was 11.44 kW which occurred at 6.46 PM for one minute. For the purpose of design, the logged data was aggregated so as to obtain average hourly power data from the data collected at a one minute rate. The average hourly power data used in the design and sizing simulation is shown on Figure 4.1. The 11.44 kW peak obtained during the logging could not appear in a graphical form in Figure 4.1 because the graph shows average hourly data only. The 11.4 kW peak load was observed for only one minute so when aggregated as hourly load, the value reduced below 11.44 to 4.6 kW as seen on Figure 4.1 . The other days of load demand data logging were marred by utility power outages so the graphical figures were incomplete for the days of data capture. The graphs for the other days are shown on Figures 4.2 to 4.6. Among the data logged, the data obtained on 1st April 2011 were complete so they were used for the design and sizing of the solar PV system.

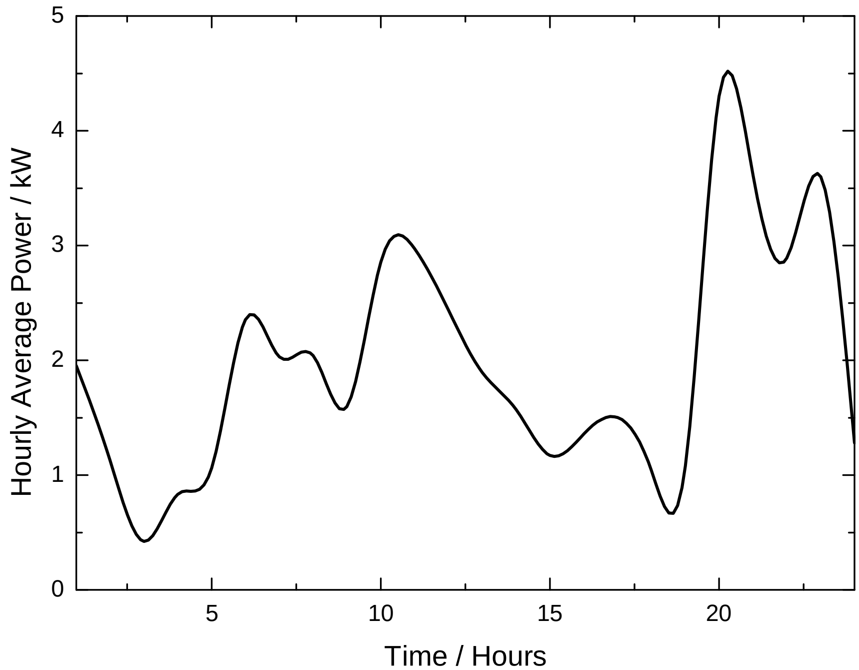


Figure 4.1: Averaged Hourly Load Profile for Court 87 Block- 2 - 1st Apr. 2011

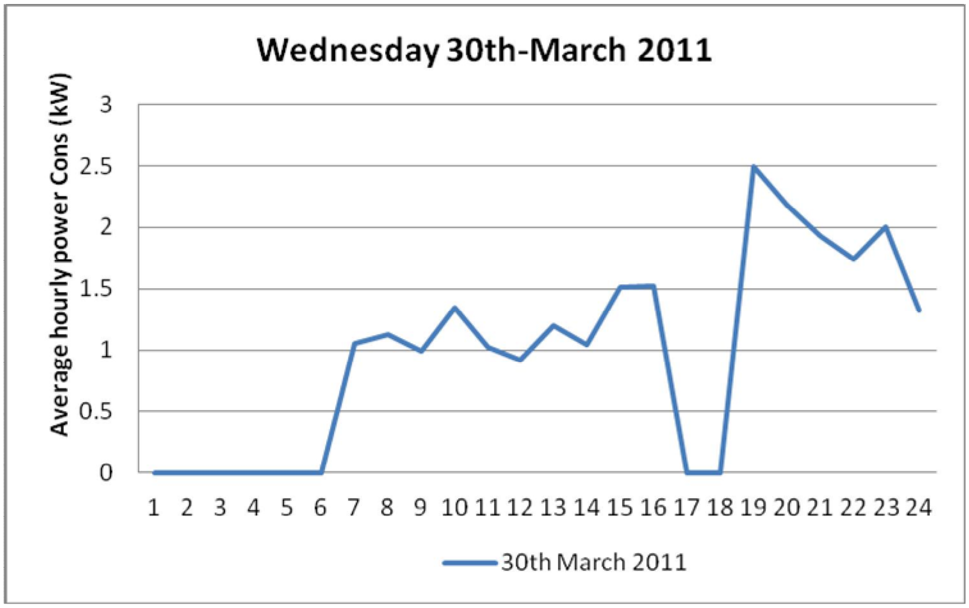


Figure 4.2: Averaged Hourly Load Profile for Court 88- Block 1- 30th Mar. 2011

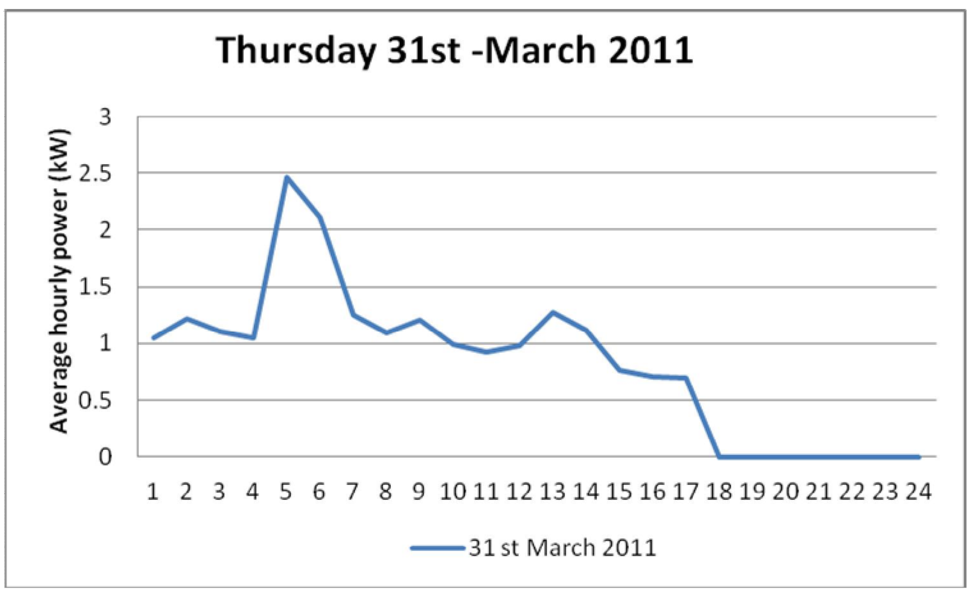


Figure 4.3: Averaged Hourly Load Profile for Court 88- Block 2- 31st Mar. 2011

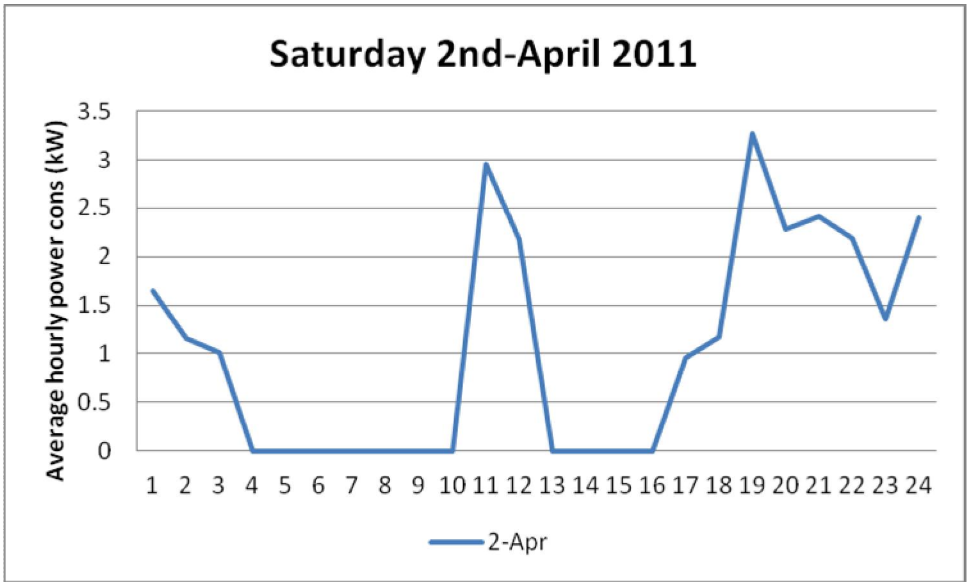


Figure 4.4: Averaged Hourly Load Profile for Court 87- Block 2- 2nd Apr. 2011

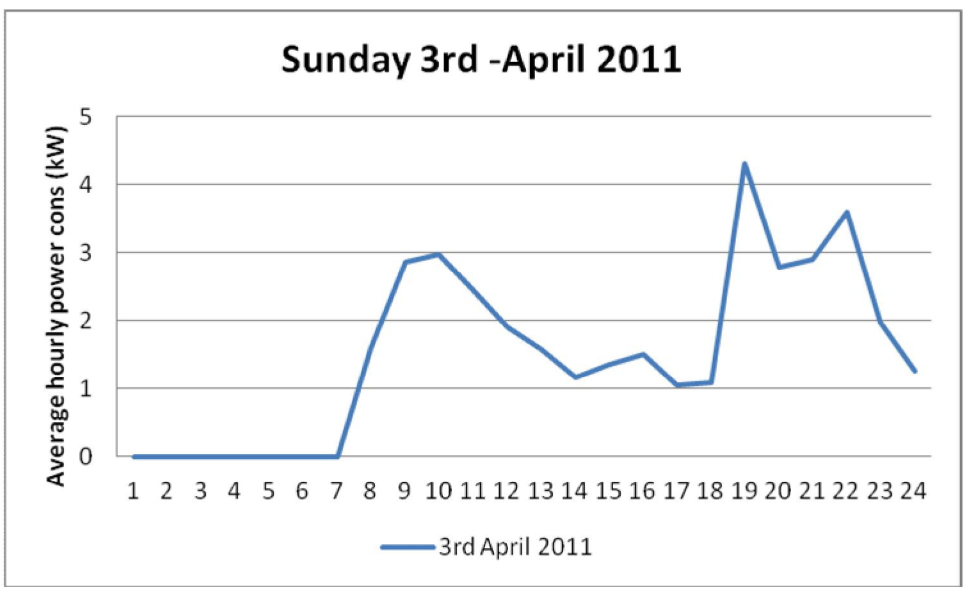


Figure 4.5: Averaged Hourly Load Profile for Court 86- Block 1- 3rd Apr. 2011

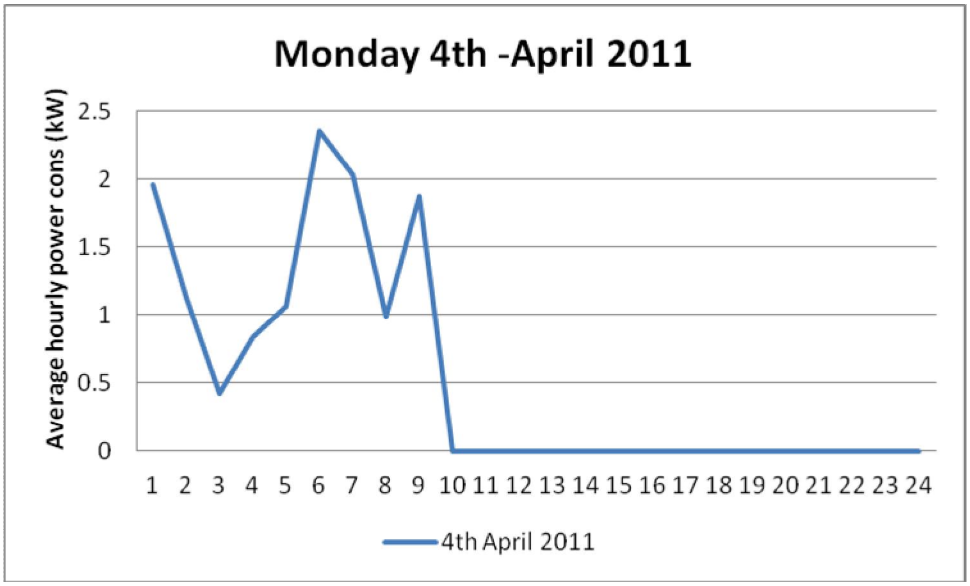


Figure 4.6: Averaged Hourly Load Profile for Court 86- Block 1- 4th Apr. 2011

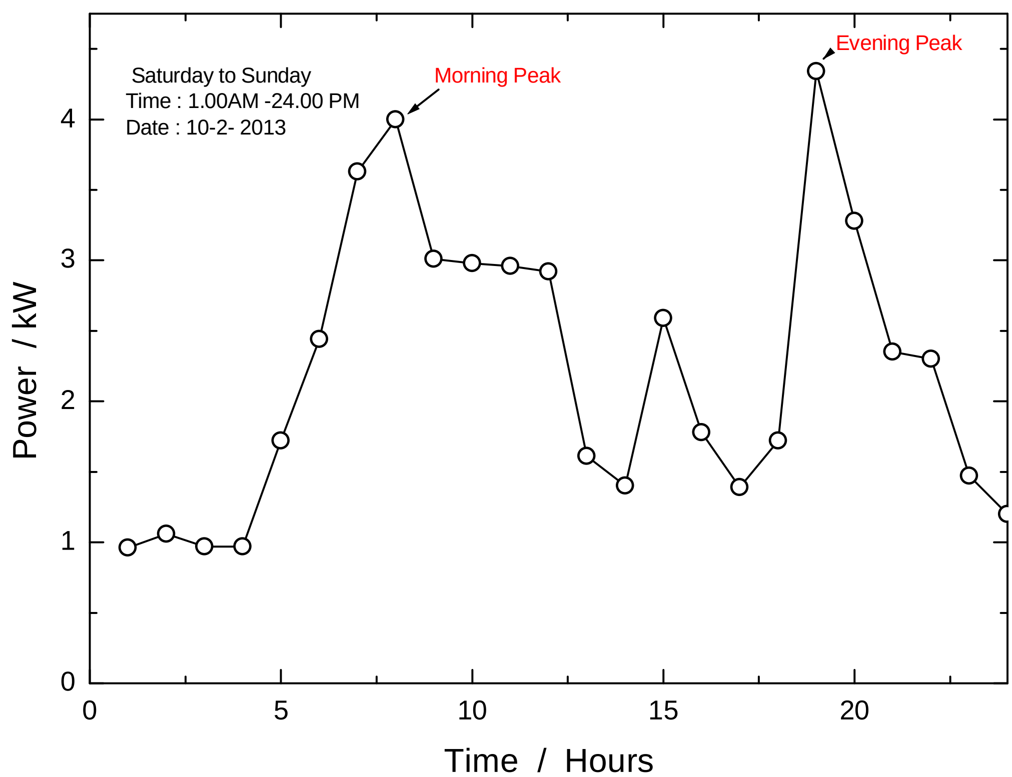


Figure 4.7: Averaged Hourly Load Profile for Court 88 Block 3- 10 Feb. 2013

Figure 4.7 shows a graphical presentation of data collected most recently at the site for only one day. The shape of the graph compared to Figure 4.1 has changed but the evening and morning peaks were still evident. The domestic load demand curve is solely driven by social behavior during that material day.

During the simulation and optimization of the design, no modifications were made on the software. A day to day random variability setting of 5% for the complete hourly energy demand for 1st April 2011 was used over the whole year while a 10% time-step to time-to time step variability was used for the same data. The random variability of ±5% was chosen because previous studies showed that domestic load varies marginally from one day to another due to the consumers' behavior [25],[27]. Random variability introduces daily and hourly perturbations to the original daily energy load data thereby creating realistic load variability for the whole year. The graphical shape of the load demand of 1st April 2011 with random variability is shown in Figure 4.8

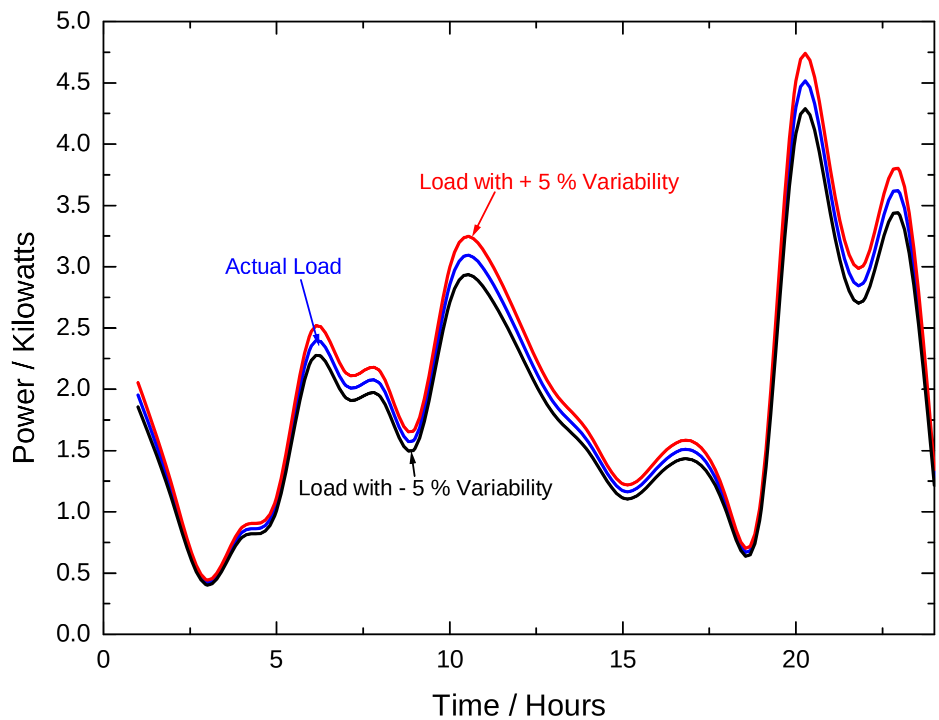
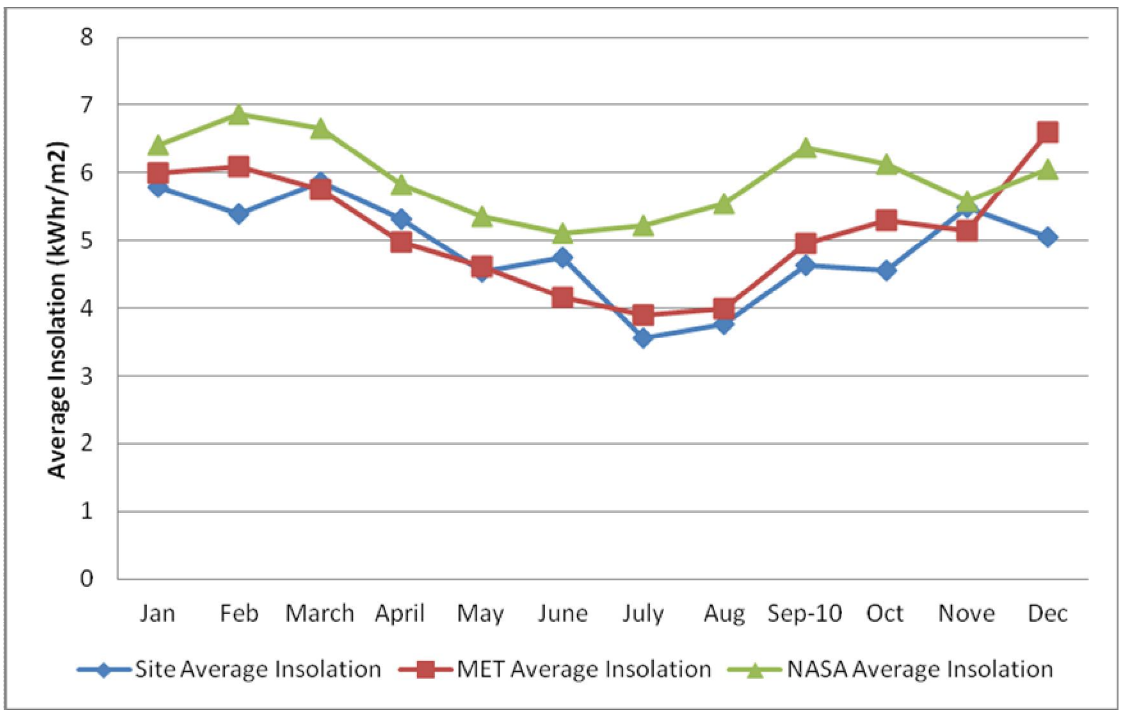


Figure 4.8: Load curve with ±5 % random variability on1st April 2011 Data

4.2.2 Solar Insolation

The solar insolation data was collected from the Embakasi Nyayo Suburb, National Aeronautics Space and Administration (NASA) website and the Meteorological department data center at Dagoreti Corner in Nairobi. The data was compiled and compared for suitability in the design and the three sources had very similar results as graphically shown on Figure 4.9. Further analysis showed that the Meteorological data was the most accurate data for design because it showed different readings for close stations whereas the NASA data showed same readings for the different stations within the country.



Source: [36],[35]

Figure 4.9: Embakasi Nyayo Suburb's Solar Insolation Profile.

Figure 4.9 shows a graphical comparison of the data obtained from the three sources. The graphs show similarities that validate the three data sources. The data from the Meteorological department was collected over a period of 20 year, while the data from the NASA satellite station is data accumulated over a period of 22 years and the site data was collected for one year. The data periods are different but the data pattern resembles a lot.

When compared, the NASA data had a resolution of one degree from the data collection satellite. This meant that for every point measured from the satellite, the solar radiation reading remained the same for every one square degree. One square degree is equivalent to 12321 kilometers square on the earth surface. Therefore the reading for Embakasi would be the same as far as Limuru, Thika, Machakos junction and Ngong. To confirm the statement, data for out span stations from Nairobi was downloaded from the NASA station and other data were obtained from the meteorological department and the data variations were noted as shown on the Tables 4.1 and 4.2. Data from Meteorological station was 20 year data while that from NASA was 22 years data.

Table 4.1: Meteorological Solar Radiation Data for Out Span Stations – kWh/m^2

STATION	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Mean**
LODWAR	7.29	7.49	7.3	7.01	7.12	7	6.82	7.11	7.46	7.32	7.01	7.26	7.18
KERICHO	6.87	7.36	6.82	6	5.71	5.67	5.45	5.71	6.13	5.72	5.69	6.52	6.13
NAKURU	7.22	7.65	6.98	6.17	6.55	6.39	6.27	6.62	6.88	6.39	5.92	6.87	6.66
NYERI	6.34	6.92	6.28	5.62	5.39	4.72	4	4.32	5.62	5.61	5.04	5.64	5.46
THIKA	6.57	6.86	6.22	5.4	4.64	4.25	3.92	4.17	5.38	5.37	5.25	6.02	5.34
KATUMANI	6.74	7.32	7.18	6.56	5.9	5.32	5.07	5.27	6.14	6.45	6.08	6.34	6.2
JKIA-Nrb	**5.99**	**6.1**	**5.75**	**4.97**	**4.62**	**4.16**	**3.89**	**3.99**	**4.95**	**5.29**	**5.14**	**6.61**	**5.12**

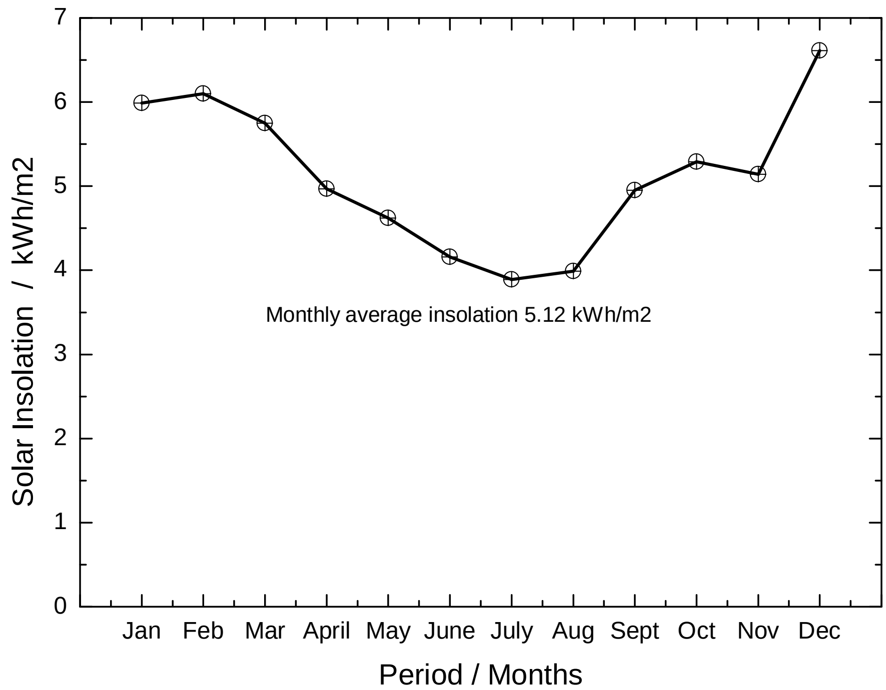
Source: [36]

Table 4.2: NASA Satellite Solar Radiation Data for Out Span Stations – kWh/m^2

STATION	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
LODWAR	6.18	6.58	6.39	5.8	5.79	5.66	5.71	6.17	6.62	6.06	5.68	5.87	6.04
KERICHO	6.19	6.68	6.46	5.74	5.5	5.36	5.24	5.58	6.08	5.79	5.42	5.9	5.83
NAKURU	6.21	6.72	6.43	5.66	5.61	5.32	5.16	5.48	6.19	5.7	5.14	5.74	5.78
NYERI	6.21	6.72	6.43	5.66	5.61	5.32	5.16	5.48	6.19	5.7	5.14	5.74	5.78
THIKA	6.41	6.94	6.41	5.58	4.95	4.37	4.27	4.56	5.72	5.77	5.23	5.81	5.5
KATUMANI	6.41	6.94	6.41	5.58	4.95	4.37	4.27	4.56	5.72	5.77	5.23	5.81	5.5
JIKA-Nrb	**6.42**	**6.86**	**6.66**	**5.83**	**5.36**	**5.11**	**5.23**	**5.55**	**6.37**	**6.13**	**5.59**	**6.06**	**5.93**

Source: [35]

From the NASA and MET data above it can be seen that the resolution and hence degree of error for NASA data is larger than that of the MET data. This is shown by the same data reading appearing for two stations like Thika and Katumani which are about 50 kilometers apart, and Nakuru and Nyeri which are about 90 kilometers apart. The MET data shows different radiation data for the four stations mentioned. Following this observation, the MET data was used during the design and sizing of the solar PV system for the ENS because of its resolution and accuracy. However the other two sets of data from NASA and site data were used for illustrating the closeness and therefore the justification for using MET data. Figure 4.10 shows a graphical illustration of the Meteorological data.



Source: [36]

Figure 4.10: MET (JKA) Solar Insolation Data for Embakasi Nyayo Suburb

4.3 Solar PV System Sizing and Simulation Results

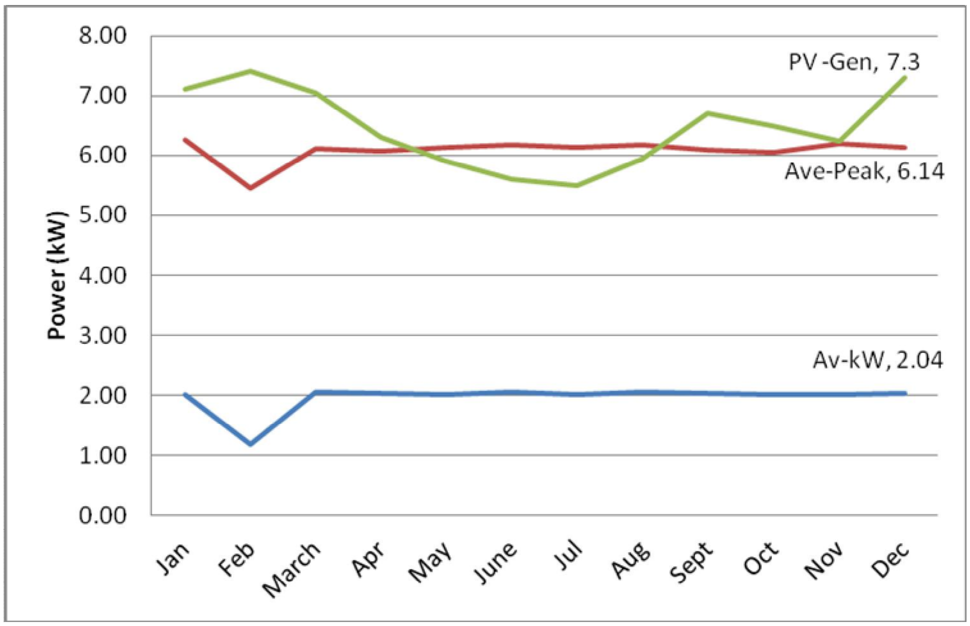
After the design and sizing of the solar PV system, the different system components sizes were determined and are presented. The simulation results graphs depict only one parameter for clarity purpose apart from the battery state of charge where the SOC and the load demand had to be compared. Other graphs illustrate the intended performance versus the simulated actual outputs.

4.3.1 Solar PV Array Size

Using the ENS model calculation in section 3.4.1.2 of Chapter 3, the total energy from the solar PV array was calculated as 12.22 kWp. But due to standard sizes of modules, the array size had to be adjusted to 12.5 kWp. The system will require some utility power import of a maximum of 2.5 kW when there is solar power deficiency. When the solar PV generation exceeds the consumers' power demand, the surplus power is released or sold to the grid. The power deficit and surplus will be varying throughout the year so it is impossible to state the instantaneous values.

Sample calculations were done using the solar array design model calculation for varying irradiance values and the results are shown in Table 1 of Appendix C. In Table 1 of Appendix C, only the peak irradiance period has been considered so as to estimate the size of the solar PV array otherwise before and after peak hours, irradiance is significant and also contributes to the daily energy captured by the array. In the sample calculations, the number of modules and output of the array were obtained as 90 modules of 140 W each and 12.5 kWp respectively. For ease of calculation the temperature was held constant at 28 ^{0}C though it changes under normal circumstances.

Using the simulations results obtained, Figure 4.11 shows the monthly peak and average hourly load demand compared to the solar PV peak power generation. The average peak power matches well with the solar PV generation apart from during the months of May June July and August. During these months, the grid power supplements the solar PV generation. This is because months of May to August have low solar insolation compared to other months of the year as depicted on Figure 4.10 that was generated from the TMY data from the meteorological department. The graph shows that the solar PV electricity is capable of handling most of the peak power requirements for a block of 8 apartments at the suburb.



Legend: Blue – Average power demand, Red – Peak power demand and Green – PV peak power generation

Figure 4.11: Comparison of Power Demand and Solar PV peak power Generation

The size of the PV array shall be 12.5 kW consisting of 90 polycrystalline modules of 140 watts each.

4.3.2 Battery Storage Capacity

The battery capacity of a solar PV system was sized for a block of 8 apartments. The battery size was determined using the daily load energy demand so the inverter efficiency was used so as to obtain the accurate storage capacity. When the battery is feeding the inverter at night, the demand from the batteries is subjected to the efficiency of the inverter so the losses at the battery and inverter must be taken care of in the sizing. The system voltage was determined by the allowable voltage drops in the cables during the charging and discharging process. The cable size and length between the charge controller and the batteries must be short so as to accommodate the allowable voltage drop and be able to fit in the terminations provided.

During the design and sizing of the battery storage, the parameters in Table 4.3 were used.

Table 4.3: Battery Storage Capacity Design Parameters

Parameter	**Value**	**Value**	**Value**
Daily energy demand, P	48.8 kWh	48.8 kWh	48.8 kWh
Days of autonomy, D	3 days	2 days	1 day
Battery depth of discharge, DOD	0.8	0.8	0.8
Battery efficiency, η	0.86	0.86	0.86
Inverter efficiency	0.95	0.95	0.95
System voltage, V	180 V DC	132 V DC	108 V DC
Battery Storage Capacity	6000 Ah	4400 Ah	3600 Ah

The ampere hour capacity required by the consumer for three days is the battery DOD capacity as calculated using Equation (2.7) given in Chapter 2. During the design of the battery storage capacity, three scenarios were considered one using 1 day of autonomy, another 2 days of autonomy and the third 3 days of autonomy. The difference observed between the systems was the storage capacity, system voltage, battery connection method and the total current from each battery bank. The three scenarios have advantages and disadvantages; technically, the system with 3 DOA has more storage and so can supply the load for a longer period. On the other hand, the 1 DOA has smaller capacity and hence will supply the load for a shorter period in case of sustained lack of irradiance. Financially the system with 3 DOA is the most expensive followed by the one of 2 DOA and lastly the one with 1 DOA. The financial analysis has been shown in section 4.6.1.

The results presented are for the 3 days of autonomy where the DOD must not exceed 80% for deep cycled batteries when in use.

The battery storage capacity was calculated as 1182.17 Ah which is 20% of the total battery storage capacity. This battery depth of discharge capacity is the amount of ampere hours that can safely be extracted from the battery bank over a daily use and also allow adequate capacity for 3 days of autonomy. To obtain the storage capacity of the bank, the storage obtained in the previous calculation was divided by the daily DOD of 20 % which obtains the size of the battery bank as 5910 Ah.

To find the number of batteries in the battery bank, the system voltage is used making sure that the level of ampere hour current is maintained at a safe level and storage space is considered. Using a system bus voltage of 180 V DC and 200 Ah batteries of 12 V DC each, the battery bank of 5910 Ah will comprise 30 batteries of two strings of 15 series connected batteries per string, that is obtained by dividing the total capacity with one battery capacity. Therefore, each block of 8 apartments will require 30 batteries of 200 Ah, 12 V DC storage capacities. The stored energy in the battery bank shall be able to supply 3 days of autonomy daily energy demand of 48.8 kWh to a block of 8 apartments. The 3 DOA is a rare situation but when it occurs the battery bank will discharge to its minimum allowable DOD of 80%.

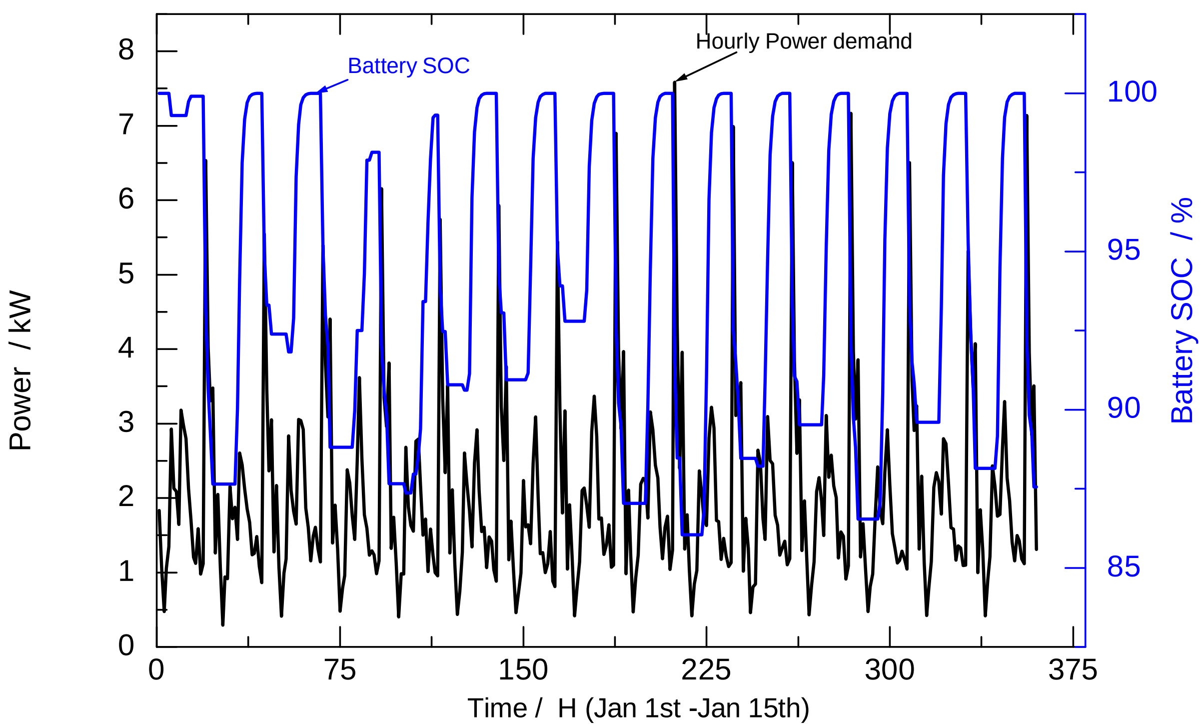


Figure 4.12: Battery State of Charge from January 1st to January 15th

Figures 4.12 to 4.16 show the software simulated results of the hourly charge capacity for the days of the year indicated. The software sampled simulation results on the graphs were picked at random for ease of explanation. The raw data can also be seen in the battery SOC raw data on Table 1D in Appendix D and for clarity sake; only data for few hours are shown. The data shows the state of charge on hourly basis for selected months only.

The battery type selected for the solar PV system is Vision 6FM200D, absorbent glass matt (AGM) sealed deep cycle lead acid battery. This battery type was selected because of its long life and ability to withstand deep discharge cycles. The nominal capacity for the battery is 200 Ah, nominal voltage is 12 V DC, efficiency is 86%, minimum state of charge is 40%, float life is 10 years, maximum charging current is 80 amperes and it has a lifetime throughput of 917 kWh. The time and month data shown on the graphs was randomly selected and the 15 days shown for each month were selected for clarity purposes because one month data would be too cramped together. All the graphs in this section are using truncated monthly data that begging at midnight every day. The results in Figure 4.12 show that the battery state of charge capacity is 100% most of the time from 1^{st} to 15^{th} of January or 00 to 360 hours of January. The results also show that few times in January, the state of charge goes below 90% but never goes below 85%. This is an indication that the batteries will be maintained at a good state of charge (SOC) considering that they have 80% minimum depth of discharge.

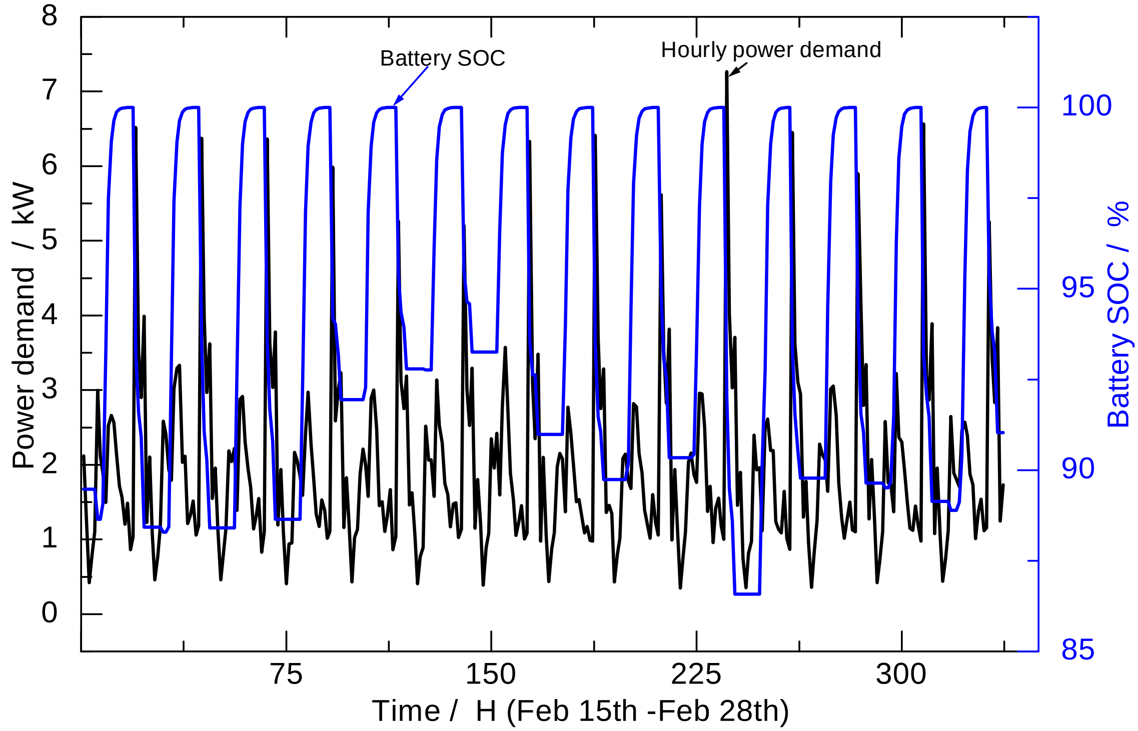


Figure 4.13: Battery State of Charge from February 15th to February 28th

Figure 4.13 also compares the battery state of charge with the hourly power demand from 15th to 28th February. The battery SOC is 100% during the last 15 days of February while the load demand is about 3.5 kW on average for most of the days. The raw data shows that the battery state of charge attains 100 % by 3 PM implying that after 3 PM, the system is able to export electrical power to the national grid and comfortably handle the evening load demand. The highest peak load demand during the 15 days is 7.4 kW.

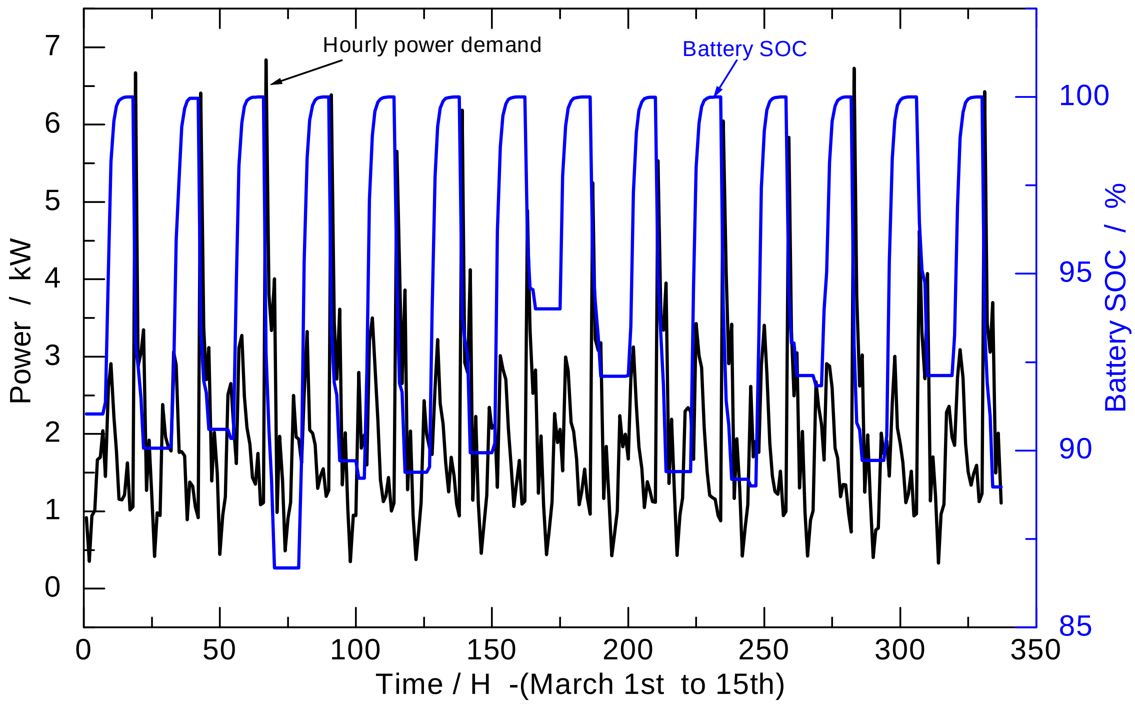


Figure 4.14: Battery State of Charge from March 1st to March 15th

Figure 4.14 shows the SOC and load demand during the first 15days of March. The SOC of the batteries is 100 % most of the days, but the average load demand is reduced to 2.5 kW.

The peak power demand for this period is 7 kW and it occurs three times during the period. The raw data shows that the peak power demands occur at 7 PM in all the three times.

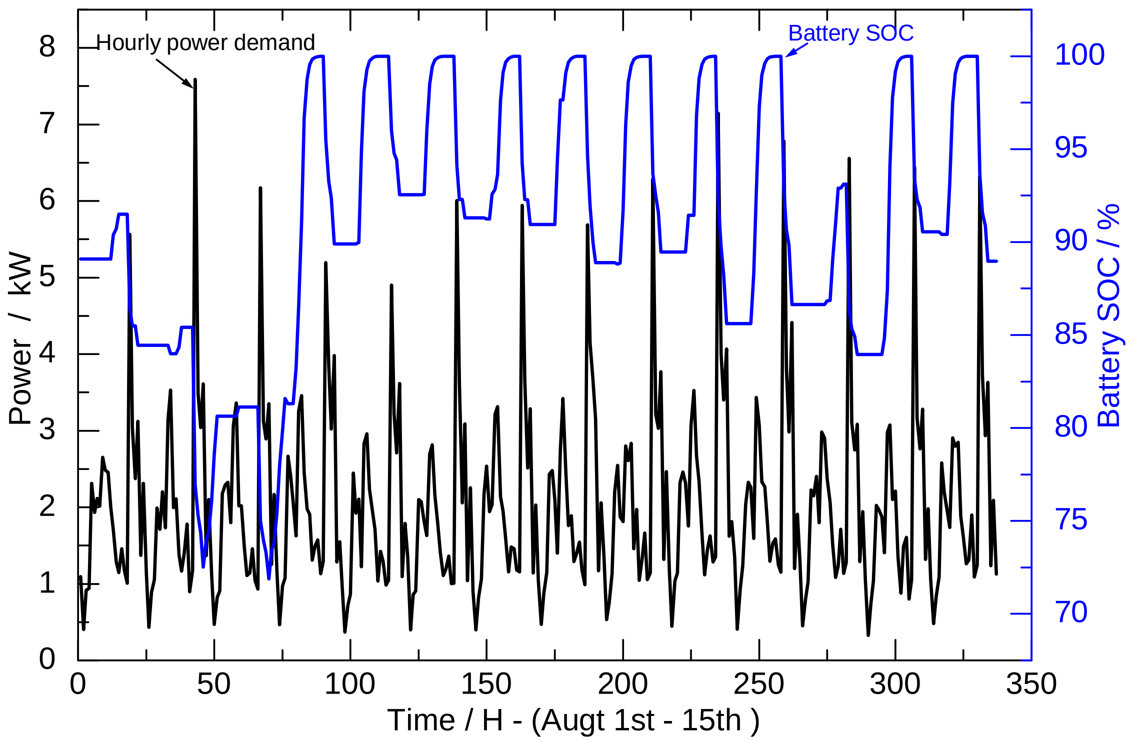


Figure 4.15: Battery State of Charge from August 1st to August 15th

Figure 4.15 shows the SOC and the load demand for the first 15 days of August shown in hours. At the beginning of August, the average SOC is low at 83 % while the peak demand rises up to 7.5 kW. This is attributed to reduced solar insolation during the period. During such periods, the solar PV system imports electrical power from the grid depending on the demand. The highest import during simulation was 2.5 kW. The period of the month shows many peak power demands occurring during the period though all of them but one exceeds 7 kW by a small margin.

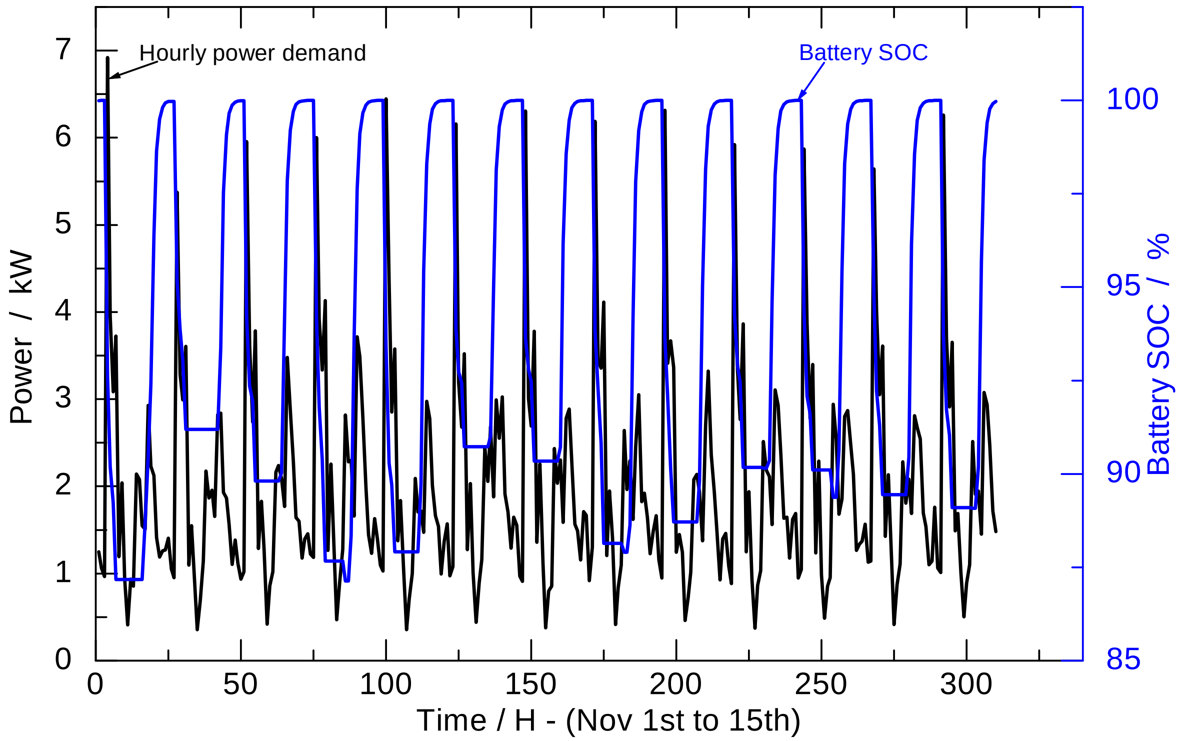


Figure 4.16: Battery State of Charge from November 1st to November 15th

Figure 4.16 shows the SOC and load demand from 1st to 15th November also shown in hours. The load demand has an average of 3.5 kW most of the captured period. The battery SOC is at 100% for most of the period. The trend shows that the battery bank is capable of handling the load. The hours showing low SOC are the hours when there is no adequate insolation where the SOC gets below 90 %. The periodic low demands at below 0.5 kW indicate the load demand at hours past midnight every day. This applies for all graphs.

4.3.3 Battery Charge Controller Size

Using the model calculations for the charge controller in 3.4.3, and the array size obtained of 90 modules of 140 Watts with a nominal voltage of 180 Volts per string for the 3 DOA and a module maximum current of 11.06 A, the array design will require connecting the modules into 6 strings of 15 modules each. Therefore the maximum open circuit voltage per string of 15 modules will be 271.5 VDC. During a charging exercise, the solar array rarely attains the open circuit voltage and short circuit current values but for safety purposes, the short circuit current and the maximum voltage of the array are used to size the charge controller. Thus, it was considered that the maximum charging voltage of the charge controller will always be equal to the maximum array string voltage of 271.5 V DC. The maximum charging current of the controller will be the sum of the maximum currents (11.06 A) in the 6 array strings multiplied with the ripple factor (1.3) of the MPPT charge controller. The ripple factor is used so as to accommodate the short circuit current of the solar PV array. The charge controller charging current will therefore be 86.27 A. This is the maximum operating current of the charge controller. Simulation results in Figures 4.17 to 4.20 shows the hourly charge controller current for the months of January, June, August and November. The same months considered in the section 4.3.2 have been considered in this section also for consistence. The graphs show the whole months charging currents unlike the previous graphs for the battery SOC. Results show that the charging current does not go beyond 80 A so the charge controller sizing agrees well with calculated results and the charging current from the solar PV array.

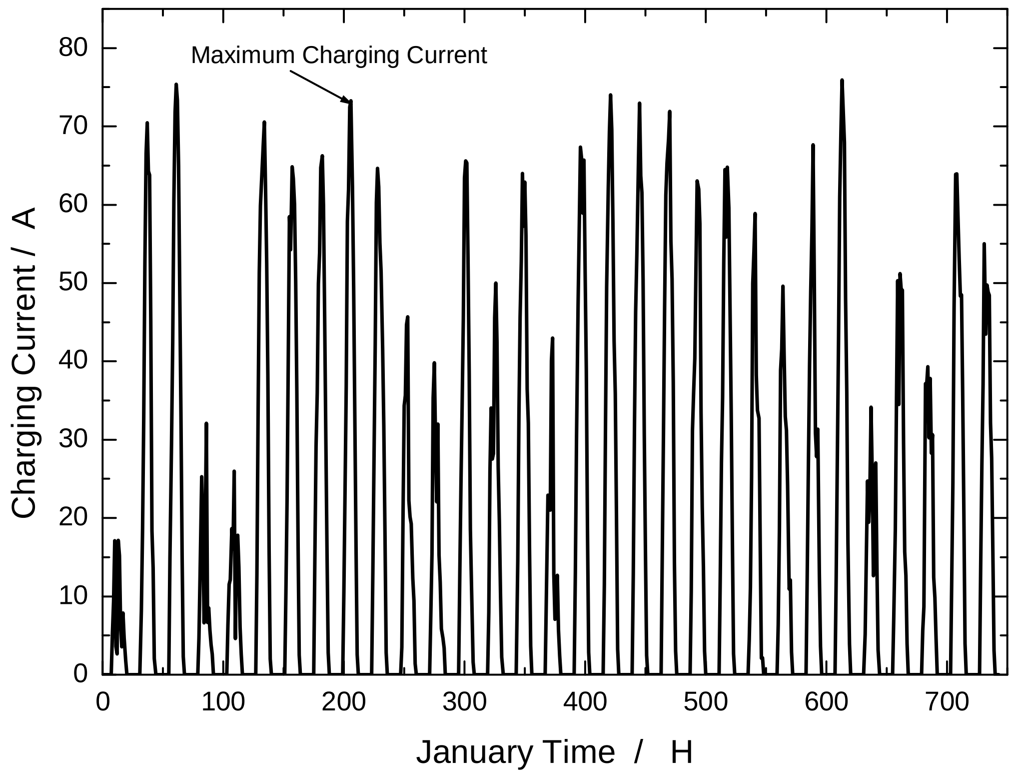


Figure 4.17: Charge Controller Charging Current for January

Figure 4.17 shows the charging current results for the whole month of January. Low charging current is experienced at the 36th, 100th, 280th 380th and 650th hours of the month. This is caused by daily weather changes. Though the current is low on those days, the rest of the time it is in the range of 50 A indicating good charging capacity.

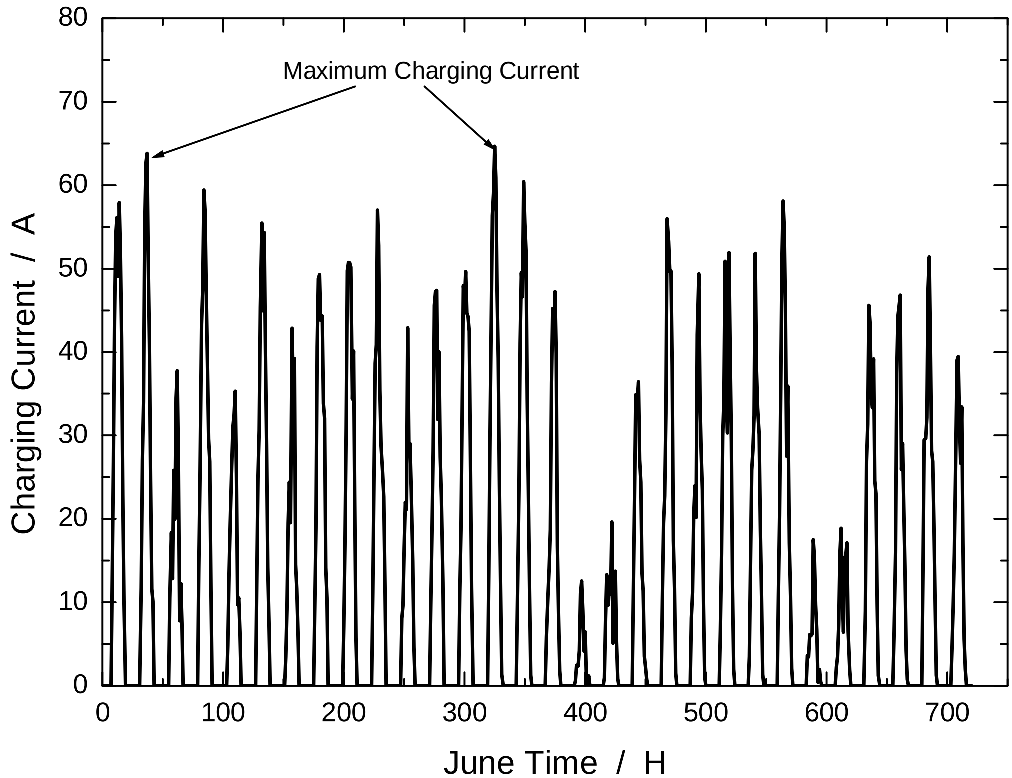


Figure 4.18: Charge Controller Charging Current for June

Figure 4.18 shows the charging current results during the whole month of June where low charging current is experienced during the 400th hour of the month and later during the 620th hour of the month. The rest of the month the charging current is at an average of 30 A with a monthly peak of 64 A making it much lower than the expected maximum charging capacity of 86.27 A. During the periods of low charging current, the consumer will be required to import the deficient power from the grid.

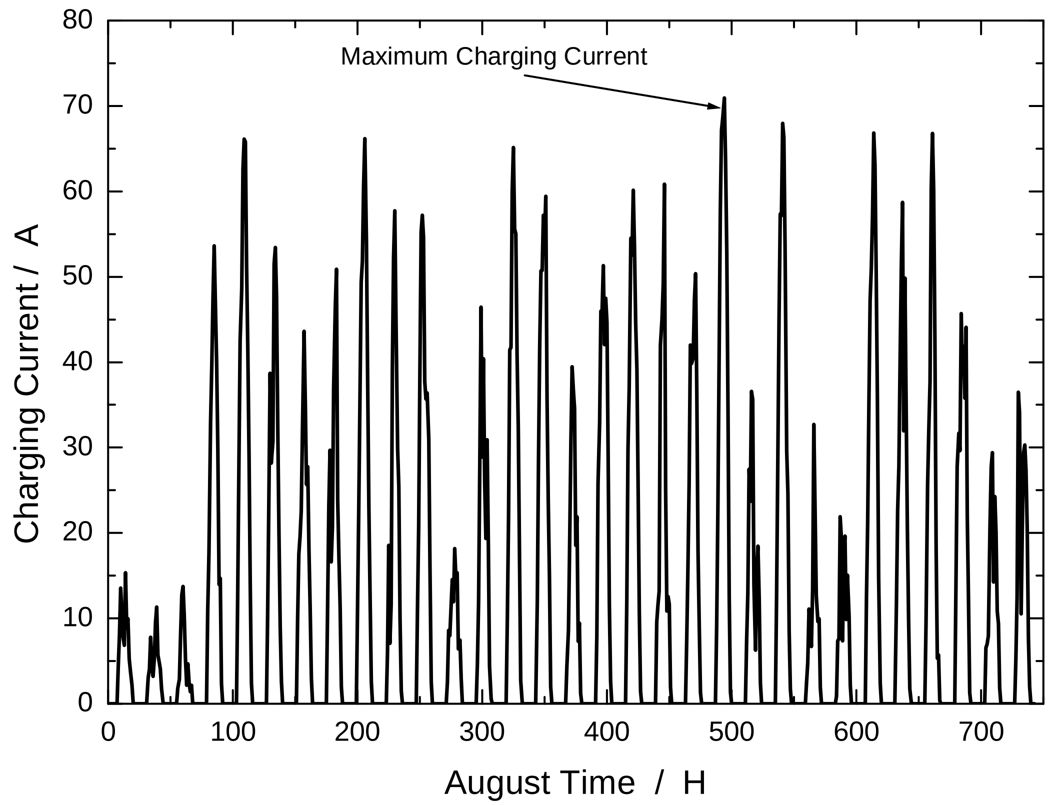


Figure 4.19: Charge Controller Charging Current for August

Figure 4.19 shows the charging current during the month of August where low charging current is experienced at the beginning of the month, near the middle of the month and 525th to 600th 725th hour of month. The peak current during this month is 72 A but the average charging current is below 30 A. This is a low insolation month so the system user has to import power from the national grid network to supplement the solar PV system.

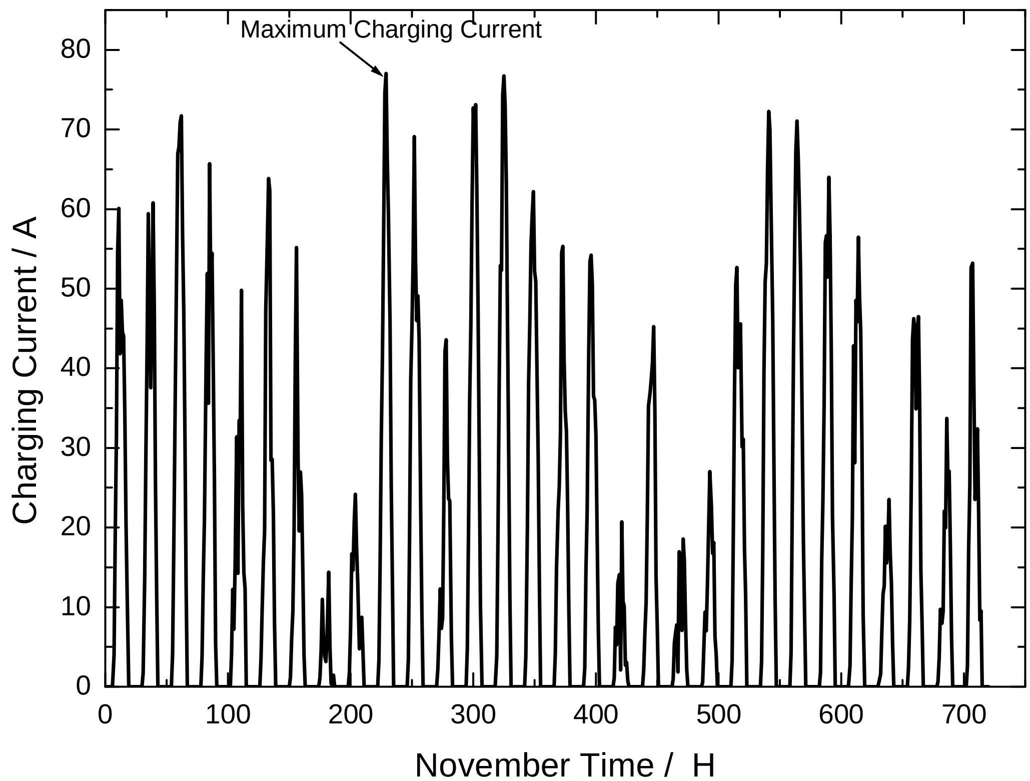


Figure 4.20: *Charge Controller Charging Current for November*

Figure 4.20 shows the charging current level during month of November. Here low charging current is experienced between the 192nd, 408th, 456th and 650th hour of the month. The charging current peak is 76 A and does not exceed 80 A.

Finally, the charge controller shall have protection mechanisms for short circuit current and over voltage. Charge controllers are rated in currents of 10 A to 500 A in steps of 10 A. Therefore a charge controller of 80 A would serve the ENS system well and was selected.

4.3.4 The Inverter Size

During the inverter sizing in section 3.4.4 of chapter 3, the logged peak power demand of 11.44 kWp was used. The inverter size must accommodate the system voltage and also be able to supply the peak power demand of the consumer. When sizing the inverter, the person sizing is guided by standard inverter specifications and parameters. Therefore, the inverter sizing was calculated using the design parameters in Table 4.4.

Table 4.4 Inverter design and sizing parameters

Parameter	Value
System voltage	180 V DC
Logged peak power	11.44 kWp
Inverter Rating Choice	7.5 kWp to 15 KWp
Inverter efficiency	95 %

The standard inverter sizes considered were 7.5 kWp, 10 kWp, 12.5 kWp and 15 kWp. In the calculation the 12.5 kWp size inverter was obtained but during the simulations, an inverter size of 10 kW was settled for and chosen. The calculation done considered only few hours of the year but the simulation exercise was run for the whole year (8,760 hours) to match the hourly peak demands and selected a 10 kW inverter as the most cost effective size. Inverters are normally made to take up to 25 % above their nominal rated peak load so this implies that the inverter selected shall be capable of supplying an extra load of 2.5 kWp for up to 2 minutes when starting AC induction machines that constitute 20 % of the load as refrigerators and washing machines.

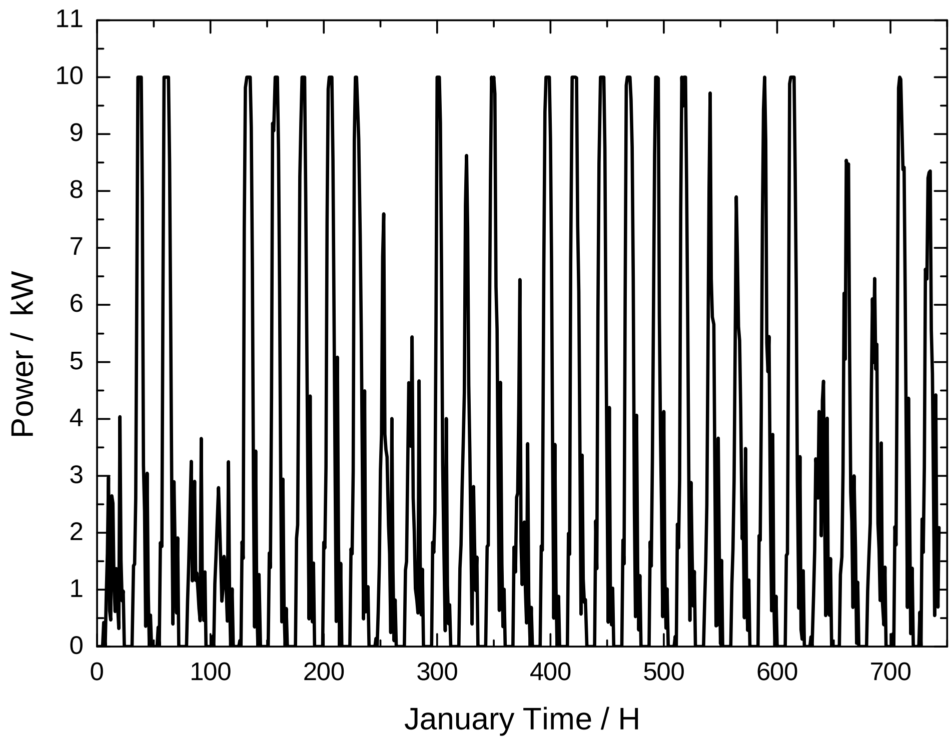


Figure 4.21: Solar PV Inverter Output for January

The inverter selected was a grid tied inverter that has control mechanisms for importing power deficiency from the grid and exporting surplus power to the grid. Figures 4.21 to 4.24 show the inverter outputs for the months of January, June, August and November. The same months have been selected again for consistence of illustration.

Figure 4.21 shows the performance of the inverter during the month of January in hours. The average load demand is 4 kW while the peak power demand is 9.8 kW. The peak power demands occur for a short time and mostly during the evening at 7 PM so the inverter will be able to accommodate the peak power demands.

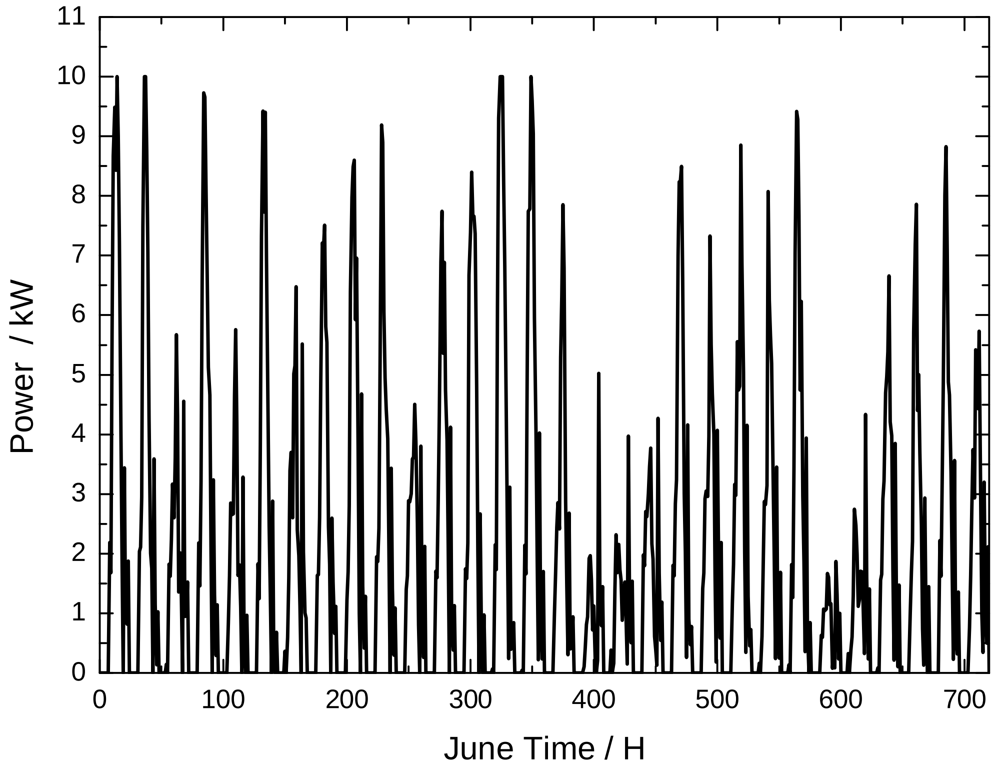


Figure 4.22: Solar PV Inverter Output for June

Figure 4.22 shows the inverter performance during the month of June in hours. During this month, the average power demand is 3.5 kW and the highest peak power demand is 10 kW. Just like the previous month, the peak demand occurs in the evening for a short period only. It is good to note that the inverter output depends on the electricity generation from the solar array and also the battery storage capacity. The month of June is one of the months where insolation is low and hence the reduced inverter average output.

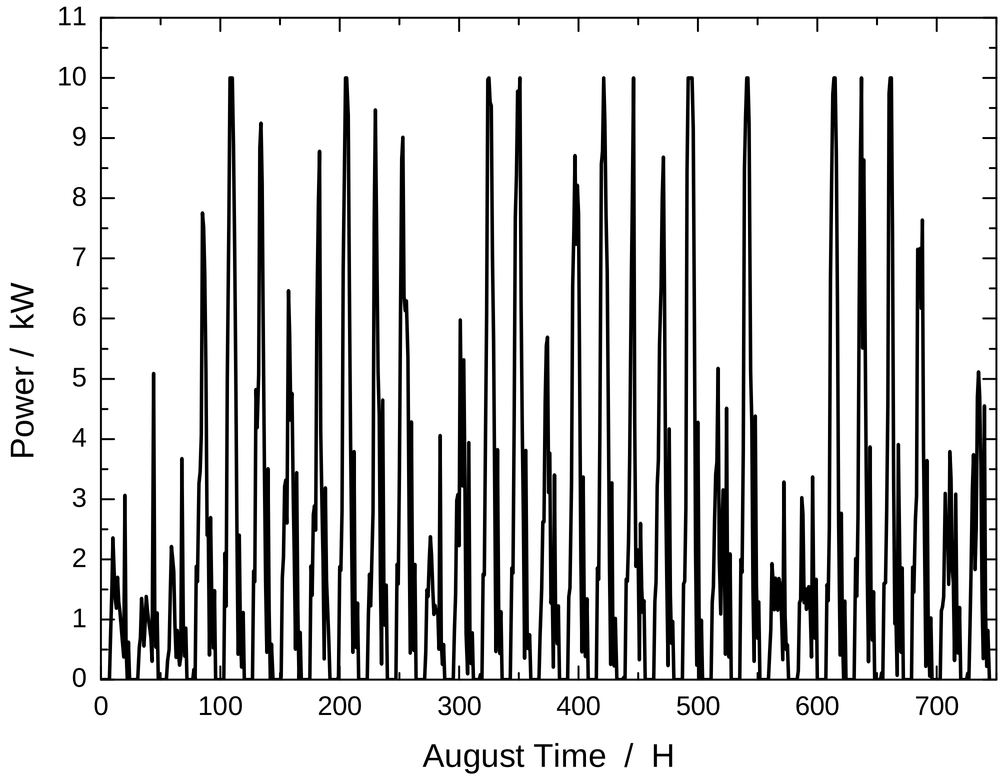


Figure 4.23: Solar PV Inverter Output for August

Figure 4.23 shows the inverter performance during the month of August in hours. The inverter output has reduced considerably to an average of 3 kW with fewer peak power demands. During this month, the inverter output is reduced again because of the reduced insolation and hence the output from the array and battery storage capacity. The deficient power during this month is supplied by the grid network through the inverter control switchgear. The amount of import is not seen because it does not pass through the inverter as seen in the schematic in Figure 2.2.

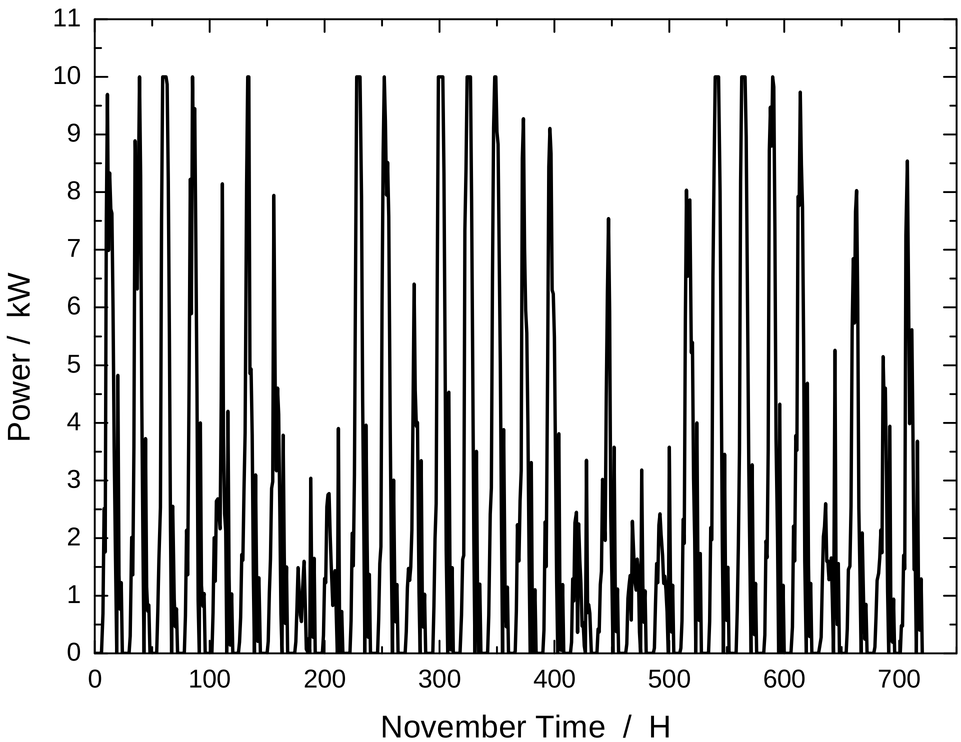


Figure 4.24: Solar PV Inverter Output for November

Figure 4.24 show the solar PV power output from the inverter for the month of November represented in graphical form. This month shows reduced inverter output during the 200th, 420th and 480th hour of the month. This trend follows the trend of the battery capacity and the array output. During such periods, the consumer imports power from the grid network. During all the captured periods; January, June, August and November, the graphs show that the inverter is capable of giving an output of up to 10 kW for most of the time apart from the months.

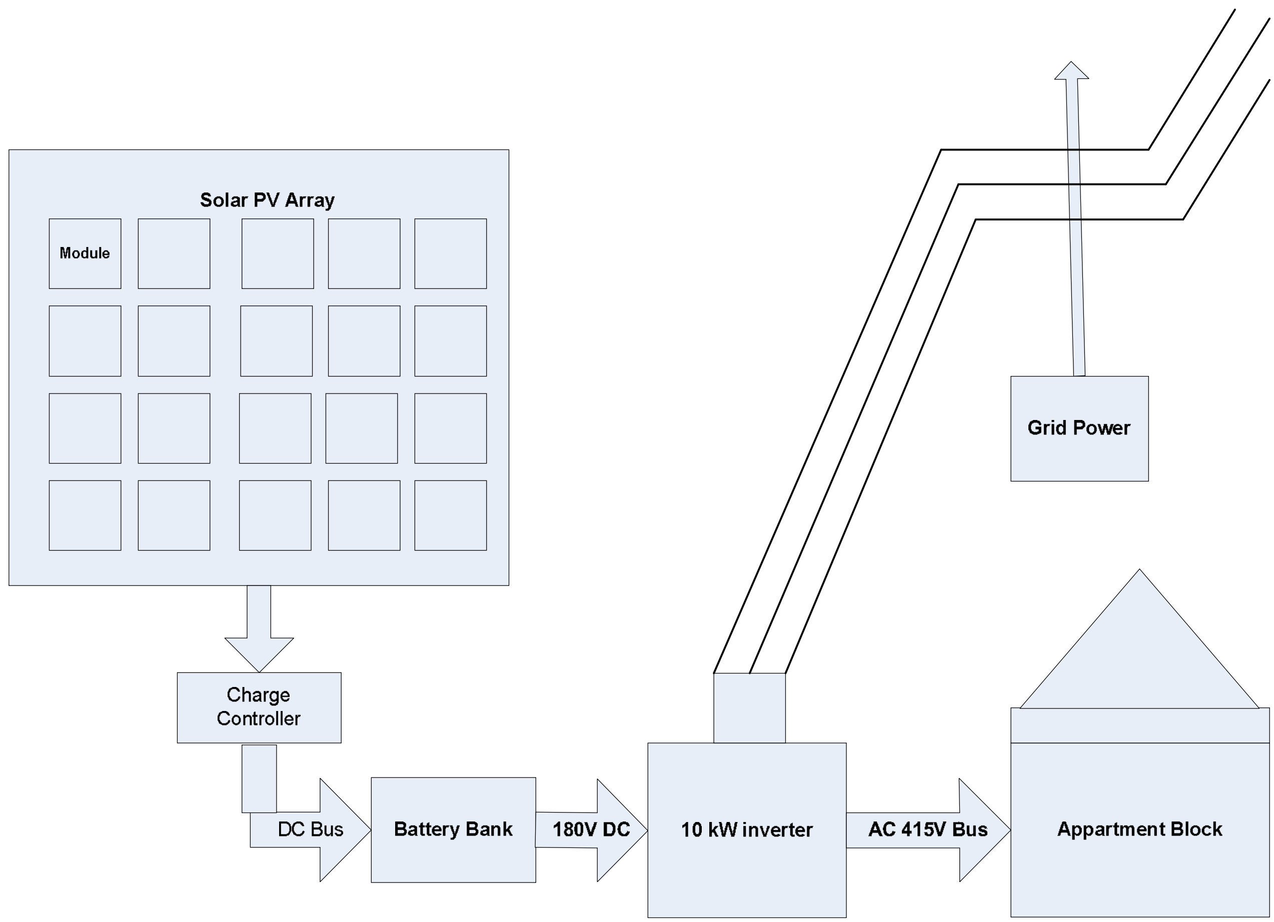


Figure 4.25: Block Diagram of the Solar Hybrid Systems at Embakasi Nyayo

Figure 4.25 shows the solar and grid hybrid system at the Embakasi Nyayo suburb. The system consists of an array of 90 x 140 watts polycrystalline modules, a 108 V DC 80A charge controller, 3600 Ampere hour battery bank and a 10 kW grid tied inverter. This system is intended to serve one block of 8 apartments.

4.4 Orientation of Solar PV Panels

It is worthy to note that the Embakasi Nyayo Suburb is an existing residential suburb and that there are two apartment block orientations in the suburb; north/south and east/west. Because the sun moves from the east to the west, the arrays on the blocks that have the north/south orientation will have more uniform and continuous exposure to solar radiation than the blocks that are east/west oriented. This is explained in the individual apartment block orientation style in the subsequent sections.

4.4.1 North - South Oriented Blocks

At the ENS there are 384 north/south oriented blocks that have a free roof space measuring 2 x 230 square meters each facing south and north on which the solar PV array can be installed at an angle equaled to the corrected latitude angle. This roof space is capable of accommodating some 146 x 140 watt solar modules on each side of the roof space where each module measures 1.62 x 0.97 meters (1.57 square meters). This roof space is exposed to the sun radiation from 8 AM to 5 PM and so it receives solar irradiation for about nine (9) hours. With a well adapted structure oriented due north, the array will be capable of achieving up to 80% of the maximum power point output of the array every day. Figure 4.26 shows the north/south oriented roof plan discussed in the section.

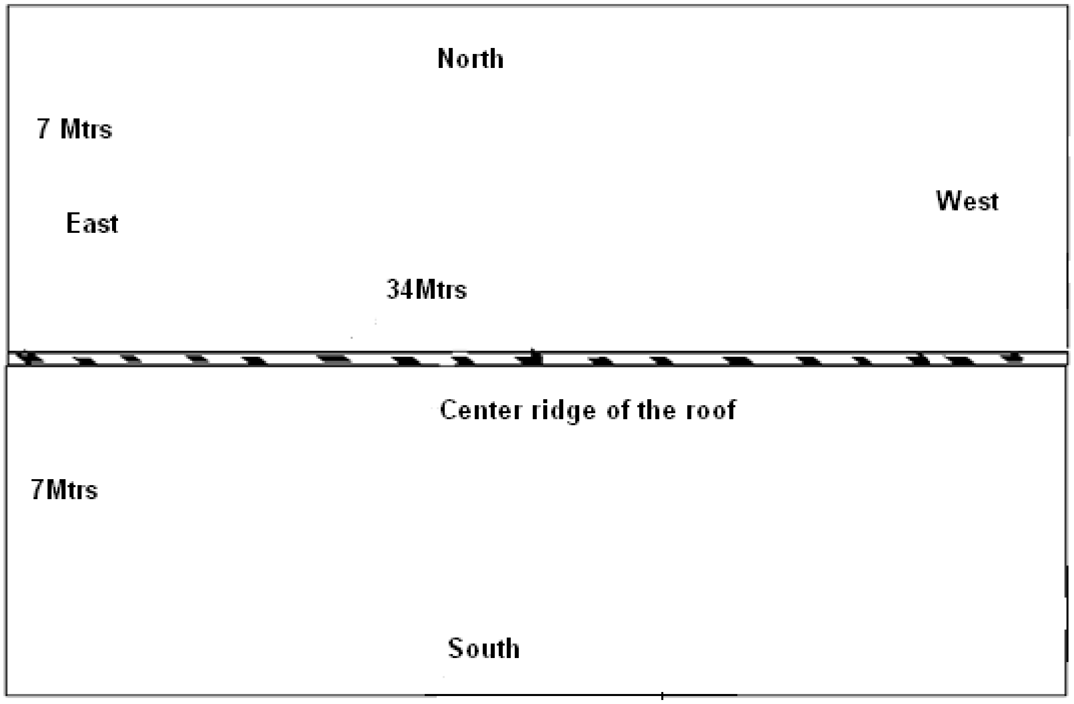


Figure 4.26: North - South Oriented Blocks Roof Plan

4.4.2 East –West Oriented Blocks

There are 96 east/west oriented blocks that have a roof space of 460 square meters. This roof space orientation receives solar radiation as early as 7 AM up to 1 PM on the eastern slope. After 1 PM the sun radiation shifts to the west and so more radiation is on the western slope up to 5.30 PM because the sun sets to the east. The eastern slope receives radiation for 6 hours while the western slope receives radiation for 5.5 hours.

Due to the roof plan orientation explained, the solar PV array for the east/west oriented block cannot face south or north because the support structure to be adapted on the roof would be too massive and unstable and would affect the structural design of the existing roof. To circumvent this challenge, the array has to be split into two such that one array string of 45 modules faces east at a slope following the profile of the roof and the other string of 45 modules faces west also following the profile of the roof.

In this type of orientation, the support structure will be simpler because it will only provide adequate spacing between the steel roof and the module base to avoid heating of the solar modules. In this type of orientation, the azimuth shall be -90 for the east facing array and +90 for the west facing array.

This way the east/west oriented blocks will be able to maximize their daily electricity output to about 80% of the maximum power point output of the array. Previous studies done using different orientations had yielded very good results especially for domestic consumers [26]. These east/west facing arrays will need to have a switching mechanism that will isolate the eastern facing string when it is shaded from the sun at 2 PM to avoid energy loss due to shading. Shading has negative effects in that it blocks conduction to all the series connected cells. Normally the 12 V DC 36 cells module has two series circuits of 18 cells each separated by two by pass diodes. So when one cell is shaded, conduction is blocked in the entire 18 cells so the current is by passed by the diode. Depending on the battery voltage, the charging current could be reduced to near zero by shading. This situation is worse when there is only one by pass diode for the 36 cells. The adverse effects of shading affect modules because they are formed by series cells which carry the same current.

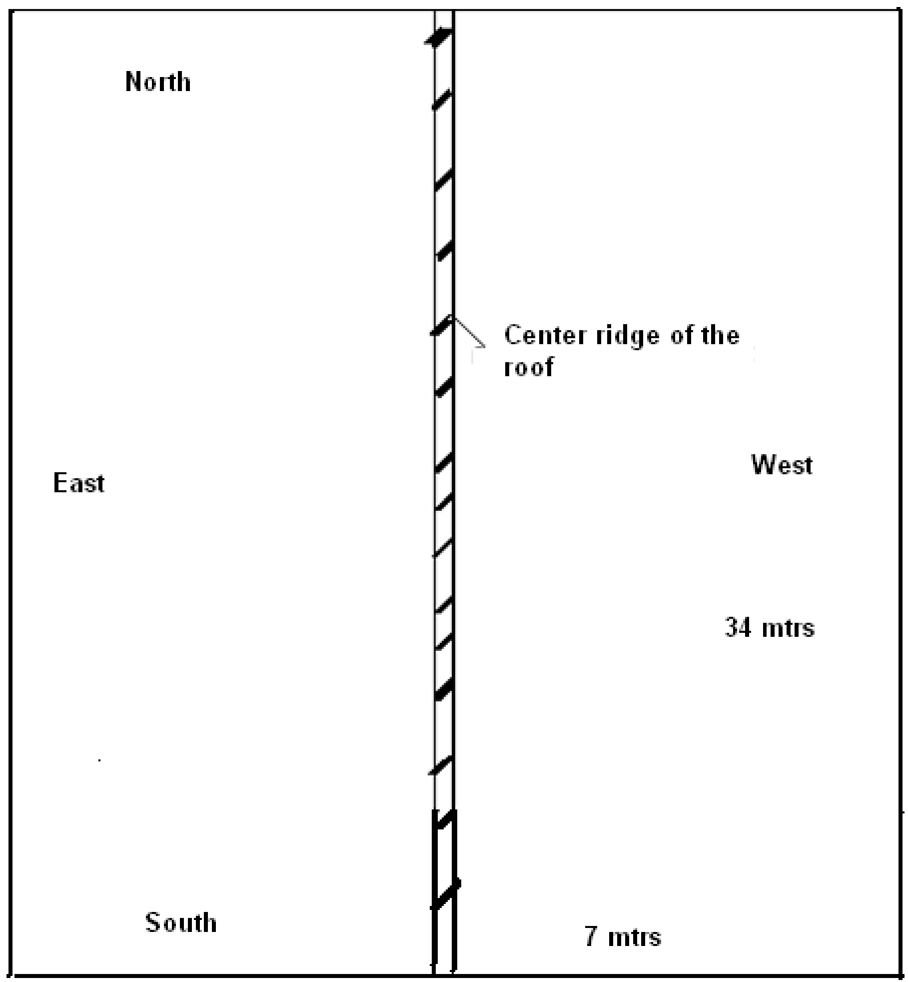


Figure 4.27: East - West Oriented Blocks Roof Plan

Figure 4.27 shows the East/West Oriented roof plan discussed in the section as explained in the sub section. Previous work by other researchers showed that domestic peak power demands occur in the morning at 6.30 AM and later in the evening at 7 PM and in the same studies, it was realized that splitting a solar PV array and having different orientations can sometimes be advantageous for domestic consumers by giving them more power during the morning and evening peaks [23].

4.5 The Aggregated Load Capacity

With successful introduction and replication of the solar PV plant at the Embakasi Nyayo suburb, it is expected that each block of 8 apartments will generate a peak power of 10 kWp though their peak power demands will be varying daily. Therefore with the 480 apartment blocks in the suburb, and applying a recommended domestic diversity factor of 1.54 (65 %) the suburb will be capable of generating a total of 6.5 kWp x 480, which works to 3120 kWp. The diversity factor is used because the individual apartment peak power demands do not occur at the same time. The factor used is a factor observed in domestic consumers apartments where the diversity factor ranges from 1.35 to 1.65 [37]. This is the estimated amount of peak power whose equivalent demand will be reduced as a domestic load peak burden from the grid. Introduction of the solar PV system will result in reducing the peak demand from the grid especially when the peak occurs between 7PM and 8.00 PM. On the other hand the total suburban annual energy generation potential as per the simulation results will be 19402 kWh from each of the 480 blocks. This gives a total electricity generation potential of 9.3 GWh per year. This generation is a substantial amount of energy when projected over the 20 year period and shall result in a lot of savings in foreign currency needed for the importation of petroleum products used to generate an equivalent amount of energy using fossil petroleum fuels. A report by the Kenya National Bureau of Statistics (KNBS) showed that in 2011, electricity generated using petroleum oil was 2800.5 GWh (44.63 %) of the total energy consumed of 6273.6 GWh that year [38]. This implies that 44.63 % of the consumer electricity bills were used to pay for petroleum related expenses.

4.6 Financial Analysis

This section presents the cost/benefit analysis of the PV system using the net present value (NPV) method. The analysis constitutes computation of the unit cost of solar PV electricity, annuity of the solar PV system and the net present value of the system. These costs are then used to compare the grid power sales and grid power purchases.

4.6.1 The Net Present Value of the System

The NPV of the system was calculated using the discounted benefits and the discounted costs of the project over the 20 year useful period of the project using Equation 3.1. During the calculation, a constant discounting rate of 10 % and a life span of 20 years were used. The annuity of the system was calculated using an interest rate of 5% for five years when the financing of the loan repayment will have reduced to zero. During the three months construction period, the operation and maintenance costs and benefits are assumed to be zero. Later into the year, all the costs are calculated at 70% of the annual cost and benefits. An array efficiency depreciation of 0.7 % per annum was also used [39]. Two scenarios were analyzed and different NPVs were obtained as shown.

4.6.2 Unit cost of solar PV energy

Using the apartment block energy that would be generated by the solar PV system as per the design amount of 48.8 kWh per day, the utility tariff that matched the case study was identified. The 48.8 kWh per day mean that the units per billing period of 30 days would be 1454.4 kWh of electricity. This consumption falls within the bracket of the utility tariff Method DC that is applicable to domestic consumers metered by the utility power company at 240 volts or 415volts and whose consumption does not exceed 15,000 kWh per billing period. The consumers at the ENS use a combined tariff method DC and tariff method IT for interruptible supply that is used for off peak electrical water heating. Therefore the tariff used in the comparison is the combined DC & IT tariff method.

The averaged consolidated cost per kWh of utility electricity was calculated using many copies of electricity bills of the interviewed residents and an average of Ksh.14.92 per kWh of electricity was obtained. This consolidated cost per kWh includes the unit base cost of a kWh and all statutory levies as per the electricity bill. The consolidated unit cost of utility electricity was computed as in Appendix E 2. The bills used for this calculation were for the period between 2008 and 2009 because the exercise was done in 2010. Table 4.6.1 shows the structure of the utility consolidated bill.

Table 4.6.1: Electricity bill structure for the Case Study

Cost item	**Unit**	**Rate in Ksh.**
Fixed charge DC & IT	Ksh.	240
Consumption on DC	kWh	2.00 to 18.75
Consumption on IT	kWh	4.85
Fuel cost charge[2]	Cts/kWh	600 to 800
Forex adjustment[3]	Ksh./kWh	0.1
ERC Levy	Ksh./kWh	0.03
VAT	16 %	Of total cost
Consolidated price	Ksh	

2 Fuel cost charge was changing depending on fuel import cost for the years 2008 and 2009,

3 Forex adjustment will change depending on the import cost dollar rate

To calculate the unit price of the solar PV energy units, the initial cost of the solar PV system, the operations and maintenance cost, depreciation and replacement cost of batteries were used. The life span of the batteries was taken as 5 years, the inverter life span as 20 years and the solar PV modules life span as 25 years. The initial cost of the system was calculated for each scenario but both scenarios had an installed capacity of 12.5 kWp. This obtained a cost of USD 2545.4 per kilowatt at Ksh.87 per dollar. The cost is low compared to countries like Germany who have 3200 Euros per kilowatt hour. This is attributed to the low cost of labor and also the source of solar PV components.

The cost per kWh of solar PV electricity was calculated as Ksh. 8.08 as calculated and provided in Appendix E 1. When compared to the consolidated cost of a kWh of utility electricity of Ksh.14.92, the kWh cost of solar PV electricity was cheaper to generate. Three NPV scenarios were analyzed and are presented below.

Scenario 1

This is the base case scenario where the financial analysis was done with immediate implementation and net metering at utility price. The Kenyan consolidated cost of utility electricity of Ksh. 14.92, a borrowing interest rate of 5% and a discounting rate of 7.5 % were considered. The analysis for 1 DOA, 2 DOA and 3 DOA are shown in Table 4.6.2. All the three options obtained negative NPVs.

Table 4.6.2: Scenario 1-Immediate implementation with net metering at utility price

System Parameter	Units	Option 1	Option 2	Option 3
Days of Anatomy	Days	3	2	1
System initial cost	Ksh	2,534,919	2,460,621	2,343,432
Solar PV array annual depreciation factor	%	0.7	0.7	0.7
Discounting rate	%	7.5	7.5	7.5
Interest rate of borrowing	%	5	5	5
Purchase price of utility energy	Ksh.	14.92	14.91	14.92
Operation and maintenance cost percentage	%	2	2	2
Solar PV System Useful life	Years	20	20	20
Installation period	Months	3	3	3
Capacity factor in percentage	%	19.28	17.67	17.77
Annual Grid sales	kWh	10184	10280	10412
Annual grid purchases	kWh	8594	8703	8851
Annual domestic energy demand	kWh	17812	17812	17812
Solar PV energy sales to grid (FIT) 12 USD cents	Ksh	10.44	10.44	10.44
Simple Payback period	Years	8.89	8.59	8.2
Net Present Value (Negative)	Ksh.	-2,433,352	-2,247,490	-1,957,411

Scenario 2

This is a breakeven scenario where the analysis was done using reduced system cost only and using the same discounting rate of 7.5 %. The cost for 1 DOA reduced to 63 % that of the 2 DOA reduced to 60 % and the one for 3 DOA reduced to 58 % of the original cost price. The three options each obtained breakeven NPVs as shown in Table 4.6.3.

Table 4.6.3: Scenario 2- Break-even Reduced Cost Only and Net Metering

System Parameter	**Units**	**Option 1**	**Option 2**	**Option 3**
Days of Anatomy	Days	3	2	1
Reduced System cost	Ksh	1470253	1476373	1476362
Solar PV array annual depreciation factor	%	0.7	0.7	0.7
Discounting rate	%	7.5	7.5	7.5
Interest rate of borrowing	%	5	5	5
Purchase price of utility energy	Ksh.	14.92	14.92	14.92
Operation and maintenance cost percentage	%	2	2	2
Solar PV System Useful life	Years	20	20	20
Installation period	Months	3	3	3
Capacity factor in percentage	%	19.28	17.67	17.72
Annual Grid sales	kWh	10184	10280	10412
Annual grid purchases	kWh	8594	8703	8851
Annual domestic energy demand	kWh	17812	17812	17812
Solar PV energy sales to grid (FIT) 12 USD cents	Ksh	10.44	10.44	10.44
Simple Payback period	Years	5.1	5.2	5.1
Net Present Value (Break-even)	Ksh.	10,116	11,416	32,563

Scenario 3

Scenario 3 is a combination of both reduced cost and reduced discounting rate. This analysis was done using reduced system cost to 74 % of the 1 DOA, 70 % of the 2 DOA and 67 % of the 3 DOA of the original cost price of the system. In this analysis, the discounting rate was also reduced from the original 7.5 % to 5 %. All the three options in this scenario obtained breakeven NPVs. The three options are shown on Table 4.6.4.

Table 4.6.4: Scenario 3- Reduced Cost and Reduced Discounting Rate at Net Metering

System Parameter	Units	Option 1	Option 2	Option 3
Days of Anatomy (DOA)	Days	3	2	1
Reduced System cost	Ksh	1,698,396	1,722,435	1,734,140
Solar PV array annual depreciation factor	%	0.7	0.7	0.7
Discounting rate	%	5	5	5
Interest rate of borrowing	%	5	5	5
Purchase price of utility energy	Ksh.	14.92	14.92	14.92
Operation and maintenance cost percentage	%	2	2	2
Solar PV System Useful life	Years	20	20	20
Installation period	Months	3	3	3
Capacity factor in percentage	%	19.28	17.67	17.72
Annual Grid sales	kWh	10184	10280	10412
Annual grid purchases	kWh	8594	8703	8851
Annual domestic energy demand	kWh	17812	17812	17812
Solar PV energy sales to grid (FIT) 12 USD cents	Ksh	10.44	10.44	10.44
Simple Payback period	Years	5.9	6	6.1
Net Present Value (Break –even)	Ksh.	57,263	17,828	15,893

From the results obtained, the project cost is high requiring negotiated borrowing interest rates and discounting rates. The major cost of the solar PV system is the solar PV array that ranges from 83 % for 1 DOA to 79.42% for 3 DOA, while the battery storage ranges from 7 % for 1 DOA to 11 % for 3 DOA and the converter cost from 10 % for 1 DOA to 9.6 % for 3 DOA of the total cost of the system. The project has a negative NPV in the base case scenario but when the cost of solar PV components reduces as envisaged to between 10% -15 % of the present prices by 2020, the project will be very attractive [40].

4.7 Summary

From the results presented in the chapter, the sizing of the components forming the solar PV system was done well and matched with the load demand. Optimization results show that the solar PV system will require grid power to complement it during the months of June, July and August when solar insolation is low. The different array orientations have been discussed and results presented. The financial analysis results show that solar PV system is expensive to set up but the unit cost of the energy generated is lower compared to the unit of utility electricity. The financial analysis results have also shown that the system has a positive breakeven NPV when the cost of the system reduces. This implies that the future of solar PV is promising. Countries like Germany, Spain and France, who are leading in solar PV penetration, had to highly subsidize their solar PV projects to speed up penetration in urban areas so Kenya can do the same. Finally the results have shown that when the system generation in the suburb is aggregated, considerable generation of electricity will be realized every year. The conclusions and recommendations of this study are presented in Chapter 5.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Highlights

This chapter presents the conclusions and recommendations of the study from the design, sizing and simulation of the solar PV system for the Embakasi Nyayo Suburb. The chapter discusses the methods used and choices made to arrive to the design and simulation of the system. Comparisons are also made to support the conclusions and recommendations. It is expected that the recommendations will be adopted to realize improvement in the use of RE in the country.

5.2 Conclusions

Considering that the extent of the comprehensive literature review did not reveal similar studies having been done in Kenya, this study is the first of its kind and has therefore created a platform for future studies. The studies done elsewhere in the world addressed effects like shading and mismatching of modules which have been well taken care of in this design. This study has addressed matters of battery storage and capacity generation of the solar PV system which was able to raise the capacity factor to 17.72 % for the whole year round. Capacity generation is the amount of the load that is supplied by the solar for a whole year. The capacity generation of the system was improved by good selection of the storage batteries (6FM200D AGM deep cycle) and the allowable grid electricity (2.5 kW) to supplement the solar PV system deficiency. Also, unlike the standalone rural cases addressed in previous studies in Kenya, in this study a solar PV and grid hybrid system for an urban suburb has been designed.

The methods used were exhaustive and the best data among the data collected, for both solar insolation and load data, were used to arrive to the design sizing simulation and optimization of the system. Using the methods in Chapter 3, the study was able to achieve the objectives within its scope. With the view that the objectives were clearly defined from the beginning, the study conducted has adequately exhausted each specific objective individually thereby fulfilling the main objective of the study. The case study was identified and the study was carried out. The data collected were analyzed and used to design the typical solar PV electricity generation system for the case study. The system designed and sized was constrained by cost of the solar PV materials and the cost of grid electricity. The energy generation in the entire case study was aggregated and the cost benefit analysis performed for the 20 year life period of the system. Following the results obtained it is concluded that the site has enough solar irradiation/insolation for electricity generation to serve individual blocks and even feed the surplus power into the grid. The solar insolation/irradiation is also enough to accommodate future load expansions when the cost allows because the free roof space is adequate. The combined case study solar PV systems in the entire suburb are capable of generating more than 3120 kWp or 3.12 MWp using a diversity of 65 %. This energy would otherwise be generated by the national grid generators. It is therefore concluded that, the project has achieved its intended goal and objective.

5.3 Recommendations

Following the conclusions made from the results obtained, the study recommends that urban solar PV generation be implemented as a mitigation measure to the reduction of the national peak power demand and annual energy demand from the KESI grid network. The recommendation is made considering that the cost of solar PV components will reduce as time progresses and that electricity generation using non-renewable methods cannot be sustained for long. Therefore, wide spread urban solar photovoltaic electricity generation should be encouraged throughout the country.

Load data logging was limited by the cost of hiring instruments during this study but longer load data logging, capturing at least one week in every month, would be advised in future studies so as to capture more load data details. This will be possible when the researchers have their own load logging instruments that will be available all the time they are needed.

Future studies can also investigate specific load variations during the days of the week, weekends and public holidays in ENS. Again further studies should be done to identify the system adjustments required, if any, for the findings of this research to be replicated in other suburbs of the country.

The scope of this study did not include energy management at the suburb and the design presented is with current consumer usage. It is recommended that future studies consider energy conservation measures in modeling the consumer load.

Due to the limitations of the scope of this study to the suburb, no data was collected from the rural areas so it is recommended that studies be carried out targeting the rural areas to identify the daily demand profile that will help in the design of a typical system suitable for the rural areas. This can be done using the same methodology used in this study with modifications where necessary. The researchers can use a rural case study location and then proceed to collect load and insolation data on site by logging methods.

The financial analysis revealed a negative NPV when the system is implemented immediately with a 5 % interest and 7.5 % discounting rate for all three options, but obtained a breakeven NPV when the cost of the system reduces. In the three scenarios, net metering was used to make the systems more attractive for implementation. It is therefore recommended that the government make necessary efforts to reduce the cost of urban solar PV systems implementation so as to speed up penetration as it was done in Europe. The government should also review the solar PV feed in tariff upwards so as to encourage grid solar PV implementation.

It is also recommended that the country implements statutory laws making Building Integrated Solar Photovoltaic (BIPV) a legal requirement for development of all urban areas. A systematic development of training human resource capacity to support and sustain the wide penetration of solar photovoltaic development in the country should also be initiated.

During the study it was realized that there are no guiding policy and regulations that protect the interest of micro and mini power generators including the solar PV electrical power generators. For the Embakasi Nyayo Suburb to become a player in the field there will be need for concerted efforts to develop a National Electric Code (NEC) that will cover small grid- interactive power systems. This code will enable the RE entities to develop appropriate policy for the micro independent power producers that would lead to introduction of the government subsidies, net metering tariff and RE favorable FITs.

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APPENDICES

APPENDIX A - Site Solar Radiation Data–Embakasi Nyayo

For The Months of July 2010 To June 2011

JUL /10		**AUG /10**		**SEPT /10**		**OCTO /10**		**NOV/ 10**		**DEC/ 10**	
Date	**kWh/m^2**	**Date**	**kWh/m^2**	**Date**	**kWh/m^2**	**Date**	**kWh/m^2**	**Date**	**kWh/m^2**	**Date**	**kWh/m^2**
1	3.56	1	0	1	0	1	3.97	1	5.56	1	5.74
2	3.24	2	4.23	2	0	2	4.36	2	6.23	2	5.23
3	3.08	3	4.76	3	0	3	0	3	5.89	3	5.06
4	0	4	3.28	4	0	4	4.63	4	5.29	4	5.26
5	3.87	5	4.56	5	0	5	3.28	5	5.08	5	0
6	3.18	6	4.28	6	5.59	6	3.51	6	4.36	6	5.28
7	3.38	7	5.13	7	5.44	7	4.5	7	0	7	6.33
8	3.89	8	0	8	3.52	8	5.28	8	6.35	8	5.66
9	3.22	9	4.22	9	5.2	9	5.02	9	4.87	9	6.45
10	3.23	10	4.54	10	4.59	10	0	10	4.34	10	5.98
11	0	11	3.39	11	5	11	1.5	11	5.39	11	6.68
12	3.89	12	4.89	12	3.25	12	5.56	12	5.19	12	0
13	3.29	13	4.48	13	3.17	13	6.23	13	6.31	13	5.78
14	3.67	14	4.67	14	2.17	14	5.89	14	0	14	5.66
15	3.55	15	0	15	4.52	15	5.29	15	4.58	15	6.34
16	3.46	16	5	16	0	16	5.08	16	5.58	16	6.56
17	3.34	17	4.57	17	5.14	17	0	17	5.64	17	6.14
18	0	18	4.28	18	6.1	18	3.37	18	4.79	18	5.65
19	3.24	19	3.98	19	0	19	3.5	19	6.27	19	0
20	3.68	20	4.49	20	7.38	20	4.16	20	4.84	20	5.82
21	3.44	21	4.38	21	5.52	21	4.66	21	0	21	6.31
22	3.67	22	0	22	2.83	22	3.21	22	4.21	22	6.87
23	3.26	23	4.45	23	0	23	4.21	23	5.67	23	6.25
24	3.78	24	4.21	24	5.85	24	0	24	5.34	24	6.34
25	0	25	4.34	25	2.76	25	4.62	25	6.27	25	0
26	3.23	26	3.98	26	7.15	26	5.31	26	5.99	26	0
27	3.13	27	4.71	27	5.86	27	5.19	27	5.67	27	5.78
28	3.56	28	4.39	28	3.77	28	4.87	28	0	28	5.98
29	4.01	29	0	29	2.48	29	6.11	29	6.54	29	5.78
30	3.38	30	4.34	30	4.64	30	5.4	30	6.23	30	5.86
Ave	**3.7595833**		**4.5645833**		**4.6331818**		**4.5657692**		**5.48**		**5.9516**

JAN /11		FEB/ 11			MAR / 11		APR / 11		MAY / 11		JUN / 11
Date	**kWhr/m2**	**Date**	**kWhr/m2**	**Date**	**kWhr/m2**	**Date**	**kWhr/m2**	**Date**	**kWhr/m2**	**Date**	**kWhr/m2**
1	4.98	1	5.89	1	6.89	1	4.56	1	0	1	0
2	0	2	6.19	2	5.23	2	5.23	2	0	2	3.23
3	5.67	3	5.39	3	5.06	3	0	3	4.82	3	3.98
4	5.73	4	4.23	4	4.26	4	3.87	4	3.64	4	4.03
5	6.48	5	6.39	5	6.61	5	3.56	5	4.89	5	0
6	6.27	6	0	6	0	6	5.28	6	4.18	6	3.22
7	5.79	7	6.88	7	6.33	7	6.33	7	5.49	7	3.05
8	6.02	8	6.84	8	6.21	8	4.89	8	0	8	3.27
9	0	9	5.63	9	6.89	9	4.22	9	4.22	9	3.11
10	6.12	10	5.59	10	5.67	10	0	10	4.78	10	3.28
11	6.26	11	5.84	11	4.89	11	3.89	11	3.89	11	3.69
12	5.89	12	5.711.86	12	5.78	12	5.32	12	5.29	12	0
13	5.76	13	0	13	0	13	5.78	13	4.38	13	4.1
14	4.98	14	3.98	14	6.78	14	4.67	14	5.48	14	3.62
15	5.02	15	4.68	15	5.97	15	5.29	15	0	15	3.35
16	0	16	4.95	16	5.09	16	4.89	16	4.87	16	4.09
17	6.27	17	5.21	17	6.93	17	0	17	4.66	17	4.11
18	5.98	18	4.63	18	4.28	18	4.26	18	4.28	18	3.56
19	6.01	19	4.94	19	5.48	19	6.34	19	4.52	19	0
20	6.65	20	0	20	0	20	5.48	20	4.89	20	3.78
21	6.93	21	6.4	21	5.44	21	5.44	21	5.32	21	3.78
22	6.31	22	5.73	22	5.67	22	5.67	22	0	22	3.45
23	0	23	4.92	23	5.89	23	6.25	23	5.09	23	3.26
24	6.02	24	5.63	24	6.25	24	0	24	5.25	24	3.97
25	6.78	25	5.21	25	6.15	25	0	25	4.99	25	3.56
26	6.13	26	6.67	26	6.23	26	5.26	26	4.37	26	0
27	5.27	27	0	27	0	27	5.23	27	4.62	27	3.67
28	6.37	28	6.92	28	5.45	28	5.45	28	4.76	28	3.13
29	6.93			29	6.39	29	4.99	29	0	29	3.57
Ave	**5.793077**		**5.364167**		**5.851852**		**5.316667**		**4.554**		**3.5544**

APPENDIX B: Embakasi Nyayo Suburb Questionnaire

LETTER TO THE RESPONDENTS

18th February 2010

Dear Resident,

I am a Masters Degree student at the Jomo Kenyatta University of Agriculture and Technology (JKUAT). In partial fulfillment for the award of this degree, I am carrying out a study on Electrical Power Enhancement in Kenya Using National Grid Connected Urban Solar Photovoltaic Electricity. I am using Nyayo Embakasi Estate as the case study and the enclosed questionnaire aims at collecting data to be used by the researcher purely for academic purposes. This information will be treated with strict confidentiality.

Your honest participation in responding, to the best of your knowledge would go a long way in making this study a success and would in turn help to improve electricity power generation and leaving standards in the country.

Yours faithfully

RESEARCHER

SECTION ONE

DOMESTIC ELECTRICAL APPLIANCES/LOAD

Kindly indicate by ticking the appropriate choice that corresponds to your situation

Available Domestic Electrical Appliances in Your Home

1. Do you have an electric cooker in your house if so how many plates does it have?

   ( ) 4Plate ( ) 3Plate ( ) 2Plate ( ) 1Plate

2. Do you have an electric cooker in your house if so does it have a grill, oven?

   ( ) Grill and Oven ( ) Grill alone ( ) Oven alone ( ) none

3. Do you have a refrigerator in your house if so what size is it?

   ( ) Small ( ) Medium ( ) Larger ( ) None

4. Do you have a freezer in your house if so what size is it?

   ( ) Small ( ) Medium ( ) Large ( ) None

5. Do you have a clothes washing machine in your house if so what type is it?

   ( ) Vertical axis ( ) Horizontal axis ( ) none

6. Do you have a clothes washing machine in your house if so what type is it?

   ( ) Cool dry ( ) Hot dry ( ) none

7. Do you have a microwave machine in your house if so what type is it?

   ( ) Small ( ) Medium ( ) Large ( ) None

8. Do you have a space heater in your house if so what type is it?

   ( ) Wall mount ( ) Portable ( ) none

9. Do you have an electric iron in your house if so what type is it?

( ) Dry ( ) Steam ( ) None

10. Do you have an electric water heater in your house if so what type is it?

( ) Immersion ( ) Portable ( ) Kettle ( ) None

11. Do you have a television in your house if so what type is it?

( ) 45inch ( ) 32inch ( ) 27inch ( ) 21inch ( ) 14inch ( ) 12inch

Type- ( ) LCD ( ) CRT ( ) Other

12. Do you have a home theater in your house if so what type is it?

( ) 3 in one ( ) 2in one ( ) none ( ) other

13. Do you have a desk top Computer in your house if so how many?

( ) One ( ) Two ( ) None ( ) Other

14. Do you have a laptop Computer in your house if so how many?

( ) One ( ) Two ( ) other state ( ) none

15. Do you have a hair dryer in your house if so what type is it?

( ) Large ( ) Medium ( ) Small ( ) Other ( ) None

16. Do you have a bread toaster in your house if so what type is it?

( ) Two slice ( ) More than two slice ( ) none ( ) other

17. Do you have a coffee maker in your house if so what type is it?

( ) Brewing ( ) Warming ( ) None ( ) other

18. Do you have filament lamps in your house if so how many are they?

( ) Five ( ) Six ( ) Seven ( ) Eight
( ) Nine ( ) other

19. Do you have compact fluorescent lamps in your house if so how many are they?

( ) Two ( ) Three ( ) Four ( ) Five ( ) Six ( ) Seven
( ) other

20. Do you have fluorescent lamps in your house if so what sizes and how many are they?

    ( ) Four feet ( ) Two feet ( ) other

21. Do you have a DVD player in your house if so how many are they?

    ( ) One ( ) Two ( ) None ( ) other

22. Do you have a VCR player in your house if so what type is it?

    ( ) Front load ( ) Top load ( ) other

23. Kindly state any other appliance that you have in your house and is not mentioned please.

SECTION TWO

ELECTRICITY SUPPLY

1. How do you rate the Kenyan electricity power supply in terms of reliability?

   ( ) Very reliable ( ) Reliable ( ) Not reliable

2. How do you rate the cost of Electricity in Kenya?

   ( ) Very expensive ( ) Expensive ( ) Moderate ( ) Cheap

3. Are you satisfied with the electricity power tariff system in Kenya?

   ( ) Satisfied ( ) Not satisfied ( ) No comment

4. On which system are you being billed for electrical power?

   ( ) Metering system ( ) Post paid ( ) Pre- Paid system

5. Have you ever been concerned about your electricity consumption in the house?

   ( ) Never ( ) Occasionally ( ) Always

6. Do you know what constitutes your electricity bill?

   ( ) Very accurately ( ) roughly ( ) No idea at all

7. Have you ever contemplated using energy saving appliances in your house?

( ) Never ( ) Occasionally ( ) Always

8. Would you accept another source of power generation?

   ( ) Strongly agree ( ) Tend to agree ( ) Tend to disagree ( ) Disagree

9. Would you be agreeing to own your own source of power generation system?

   ( ) Strongly agree ( ) Tend to agree ( ) Tend to disagree ( ) Disagree

10. Would you be agreeing to set up your own solar PV power generation system?

   ( ) Strongly agree ( ) Tend to agree ( ) Tend to disagree ( ) Disagree

11. What is your opinion about renewable energy?

   ( ) Very reliable ( ) marginally reliable ( ) Not reliable

12. Which among the following renewable energy resources would you prefer?

   ( ) Biogas ( ) Wind ( ) Solar ( ) Other

Kindly fill the table below with information from your electricity bills as accurately as you can. The

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Units-2008												
Units-2009												

Thank you very much for your cooperation

APPENDIX C: Output of a 90 x 140 Watts Module Solar Photovoltaic Array

Insolation (W/m^2)	Module Rating (W)	Ambient Temp ^0C	Module output (W)	Modules	Array Output (W)
900	140	28	103.4	99.5	10300
905	140	28	104.0	99.0	10300
910	140	28	104.6	98.4	10300
915	140	28	105.2	97.8	10300
920	140	28	105.7	97.4	10300
925	140	28	106.3	96.8	10300
930	140	28	106.8	96.4	10300
935	140	28	107.4	95.8	10300
940	140	28	108.0	94.3	10300
945	140	28	108.6	94.8	10300
950	140	28	109.2	94.3	10300
955	140	28	109.7	93.8	10300
960	140	28	110.3	93.3	10300
965	140	28	110.9	92.8	10300
970	140	28	111.5	92.4	10300
975	140	28	112.1	91.9	10300
980	140	28	112.6	91.4	10300
985	140	28	113.2	91.0	10300
990	140	28	113.8	90.5	10300
995	140	28	114.4	90.1	10300
1000	140	28	114.9	89.6	10300
1005	140	28	115.5	89.2	10300
1010	140	28	116.1	88.7	10300
1015	140	28	116.7	88.3	10300
1020	140	28	117.2	87.9	10300
1025	140	28	117.8	87.4	10300
1030	140	28	118.4	87.0	10300
1035	140	28	118.9	86.6	10300
1040	140	28	120.1	85.8	10300
1050	140	28	120.7	85.3	10300
1055	140	28	121.3	85.0	10300
1060	140	28	121.8	84.5	10300
1065	140	28	122.4	84.1	10300
1070	140	28	123	83.7	10300
1075	140	28	123.6	83.4	10300
1080	140	28	124.1	83.0	10300
1085	140	28	124.7	82.6	10300
1090	140	28	125.3	82.2	10300
1095	140	28	125.9	82.0	10300
1100	140	28	126.4	81.5	10300

APPENDIX D: Battery State of Charge in Percentage for Selected Period

Hours	Jan 1-15	Feb 15-28	Mar 1-15	Aug 1-15	Nov 1-15
1	100	91.37	91.03	89.097	89.639
2	100	89.47	91.03	89.097	89.639
3	100	89.47	91.03	89.097	89.639
4	100	89.47	91.03	89.097	89.639
5	100	89.47	91.03	89.097	89.639
6	99.29	89.47	91.03	89.097	89.639
7	99.29	89.47	91.03	89.097	89.639
8	99.29	89.47	91.03	89.097	90.744
9	99.29	88.64	91.37	89.097	95.782
10	99.29	88.64	95.07	89.097	98.428
11	99.29	89.07	98.16	89.097	99.414
12	99.29	93.27	99.32	89.097	99.782
13	99.74	97.49	99.74	89.097	99.919
14	99.9	99.07	99.9	90.383	99.97
15	99.9	99.65	99.96	90.714	99.989
16	99.9	99.87	99.99	91.5	99.996
17	99.9	99.95	100	91.5	99.998
18	99.9	99.98	100	91.5	99.999
19	99.9	99.99	100	91.5	99.999
20	93.16	100	93.03	86.384	91.949
21	90.63	100	92.4	85.485	89.684
22	89.28	100	91.48	85.485	88.411
23	87.65	93.29	90.07	84.448	86.361
24	87.65	91.58	90.07	84.448	86.361
25	87.65	90.92	90.07	84.448	86.361
26	87.65	88.43	90.07	84.448	86.361
27	87.65	88.43	90.07	84.448	86.361
28	87.65	88.43	90.07	84.448	86.361
29	87.65	88.43	90.07	84.448	86.361
30	87.65	88.43	90.07	84.448	86.361
31	87.65	88.43	90.07	84.448	86.361
32	87.65	88.43	90.07	84.448	86.829
33	90.03	88.29	90.15	84.448	91.829
34	94.13	88.29	92.15	84.448	96.956
35	97.81	88.44	95.96	83.986	98.865
36	99.18	93.08	97.72	83.986	99.577
37	99.7	97.42	99.15	83.986	99.842

Hours	Jan 1-15	Feb 15-28	Mar 1-15	Aug 1-15	Nov 1-15
38	99.89	99.04	99.68	84.351	99.941
39	99.96	99.64	99.88	85.424	99.978
40	99.98	99.87	99.96	85.424	99.992
41	99.99	99.95	99.96	85.424	99.997
42	100	99.98	99.96	85.424	99.999
43	100	99.99	99.96	85.424	99.999
44	94.92	100	93.43	76.932	93.781
45	93.3	100	91.97	75.28	91.856
46	93.3	100	91.64	74.377	90.629
47	92.39	93.53	90.6	72.521	89.229
48	92.39	91.06	90.6	73.91	89.229
49	92.39	90.28	90.6	74.396	89.229
50	92.39	88.41	90.6	76.098	89.229
51	92.39	88.41	90.6	78.586	89.229
52	92.39	88.41	90.6	80.644	89.229
53	92.39	88.41	90.6	80.644	89.229
54	91.82	88.41	90.59	80.644	89.229
55	91.82	88.41	90.34	80.644	89.229
56	92.88	88.41	90.34	80.644	91.168
57	97.35	88.41	94.78	80.644	96.711
58	99.01	88.41	98.05	80.644	98.774
59	99.63	88.41	99.27	80.644	99.543
60	99.86	92.74	99.73	81.129	99.83
61	99.95	97.3	99.9	81.129	99.936
62	99.98	98.99	99.96	81.129	99.976
63	99.99	99.62	99.99	81.129	99.991
64	100	99.86	99.99	81.129	99.997
65	100	99.95	100	81.129	99.999
66	100	99.98	100	81.129	100
67	100	99.99	100	81.129	100
68	95.16	100	92.76	75	95.74
69	92.98	100	90.58	73.957	94.168
70	91.99	100	89.19	73.303	93.402
71	88.81	93.55	86.68	71.876	92.112
72	88.81	91.67	86.68	73.406	92.112
73	88.81	90.78	86.68	73.81	92.112
74	88.81	88.64	86.68	75.471	92.112
75	88.81	88.64	86.68	77.964	92.112
76	88.81	88.64	86.68	79.835	92.112

Hours	Jan 1-15	Feb 15-28	Mar 1-15	Aug 1-15	Nov 1-15
77	88.81	88.64	86.68	81.578	92.112
78	88.81	88.64	86.68	81.298	92.112
79	88.81	88.64	86.68	81.298	92.112
80	88.81	88.64	86.68	81.298	92.396
81	89.97	88.64	89.81	83.218	95.479
82	92.5	88.64	95.34	86.496	98.316
83	92.5	88.64	98.26	91.081	99.372
84	92.5	92.34	99.35	96.677	99.766
85	94.3	97.15	99.76	98.761	99.913
86	97.88	98.94	99.91	99.538	99.967
87	97.88	99.6	99.97	99.828	99.988
88	98.13	99.85	99.99	99.936	99.995
89	98.13	99.94	100	99.976	99.998
90	98.13	99.98	100	99.991	99.998
91	98.13	99.99	100	99.991	99.998
92	92.03	100	93.51	95.492	93.322
93	90.62	100	91.92	93.25	91.365
94	89.85	100	91.57	92.375	90.001
95	87.66	94.18	89.71	89.902	88.267
96	87.66	94.03	89.71	89.902	88.267
97	87.66	93.17	89.71	89.902	88.267
98	87.66	91.94	89.71	89.902	88.267
99	87.66	91.94	89.71	89.902	88.267
100	87.66	91.94	89.71	89.902	88.267
101	87.66	91.94	89.71	89.902	88.267
102	87.36	91.94	89.22	89.902	88.267
103	87.36	91.94	89.22	89.902	88.267
104	87.36	91.94	89.22	89.984	88.424
105	87.96	91.94	92.25	94.867	88.424
106	87.96	91.94	97.11	98.088	88.451
107	88.56	92.28	98.92	99.287	92.158
108	89.39	97.12	99.6	99.734	92.236
109	93.41	98.93	99.85	99.901	97.108
110	93.41	99.6	99.94	99.963	98.922
111	95.92	99.85	99.98	99.986	99.598
112	97.93	99.94	99.99	99.995	99.85
113	99.23	99.98	100	99.998	99.944
114	99.31	99.99	100	99.999	99.979
115	99.31	100	100	99.999	99.979

Hours	Jan 1-15	Feb 15-28	Mar 1-15	Aug 1-15	Nov 1-15
116	93.89	100	94.73	95.987	92.971
117	92.47	100	91.9	94.768	90.721
118	92.47	100	91.66	94.418	90.479
119	90.78	95.39	89.38	92.555	88.76
120	90.78	94.36	89.38	92.555	88.76
121	90.78	93.94	89.38	92.555	88.76
122	90.78	92.79	89.38	92.555	88.76
123	90.78	92.79	89.38	92.555	88.76
124	90.78	92.79	89.38	92.555	88.76
125	90.78	92.79	89.38	92.555	88.76
126	90.61	92.79	89.38	92.555	88.435
127	90.61	92.79	89.38	92.555	88.435
128	91.13	92.79	89.53	92.561	88.435
129	96.7	92.76	93.95	95.948	89.914
130	98.77	92.76	97.75	98.49	90.667
131	99.54	92.76	99.16	99.437	96.524
132	99.83	96.17	99.69	99.79	98.704
133	99.94	98.57	99.88	99.922	99.517
134	99.98	99.47	99.96	99.971	99.82
135	99.99	99.8	99.98	99.989	99.933
136	100	99.93	99.99	99.996	99.975
137	100	99.97	100	99.998	99.991
138	100	99.99	100	99.999	99.997
139	100	100	100	99.999	99.997
140	94.27	100	93.84	94.149	94.83
141	93.06	100	93.14	92.28	92.894
142	93.05	100	92.65	92.28	92.548
143	90.94	95.49	89.94	91.297	90.365
144	90.94	94.64	89.94	91.297	90.365
145	90.94	94.59	89.94	91.297	90.365
146	90.94	93.26	89.94	91.297	90.365
147	90.94	93.26	89.94	91.297	90.365
148	90.94	93.26	89.94	91.297	90.365
149	90.94	93.26	89.94	91.297	90.365
150	90.94	93.26	89.94	91.297	90.365
151	90.94	93.26	89.94	91.238	90.365
152	91.16	93.26	90.2	91.238	90.365
153	94.46	93.26	96.22	92.579	90.365
154	97.94	93.26	98.59	92.823	91.03

Hours	Jan 1-15	Feb 15-28	Mar 1-15	Aug 1-15	Nov 1-15
155	99.23	93.26	99.47	93.629	96.503
156	99.71	96.63	99.8	97.627	98.697
157	99.89	98.74	99.93	99.115	99.514
158	99.96	99.53	99.97	99.67	99.819
159	99.99	99.83	99.99	99.877	99.932
160	99.99	99.93	100	99.954	99.975
161	100	99.98	100	99.983	99.991
162	100	99.99	100	99.994	99.991
163	100	100	100	99.994	99.991
164	95.09	100	96.01	94.248	93.67
165	93.91	100	94.59	92.281	90.88
166	93.91	100	94.55	92.259	90.013
167	92.79	93.61	94.01	90.945	87.516
168	92.79	92.62	94.01	90.945	87.516
169	92.79	92.62	94.01	90.945	87.516
170	92.79	90.98	94.01	90.945	87.516
171	92.79	90.98	94.01	90.945	87.516
172	92.79	90.98	94.01	90.945	87.516
173	92.79	90.98	94.01	90.945	87.516
174	92.79	90.98	94.01	90.945	87.516
175	92.79	90.98	94.01	90.945	87.516
176	93.77	90.98	94.01	90.945	87.516
177	97.68	90.98	97.77	94.411	88.08
178	99.14	90.98	99.17	97.633	88.08
179	99.68	90.98	99.69	97.633	88.08
180	99.88	93.93	99.88	99.119	88.08
181	99.96	97.74	99.96	99.671	88.08
182	99.98	99.16	99.98	99.878	89.287
183	99.99	99.69	99.99	99.954	89.287
184	100	99.88	100	99.983	89.287
185	100	99.96	100	99.994	89.287
186	100	99.98	100	99.998	89.287
187	100	99.99	100	99.998	89.287
188	92.66	100	95.41	94.674	84.219
189	90.21	100	94.2	91.926	83.016
190	89.49	100	93.24	89.987	82.553
191	87.04	93.47	92.1	88.899	79.805
192	87.04	91.47	92.1	88.899	80.977
193	87.04	91.05	92.1	88.899	80.977

Hours	Jan 1-15	Feb 15-28	Mar 1-15	Aug 1-15	Nov 1-15
194	87.04	89.74	92.1	88.899	80.977
195	87.04	89.74	92.1	88.899	80.977
196	87.04	89.74	92.1	88.899	80.977
197	87.04	89.74	92.1	88.899	80.977
198	87.04	89.74	92.1	88.899	80.977
199	87.04	89.74	92.1	88.819	80.977
200	87.04	89.74	92.1	88.862	80.977
201	90.13	89.74	92.12	91.731	83.218
202	94.46	89.74	93.51	96.286	83.218
203	97.94	90.2	97.3	98.616	84.326
204	99.23	94.37	98.99	99.484	86.233
205	99.71	97.9	99.63	99.808	87.594
206	99.89	99.22	99.86	99.928	88.618
207	99.96	99.71	99.95	99.973	88.618
208	99.99	99.89	99.98	99.99	88.618
209	99.99	99.96	99.99	99.996	88.731
210	100	99.98	99.99	99.999	88.731
211	100	99.99	99.99	99.999	88.731
212	91.51	100	94.93	93.673	82.217
213	88.47	100	93.24	92.481	81.206
214	88.47	100	91.83	91.596	81.206
215	86.04	94.8	89.4	89.472	79.99
216	86.04	93.08	89.4	89.472	81.497
217	86.04	92.54	89.4	89.472	81.497
218	86.04	90.34	89.4	89.472	81.497
219	86.04	90.34	89.4	89.472	81.497
220	86.04	90.34	89.4	89.472	81.497
221	86.04	90.34	89.4	89.472	81.497
222	86.04	90.34	89.4	89.472	81.497
223	86.04	90.34	89.4	89.472	81.497
224	86.81	90.34	89.4	89.472	82.168
225	91.02	90.34	94.67	91.437	87.324
226	96.66	90.34	98.01	91.437	92.885
227	98.75	90.43	99.26	91.437	97.349
228	99.54	93.37	99.72	96.811	99.012
229	99.83	97.28	99.9	98.811	99.632
230	99.94	98.99	99.96	99.557	99.863
231	99.98	99.62	99.99	99.835	99.949
232	99.99	99.86	99.99	99.938	99.981

Hours	Jan 1-15	Feb 15-28	Mar 1-15	Aug 1-15	Nov 1-15
233	100	99.95	100	99.977	99.993
234	100	99.98	100	99.991	99.997
235	100	99.99	100	99.991	99.997
236	92.51	100	94.08	92.234	93.386
237	91.49	100	91.41	89.743	90.105
238	90.21	100	90.73	88.238	89.635
239	88.46	92.04	89.19	85.619	87.351
240	88.46	89.49	89.19	85.619	87.351
241	88.46	88.6	89.19	85.619	87.351
242	88.46	86.58	89.19	85.619	87.351
243	88.46	86.58	89.19	85.619	87.351
244	88.46	86.58	89.19	85.619	87.351
245	88.46	86.58	89.19	85.619	87.351
246	88.21	86.58	89	85.619	87.351
247	88.21	86.58	89	85.619	87.351
248	88.21	86.58	89	85.619	89.623
249	90.92	86.58	93.11	88.291	96.135
250	94.76	86.58	97.43	92.679	98.559
251	98.05	86.58	99.04	97.273	99.463
252	99.27	90.17	99.64	98.983	99.8
253	99.73	92.74	99.87	99.621	99.925
254	99.9	97.3	99.95	99.859	99.972
255	99.96	98.99	99.98	99.947	99.99
256	99.99	99.62	99.99	99.98	99.996
257	99.99	99.86	100	99.993	99.999
258	100	99.95	100	99.997	99.999
259	100	99.98	100	99.997	99.999
260	93.32	99.99	94.43	92.845	94.98
261	91.06	100	93.04	90.656	92.929
262	90.89	100	93.04	89.845	92.02
263	89.52	93.41	92.12	86.648	90.032
264	89.52	91.54	92.12	86.648	90.032
265	89.52	90.53	92.12	86.648	90.032
266	89.52	89.78	92.12	86.648	90.032
267	89.52	89.78	92.12	86.648	90.032
268	89.52	89.78	92.12	86.648	90.032
269	89.52	89.78	92.12	86.648	90.032
270	89.52	89.78	91.83	86.648	90.032
271	89.52	89.78	91.83	86.648	90.032

Hours	Jan 1-15	Feb 15-28	Mar 1-15	Aug 1-15	Nov 1-15
272	89.52	89.78	91.83	86.648	90.032
273	91.09	89.78	93.98	86.648	90.918
274	95.14	89.78	95.03	86.648	90.918
275	98.19	89.78	98.15	86.648	90.918
276	99.33	94.52	99.31	86.843	93.323
277	99.75	97.96	99.74	86.858	97.513
278	99.91	99.24	99.9	89.058	99.073
279	99.97	99.72	99.96	90.998	99.654
280	99.99	99.89	99.99	92.908	99.871
281	99.99	99.96	100	92.908	99.952
282	99.99	99.99	100	93.124	99.982
283	99.99	99.99	100	93.124	99.982
284	92.19	100	92.94	86.348	94.398
285	89.75	100	90.79	85.344	92.884
286	88.81	100	90.59	84.928	92.123
287	86.54	94.32	89.72	83.954	90.412
288	86.54	91.55	89.72	83.954	90.412
289	86.54	91.05	89.72	83.954	90.412
290	86.54	89.64	89.72	83.954	90.412
291	86.54	89.64	89.72	83.954	90.412
292	86.54	89.64	89.72	83.954	90.412
293	86.54	89.64	89.72	83.954	90.412
294	86.54	89.64	89.72	83.954	90.412
295	86.54	89.64	89.72	83.954	90.412
296	87.11	89.64	90.42	83.954	92.245
297	90.55	89.51	95.34	84.842	97.112
298	95.37	89.51	98.26	87.39	98.923
299	98.27	89.68	99.35	94.055	99.599
300	99.36	91.52	99.76	97.785	99.85
301	99.76	96.27	99.91	99.174	99.944
302	99.91	98.61	99.97	99.692	99.979
303	99.97	99.48	99.99	99.885	99.992
304	99.99	99.81	100	99.957	99.997
305	100	99.93	100	99.984	99.999
306	100	99.97	100	99.984	100
307	100	99.99	100	99.984	100
308	93.31	100	96.45	93.403	92.442
309	91.5	100	95.1	92.293	90.018
310	90.83	100	94.75	91.854	89.922

Hours	Jan 1-15	Feb 15-28	Mar 1-15	Aug 1-15	Nov 1-15
311	89.6	93.21	92.12	90.553	87.44
312	89.6	92.07	92.12	90.553	87.44
313	89.6	91.46	92.12	90.553	87.44
314	89.6	89.14	92.12	90.553	87.44
315	89.6	89.14	92.12	90.553	87.44
316	89.6	89.14	92.12	90.553	87.44
317	89.6	89.14	92.12	90.553	87.44
318	89.6	89.14	92.12	90.416	87.44
319	89.6	89.14	92.12	90.416	87.44
320	89.6	89.14	92.12	90.416	89.636
321	93.25	88.89	93.26	93.183	96.067
322	97.41	88.89	96.91	97.461	98.534
323	99.04	88.89	98.85	99.054	99.454
324	99.64	89.12	99.57	99.647	99.796
325	99.87	90.4	99.84	99.868	99.924
326	99.95	95.34	99.94	99.951	99.972
327	99.98	98.26	99.98	99.982	99.989
328	99.99	99.35	99.99	99.993	99.996
329	100	99.76	100	99.997	99.999
330	100	99.91	100	99.999	99.999
331	100	99.97	100	99.999	99.999
332	95.3	99.99	93.45	93.62	94.145
333	92.4	100	91.9	91.587	92.551
334	90.76	100	90.97	90.862	92.551
335	88.14	95.39	88.97	88.976	90.547
336	88.14	93.83	88.97	88.976	90.547
337	88.14	93.27	88.97	88.976	90.547
338	88.14	91.03	88.97	88.976	90.547
339	88.14	91.03	88.97	88.976	90.547
340	88.14	95.34	88.97	88.976	90.547
341	88.14	98.26	88.97	88.976	90.547
342	88.14	99.35	88.55	88.976	90.499
343	88.14	99.76	88.55	88.976	90.499
344	89.16	99.91	88.55	89.303	91.96
345	94.5	99.97	92.67	93.604	97.006
346	97.95	99.99	97.27	97.617	98.884
347	99.24	100	98.98	99.112	99.584
348	99.72	100	99.62	99.669	99.845
349	99.89	95.39	99.86	99.877	99.942

Hours	Jan 1-15	Feb 15-28	Mar 1-15	Aug 1-15	Nov 1-15
350	99.96	93.83	99.95	99.954	99.978
351	99.99	93.27	99.98	99.983	99.992
352	99.99	95.34	99.99	99.994	99.997
353	100	98.26	100	99.998	99.999
354	100	99.35	100	99.999	100
355	100	99.76	100	99.999	100
356	92.26	99.91	95.48	93.64	93.524
357	89.83	99.97	93.4	92.774	91.905

Appendix E-1: Calculation of the Solar PV energy Unit cost

To calculate the unit price of the solar energy units, the cost of the plant from the HOMER design.

The initial cost of the plant	USD	33350.72	Ksh.2768110
Components			
Solar PV array 180VDC	kW	12.5	
Storage battery bank 180VDC	AH	6000	
Power converter 180VDC	kW	10	
Costs over the life of the plant			
Initial cost of plant	Ksh	2768110	
Operation and Maintenance 5th year	Ksh	249129.9	
Operation and Maintenance 10th years	Ksh	179927.2	
Operation and maintenance 15th year	Ksh	110724.4	
Operation and maintenance 20th year	Ksh	41521.65	
Total loan repayment interest at 5 %	Ksh	351780	
		3701193	
Total annual energy generated by plant is	kWh	**22896**	
Total energy generated by plant in 20 years is	kWh	457920	
Cost per unit of solar PV energy	Ksh.	**8.08262**	
Cost of energy at the Small commercial tariff due to fuel cost adjustment and other statutory levies.	Ksh.	**9.46**	
Data collected show that the cost is	Ksh.	**14.92**	

Appendix E -2: Consolidated Unit Cost of Grid Electricity for Nyayo Embakasi

Court	88			88			88			87		
2008/	**Block 4 /32**			**Block 4/25**			**Block 3/22**			**Block 10/82**		
2009/	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**
Jul	326	4820	14.785	237	3509	14.806	149	2206	14.81	158	2320	14.6835
Aug	262	4255	16.24	227	3650	16.079	110	1778	16.16	162	2600	16.0494
Sept	291	4645	15.962	218	3475	15.94	344	5429	15.78	117	1845	15.7692
Oct	296	4586	15.493	212	3230	15.236	76	1160	15.26	195	2955	15.1538
Nov	319	4834	15.154	221	3331	15.072	99	1506	15.21	199	2982	14.9849
Dec	305	4320	14.164	273	3850	14.103	129	1820	14.11	204	2862	14.0294
Jan	345	4626	13.409	277	3760	13.574	165	2201	13.34	210	2801	13.3381
Feb	348	4570	13.132	259	3350	12.934	136	1765	12.98	227	2928	12.8987
Mar	387	4892	12.641	302	3756	12.437	142	1762	12.41	239	2958	12.3766
Apr	334	4360	13.054	251	3231	12.873	178	2310	12.98	187	2401	12.8396
May	341	4638	13.601	210	2850	13.571	133	1820	13.68	219	2945	13.4475
Jun	373	4925	13.204	190	2580	13.579	167	2200	13.17	202	2650	13.1188
Consolidated cost			**14.237**			**14.184**			**14.16**			**14.0575**

Court	87			86			86			88		
2008/	**Block 3 /20**			**Block 3 /22**			**Block 2 /16**			**Block 2 /13**		
2009/	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**
Jul	238	3520	14.79	204	3001	14.711	177	2600	14.69	94	1385	14.734
Aug	215	3450	16.047	218	3500	16.055	134	2140	15.97	87	1400	16.092
Sept	190	3000	15.789	254	4000	15.748	127	2000	15.75	88	1402	15.9318
Oct	263	4000	15.209	230	3500	15.217	119	1800	15.13	94	1430	15.2128
Nov	203	3050	15.025	200	3100	15.5	187	2800	14.97	106	1610	15.1887
Dec	426	6001	14.087	199	2800	14.07	157	2200	14.01	124	1756	14.1613
Jan	208	2780	13.365	240	3200	13.333	180	2450	13.61	135	1860	13.7778
Feb	298	3850	12.919	271	3560	13.137	165	2660	16.12	154	2001	12.9935
Mar	384	4750	12.37	324	4100	12.654	219	2710	12.37	169	2140	12.6627
Apr	443	5700	12.867	311	4090	13.151	179	2340	13.07	194	2507	12.9227
May	334	4560	13.653	312	4230	13.558	159	2350	14.78	170	2360	13.8824
Jun	537	7050	13.128	321	4236	13.196	165	2120	12.85	152	2010	13.2237
Consolidated cost			**14.104**			**14.194**			**14.44**			**14.2319**

Average consolidated cost per kWh of utility electricity ENS

Court	86			86			40			88		
2008/	Block 6/42			Block 4 /26			Block 1 /5			Block 2 /15		
2009/	kWh	Cost	PU	kWh	Cost	PU	kWh	Cost	PU	kWh	Cost	PU
Jul	192	2862	14.906	332	5000	15.06	336	5020	14.94	163	2598	15.9387
Aug	211	3540	16.777	218	3500	16.055	203	3433	16.91	128	2200	17.1875
Sept	183	2987	16.322	254	4000	15.748	199	3240	16.28	127	2110	16.6142
Oct	264	4122	15.614	267	4491	16.82	183	2862	15.64	114	1798	15.7719
Nov	200	3050	15.25	213	3755	17.629	177	3050	17.23	178	2796	15.7079
Dec	426	6001	14.087	179	2649	14.799	166	2460	14.82	165	2460	14.9091
Jan	241	3398	14.1	222	3308	14.901	239	3398	14.22	180	2502	13.9
Feb	176	2322	13.193	280	3942	14.079	225	3148	13.99	175	2756	15.7486
Mar	62	982	15.839	314	4623	14.723	247	3521	14.26	200	2640	13.2
Apr	421	5700	13.539	309	4359	14.107	201	2800	13.93	177	2234	12.6215
May	334	4560	13.653	302	4199	13.904	139	2136	15.37	162	2256	13.9259
Jun	140	2010	14.357	321	4000	12.461	140	2010	14.36	183	2655	14.5082
Consolidated cost			**14.803**			**15.024**			**15.16**			**15.0028**

Court	88			86			40			40		
2008/	Block 5/40			Block 6 /46			Block 3 /18			Block 2 /11		
2009/	kWh	Cost	PU	kWh	Cost	PU	kWh	Cost	PU	kWh	Cost	PU
Jul	311	4760	15.305	308	4548	14.766	142	2394	16.86	312	4867	15.5994
Aug	258	4356	16.884	298	4367	14.654	125	1998	15.98	236	3542	15.0085
Sept	286	4729	16.535	321	5234	16.305	132	2240	16.97	196	3329	16.9847
Oct	296	4586	15.493	230	3500	15.217	128	1811	14.15	218	3405	15.6193
Nov	212	3744	17.66	106	1652	15.585	167	2803	16.78	202	3348	16.5743
Dec	299	4134	13.826	199	2800	14.07	161	2389	14.84	122	1834	15.0328
Jan	344	4492	13.058	234	3200	13.675	177	2499	14.12	172	2499	14.5291
Feb	308	4220	13.701	271	3763	13.886	174	2683	15.42	189	2822	14.9312
Mar	341	4749	13.927	324	4100	12.654	186	2654	14.27	185	2598	14.0432
Apr	278	3900	14.029	311	4359	14.016	156	2198	14.09	165	2135	12.9394
May	280	4256	15.2	305	4230	13.869	142	2065	14.54	172	2500	14.5349
Jun	274	3878	14.153	321	4236	13.196	163	2500	15.34	176	2744	15.5909
Consolidated cost			**14.981**			**14.325**			**15.28**			**15.1156**

Average consolidated cost per kWh of utility electricity ENS

Court	5			87			5			88		
2008/	**Block 3/20**			**Block 5 /38**			**Block 2 /9**			**Block 4 /28**		
2009/	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**
Jul	446	4609	10.334	321	4987	15.536	231	3510	15.19	196	3120	15.9184
Aug	312	4800	15.385	227	3617	15.934	222	3463	15.6	175	2480	14.1714
Sept	262	4200	16.031	253	3978	15.723	204	3312	16.24	202	2912	14.4158
Oct	291	4600	15.808	274	4322	15.774	198	3008	15.19	183	2766	15.1148
Nov	284	4500	15.845	266	3827	14.387	200	3240	16.2	192	3122	16.2604
Dec	309	4800	15.534	189	2743	14.513	185	2879	15.56	200	3146	15.73
Jan	299	4300	14.381	180	3299	18.328	217	3288	15.15	205	3220	15.7073
Feb	305	4600	15.082	231	3825	16.558	264	4320	16.36	182	2822	15.5055
Mar	322	4500	13.975	311	4532	14.572	252	3644	14.46	166	2453	14.7771
Apr	318	4800	15.094	299	4159	13.91	196	2914	14.87	221	3744	16.9412
May	309	4800	15.534	289	4200	14.533	187	2731	14.6	198	3341	16.8737
Jun	341	4600	13.49	318	4115	12.94	201	3000	14.93	167	2655	15.8982
Consolidated cost			**14.708**			**15.226**			**15.36**			**15.6095**

Court	86			5			40			40		
2008/	**Block 7 /53**			**Block 3 /22**			**Block 2/16**			**Block 2 /14**		
2009/	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**
Jul	308	4548	14.766	142	2394	16.859	251	4150	16.53	199	3467	17.4221
Aug	298	4367	14.654	125	1998	15.984	309	4722	15.28	302	4723	15.6391
Sept	321	5234	16.305	132	2240	16.97	228	3842	16.85	194	3299	17.0052
Oct	230	3500	15.217	128	1811	14.148	234	3912	16.72	214	3378	15.785
Nov	106	1652	15.585	167	2803	16.784	222	3682	16.59	193	3244	16.8083
Dec	199	2800	14.07	161	2389	14.839	252	4108	16.3	265	4100	15.4717
Jan	234	3200	13.675	177	2499	14.119	217	3200	14.75	164	2256	13.7561
Feb	271	3763	13.886	174	2683	15.42	210	3156	15.03	178	2789	15.6685
Mar	324	4100	12.654	186	2654	14.269	194	2644	13.63	176	2598	14.7614
Apr	311	4359	14.016	156	2198	14.09	237	3724	15.71	217	3920	18.0645
May	305	4230	13.869	142	2065	14.542	222	3644	16.41	181	2780	15.3591
Jun	321	4236	13.196	163	2500	15.337	215	3350	15.58	156	2328	14.9231
Consolidated cost			**14.325**			**15.28**			**15.78**			**15.8887**

Average consolidated cost per kWh of utility electricity ENS

Court	88			5			38			87		
2008/	**Block 3 /17**			**Block 4/27**			**Block 2/14**			**Block 5/34**		
2009/	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**
Jul	128	2099	16.398	108	1656	15.333	159	2563	16.12	196	3044	15.5306
Aug	186	2887	15.522	130	2189	16.838	302	5321	17.62	243	3760	15.4733
Sept	123	1956	15.902	98	1389	14.173	176	2534	14.4	222	3688	16.6126
Oct	120	1974	16.45	86	1438	16.721	100	1678	16.78	227	3497	15.4053
Nov	136	2366	17.397	110	1840	16.727	78	1239	15.88	208	3292	15.8269
Dec	182	2751	15.115	156	2233	14.314	153	2249	14.7	244	4128	16.918
Jan	159	2392	15.044	145	1978	13.641	127	1857	14.62	238	3140	13.1933
Feb	163	2599	15.945	134	2132	15.91	132	1932	14.64	232	3058	13.181
Mar	143	2384	16.671	138	2148	15.565	130	1771	13.62	228	2944	12.9123
Apr	185	2674	14.454	196	3156	16.102	142	2287	16.11	265	4090	15.434
May	153	2243	14.66	169	2289	13.544	131	1799	13.73	243	3658	15.0535
Jun	186	2460	13.226	157	2168	13.809	137	2166	15.81	217	3149	14.5115
Consolidated cost			**15.565**			**15.223**			**15.34**			**15.0044**

Court	38			86			88			38		
2008/	**Block 7 /56**			**Block 4 /31**			**Block 4/26**			**Block 2 /10**		
2009/	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**	**kWh**	**Cost**	**PU**
Jul	156	2328	14.923	213	3124	14.667	260	4253	16.36	220	3148	14.3091
Aug	194	3144	16.206	256	4122	16.102	326	4921	15.1	238	3502	14.7143
Sept	177	2788	15.751	216	3499	16.199	289	4639	16.05	220	3345	15.2045
Oct	163	2638	16.184	208	3122	15.01	287	4519	15.75	210	3144	14.9714
Nov	188	2944	15.66	228	3209	14.075	302	4710	15.6	220	3254	14.7909
Dec	214	3278	15.318	245	3554	14.506	320	4980	15.56	266	3650	13.7218
Jan	239	3428	14.343	238	3209	13.483	307	4355	14.19	238	3422	14.3782
Feb	218	2928	13.431	241	3429	14.228	318	4558	14.33	224	3214	14.3482
Mar	222	2958	13.324	258	3639	14.105	346	4622	13.36	212	3156	14.8868
Apr	219	2945	13.447	306	4120	13.464	387	4968	12.84	249	3156	12.6747
May	189	2867	15.169	267	3844	14.397	321	4582	14.27	198	2659	13.4293
Jun	178	2754	15.472	214	3344	15.626	302	4324	14.32	187	2394	12.8021
Consolidated cost			**14.936**			**14.655**			**14.81**			**14.1859**

Legend;- Block x/y; x is the block number and y is the apartment number the consolidated cost of utility electricity was calculated for 32 apartments in ENS as Ksh. 14.92.

APPENDIX F: List of Publications

G.G. Kidegho, M.S. Mbogho, and A.O. Akumu “Electrical power enhancement in Kenya using national grid connected urban solar photovoltaic electricity” in the First Scientific Conference of Masinde Muliro University (Kakamega Kenya) August 2010

G. G. Kidegho, M.S Mbogho and A.O. Akumu “A study of the effects of urban domestic electrical load burden on the electricity generation industry of Kenya” in the KSEEE & JSEM international conference (Multimedia University) August 2010

G.G. Kidegho, C.M. Maina “Study of an urban domestic composite load model suitable for solar PV and grid hybrid system” the 4th Scientific conference of Jomo Kenyatta University of Agriculture and technology December 2010