Department of Mechanical and Aerospace Engineering

Modelling and Simulation of a Solar Photovoltaic Air Conditioning System for Cooling an Office Building in Lagos, Nigeria

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This project is dedicated to the Almighty God and the Lord Jesus Christ for giving me the enablement to start and finish the work.

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Abstract

The need for off-grid cooling systems is pivotal to meeting cooling demands for developing countries located in tropical climates as a result of hot weather conditions and inadequate power supply. This thesis proposes a solar PV powered air-conditioning system as a suitable off-grid solution to meet the cooling demand for the ground floor office of a commercial building in Lagos, Nigeria. The goal behind the proposed off-grid cooling system is to reduce the load on the weak grid infrastructure and offset all unit electricity costs associated with cooling load. The aim of the project is to carry out modelling and simulation analysis for the ground floor office to determine the required cooling load using ESP-r software. The solar PV and battery requirements were analysed using Excel Spreadsheet. The results from the analysis showed that for a peak cooling load of 9.37kW, an off-grid cooling system made up of an air-conditioner having a maximum nominal capacity of 10.55kW, a solar PV array of surface area 23m^2 and a battery size of 24V 440Ah will be required to meet the cooling demand for the ground floor office.

CHAPTER 1: Introduction

The focus of this section is to showcase the need for an off-grid solution to meet cooling demand amongst other energy demands in tropical regions, due to harsh weather conditions and inadequate power supply. This chapter discusses the crisis marring Nigeria`s energy network and advocates the need for off-grid systems. The chapter also highlights a brief summary of the work covered.

Chapter 2 gives a detailed literature review on the potentials for solar PV in Nigeria and an overview of building and construction practices in Nigeria. Chapter 3 explains the objectives of the project, problem the project intends to solve (i.e. the goal behind the project) and states the steps that will be taken for the research methodology. Chapter 4 showcases the procedures of, and results from the modelling and simulation analysis. Chapter 5 gives a detailed discussion about the upshots of the results derived from the modelling analysis and opines on the workability of the proposed system. Chapter 6 concludes the thesis and hints on suggestions that will enhance the practical deployment of the proposed off-grid cooling system .

1.1 Nigeria`s energy crisis and the need for off-grid cooling systems

Nigeria is endowed with diverse natural resources which includes large reserves of fossil fuels (Crude Oil, Natural Gas and Coal) and renewable energy sources (hydroelectricity, solar, wind and biomass). However, sundry factors, most especially corruption, have impeded the maximum utilization of these sources to meet overall energy demand of the nation. Since gaining independence from Great Britain in 1960 till present, Nigeria`s economy has been marred by inadequate power supply to foster economic growth and development. Currently, there are nine energy generation plants in the country, three of which are hydro-powered, while the other six are thermal power plants (Energy Commission of Nigeria, 2008)

 The total installed capacity of the power plants is 6000MW although the energy generated has been observed to be lower than installed capacity due to lack of maintenance, weak grid infrastructure, interruption of fuel supply to thermal plants and a percentage of energy generated

being exported to a neighbouring country- Niger Republic (Uyigwe et al., 2009).The installed generating electricity capacity in Nigeria consists of 1900MW of hydropower generation and 3396MW of thermal power generation (Kasimu, 2000). A prominent Nigerian newspaper named PUNCH reported findings as of September 11 2009 that the country`s energy generation is about 2000MW. Research and Statistics has predicted Nigeria`s energy demand to be 35000MW in 2015 and will increase to 105,000MW in 2025 and 164,000MW in 2030 (Ibitoye and Adenikiju, 2006).

Oyedepo (2012) outlined and reviewed some of the most important energy conservation opportunities and renewable energy options in Nigeria. He opined that there is an incremental concern on the need to integrate renewable energy sources in Nigeria, considering the low rate of socio-economic infrastructure achieved by over dependence on fossil fuels. The over dependence on fossil fuels can be expressed as one of the upshots of corruption that has been the bane of the Nigerian economy. National Technical Working Group on Energy Sector (2009) estimated the supply capacities of renewable sources as thus; hydro-resources (small and large hydropower) have an estimated capacity of 14,750MW, solar radiation is estimated at $3.5 - 7.0$ KWh/m^2/day, wind energy has a potential of 150,000 terra joules per year (generated by an average wind speed of $2.0 - 4$ m/s) and biomass has an estimated capacity of 144 million tonnes per year.

According to the Energy Commission of Nigeria (2008), the Federal Government approved the National Energy Policy (NEP) in 2003 to propose sustainable means of harnessing and utilising all energy resources. Cardinal elements in the national policy emphasises on the development and application of renewable energy technologies and they are as follows:

(i)   To develop, promote and harness the renewable energy resources of the country and incorporate all viable ones into the national energy mix.
(ii)   To promote decentralised energy supply, especially in rural areas, based on RE resources.
(iii)   To promote efficient methods in the use of biomass energy resources.
(iv)   To deemphasise and discourage the use of wood as fossil fuels.
(v)   To keep abreast of international developments in renewable energy technologies and applications.

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The need for cooling systems in tropical regions in general and temperate regions during summer as a result of hot weather conditions is pivotal to having thermal comfort. As a result, a large percentage of electricity generated in countries with hot climatic conditions is channelled towards meeting cooling demand in buildings. In Nigeria where the average weather temperature is about 27°C, most of the energy demand that comes from commercial and industrial buildings are attributed to cooling demand irrespective of the season- Dry or Rainy (Uyigwe et al., 2009).

Sivak (2009) examined the potential energy demand (average annual cooling and heating degree days) for cooling in 50 largest metropolitan areas of the world and assessed the incremental demand it would create on top of the energy demand. Lagos, the focus of this research, had an average annual cooling degree day of 2653°C. His assessment indicated that air-conditioning is rare in most developing countries that have hot climates primarily due to the cost of air-conditioning appliances and the cost of energy. He opined that there is a likelihood of an increase in air-conditioning as the personal income of residents in developing countries rise. The opinion of Sivak (2009) can be viewed to be attainable if energy cost reduces and government initiatives are set up and implemented to improve poverty alleviation.

The astronomical gap between the country`s energy demand and supply has sparked up a plethora of energy policies by successive governments to help reduce the gap with a long term pursuit of solving the problem. An optimum way inter alia to bridge this gap is firstly, to disaggregate the total energy demand of the country into segments such as cooling demand, heating demand, lighting demand, and other energy demands, and secondly, advocate for standalone energy systems to meet a certain segment of the energy demand (e.g cooling demand). This will offset total dependence on the current inadequate power supply from conventional power generation to meet energy demand. In light of this, a solar photovoltaic powered air-conditioning system is proposed to meet the cooling demand for the ground floor of a single occupant office unit in a commercial building in Lagos, Nigeria.

CHAPTER 2: Literature Review

2.1 Solar PV Potentials for Nigeria

Nigeria`s tropical climate naturally makes it suitable for harnessing solar resources. Njoku(2013) estimated Solar PV electricity generation potentials for all states in Nigeria by establishing a linear equation between energy generation potential and solar insolation, and discovered that the annual energy generation potential generally increases with latitude, hence in Nigeria`s case, the extreme southern part of Nigeria (Niger Delta) had the lowest energy generation potential of 1,150kW.h/kW$_p$ for horizontal collectors and 1,200kW.h/ kW$_p$ for tilted collectors, while the extreme north of the country (Sokoto State) had the highest energy potential of 1,705kW.h/kW$_p$ for horizontal collectors and 1815 kW.h/kW$_p$ for tilted collectors. Lagos, the focus of this research, had a potential of 1294 kW.h/kW$_p$ for horizontal collectors and 1339 kW.h/kW$_p$ for tilted collectors. The results from his research evinced that, the use of solar PV in any part of the country to meet energy demand can be seen to be technically feasible.

Several Solar PV installations have been carried out in different parts of the country with the aim of meeting energy demand by harnessing solar resources within such areas. Ismail et al. (2012) embarked on performance assessment of installed 4.5kW Solar PV systems in Oke-Agunla area of Ondo State in Nigeria. The results from their assessment indicated that the Solar PV systems were underutilised due to system faults and reduction in efficiency as a result of poor maintenance, and technical defects being handled by fledgling project managers.

Agbo and Oparaku (2006) assessed the principles and technology of solar water heating, and their future prospects in Nigeria. The results from their assessment indicated that the level at which Solar Water Heating technology is being used in the Nigerian economy is extremely low despite the fact that there are potentials for this technology and several researches have been carried out about the profitability of the technology in the country. According to Oyedepo(2012), heating equipments through cooking and water heaters consume about 60% of energy used in households. Hence, the use of solar water heating technologies as mentioned in (Agbo and Oparaku 2006) will help reduce the high level of heating demand in households.

Oparaku (2002) examined the problems in the electricity supply system in Nigeria, as well as the status and potentials of Photovoltaics for village electrification and telecommunications. He highlighted several Solar PV installations across rural villages where 80% of households had no access to electricity grids and how the Solar PV systems met some of the energy demands. Several solar PV installations for telecommunication masts which offset the cost of procurement of diesel for diesel-powered generators used to power the masts, were also highlighted in his research. Although, there were issues of intermittent breakdowns due to technical faults with Solar PVs, he concluded that PV-powered village electrification systems have ameliorated the standard of living in rural villages and PV-powered telecommunication systems have improved the efficacy of the telecommunications network while offsetting the costs spent on diesel fuel.

Adaramola (2014) examined the feasibility of a solar PV-grid tied energy system for electricity generation and also investigated the techno-economic performance of a combination of 80kW solar PV and 100kW grid connection. He advocated for the use of the electricity grid to store excess energy from the Solar PV in lieu of batteries, thus reducing the capital cost of the Solar PV system and the unit cost of electricity. Although his research admitted the electricity challenges faced in urban areas due to intermittent power supply as a result of inadequate generation and distribution capacity, the results from his analysis indicated that a combination of an 80kW Solar PV and 100kW power from the grid will generate an annual electricity of 331,536 kWh with solar PV contributing 40.4% of the electricity produced.

Oko et al. (2012) conducted a design and life cycle cost analysis and simulation study of PV systems for the CAD/CAM laboratory at the University of Port-Harcourt in the Port-Harcourt area of Nigeria. The results from their analysis unfortunately showed a unit electricity cost that is higher than that for the municipal supply in the region. They however opined that the unit electricity costs will drop to a reasonable value if the capital and installation costs of the PV system components are either reduced or subsidised.

Several researches carried out in the literature for the deployment of Solar PV systems for different scenarios in several parts of the country can be seen to have yielded positive results in terms of meeting energy demand as required. However, the results from these analyses have indicated sundry prevalent issues associated with long-term deployment of Solar PVs. Hence, it

is imperative that detailed research be carried out in solving the long-term problems associated with deployment of Solar PV systems in Nigeria.

2.2 Overview of Building Construction in Nigeria

Primary materials used in construction of buildings in Nigeria include, but are not limited to, corrugated roofing sheets, cement block for walls and foundations, wood for doors and door/window frames, glass for window panes and reinforced concrete for slabs, beams and columns (Ukoha and Beamish 1997).

Fig. 1: Construction phase of a storey building in Nigeria

Building standards and regulations in Nigeria came into inception in 2006 but prior to that, the building construction industry was in a state of rollercoaster bombarded by diverse unqualified

individuals undertaking construction projects, thus leading to the use of untested and uncertified materials and components (Mbamali and Okotie, 2012). The upshot of the mediocre constructions carried out by fledgling contractors was *inter alia* the incessant collapse of buildings and fire infernos and as a result of this, the National Council on Housing and Urban Development established a National Building Code with the aim of offering solutions to the innocuous trends in the building construction industry (Mbamali and Okotie, 2012). Despite the efforts of the National Council on Housing and Urban Development as mentioned in (Mbamali and Okotie, 2012), the enforcement and application of the National Building Code has encountered several setbacks nationwide as there are still present occurrences of fire infernos and collapse of buildings as a result of poor building standards.

Lawal and Ojo (2011) examined how building design characteristics, thermal performance of buildings, thermal control in buildings affect prevention of overheating of buildings, reduction of other heat gains, as well as thermal comfort and human performance by carrying out a field survey of the thermal performance of four residential buildings in Ibadan, Nigeria. The results from their research indicated that material selection, openings, orientation and provision of vegetation around buildings contributed to the thermal comfort of occupants of residential buildings in Ibadan, Nigeria.

Ukoha and Beamish (1997) examined the resident satisfaction with public housing in a public housing district in Abuja, Nigeria and the relationship of satisfaction with specific housing features to overall housing satisfaction. The results from their study showed that most of the residents were not satisfied with individual housing features such as the plumbing, lighting, floors, windows, doors, and finishing. In most cases, building designs drawn by architects reflect the requirements of clients but ulterior motives of builders alter these requirements with a major aim of maximising profit at the expense of customer satisfaction (Mbamali et al., 2004).

Research studies carried out on the status of energy efficiency in Nigerian buildings have been seen to be disparaging. Iwaro and Mwasha (2010) investigated the implementation status of building energy standards in 60 developing countries which included Nigeria, and its implication for sustainable energy efficient designs in buildings. The results from their investigations indicated that 42% of developing countries have no building energy standards which included Nigeria.

Majid and Hussaini (2011) made attempts to verify the current level of energy efficiency design practice in Nigeria as a result of the dominant issue of inefficient households. The results from their analysis indicated that there was an obvious pattern of disorganised activities within the building sector and also an existing gap in energy efficiency consideration and architectural practice in Nigeria. There are a plethora of reasons for these gaps but are not limited to corruption, lack of professional expertise in energy efficiency related issues, discord in execution of roles for all parties (architects, engineers, quantity surveyor, and builder) involved in the building construction (Mbamali et al., 2004).

Abimaje and Akingbohungbe (2013) discussed the capacity of energy efficiency in housing Nigeria to serve as a panacea to climate change. They opined that a major issue with Nigerian housing is the use of imported materials and construction techniques to satisfy the ego of modern Nigerians. They stated that control measures are required to reduce the impact of solar radiation on houses. In as much as Abimaje and Akingbohungbe (2013) opined the need for control measures in buildings, their research did not take into consideration the feasibility of implementing such control measures in buildings.

There is a prevalent absence of pertinent data and proper documentation of material properties used in building construction in Nigeria and as a result, there are difficulties in carrying out detailed modelling and simulation analyses for determining energy requirements in buildings (Obanor and Egware, 2003). According to Obanor and Egware (2003), "the non-availability of recent climatic design data have led to the usage by local building service engineers, of air-conditioning system design data produced by foreign organisations like ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) and CIBSE (Chartered Institution of Building Service Engineers), which more often than not, results in the incorrect estimation of space cooling loads and thus, ultimately affecting the design of air-conditioning systems for buildings". Based on the analysis carried out by Obanor and Egware (2003), it is important to note that for Nigerian buildings to become energy efficient, it is pivotal that all pertinent thermal and material properties used in construction from start to finish are researched and documented so as to enable accurate modelling and design to meet energy efficiency standards. This task can be effectuated through the establishment of policies and legislations by the various building and construction regulatory organisations in Nigeria.

CHAPTER 3: Project Objectives and Research Methodology

Most office buildings in Lagos, Nigeria are storey buildings, flooded with air-conditioning systems, and they are either powered by the electricity grid or diesel generators. This project aims to model and carry out simulations for a solar photovoltaic air-conditioning system to meet the cooling demand of an office located on the ground floor of an office building in Lagos, Nigeria. This technology, if proven feasible, will provide two major energy efficient solutions;

- To reduce the load on the weak grid infrastructure.
- To offset all unit electricity costs from the municipal grid supply associated with cooling demand.

The system components are:

(i)   a Solar PV incorporated with

(ii)   an air-conditioning unit and

(iii)   an Auxilliary Storage (Batteries).

The research methodology for this project is as follows;

Step 1: Build a model of the office from scratch on ESP-r software, using relevant parameters such as climate data, material and optical properties, zone construction and orientation, and zone controls, to determine the cooling demand for the office.

Step 2: Get suitable COP values for the air-conditioning system from manufacturer`s data and use the values to model for the required electrical power necessary to meet the cooling demand for the office.

Step 3: Get solar insolation data for the site location and use the data to model for the size of the Solar PV array that will generate a power output adequate to meet the electrical energy demand of the air-conditioning system.

Step 4: Model for the size of the battery storage that will store excess power output from the Solar PV and supply auxiliary power to meet electrical demands during peak periods.

CHAPTER 4: Modelling and Simulation

4.1 Step 1: Building the model to determine the cooling demand.

In view of deriving necessary parameters to generate the cooling demand profile for the ground floor of an office, a base case model for a single occupant office was built using ESP-r software.
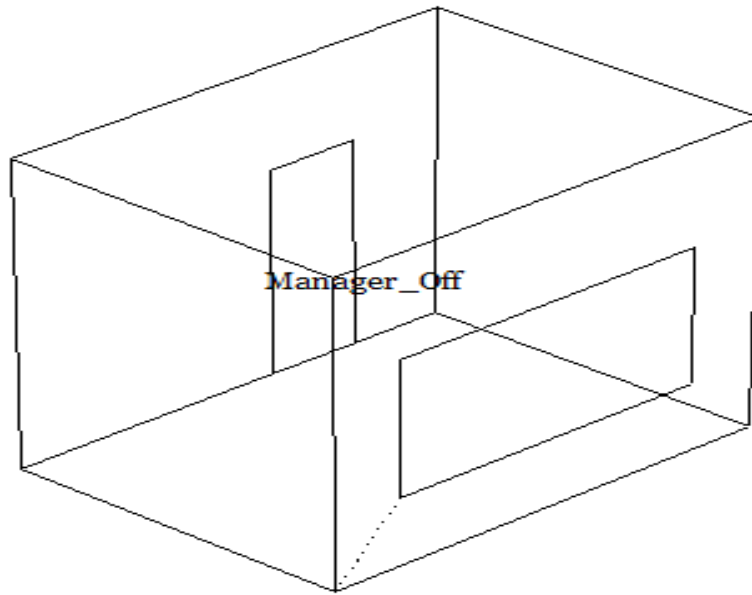

Fig 2: base case model for a single occupant office in Nigeria

Fig 3: Typical view of a single occupant office in Nigeria

4.1.1 Model Geometry, Construction, and Attribution

The model depicted in Figures 2 and 3 represents a ground floor for a single occupant office which has a floor area of 75 square metres and a volume of 675 cubic metres. The office has a length of 10m, a width of 7.5m, and a height of 9m. The office has a double-glazing located on the south wall which is subject to external weather conditions. The east, west, and north partitions are all interior parts of the building. The door is located on the north partition of the building. The floor represents the ground/entry floor of the building. The ceiling has the same surface layers (inverted) as the entry floor for the first floor of the building. The model is a single zone model which is labelled as "Manager_ Off". The table below shows the materials used for construction of the model.

Table 1: Model Construction Materials and Properties

Surface	Surface Layer	Conductivity (W/m-k)	Density Kg/m^3	Specific Heat (J/Kg-K)	Emissivity	Absorptivity	Thickness (mm)	Material
South Wall	1	0.96	2000	650	0.9	0.7	100	Light Brown Brick
	2	0.04	250	840	0.9	0.3	75	Glass Wool
	3	0	0	0	0	0	50	Air Gap
	4	0.44	1500	650	0.9	0.65	100	Breeze Block
North, West & East Partitions	1	0.51	1400	1000	0.9	0.25	240	Inner Painted White Block
Ceiling	1	0.6	500	750	0.9	0.65	10	Floor Tiles
	2	1.4	2100	653	0.9	0.65	150	Heavy Mix Concrete
	3	0	0	0	0	0	100	Air Gap
	4	0.04	250	840	0.9	0.3	50	Glass Wool
	5	0.03	290	2000	0.9	0.6	10	Ceiling Mineral

Floor	1	1.28	1460	879	0.9	0.85	200	Earth Sand
	2	1.28	1460	879	0.9	0.85	200	Earth Sand
	3	1.28	1460	879	0.9	0.85	200	Earth Sand
	4	0.52	2050	184	0.9	0.85	150	Gravel
	5	1.4	2100	653	0.9	0.65	150	Heavy Mix Concrete
	6	0.6	500	750	0.9	0.65	10	Floor Tiles
Glazing	1	0.76	2710	837	0.83	0.05	6	Glass Plate
	2	0	0	0	0	0	12	Air Gap
	3	0.76	2710	837	0.83	0.05	6	Glass Plate
Door	1	0.19	700	2390	0.9	0.65	25	Oak Wood

4.1.2 Model Operational Schedules

Zone Casual Gains (Occupancy, Lights & Equipments) were defined for the model to estimate the operational characteristics for each day type (weekdays, Saturday, Sunday, and holiday) and air flow schedules were also defined.
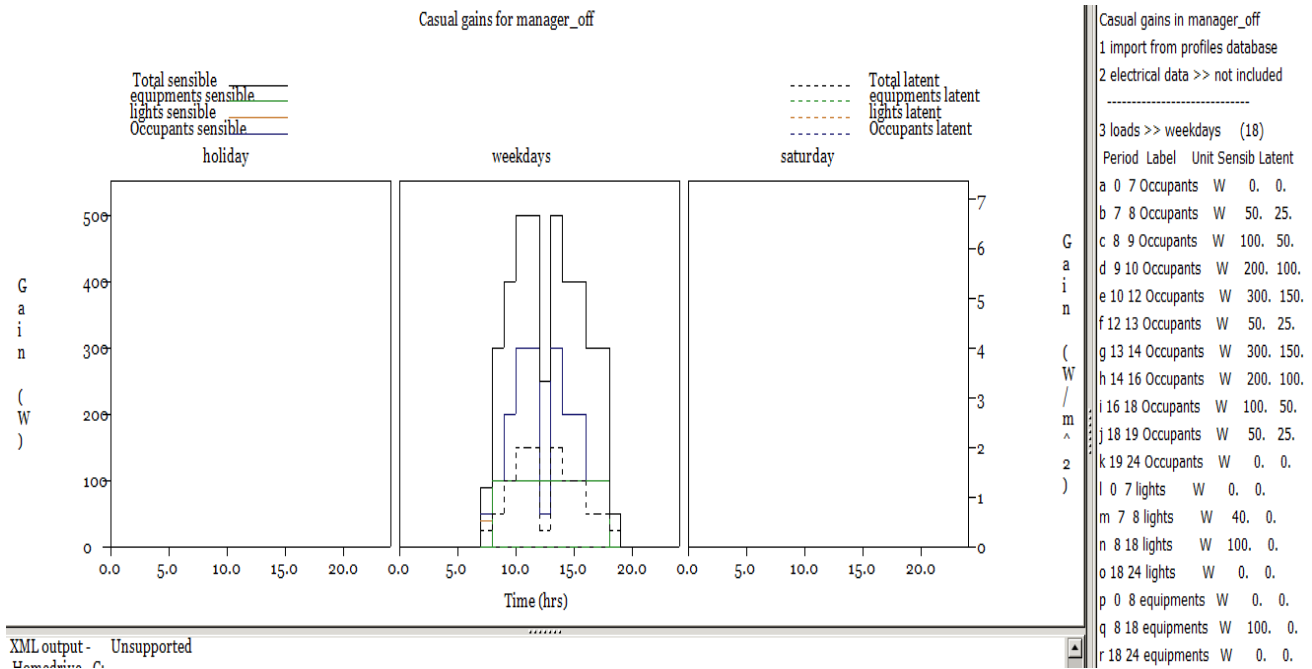

Fig.4: Casual gains for the office

Fig.4 shows the casual gains profile for occupancy, lighting, and equipments in the office. Saturday, Sunday and Holidays had no casual gains because offices are not opened during such periods, thus the absence of any kind of activity. Only weekdays had casual gains due to work activities. Each occupant is set to have a peak sensible gain of 100W and a peak latent gain of half the value of the sensible gain (i.e. 50W). Hence, peak sensible gains of 200W for occupants, at a given period indicate two people present in the office during such time. The same principle can be likened to peak sensible gains of 300W for occupants- i.e. three people present. It can be observed from Fig.4 that peak sensible and latent gains for occupants between (12:00 and 13:00 hours) dropped from (300W/150W) to (50W/25W). This indicates break-time during office hours, hence no occupants in the office during that period.

Lightings and Equipments have zero latent casual gains, however sensible gains are estimated based on respective power outputs from the appliance (lighting or equipment) for given set

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periods. The office is presumed to use 20W of fluorescent lighting. Hence, a 40W lighting gain between (08:00 and 09:00 hours) indicates two fluorescent tubes switched on. This could be due to cleaners switching on the light to clean the office. A 100W lighting gain shows all five fluorescent tubes switched on during office hours. The equipments in the office include a desktop computer, and a printer/photocopier. These appliances have been estimated to have a sensible gain of 100W and are operational between the hours of (09:00 and 18:00 hours). Hence, it can be inferred from the casual gains profile for occupancy, lighting, and equipment that office working hours are between 09:00 to 18:00.
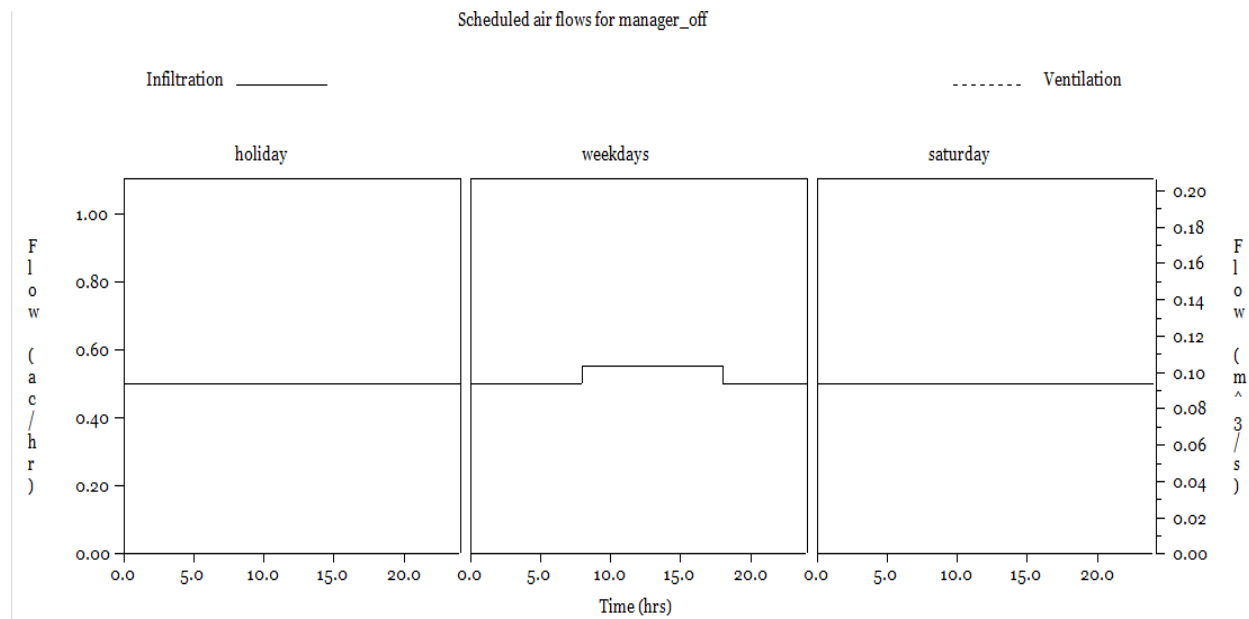

Fig. 5 Air flow schedules

As shown in fig.5, air flow rates (infiltration) were scheduled at 10litres/second/person during weekdays only, while minimum airflow rates throughout the week were scheduled at 0.5ac/h.

Due to unavailability of a weather file for Lagos, Nigeria, on ESP-r, a suitable weather file, Accra Ghana, which has similar climatic conditions (Sub-Saharan Tropical Climate) with Nigeria was imported from EnergyPlus Energy Simulation Software website and used for simulation for different seasons of the year. The Sub-Saharan Tropical Climate has two seasons; rainy season which spans between April and October, and dry season which spans between October and March. Based on the weather file used for simulation, the model can be said to be located at latitude 5.17°N and has a longitude difference of -0.17°.
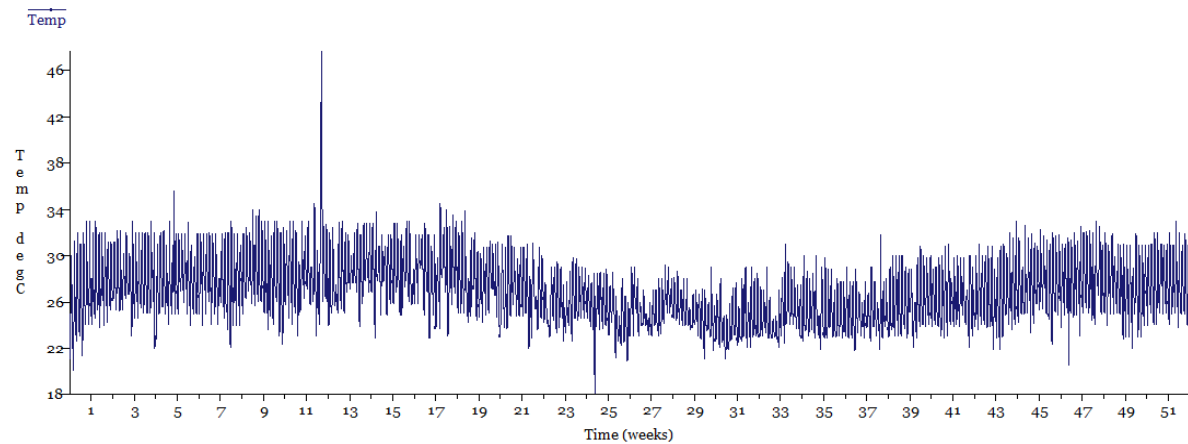
Fig 6: Weather Profile

The weather profile, Fig.6, shows that the average peak ambient temperature for the five months of the year (January to May) is about 33°C while the lowest set of ambient temperatures can be said to be about 24°C within the same period. The months of June, July and August showed a drop in average peak ambient temperature from about 33°C to about 30°C while the lowest set of ambient temperatures can be said to be about 24°C. September to December indicated a return to the same average peak ambient temperature that occurred within the first five months which is about 33°C while the lowest set of ambient temperatures remained the same at 24°C. Although there were few exceptions such as peak ambient temperature of over 46°C at the end of March and very low set of ambient temperatures of 18°C in early July and 20°C at mid-November. A detailed examination of the weather profile enabled the selection of the best fit weeks to carry out weekly simulations for different seasons of the year. The table below shows the best fit weeks:

Table 2: Best Fit Weeks

Seasons	Best Fit Weeks	Heating Degree Days (°C)	Cooling Degree Days (°C)
Early Rainy Season	10-Jul to 16-Jul	0	33.58
Late Rainy Season	22-Sep to 28-Sep	0	32.35
Early Dry Season	15-Nov to 21-Nov	0	45.0
Mid Dry Season	29-Jan to 04-Feb	0	47.05
Late Dry Season	15-Mar to 21-Mar	0	52.48

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4.1.3 Zone Controls

Sensor and Actuator zone controls were setup for weekdays only, based on the following manufacturer data.

Table 3: Manufacturer Data for Air-Conditioning Unit

Brand Name	LG MULTI$\mathbf{F}$DX
Model Number	UHXM90BA0
Nominal Capacity (Cool) (Min-Rated-Max)	1850W – 8880W – 10550W
Nominal Capacity (Heat) (Min-Rated-Max)	2220W – 10100W – 12100W
Nominal Input (Cool) (Min-Rated-Max)	720W – 2500W – 3160W
Nominal Input (Heat) (Min-Rated-Max)	880W – 2300W – 3870W
EER/COP (cool)	3.52
COP (Heat)	4.39
Air Flow Rate	883 litre/sec
Cooling Operating Conditions	Indoor Temperature: 27°C Outdoor Temperature: 35°C
Heating Operating Conditions	Indoor Temperature: 20°C Outdoor Temperature: 7°C

Zone controls were set to sense a 50-50 mix of air and radiant temperatures.

The following values from Table.3 were used to define the sensor and actuator zone controls

Table 4: Zone Control Period Data

Cooling Set-Point Temperature	27°C
Heating Set-Point Temperature	20°C
Maximum/Minimum Cooling Capacity	10550W(Max) / 1850W(Min)
Maximum/Minimum Heating Capacity	12100W(Max) / 2220W (Min)

4.1.4 Simulations

Having built the model from scratch on ESP-r, simulations were run to analyze the cooling demands of the office for different seasons of the year.
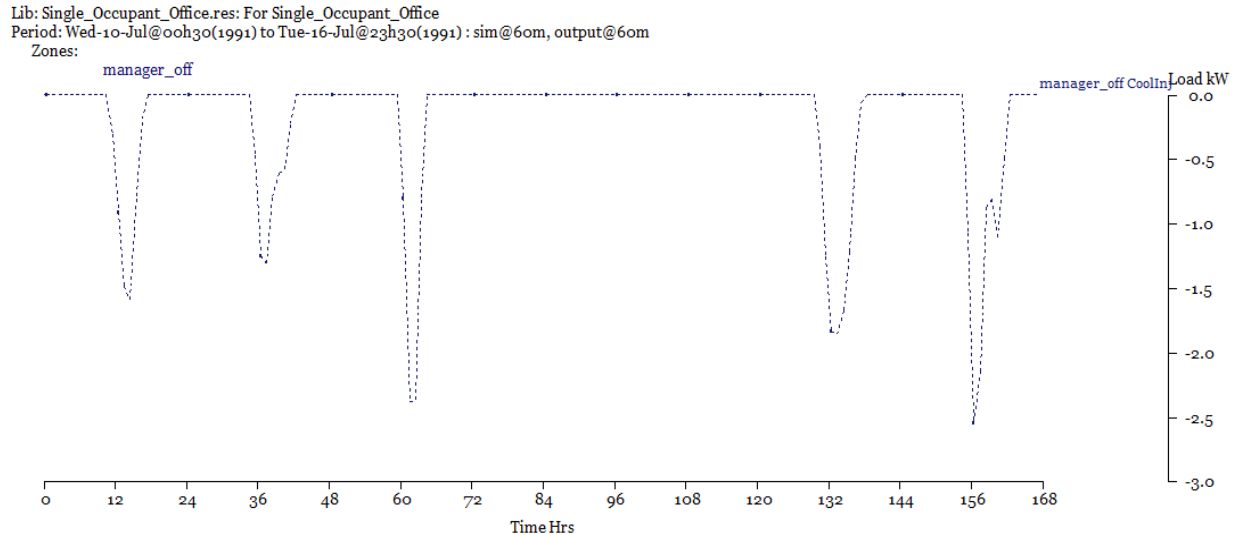

Fig 7: Cooling Demand for Early Rainy Season

The graph in Fig.7 shows the cooling demand profile for the office during early rainy season. The simulation period was from Wednesday of the week to Tuesday of the following week. The graph shows that cooling loads reached peaked values at mid-day. There was no cooling load on weekends as actuator controls are not program to function on such days. However, it can be observed from the graph, that the maximum cooling load for early rainy season is 2.54kW.
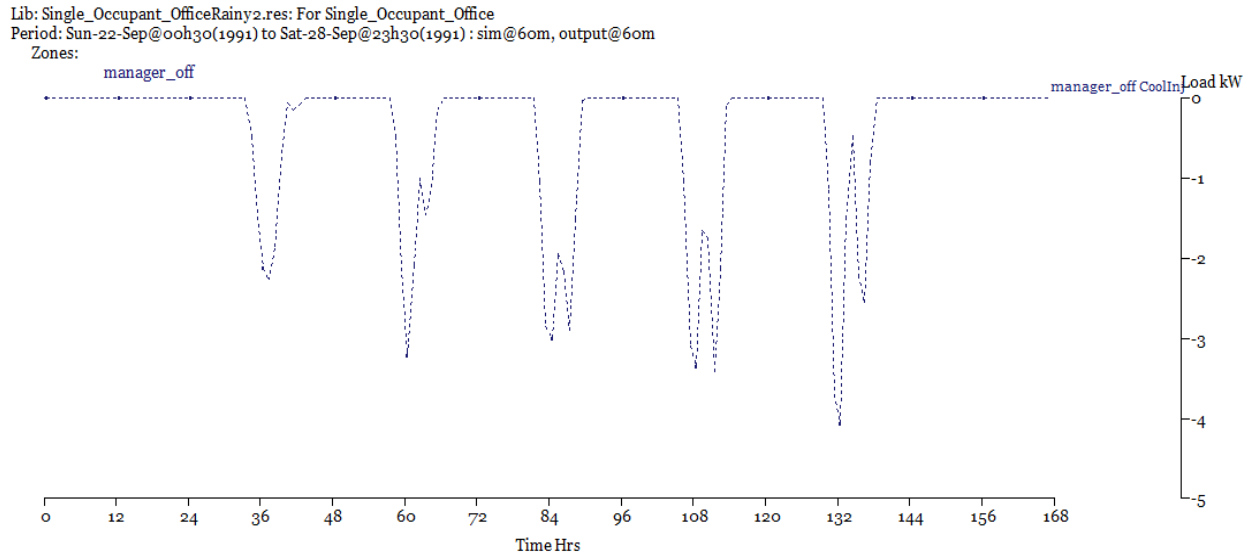

Fig 8: Cooling Demand for Late Rainy Season

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The graph in Fig.8 shows the cooling demand profile for the office during late rainy season. The simulation period was from Sunday to Saturday. The graph shows that cooling loads reached peaked values at mid-day. There was no cooling load on weekends as actuator controls are not program to function on such days. However, it can be observed from the graph, that the maximum cooling load during the late rainy season is 4.06kW

Lib: Single_Occupant_OfficeDry1.res: For Single_Occupant_Office
Period: Fri-15-Nov@00h30(1991) to Thu-21-Nov@23h30(1991) : sim@60m, output@60m
Zones:
manager_off
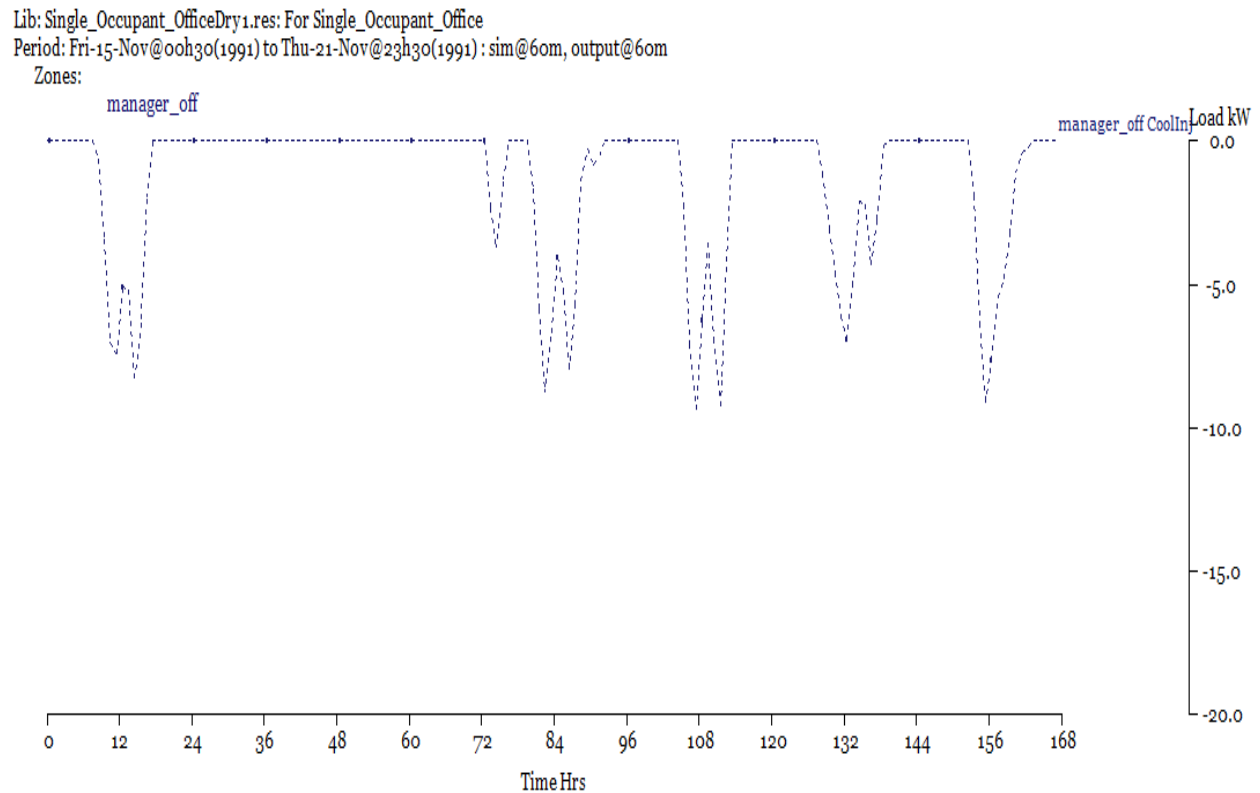
manager_off CoolIn-Load kW

Time Hrs

Fig 9: Cooling Demand for Early Dry Season

The graph in Fig.9 shows the cooling demand profile for the office during early dry season. The simulation period was from Friday of the week to Thursday of the following week. The graph shows that cooling loads reached peaked values at mid-day. There was no cooling load on weekends as actuator controls are not program to function on such days. However, it can be observed from the graph, that the maximum cooling load during the early dry season is 9.37kW
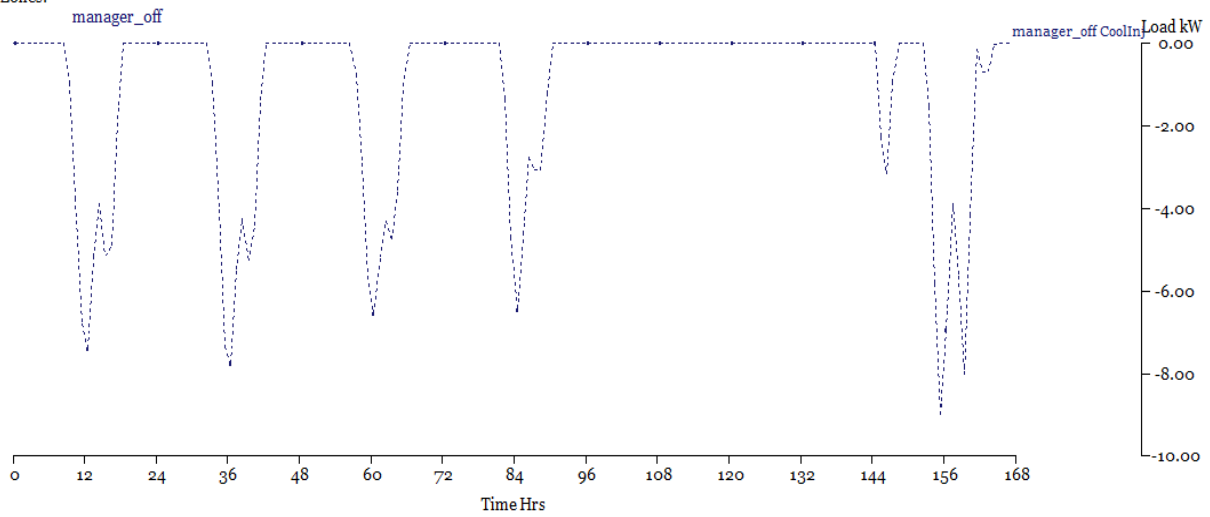
Fig 10: Cooling Demand for Mid Dry Season

The graph in Fig.10 shows the cooling demand profile for the office during mid dry season. The simulation period was from Tuesday of the week to Monday of the following week. The graph shows that cooling loads reached peaked values at mid-day. There was no cooling load on weekends as actuator controls are not program to function on such days. However, it can be observed from the graph, that the maximum cooling load during the mid-dry season is 9.01kW.
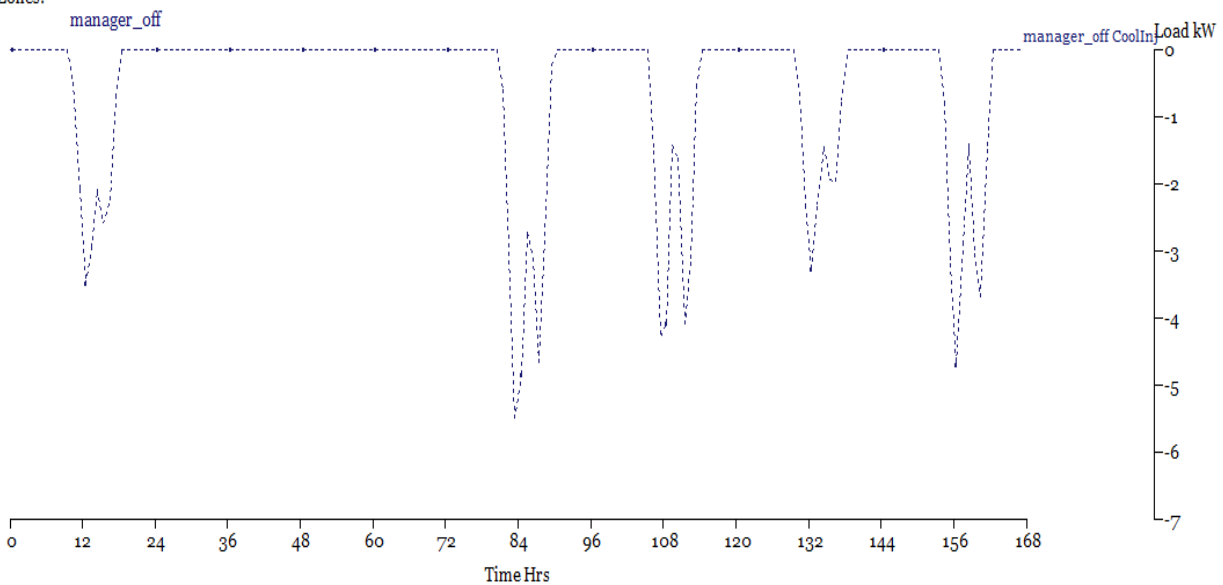

Fig 11: Cooling Demand for Late Dry Season

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The graph in Fig.11 shows the cooling demand profile for the office during late dry season. The simulation period was from Friday of the week to Thursday of the following week. The graph shows that cooling loads reached peaked values at mid-day. There was no cooling load on weekends as actuator controls are not program to function on such days. However, it can be observed from the graph, that the maximum cooling load during the late dry season is 5.5kW

Having observed the cooling demand profiles for five different periods of the year, the maximum peak cooling load of 9.37kW occurred during the early dry season. As a result, the cooling demand profile for the early dry season (November) is regarded as the most optimum profile to be used for deriving the electrical load of the air-conditioning system and the power output from the Solar PV.

4.2 Step 2: Modelling for electrical load profile of the air-conditioning unit

COP values vary with respect to outdoor temperatures. However, due to the unavailability of COP curves/values from manufactures data, an average COP value from manufacturer`s data listed in Table.3, COP_{cool} of 3.52, is used to generate the electrical load profile for the air-conditioner from Excel Spreadsheet.

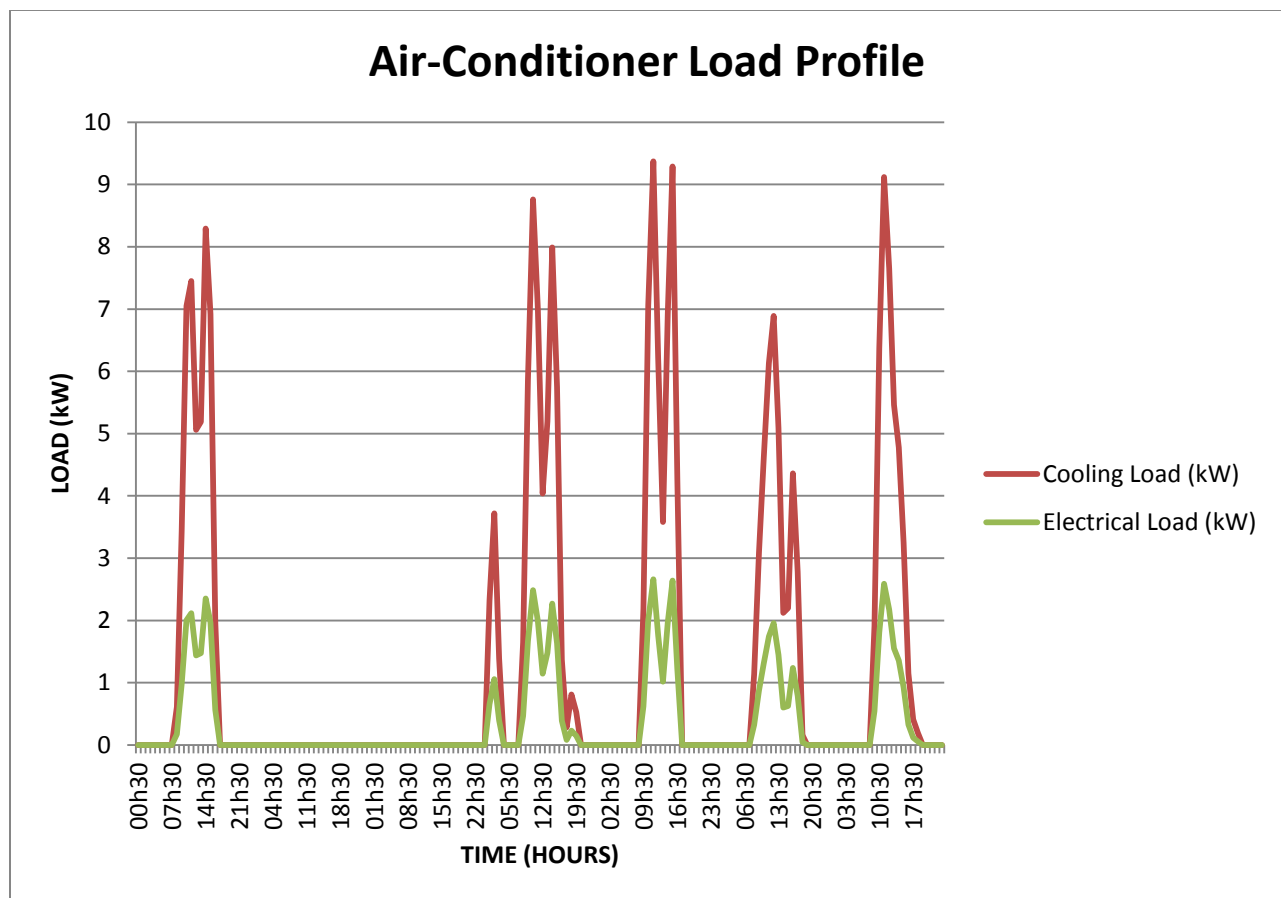$$COP_{cool} = \frac{Cooling\ Load\ (kW)}{Electrical\ Load\ (kW)}\ .$$

Fig.12 Air-Conditioner Load Profile

The cooling load was derived from the graph in fig. 9 which showcased the cooling demand profile for the early dry season (November). It can be observed from the graph in fig.12 that for a peak cooling load of 9.37kW, the peak electrical power input required by the AC unit is 2.67kW.

4.3 Step 3: Modelling for Solar PV output power and size

Lagos is located at latitude 6.4531°N and 3.3958°E. The monthly averaged solar insolation values for horizontal surfaces for 44,016 regions, generated on a nested grid that has a resolution of one degree latitude globally and longitudinal resolution ranging from, one degree in the tropics and subtropics, to 120° at the poles, can be culled from NASA Surface meteorology and Solar Energy (NASA-SSE) website. In light of this, the monthly averaged insolation values for horizontal surfaces (a horizontal solar PV array in this case) in Lagos, Nigeria, was extracted.

Optimum tilt angles for Lagos, Nigeria lies between 11.5° and 17.5°(Njoku, 2003). In most cases, the worst case scenarios for both power absorbed by, and power output from, a PV array is when it lies at horizontal i.e. at 0°. Hence, this work aims to model for the worst case scenario of power generated by the PV to meet the electrical demand of the air-conditioning unit. The table below shows the averaged monthly solar insolation on a horizontal surface in Lagos, Nigeria for the month of November (Early Dry Season).

Table.5: Averaged monthly solar insolation on a horizontal surface in Lagos, Nigeria.

Latitude 6.453, Longitude 3.396 Time (hours)	November (Early Dry Season) (Solar Insolation on PV array) Power Absorbed (kW/m^2)	Power Output from PV array (kW) η = 15.63%
@ 00	n/a	0
@ 03	n/a	0
@ 06	0.05	0.1813
@ 07	0.197	0.7144
@ 08	0.343	1.2438
@ 09	0.49	1.7768
@ 10	0.557	2.0187
@ 11	0.623	2.259
@ 12	0.69	2.502
@ 13	0.58	2. 1032
@ 14	0.47	1.7043
@ 15	0.36	1.3054

Time (hours)	Solar Insolation on PV array	Power Output from PV
@ 16	0.243	0.8822
@ 17	0.127	0.4591
@ 18	0.01	0.0363
@ 19	0	0
@ 20	0	0
@ 21	n/a	0

Table 6: Solar Manufacturer Data

Model Name	Canadian Solar
Model Number	CS6X-300P
Nominal Maximum Power (STC)	300W
Module Efficiency (STC)	15.63%
Module Dimension	1954 x 982 x 40mm

The peak electrical power required by the air-conditioning unit as shown in fig.12 is 2.67kW. However, a solar PV array that will generate a peak power output of 2.5kW was investigated, with the stipulation of storing excess energy generated on periods with low cooling demand and reusing the stored energy to meet cooling demand at peak periods. From table.5, the peak average solar insolation is 0.69kW/m^2. This value, coupled with a peak PV module efficiency of 15.63% (STC) extracted from manufacturers data in table.6, was used to generate the size of the solar PV array.

Power Output from PV (kW) = PV efficiency * Power Absorbed by PV (kW/m^2) * Area (m^2)
2.5 (kW)   = 0.1563   * 0.69 (kW/m^2)   * Area.
From this equation, the surface area for the PV array of 23.2m^2 was derived, and this area was used to generate PV power outputs (kW) for all given values of solar insolation (kW/m^2) gotten from (NASA-SSE) website as shown in Table. 4. From table.5, the module area is 1954 * 982 = 1,918,828mm^2 = 1.92m^2. Hence, for a total surface area of 23.2m^2 for the PV array, the total number of required PV modules will be $\frac{23.2m^2}{1.92m^2} = 12$ modules.

The values of PV power outputs (kW) and the periods of subsequent power generation (hours) was used to generate a solar PV power output profile from Excel Spreadsheet.

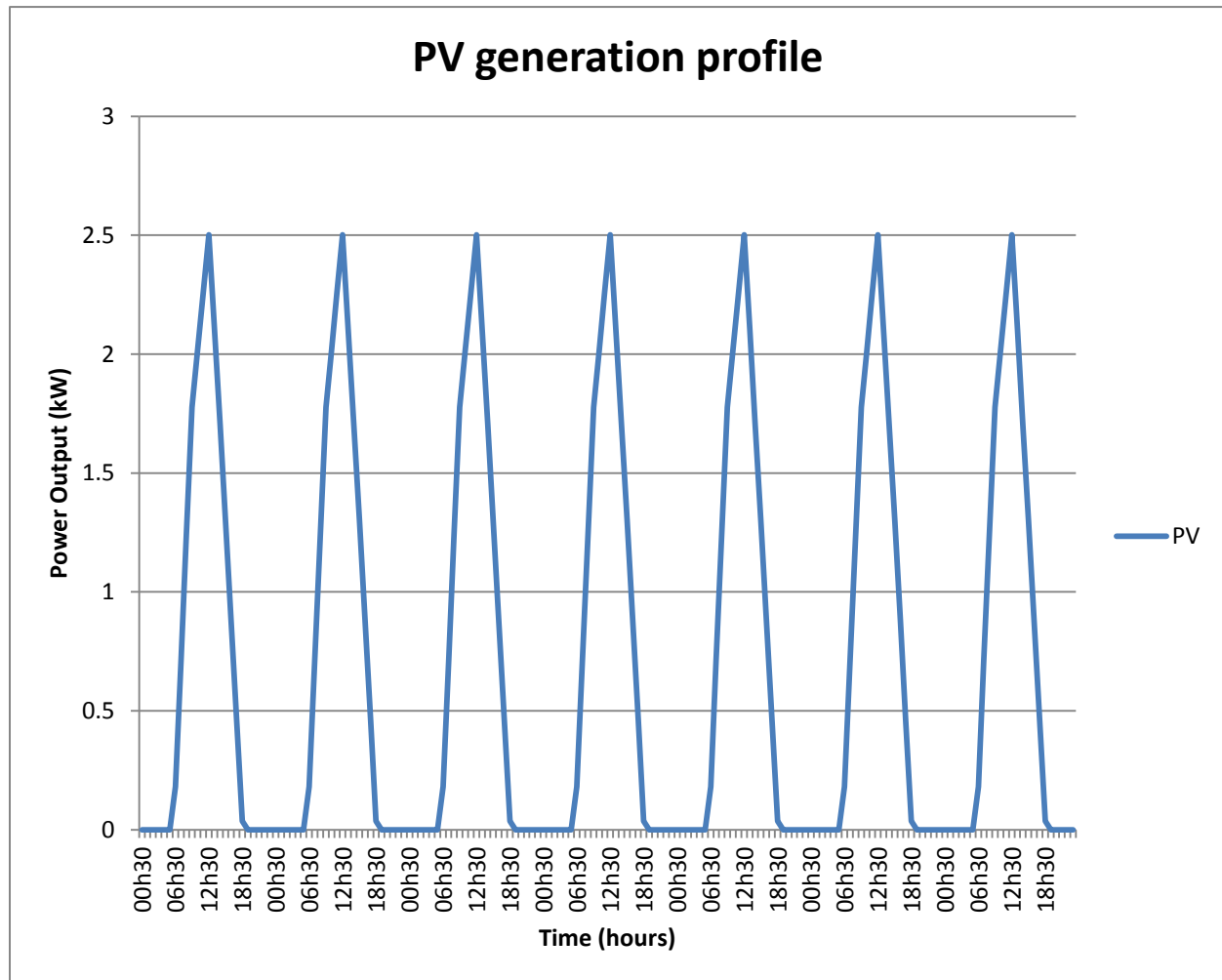Fig.13: PV generation profile for early dry season (November)

The graph in fig.13 above shows the power output from the PV array having constant peaks of 2.5kW throughout the week. These idealistic values are as a result of the unavailability of daily and weekly solar insolation values for Lagos, Nigeria. As a result, the average monthly solar insolation for November was used to plot the graph.
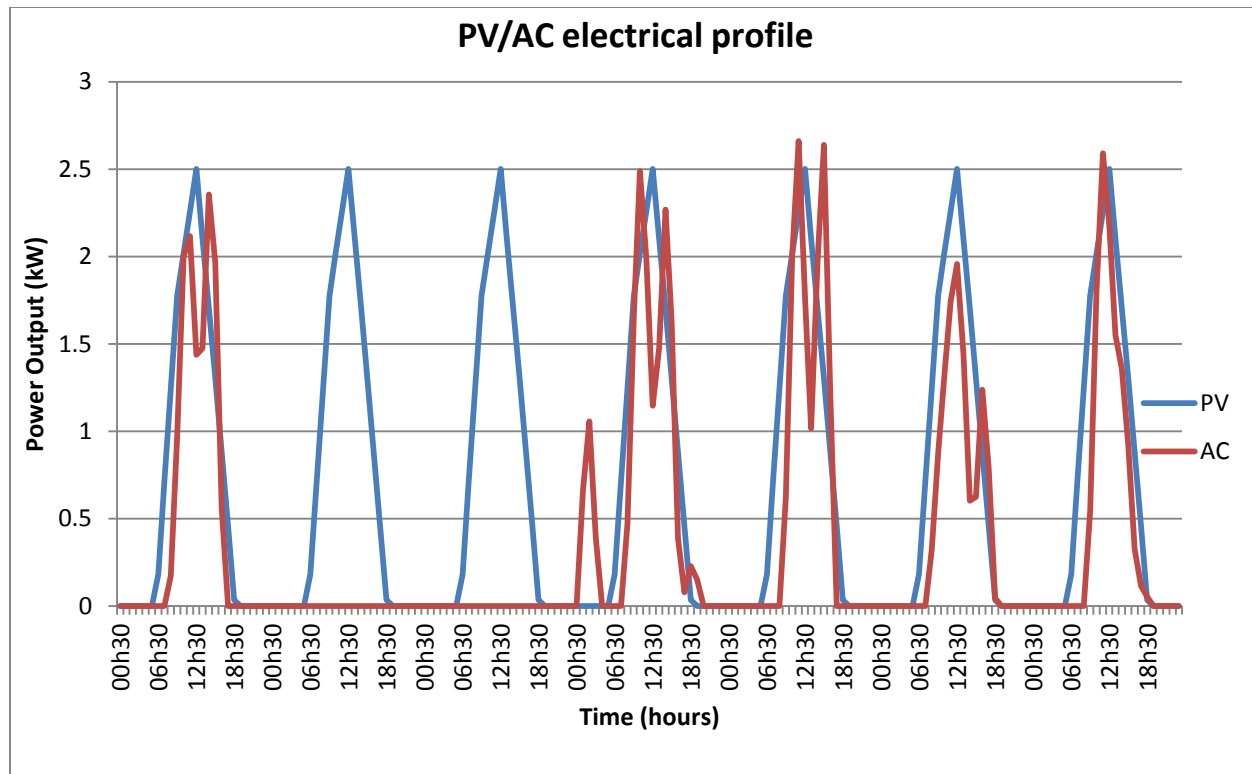
Fig.14: PV/Air-Conditioner electrical profile

The graph in fig.14 shows an integration of data derived for the electrical demand from the air-conditioner in fig.12 and power output from the solar PV in fig.13. This integration was carried out using Excel Spreadsheet to analyze the level of match between electrical demand from the AC and power supply from the PV. The graph shows a week performance profile of the PV/AC system starting from Friday of the week to Thursday of the following week. It can be observed that Saturday and Sunday has no electrical demand as a result of non-working days at weekends in the office, thus the air-conditioning unit is switched off.

Friday shows the PV generating excess power in the morning, thus exceeding electrical demand by the AC, until hours after noon where electrical demand was higher than power supplied by the PV. The PV generated power throughout the weekend despite that the air-conditioner was switched off. There was a peak electrical demand of 1.05kW during the early hours of Monday without any power supply from the PV. Later on, excess power was generated by the PV array until noon when electrical demand was higher than power supplied by the PV. A similar pattern can be observed on Tuesday with peak electrical demand higher than peak power output from PV at noon. The PV power supply met most of the electrical demand for Wednesday and

Thursday except for later hours of Wednesday and noon on Thursday where electrical demand exceeded power output from the PV.

The inability of the solar PV to supply adequate power to the air-conditioner at every instant of time during working hours evinces the need to model for an auxiliary supply that will store the excess power output from the PV during periods of low electrical demand, and re-supply the air-conditioning unit system with the deficient power required to meet peak electrical demand.

4.4 Step 4: Modelling for Battery Storage

In pursuit of meeting the electrical demand for the air-conditioner at periods when the PV array could not supply adequate power (deficit electrical demand) as shown in fig.14, this work models for a rechargeable battery size using Excel Spreadsheet.
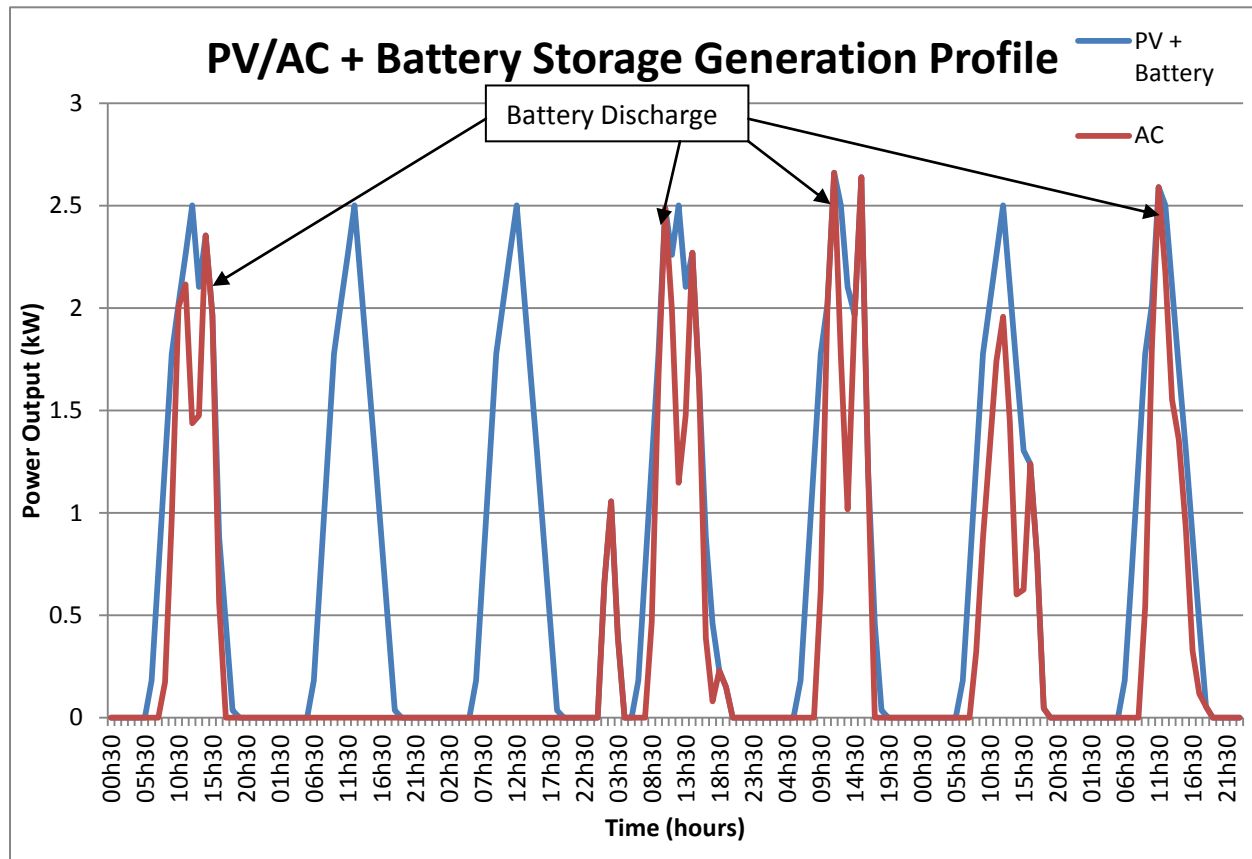

Fig.15: PV/AC/Battery generation profile

In this scenario, the model assumes the battery as a charging and discharging storage facility with a roundtrip efficiency of 85% and having an initial fully charged state. The graph in fig.15 shows the PV/AC supply-demand profile with battery storage installed to supply auxiliary power required to meet deficit electrical demand. It can be observed from the graph when compared with the graph in fig.14, that with the battery installed, the periods throughout the week when the PV output could not meet the electrical demand of the air-conditioner, have now been supplemented by auxiliary power from the batteries. The periods that show a perfect alignment of the profile curves (both AC and PV) are periods when the battery discharged power to meet

the deficit electrical demand of the AC. The battery discharges only 85% of excess power it receives from charging by the PV module. Hence, from the graph, it is evident that all electrical load required by the air-conditioner have been supplied by power outputs from both the solar PV and batteries. The excess power supplied by the PV after recharging the batteries was exported to grid and there was no need for grid import.

4.4.1 Battery Capacity

Having modeled for the power supply profile (PV + Batteries) to meet the electrical demand (Air-Conditioner), Excel spreadsheet was used to quantify the maximum load (deficit electrical demand) that the battery will be required to supply for a certain discharge period and this load from the results analysis was 2.11kW. Most lead acid batteries have depth of discharge cycles of 80%, 50%, 20% and 10%. "Battery life is directly related to how deep the battery is cycled each time. If a battery is discharged to 50% every day, it will last about twice as long as if it is cycled to 80% and if it is cycled to only 10% depth of discharge, it will last about 5 times as long as one cycled to 50%" (Born, 2000). Thus, a battery selection of 20% depth of discharge was selected in pursuit of having a long battery lifespan.

In this model, the maximum depth of discharge of 20% equals the maximum load. i.e. D.O.D = 20% = 2.11kW. However, since batteries are quantified with respect to time; then, D.O.D = 20% = 2.11kWh = 2110Wh. An assumption of a nominal voltage of 24V was applied. The maximum discharge capacity based on a 20% depth of discharge is $\frac{2110Wh}{24V}$ = 88Ah.

It is important to note that 88Ah represents the maximum discharge capacity which is just 20% of the total battery capacity. Hence, the overall battery capacity required to meet the deficit electrical demand for the air-conditioner is $\frac{88Ah}{20\%}$ = 440Ah.
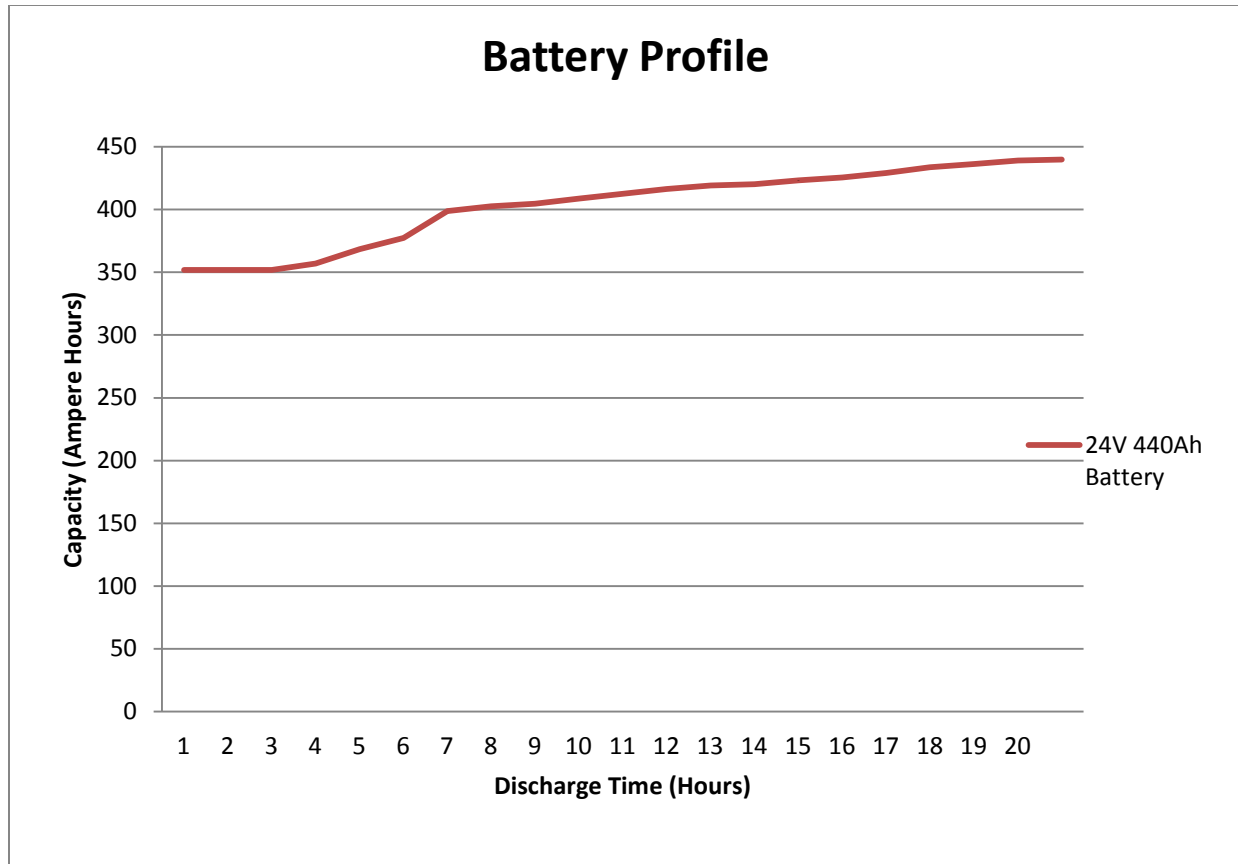
Battery Profile

Fig.16 Battery Profile

The graph in fig.16 shows the battery discharge profile of the sized 24V 440Ah battery. Most batteries are designed to have a maximum discharge time of 20 hours. In this case, the maximum discharge rate is 352Ah at 88A for one hour. Likewise, the minimum discharge rate is 440Ah at 4.4A for 20 hours.

CHAPTER 5: Discussion

The steps required for the research methodology of this work have been carried out and the results from the modelling and simulation analysis show that to meet the cooling demand for the 75 square metre ground floor office of a building in Lagos, Nigeria, without grid connection, an off-grid cooling system made up of ;

- an air-conditioning unit having a maximum cooling capacity of 10.55kW and a C.O.P of 3.52
- a 23 square metre PV array (which consists of 12, 1.9 square metres, PV modules with each module having a generation capacity of 300W) having a generation capacity of 2.5kW with an efficiency of 15.63%
- a series-parallel connection of a battery size of 24V 440Ah

will need to be installed. For this kind of installation to be made in practice, several logistics will need to be taken into consideration. It is noteworthy to understand that this proposed off-grid cooling system will only meet the cooling demand of one of the offices located on the ground floor amongst other offices, coupled with other offices located on different floors within the same building.

A practical view of the installation of this off-grid cooling system will require an external land-mass area (at least $23m^2$) for the PV installation, and an internal space for the battery storage. From the standpoint of a microscopic view, a long-lasting solution can be said to have been provided to meet the cooling demand for an office. However, the applicability of this solution in terms of large scale deployment in other offices within the same building undermines the technical feasibility of the off-grid cooling system. Office buildings if built to several floors usually have limited external space around it. Hence, for this proposed system to be deployed in multiple offices, large land-spaces will be required for installations of all the solar PVs that will be required to power the air-conditioners in all the offices. This will definitely be a huge task to achieve and as a result, the plausibility of the cooling system being adopted by office occupants as an off-grid solution to meeting cooling demand seems unlikely.

An economic perspective of this proposed off-grid system indicates a high cost of procurement without a convincing incentive of offsetting unit electricity costs in the long run. A review of several literatures on solar PV potentials for Nigeria have all indicated prevalent problems associated with the long-term use of solar PV sources to meet energy demand. The main drive behind the championing of sustainability of energy systems lies under the aegis of cost effectiveness. This proposed solution, despite the fact that it cannot be said to be cost-effective in terms of capital costs, offers no plausibility of being cost effective in the long run, as subsequent research has shown solar PV to be unreliable for long term usage in Nigeria.

The steps carried out in the research methodology i.e. modelling and simulation can be said to be simplistic rather than detailed. The unavailability of pertinent data that will enhance detailed modelling resulted in the use of reasonable assumptions where necessary. For instance, the electrical demand for the air-conditioner was derived by using an average annual C.O.P value of 3.52kW extracted from manufacturer data which ought not to have been so, as C.O.P values change with respect to variations in ambient temperature. Also, the calculations used to evaluate the surface area of the PV array neglected several thermal properties like cell temperature of the module, surface emissivity and absorbtivity values, and the nominal input and output current and voltage. The battery sizing procedure on Excel Spreadsheet, did not take into consideration, the lifecycle period of the batteries, self-discharging of the batteries and the performance of the charge controller in terms of preventing overcharging and deep discharging. The performance of the D.C-A.C inverter in terms of conversion of D.C power supplied by the PV and batteries to A.C was also neglected.

Building the model from scratch on ESP-r had limitations during the selection of parameters on the software. Firstly, the weather file used to determine the variations in cooling demand was not for Lagos, Nigeria but Accra, Ghana. Also, the most of the material properties used for the building constructions were the ones available on the software. Although, ESP-r gives room for creation of new materials, research in the literature on Nigerian buildings shows a prevalent absence of pertinent data for properties of materials used in building construction. This limited the model construction to selection of material properties within the context of the software. As a result of neglecting vital parameters and making several assumptions, the results gotten from the research methodology can be said to be idealistic and likened to that derived from a scope study.

CHAPTER 6: Conclusion and Future Recommendations

The aim of this project is to model and carry out simulations of a solar PV powered air-conditioner to meet the cooling demand for a single occupant office located on the ground floor of a building in Lagos, Nigeria. The modelling and simulations was done with the use of ESP-r software and Excel Spreadsheet. The results gotten from the simulation for the cooling demand and PV with batteries have been analysed, most of which have shown to be idealistic due to limitations in availability of pertinent data and subsequent assumptions of key parameters.

More detailed modeling can be carried out in the building procedure using ESP-r to determine a more precise result for cooling load. This could be achieved by creating a weather file for Lagos, Nigeria either on ESP-r or on similar compatible software. Variations in the occupancy schedules for different days of the week can also enhance the accuracy of the results for the required cooling demand. Neglected factors like shading and insolation, and lighting controls can aid in producing realistic values for the cooling load. Also, research could be carried out to document the material properties used in Nigerian building constructions as this data is currently unavailable.

The plausibility of adapting the proposed off-grid cooling system to different buildings and several locations within the country (for example, rural areas) can also be investigated. Daily or weekly values of solar insolation for Lagos as well as data showcasing the variations in solar geometry of the location, if made available, can help in estimating a high degree of accuracy for sizing the PV array.

It is noteworthy to understand that upshot from the results analysis of this project is not to undermine or discard the possibility of achieving the goals behind the project but to evince the limitations that needs to be surmounted in meeting these goals. The goals behind the project which is to reduce the load on the weak grid infrastructure and offset all unit electricity costs associated with cooling demand can be said to be farfetched as a result of practical limitations in making the proposed off-grid cooling system technically feasible and economically viable. These limitations can be ameliorated if the aforementioned suggestions that can enhance detailed modelling are taken into consideration.

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APPENDIX

Fig. 17 Solar PV powered Air- Conditioner (window unit)

Fig. 18 Solar PV powered Air-Conditioner (split unit)