Optimal Sizing of a Standalone Photovoltaic (PV) System for Residential Customers Considering Electricity Consumption Patterns: A Case Study of Ibadan City, Nigeria

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Abstract

With the regular electricity outages and the growing demand for electricity in Nigeria, households are now depending heavily on generators powered by fossil fuels such as diesel and gasoline as their major source of electricity. Solar energy has been identified as a good alternative to meet the country's growing demand. However, the stochastic nature of electricity consumption among different households makes it complicated to select an optimal system size.

This study investigates the appliance-related factors that contribute to the increasing rate of residential electricity consumption in Nigeria and selection of an optimal system for different sociodemographic groups. In this location, where electricity consumption data is unavailable, a questionnaire survey was employed to closely predict the electricity consumption patterns of low-, middle- and high-income households in Ibadan city, Nigeria and a residential load profile was created. The study results show that incandescent bulbs, which inherently have a higher rate of electricity consumption than energy-saving bulbs, are still being used in almost every household in the city. Also, low-income households own more electric fans than households in the high-income group, and households in the high-income group own more air conditioners.

The methodology employed in this study enabled the realistic prediction of stochastic household electrical load which influences the optimal sizing of a standalone photovoltaic system (SAPVS) as an alternative source of electricity. The system advisor model (SAM) software was then used to simulate the proposed system performance to determine its feasibility, based on economic criteria such as levelised cost of energy (LCOE). Results show that, taking the electricity consumption pattern into consideration, an optimally sized SAPVS has a lower LCOE than diesel and gasoline generators.

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Onyeka Collins Egbon

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Ethics Approval

A pilot test for this study was carried out in September, 2018 to test the efficacy of the questionnaire for data collection and the ability of respondents to comprehend it. The ethics approval was obtained from Auckland University of Technology Ethics Committee on October 9, 2018. Approval number 18/339.

Chapter 1 Introduction

1.1 Background overview

In Nigeria, connecting households of rural or remote communities to the utility grid is usually not feasible because of the increasing population and high capital cost involved in expanding the grid in these areas. Even the major communities and cities that are connected to the grid often experience frequent electricity outages which makes the grid very unreliable [1, 2]. As electricity outage is a regular phenomenon in Nigeria, the majority of households depend heavily on other sources of energy which are generally classified as fossil fuels.

Also, energy consumption in Nigeria is increasing exponentially [3, 4]. The residential sector has the highest rate of energy consumption when it is compared to other sectors. The residential sector represents 37% of the total energy consumption and this consumption rate grew by 14% between the years 2000 and 2011 [5]. The rapidly growing rate of energy consumption in the residential sector makes it the centre of attention for energy conservation measures. Factors affecting the increase in energy consumption in developing countries, especially in Africa, were identified to be population, industrialisation, urbanisation and economic growth [5], while other factors affecting the residential sector increases due to socioeconomic, dwelling and appliance-related factors [6].

Nigeria’s median residential electricity consumption has been estimated to be around 8 to 27kWh per capita which varies through geographical zones [7], the North East and South West are having the highest rate of electricity consumption. In Nigeria, which has a population of 190 million people and an average annual population growth rate of 2.8% [8], the annual energy consumption is expected to grow between 11.5% to 13% in the next twenty years [9]. This increase in energy demand means that fossil fuels cannot supply the energy needed by the populace. As the price of oil is constantly increasing, and with the predicted end of world oil production not too far away [10], the search for alternative sources of energy that are clean and cost-effective is necessary to meet the growing energy demand. Thus, there is an urgent need to plan the energy sector of the country and shift to alternative sources of energy. In addition, energy conservation or optimisation measures are essential in order to meet this exponential growth.

Renewable energy technologies are emerging as alternative sources of energy which are pollution free [11], such as solar, wind, biomass and geothermal. Cost-effective ways of harnessing these clean and sustainable sources of energy, and ways in which the environment can be made safe from the carbon emission resulting from the use of fossil fuels, are being constantly researched, yet there is low adoption of these energy sources in developing countries. Even though these energy sources can be used for many purposes such as for generating electricity, cooling, heating and transportation, many households in developing countries are yet to fully embrace these clean energy sources due to their high initial cost of installation, uncertainty and intermittent nature [12].

Renewable energy is expected to become the fastest growing global energy source with an average consumption increase of 2.3% per annum between 2015 and 2040 [13]. However, as the use of renewable sources of energy, such as solar and wind energy, is projected to rise continually, the use of other fossil fuel sources, such as petroleum and diesel, is also projected to rise as a result of increasing population and demand [14]. Renewable energy is a possible solution to the increasing energy demand and some of these energy sources are already popular and are being used all over the world.

1.2 Motivation

Solar energy is becoming increasingly popular and is more abundantly available in Nigeria than other renewable energy sources [15]. Presently, the Nigerian Electricity Regulatory Commission (NERC) has created an off-grid electrification strategy as part of the Power Sector Recovery Program (PSRP) by approving an off-grid solar rooftop generation capacity of 5,000MW [16]. Also, a feed-in tariff system was recently signed into law by NERC in 2016 to promote self-generation and reduce overloading of the national grid [17].

In the Western African region, the Economic Community of West African States (ECOWAS) is keen on establishing a clean, efficient and favourable environment for investments in renewable energy technologies. It has started this by placing a target on promoting renewable energy in the region to 35% in 2020 and 48% in 2030 [18]. One of the renewable energies being considered is solar energy because of its abundance in the region.

With the PSRP introduced, households are now gradually adopting solar energy as an off-grid system rather than grid-tied system, due to the unreliability of the grid as a result of frequent electricity outages. Because electricity outage is a regular occurrence in Nigeria [1, 2], households prefer the off-grid distribution system to be self-sustainable rather than depending on the grid. Currently, more than US$20 billion has been invested in off-grid solar power projects in Nigeria [19].

1.3 Problem statement

As electricity consumption is increasing exponentially and with the frequent electricity outages in the residential sector of Nigeria, most households now depend heavily on diesel and gasoline generators [20] as a major source of energy to meet their electricity demand. However, the off-grid or standalone photovoltaic system (SAPVS) has been identified as a good alternative to diesel or gasoline generators and grid extensions for residential applications because they are pollution-free, maintenance-free, noiseless and solar energy is abundantly available in the region [15]. The key problem is selecting an optimal SAPVS capacity that will ensure minimum system cost while maximising the system reliability in order to avoid over-sizing or under-sizing of the system to meet the consumption demand of households.

The stochastic nature of electricity consumption, especially for residential application, makes the process of achieving this optimisation more complicated. Different households often show differences in electricity consumption patterns according to their sociodemographic circumstances [6] and, if this is not taken into consideration, a system may be over-sized which could increase the overall cost.

Another issue is the reliability of SAPVS. Most rooftop solar PV systems are unable to meet the electrical demand during peak hours, which are mainly in early mornings and late in the evening for residential applications [21], whereas the optimum peak output of a PV system occurs around afternoon when there is maximum solar irradiation [22]. For this reason, a storage system in the form of battery is often required to store the excess energy generated during the PV system’s optimum output. However, batteries are still expensive and can contribute 35% of the total system cost [23], which makes the system unattractive to customers. However, it is only a matter of time before a breakthrough is achieved in battery storage systems [22].

1.4 Research question

From the problem statement and discussion above, two major research questions can be coined:

- What are the factors contributing to the stochastic nature of residential electricity consumption in Nigerian households?
- How can these factors influence the optimal sizing of a SAPVS as an alternative source of electricity for residential customers in Nigeria?

1.5 Scope of study

This study explores the effect of stochastic nature of electricity consumption pattern in sizing a SAPVS for residential application, as other studies have not emphasized the dynamic nature of residential load profile when sizing a SAPVS. The method most widely used for sizing by other studies is the heuristic approach [24], which is simply a way of sizing based on the average load demand of a house without considering the dynamic nature of individuals or the load usage behaviour of individual households. The problem with this method is that, most times, systems can be over-sized which makes it very expensive and unaffordable for the households. Also, the load profile is not constant because it changes in different households. The way a household uses electricity is most likely different from the way another household uses electricity; therefore, it will be incorrect to depend on the average load profile when sizing a SAPVS. To optimally and accurately size a SAPVS that would be cost-effective and reliable, the variation in electricity consumption patterns of households which produce a realistic load profile needs to be considered [25].

The variation in the residential electricity consumption patterns or load profile of households is dependent on certain factors as earlier identified in Section 1.1, and these factors can be grouped into three, namely: dwelling factors, appliance factors and socioeconomic or sociodemographic factors [6]. The dwelling factors include the type of building, age of the building, number of rooms, total floor area, e.t.c. The appliance factors include ownership of appliances, frequency of appliance use and power demand of appliances. The socioeconomic factors include number of people living in the house, their employment status, age, education level, income and family composition including the presence of children. When the load profile of a household is obtained considering these factors, the optimal and most cost-effective sizing method for selecting a SAPVS can be achieved. In this study, Ibadan city is selected as the location for investigation.

Ibadan city, Nigeria, is an interesting case study to explore the stochastic nature of residential load profile because it is the largest indigenous or traditional urban city in Sub-Saharan Africa, which is comprised of households with heterogenous sociodemographics, different building types, and is the most multicultural city in Sub-Saharan Africa [26, 27]. This makes it an ideal location to better understand the dynamic or stochastic nature of the load profile in a typical African city. In the city, land is mainly used for residential purposes, which occupy 61.4% of the total land in the metropolitan area [28]. It is among the cities in West Africa with the most rapidly increasing population, with a growth of 100,000 inhabitants annually [27]. This city will give an excellent representation of the stochastic nature of residential load profile and the factors contributing to the increase in electricity consumption in a typical African city.

1.6 Aim of study

The aim of this study is to determine the feasibility of optimally sizing a SAPVS considering the stochastic nature of residential electricity consumption as borne out by the different sociodemographics in a case study of Ibadan city, Nigeria.

As earlier identified in Section 1.5 the sizing method used for a SAPVS can have a significant positive effect on the overall cost of the system. This study considers the solar irradiation of the location, ambient temperature and the stochastic nature of residential load profile as input when sizing a SAPVS to prevent over-sizing or under-sizing of the system.

Because residential load profile is stochastic, it is essential to determine what makes the load profile of different households stochastic and how an accurate SAPVS can be sized to match its stochastic nature. If this method is developed, it will provide a cost-effective and reliable system which can be afforded by all households according to how they use electricity in their houses.

There are several studies on the factors affecting residential electricity consumption in developed countries [6, 29-34], but these factors may not necessarily apply to a developing country like Nigeria due to differences in geographical location, human behaviour, weather conditions and building characteristics.

In Nigeria, there are few studies on residential electricity consumption [4, 7, 20, 35]. But to the author’s knowledge, no study has laid emphasis on the factors affecting residential electricity consumption and how the stochastic nature of the residential load profile can be determined. The closest to this study on residential electricity consumption in Nigeria [7] did not elaborate on household daily electricity consumption and suggested that the findings were only an average estimate and cannot be used for all geographical zones in the country. This research further aims to bridge this gap by investigating the dynamic nature of residential electricity consumption in a typical African community using Ibadan city as a case study.

1.7 Objectives of study

To achieve this research aim, the following objectives are considered necessary:

- Develop a method of predicting a realistic electricity consumption pattern of a household according to sociodemographic group.
- Determine the reliability of electricity supply in Ibadan city.
- Size and simulate an optimum SAPVS based on a household electricity consumption pattern.
- Evaluate the economic adoption feasibility of the proposed system.

1.8 Contribution to knowledge

This study is the first of its kind, particularly in Nigeria. The thesis will contribute in advancing knowledge in the following ways by:

- Identifying appliance-related factors leading to high residential electricity consumption amongst different sociodemographic groups in Ibadan city, Nigeria.
- Providing a method of modelling a realistic residential load profile for different sociodemographic groups where load consumption data is unavailable.
- Providing a new approach to optimally size a SAPVS considering the stochastic nature of the residential load profile as borne out by studying different sociodemographic groups.

1.9 Organisation of thesis

This thesis has seven chapters. The present chapter, Chapter 1, provides a background overview of the research, its motivation, the aim of the study, scope of the study, problem statement, objectives, research questions and contribution to knowledge.

Chapter 2 provides a further background study prior to commencing this research. It is divided into two parts. In part one, the various techniques of modelling residential energy consumption, factors affecting residential electricity consumption and the energy trends in the Nigerian residential sector are discussed. Part two provides a background overview of solar energy potential in Nigeria, PV system configuration, battery storage and economic feasibility criteria. Chapter 3 provides a comprehensive literature review on SAPVS sizing methods employed to date. It provides the summary which forms the foundation of this research.

Chapter 4, is divided into three parts. Part one discusses the survey methodology used in generating a realistic residential load profile and the categorisation of different sociodemographic groups in Ibadan city. Part two discusses the method used to determine the reliability of electricity supply in Ibadan city, and part three provides an optimal sizing methodology of a SAPVS and the method for assessing economic adoption feasibility. The research results and findings, as well as the optimised system performance and economic feasibility, are presented in Chapter 5. Chapter 6 provides further discussion of the research outcome and Chapter 7 provides the conclusion, along with a consideration of limitations, recommendations and further research work.

1.10 Resources and software

Microsoft Excel: A spreadsheet developed by Microsoft used for data analysis.

Meteonorm: A licensed solar resource website where a typical meteorological year (TMY) data for any location is obtained.

System Advisor Model (SAM): Technical and economic software developed by the National Renewable Energy Laboratory (NREL) and used to simulate the performance of renewable energy systems. It is mainly used by project managers and engineers.

Chapter 2 Theoretical overview

This chapter gives the theoretical background of energy consumption, energy trends in the Nigerian residential sector and an overview of solar energy potential in Nigeria. Various techniques of modelling residential energy consumption, factors affecting residential electricity consumption and the load profile model are presented in sections 2.1, 2.2 and 2.3 respectively.

2.1 Techniques of modelling residential energy consumption

The energy consumption of the industrial, agricultural, commercial and transportation sectors are better documented because of the high level of regulation, self-interest, centralised ownership and expertise in reducing energy consumption, unlike the residential sector [21]. The residential sector has a high level of undefined energy consumption which could be due to varying occupant behaviour, time of occupancy, the wide varieties of structural sizes, and privacy issues which hinder the collection and distribution of energy data [21, 36].

The three major uses of domestic energy are lighting and appliances, space heating and cooling, and domestic hot water [21]. Modelling of energy consumption for the above mentioned use is necessary for determining energy supply requirements, and the changes in the energy consumption of a household due to the upgrade or addition of appliances. Such models can guide policy decision makers on technology incentives, new building codes and energy supply requirements, especially in Nigeria where electricity outage is common.

The various techniques for modelling residential energy consumption are broadly grouped into two approaches: The “top-down” (econometric) approach and the “bottom-up” (engineering and statistical) approach [21].

The top-down approach makes the use of historical energy consumption data usually obtained from energy suppliers for determining long-term energy consumption patterns with the aim of determining supply requirements. The variables that are used for this approach are econometric indicators such as gross domestic product, employment rates, climatic conditions, population, price indices, and the housing construction and demolition rate. The disadvantage of this approach is that it cannot model the changes that are not reflected in demographics such as behavioural changes [37] and it treats the whole residential sector as an energy sink rather than distinguishing individual end users. This lack of detail on individuals' energy consumption makes it difficult to identify key areas of improvement with regards to the reduction in energy consumption (demand-side management).

The bottom-up approach is better used to model energy consumption because it can model the stochastic changes that are reflected by the demographics and behaviour [37]. This approach can be categorised into two methods: the statistical method and the engineering method.

The statistical method relies on historical data and types of regression analyses which are used to attribute household energy use to particular end uses [21]. If the relationship between end uses and energy consumption is identified, this model can be used to predict the energy consumption of households. The engineering method, on the other hand, gives a more realistic model by taking into consideration appliance usage and appliance power rating when predicting residential energy consumption.

The most commonly used variables in the bottom-up approach are appliance usage, duration of occupancy, climatic condition and location [21, 38]. These detailed variable inputs make it possible to model the behavioural and demographic changes in different households, and by doing so the areas that require a reduction in energy consumption or areas of energy improvement can be identified. The major difference between the top-down and bottom-up approaches is that the top-down approach starts with aggregate information and then disaggregates it down as much as possible while the different methods of the bottom-up approach start with detailed disaggregated data and then aggregate the data as much as possible [37].

2.2 Factors affecting residential electricity consumption

Information on the factors affecting residential electricity consumption is necessary for implementing energy efficiency strategies or policies as a way of reducing consumption or predicting future consumption. The electricity consumption of a household is dynamic; the way one household uses electricity is most likely different from the way another household uses electricity due to certain factors. Some of the factors that have an effect on residential electricity consumption include weather conditions, electricity prices, number of electric appliances, energy system within a building, occupant behaviour and sociodemographic factors [39, 40]. The factors that have a positive effect on domestic electricity consumption are socioeconomic factors, dwelling factors and appliance-related factors [6]. However, another study showed that the most significant influencing factors are geographical location and environmental factors such as winter and summer seasons [41, 42]. Due to these disparities in findings, the factors affecting residential electricity consumption can be broadly divided into sociodemographic and seasonal factors [40].

2.3 Residential load profile model

Load profiling is one of the most appropriate methods of determining household electricity consumption and utility companies can categorise customers based on their load profile [43]. Detailed information on domestic electricity consumption pattern is vital in understanding the occupant behaviour of a household and serves as the basis for energy reduction policies, tariff design for various types of customers and the design of load management initiatives to meet peak demand. However, the load profile of two households may be entirely different. Every customer shows differences in electricity consumption patterns [29]. Figure 1 shows the load profile of two individual customers for a random day [29].

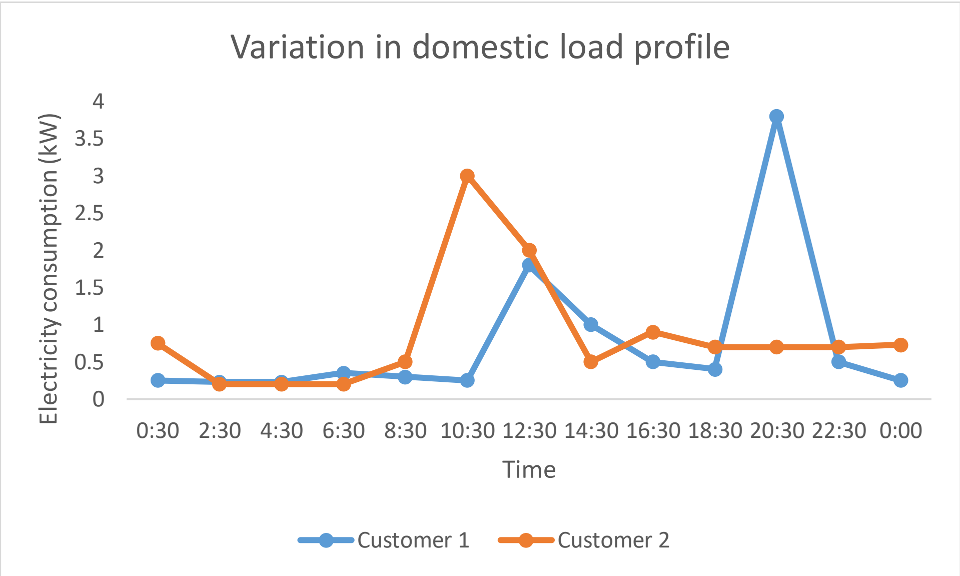


Figure 1: Daily load profile for two domestic customers [29]

It can be seen that there is a huge difference in the consumption pattern of the customers, with customer one having two significant peaks around early afternoon and evening time, while customer two has just one significant peak in the late morning and no significant peak in the afternoon or evening time. The differences in the load profile of the customers may be due to seasonal or sociodemographic factors as earlier identified in Section 2.2.

To obtain a realistic residential load profile for a household, the load profile can be modelled with regard to sociodemographic factors which may have a strong correlation with electricity consumption patterns. The greatest challenge in modelling a residential load profile is obtaining information on sociodemographic variables and household behaviour because of its stochastic nature. It is necessary to understand the sociodemographic factors of a household rather than just the measured consumption data because occupant behaviour could be one of the key ways of achieving greater energy efficiency. People often show differences in occupancy and behaviour according to their sociodemographic factors such as age, sex, education, income and cultural background, all of which influences electricity consumption [44, 45].

Several studies have modelled residential load profile using different approaches for data collection such as the use of interviews or questionnaire surveys, metering devices, smart meters and electricity bills. Most of the literature studied combined a survey with measuring devices [29, 46-52] or electricity bills obtained for a period of time [53] in modelling the load profile of a household, while others used only a survey [36, 54-56]. Some other studies [57-59] employed fuzzy logic and artificial neural networks for modelling residential load profile. The method for modelling residential load profile is subject to the availability of data, cost, availability of equipment, geographical location, regulatory requirements and purpose of research [37].

To model a realistic load profile for a community with similar characteristics or interests, such as income level or employment type, three major inputs are required: firstly, sociodemographic information such as income level, type of household, age, or sex; secondly, the electrical appliance consumption, such as appliance ownership level; and finally, daily occupancy information. These items of information have a relationship with the behaviour of occupants in a household with respect to their daily appliance usage and time of use [39].

Modelling the realistic load profile of a community with similar characteristics will help in electricity saving initiatives and as a way of matching supply and demand behaviour to power appliances at home, as well as improving the adoption, efficiency and cost of renewable energy systems. In addition, utility companies can properly design load management programmes and tariff strategies by grouping customers according to their consumption profile [43]. It will also help individuals in understanding their electricity consumption, leading to a change in consumer behaviour to reduce overall consumption.

Considering the challenge of obtaining household electricity consumption data in Nigeria, a survey could be a good source of detailed residential electricity use data in Nigeria where the majority of the households are unmetered [60] and electricity consumption cannot be monitored [7]. Also, electricity bills are over-estimated by the utility companies which make them unreliable as an input for modelling [60].

In order to understand residential electricity consumption, equation (1) can be used to determine the sample size for any study location [52, 61].

$$sample\ size = \frac{Z^2 \times r(1-r) \times f \times k}{p \times n \times e^2} \quad (1)$$

where Z is the z-score, r is an estimate of the key indicator to be measured, f is the sample design effect, k is a multiplier which accounts for the rate of non-response, p is the population to be surveyed, n is the average household size, and e is the margin of error expressed as a percentage of r.

At a confidence level of 95%, the z-score is 1.96, k is 1.1, e is 10% of r (e=0.1r) and the sample design effect f is assumed to be 2.0 [61].

2.4 Energy trends in the Nigeria residential sector

In Nigeria, 70% of the population depend heavily on fossil fuels and wood as their major source of domestic energy [4, 20]. The fuels most commonly consumed are firewood, gasoline, diesel and kerosene, with firewood being 68% of the total consumption [4]. As a result of this use of firewood, there is a gradual depletion of the natural vegetation because of deforestation from the excessive cutting of trees to satisfy domestic energy usage.

The residential sector has the highest rate of electricity consumption (37%) compared to other sectors [4]. Activities that consume most of this energy include cooking, lighting and electrical appliances usage, yet only 30% of the population has access to electricity supply in Nigeria due to power outages and other factors [20].

Frequent power outage is a regular phenomena in the Nigerian transmission and distribution system which makes the grid very unreliable [2]. The major power stations in Nigeria are hydro and thermal power plants [62]. The total energy generated from the power plants is 6,200MW out of which 1,920MW is generated from hydro and 4,280MW is generated from thermal gas-fired plants [62]. This energy generated is currently not enough to supply the energy required in a country with a population of 190 million people.

The Nigerian electricity network is comprised of 11,000km transmission lines with 330kV and 132kV feeders, 24,000km of sub-transmission line with 33kV feeders, 1,900km of distribution line with 11kV feeders and 22,500 substations [62]. Feeders are electrical transmission lines that transfer electric power from a substation to transformers for electricity distribution. In order to investigate the reliability of a distribution system, the feeder must have the capacity to supply the electric power required to customers on a 24-hours-a-day basis without interruption [63].

2.5 Solar energy potential in Nigeria

Considering the location of Nigeria in Sub-Saharan Africa (Latitude 9.0820°N and Longitude 8.6753° E), the amount of available solar energy is enormous [15]. Nigeria is estimated to have an average sunshine duration of 12 hrs/day [66] with solar radiation of 22.88MJ/m^2/day for the northern part of the country, 18.29MJ/m^2/day for the central part and 17.08MJ/m^2/day for the southern part [66]. Solar radiation is high in Nigeria and this makes it a good location for photovoltaic (PV) system adoption.

A PV system is a renewable energy power system that is designed to supply electricity utilising sunlight. It is composed of solar cells which are arranged in series to form a PV module and these modules absorb and convert sunlight into electricity. An important element in the PV system is determining how many modules should be connected in series or parallel to generate the desired amount of energy. A combination of PV modules is termed an array. An arrangement of several interfacing components is required to convert, store and distribute electrical energy generated by a PV array. Such components include an inverter, a charge controller and the balance of the system (BOS), such as cables and batteries for storing excess energy, depending on the functional requirement and the type of system.

SAPVSs are becoming popular in Nigeria as a result of government incentives for rooftop solar PV and the constant electricity outages from the grid. The system performs independently by relying on solar irradiation during the day to supply the required electrical energy. Due to the intermittent nature of sunshine, and for reliability, this type of system usually requires a battery for storing excess energy generated during the day, to be used at night when there is no sunshine or during cloudy days.

For most residential applications, lead-acid batteries are incorporated due to their lower cost and availability [12]. The system may also require a charge controller to protect the battery from damage as a result of excessive charging and discharging and, in some cases, the inverter may have an inbuilt charge controller which makes the need for an external charge controller unnecessary [12]. An inverter is used to convert generated DC voltage to AC voltage in satisfying AC load.

For places with no access to electricity or places with unreliable power supply, a SAPVS is most commonly used. This type of system is also a good alternative to provide power in cases of emergencies or natural disasters such as earthquakes, typhoons and hurricanes.

2.6 Standalone PV system size optimisation

Optimising the size of a PV system has a significant effect in the residential sector, however, the intermittent nature of sunshine and the dynamic nature of electrical demands have made achieving an accurate optimisation a complicated task. The various optimal sizing techniques for PV system have been extensively reviewed in [24] and can be grouped into the intuitive method, the numerical method, the analytical method and other methods such as a genetic algorithm, fuzzy logic and particle swarm optimisation which are generally classified as artificial intelligence techniques.

2.6.1 Intuitive method

The studies on SAPVS optimisation utilising the intuitive method for energy supply in Palestine [76, 78], Pakistan [73], Nigeria [15] and India [79] showed that the method is only a simplified approach to calculating the size of a PV system without considering the stochastic nature of solar radiation, electricity consumption pattern and the interaction between the subsystem component. This method makes a quick estimate of household average consumption [15, 73, 76] and the lowest monthly or annual average solar radiation [79] as the criteria in choosing the number of panels and battery storage capacities. Also, this method does not give a direct relationship between the capacity of PV system components and the system's reliability [15, 73, 76, 78, 79]. The major disadvantage with this method is that, in most cases, the system is either over-sized or under-sized, thereby reducing reliability and increasing the life cycle cost of the system.

2.6.2 Numerical method

The numerical method takes into account the stochastic nature of solar radiation and considers the interaction between load demand, available solar radiation and battery bank capacity [71, 80-82]. It also gives a direct relationship between the capacity of PV system components and its reliability [69, 71, 83, 84]. In most studies that utilised the numerical method, optimisation is usually achieved by considering the uncertainty or the stochastic nature of solar radiation as the most important criterion when sizing a PV system by simulating hourly solar radiation data and average load demand [69, 82, 84-87]. Other studies combined the numerical method with Markov transition matrices as a way of stimulating the stochastic nature of the amount of cloud in the sky to optimally size a SAPVS [25, 68, 70]. The advantage of this method is that the results of these studies can be extended to the stochastic nature of load profiles, especially for residential applications.

According to the literature studied, the numerical method is considered more accurate than the intuitive method because it requires mathematical modelling and system simulation in optimisation rather than making a quick estimate. Also, the system has a higher reliability when the numerical method is utilised compared to when the intuitive method is used.

2.6.3 Analytical method

In the analytical method, simple mathematical equations are usually used to describe the optimum size of a PV system and battery storage as a function of its reliability [88-90]. However, a computer simulation can additionally be used to obtain the performance of the proposed system after deriving a simplified mathematical equation to determine the PV and battery optimum values [90].

In some cases, the numerical method is considered more accurate than the analytical method and a new analytical method as accurate as the numerical method is usually proposed as a solution [89]. The advantage of the analytical method is that it provides a very simple way of calculating the optimum size of a SAPVS by using mathematical equations. However, the disadvantage of this method is that it is difficult to find the coefficients of these equations and it is location dependent.

2.6.4 Other methods

A genetic algorithm (GA) and an artificial neural network (ANN) have been used as alternatives [91] or combined with numerical and analytical methods in determining the optimum size of a SAPVS [92-94]. The limitation of these methods is that the authors failed to provide information regarding the type of metrological data used. These methods would be better understood if either hourly or daily data are stated. In addition, the optimum pair of PV array and battery storage needs to be searched for since only the sizing curves are usually estimated.

The intuitive sizing method and the ANN model have also been combined in predicting PV optimum configuration [95]. The advantage of this approach is that the size of the PV array can be controlled daily using a specific controller. However, the disadvantage of this study is that the authors refused to mention the methodology used for controlling the size of the PV which makes the applicability questionable.

Other studies have employed a computer model as a tool in optimising a SAPVS as well as its economic analysis. Computer simulation tools such as HOMER [67, 77, 96] and SAM have been used to optimise a SAPVS in India [67] and Uganda [75]. Moreover, the SAM computer model has been compared with other simulation tools such as Sunny design and Blue sol and has proven to be better in determining the performance of a SAPVS [67]. Figure 2, below, shows the block diagram of a typical SAPVS.

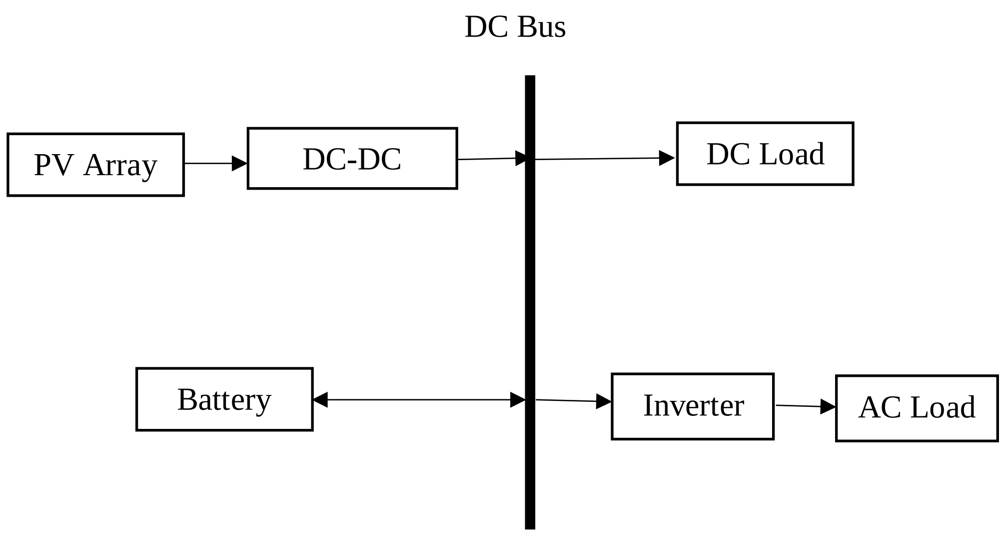


Figure 2: Standalone PV system

2.6.5 SAPVS component selection

The SAPVS component selection process as discussed in [12, 25, 67-72] describes how the number of PV modules, inverter, charge controller, DC cables and batteries for any residential load demand can be optimally selected. PV modules must be connected in series or parallel to produce the required power output to match load demand. Equations (2) and (3) are used to determine the number of modules in series (N_S) and parallel (N_P)

respectively, while equation (4) gives the formula used to determine the total number of PV modules (N_T) required.

$$N_S = \frac{V_S}{V_m} \tag{2}$$

where V_S is the system nominal voltage and V_m is the module voltage.

$$N_p = \frac{L_{energy}}{\eta_{pv} \times D_f \times NO_h} \tag{3}$$

where L_{energy} is the total electrical demand in kWh, η_{pv} is the efficiency of PV, D_f is module derate factor and NO_h is the number of sun hours.

$$N_T = N_S \times N_P \tag{4}$$

For an efficient PV array design, losses in the system can be accounted for by dividing the power demand (E) by the products of all the system component efficiencies [67]. Component efficiency can be obtained from the manufacturer's data sheet.

For inverters, the selected capacity must be a little above the total AC load demand [67], though it has also been stated more precisely that the capacity selected must be 20% higher than the total power of the required load demand [73]. The equation to determine the power input to inverter (P_{inv}) is given in equation (5).

$$P_{inv} = \frac{P_{daily}}{\eta_{inv}} \tag{5}$$

where P_{daily} is the daily maximum energy requirement and η_{inv} is the inverter efficiency.

Optimum capacity of the battery storage system is essential to avoid an unnecessarily expensive design since the battery has a significant contribution to the overall system cost as discussed in Section 1.3.

To determine the number of series connected batteries (N_{bs}), equation (6) is used [67].

$$N_{bs} = \frac{V_{bus}}{V_{bat}} \tag{6}$$

where V_{bat} is the nominal voltage of individual battery and V_{bus} the DC bus voltage.

Connecting batteries in parallel (N_{bp}) has an influence on the capacity of the battery [67], and equation (7) shows how it is achieved.

$$N_{bp} = \frac{N_b}{N_{bs}} \tag{7}$$

To determine the total number of batteries required (N_b), equation (8) is used.

$$N_b = \frac{B_{cap}}{S_{cap}} \tag{8}$$

where S_{cap} is the selected battery bank capacity in Ah usually specified by the manufacturer and B_{cap} is the required capacity of the battery bank in Ah.

If autonomy days (A_{days}) are required, the energy storage capacity of battery bank (B_{cap}) can be determined using equation (9). Autonomy days are the number of days the battery can independently supply the energy demand from the stored energy on low solar radiation days or cloudy days. Autonomy days are usually set between 1 day and 4 days [74].

$$B_{cap} = \frac{L_{energy} \times A_{days}}{B_{loss} \times DOD} \tag{9}$$

where L_{energy} is the load demand in kWh, B_{loss} is the battery loss and DOD is the maximum permissible depth of discharge. All lead-acid batteries have a DOD which is usually specified by the manufacturer. To determine a battery's real state of charge, knowledge of the initial state of charge is necessary as well as the charge or discharge time and current.

The instantaneous state of charge (SOC) of a battery is used to determine its charging and discharging state. The equation for determining the instantaneous SOC of a battery is given in equation (10) [40].

$$SOC(t) = SOC(t-1)\left(1 - \frac{\sigma \Delta t}{24}\right) + \frac{I_{bat(t)} \Delta t \eta_{bat}}{B_{cap}} \tag{10}$$

where σ is the self-discharging rate of the battery depending on the accumulated charge, Δt is the length of time step, η_{bat} is the battery charge efficiency and B_{cap} is the battery capacity. The current of a battery (I_{bat}) at a given time (t) can be determined using equation (11).

$$I_{bat}(t) = \frac{P_{pv}(t) - P_{load}(t)}{V_{bat}(t)} \quad (11)$$

where $P_{pv}(t)$ is the power generated by the PV modules, $P_{load}(t)$ is the load demand and $V_{bat}(t)$ is the voltage of the battery.

Optimum size and the correct type of DC cables are also required when selecting SAPVS components. The battery DC to inverter cable and the SAPVS to inverter DC cable are the two types of DC cables identified [67]. The equations for determining the maximum continuous input current for inverter cabling (I_{inv}), current rating of DC cable (I_{DC}) and voltage drop ($V_{drop,DC}$) in the DC cable are given in equations (12), (13) and (14) respectively.

$$I_{inv} = \frac{Maximum\ power}{\eta_{inv} \times V_{battery}} \quad (12)$$

$$I_{DC} = I_{PV} \times 1.25 \quad (13)$$

Where 1.25 is set as a factor margin between the PV modules and the load current [74].

$$V_{drop,DC} = \frac{2 \times L_{DC,cable} \times I_{DC} \times \rho}{A_{DC,cable}} \quad (14)$$

where $L_{DC,cable}$ is the length of the cable, ρ is the resistivity of the DC cable and $A_{DC,cable}$ is the area of DC cable.

2.7 Economic feasibility

The major criteria for determining the economic feasibility and benefits of a SAPVS are life-cycle cost (LCC) and levelised cost of energy (LCOE) [73-75]. However, other criteria such as net present value (NPV), simple payback period (SPBP), benefit–cost ratio (BCR) and internal rate of return (IRR) are also used [59, 76, 77].

The LCC of the system sums up the total cost of system components such as the PV array cost (C_{pv}), battery cost (C_{bat}), inverter cost (C_{inv}), cost of installation ($C_{install}$), battery replacement cost ($C_{bat\ rep}$), inverter replacement cost ($C_{inv\ rep}$) and the operation and maintenance cost ($C_{O\&M}$) for the system life span period in years [74]. Equation (15) shows how LCC can be determined [74].

$$LCC = C_{pv} + C_{bat} + C_{inv} + C_{install} + C_{bat\ rep} + C_{inv\ rep} + C_{O\&M} \tag{15}$$

LCOE is determined by dividing the annualised cost of producing electricity ($LCC_{1\ year}$) with the total useful electrical energy generated from the PV (E_{PV}). Equation (16) shows how this is achieved [74]. Annualised cost consists of annual capital cost, annual replacement cost, annual maintenance and operation cost over a period of time.

$$LCOE = \frac{LCC_{1\ year}}{E_{PV}} \tag{16}$$

$$LCC_{1\ year} = \frac{LCC}{\left[\frac{(1+i)^N}{i(1+i)^N}\right]} \tag{17}$$

where i is the market interest rate and N is the system life span in years.

The NPV of a system is determined using equation (18) [59].

$$NPV = \sum_{n=0}^{k} \frac{CF_n}{(1+IRR)^n} \tag{18}$$

where k is the life span of investment, CF_n is the cashflow or initial investment at period n, and IRR is the internal rate of return.

2.8 System reliability indices

Reliability indices are indicators or parameters used by system planners to measure the quality of electric power being supplied to customers. These reliability indices are necessary for system planners and operators to know what to improve, or what is required to supply uninterrupted power to customers or to improve the robustness of the system. Reliability indices measure the duration of power outage, frequency of outages, availability and time of restoration. The three most common reliability indices used to measure the reliability of a distribution system are System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI) and Customer Average Interruption Duration Index (CAIDI) [2, 63, 64].

SAIDI is defined in equation (19). It is the duration of power interruption to customers per year [65]. This index measures the total duration of power outage to all customers served.

$$SAIDI = \frac{\sum N_i \, r_i}{N_T} = \frac{Total\ outage\ duration\ in\ hours}{Number\ of\ customers\ supplied} \tag{19}$$

where N_i is the total number of customer interruption by each incident, r_i is the time of restoration of each incident and N_T is the total number of customers connected at that time during the incident.

The number of times per year power supply to a customer is interrupted is defined in equation (20). This index measures the frequency of interruption per customer.

$$SAIFI = \frac{\sum N_i}{N_T} = \frac{Frequency\ of\ outages}{Number\ of\ customers\ supplied} \tag{20}$$

The length of power interruption according to the number of customers affected by the incident is defined in equation (21). This index measures the average duration of power outage for each customer affected.

$$CAIDI = \frac{SAIDI}{SAIFI} = \frac{Sum\ of\ customer\ interruption\ duration}{Total\ number\ of\ customers\ interrupted} \tag{21}$$

Renewable energy such as solar can help in meeting the growing demand and addressing the problem of the regular power outages in Nigerian residential sector. Some major projects are currently being implemented while others are being commissioned. At present, the country has invested more than US$20 billion in solar power projects [19] with the aim of reducing reliance on the national grid by building SAPVS in rural and urban centres to support electricity supply in the country.

2.9 Summary of literature

A theoretical review of residential electricity consumption, techniques of modelling a residential load profile, energy trends in the Nigerian residential sector, the potential for solar energy in Nigeria and SAPVS configuration, as well as economic feasibility criteria, has been presented. The method of determining sample size and data collection in locations where electricity consumption data is unavailable has been identified. This method will be employed to closely predict a realistic load profile for different sociodemographic groups in Ibadan city, Nigeria. Reliability indices used to determine the reliability of electricity supply in any location have also been presented. In section 2.5, solar radiation was identified to be high in Nigeria which makes it a good location for SAPVS implementation. These theoretical reviews constitute the foundation for this study.

From the literature reviewed, different approaches have been used to optimise the size of a SAPVS but no emphasis has been placed on considering the stochastic nature of residential electricity consumption patterns as borne out by different sociodemographic groups. The studies in [25, 40] identified solar radiation and the load profile of households as stochastic and noted that sizing a SAPVS based on the average load demand can lead to over-sizing or under-sizing of the system for a group of customers. However, only the stochastic nature of solar radiation was considered for optimisation in [25].

Two major limitations to the optimal sizing of a SAPVS were identified in [80]. The first limitation is the use of only monthly or daily solar radiation data and an average load demand as input when sizing [15, 73, 78, 79]. The second limitation is calculating system cost before determining the optimal size of the system [15, 71, 84]. The authors identified that using average load demand when sizing can lead to over-sizing of the system for a group of customers but only discovered this at the end of their study.

A comprehensive literature review in [6] identified that appliance-related factors affecting the rate of residential electricity consumption have been studied less frequently than other factors. It is, therefore, necessary to investigate these appliance-related factors and the stochastic nature of residential electricity consumption in achieving an accurate optimisation since consumption patterns of households differ. This present study aims to address these limitations and bridge the gap by proposing an approach to sizing a SAPVS which considers the stochastic nature of residential electricity consumption.

Chapter 3 Methodology

This chapter introduces the method that is used to conduct a survey of low-income, middle-income and high-income households in Ibadan city, Nigeria. The second section shows way of finding a realistic residential load profile was obtained from the survey data, appliance categorisation, appliance power rating and period of usage. The subsequent sections discuss the methods that is utilized to determine the reliability of electricity supply in Ibadan city and the sizing method of a SAPVS, its economic analysis as well as battery and PV component selection.

3.1 Residential electricity consumption survey

The modelling of residential electricity consumption is highly complex due to its stochastic nature; however, data input from household sociodemographic variables and information on electrical appliance usage can make the modelling process less complicated and more realistic. Therefore, for this study, a questionnaire tool was employed to obtain household electrical appliance usage and sociodemographic variables in order to understand the behaviour of occupants. The survey data was further used to model a residential load profile for a typical household.

3.1.1 Background on the study location

Ibadan city is the largest traditional city in Sub-Saharan Africa and home to 2,889 people per square kilometre [27]. The city is located on 7.3775° N and 3.9470° E in the south-western part of Nigeria. It is the capital of Oyo state and the metropolis has a population of 3 million people [27].

The city, just like every other part of Nigeria, has two major seasons, the wet and dry seasons, which could control the effects of solar radiation and PV performance [97]. The wet season is influenced by the tropical marine air from the Atlantic Ocean while the dry season, also known as harmattan, is accompanied by a dry dusty wind from Sahara Desert influenced by the tropical continental airmass [97]. The way the city is structured shows that majority of the land is used for residential purposes, which makes it a good location for this study.

In this study, the members of the sample population were classified based on income level as income has a significant positive relationship to household electricity consumption [6]. Households were classified into low-income, middle-income and high-income groups based on the Federal Government of Nigeria housing policy average annual income of ₦100,000 (US$400), ₦1,400,000 (US$4,000) and ₦4,000,000 (US$13,000) respectively [98-100].

A comparative study of locational variation in Ibadan city has been done previously [101]. The study identified Bodija (7.376° N and 3.907° E) as a residential area occupied by the high-income earners, Molete (7.359° N and 3.881° E) as a residential area occupied by the middle-income earners, and Mapo (7.366° N and 3.897° E) as an area occupied by low-income earners.

3.1.2 Design of questionnaire

The questionnaire used to obtain data in this study was designed to capture the dwelling characteristics, sociodemographic characteristics and major electrical appliance usage with duration and frequency of use. Section 1 of the questionnaire captures the household dwelling characteristics, Section 2 captures the sociodemographic characteristics, Section 3 captures lighting use pattern, and Section 4 captures the appliance ownership, duration and period of use. A sample of the questionnaire is shown in Appendix D.

The content of the questionnaire is similar to the study conducted in [52] in Tema city, Ghana. However, the major difference is that the questionnaire used in this study considers each household electrical appliance duration of use as well as the period of usage.

The major daily electrical appliances considered here were frequency selected based on Nigerian household electrical appliance use as studied in [7]. These appliances were categorised into cooking, entertainment, laundry, cooling and lighting, as shown in Table 1 below. The appliances were selected according to their possible contribution to the daily load curve, basic appliances found in a typical household and appliances with high power ratings. Space heating appliances were not considered for this study because, in Nigeria, households are more concerned with cooling rather than heating because of high temperatures.

Table 1: Electrical appliance categorisation

Category	**Appliances**
Cooking	Microwave, Electric kettle, Hot plate cooker, Food blender, Water boiler and Electric oven.
Cooling	Refrigerator, Freezer, Air conditioner, and Electric fan.
Entertainment	Computer/Laptop, Television, Video game, Mobile phone and Radio/Home theatre.
Laundry	Washing machine and Electric Iron
Lighting	Incandescent bulb and Energy-saving bulb.

As frequency and duration of appliance use can have a significant effect on residential consumption patterns, the questionnaire was designed to capture this information as well. The period of use was classified into morning (6am to 12pm), afternoon (12pm to 6pm), evening (6pm to 12am) and night (12am to 6am), as shown in Table 2.

Table 2: Period of appliance usage

Period	**Time**
Morning	(6am – 12pm) or 06:00 to 12:00
Afternoon	(12pm – 6pm) or 12:00 to 18:00
Evening	(6pm – 12am) or 18:00 to 00:00
Night	(12am – 6am) or 00:00 to 06:00

The questionnaire was also designed to capture the employment type of respondents. The reason is to investigate the correlation between the period of appliance use and employment, as employment type may have an influence on occupancy or period of appliance use. For example, a full-time employee would mostly leave the house in the morning for work and maybe return home for lunch if he lives close by, or else would return in the evening. High school children may also follow the same pattern depending on the household. A flowchart of the research methodology and questionnaire framework employed for this study is shown in Appendix E.

3.1.3 Method of participant recruitment

Flyers, as shown in Appendix C, and an advertisement aired on a local radio station, were designed to recruit participants for this study. A local radio station which broadcasts in Yoruba language, as the native language of the city, was used specifically to target the illiterate households. An information sheet in English or Yoruba language (depending on their preferred language) was distributed to the potential participants who indicated their interest in taking part in the study. Questionnaires were later distributed to participants who were willing to continue with the study after going through the information sheet.

A research assistant was employed to assist in distributing the flyers, information sheet and questionnaires because of the limited project time. For illiterate households encountered during the survey, the questionnaire was read to them in Yoruba language and their responses were recorded by the researcher on their behalf.

The survey was carried out between the months of November 2018 and January 2019 which is the dry season period in Nigeria [102]. Therefore, the effect of seasonal variation could not be determined.

Based on the statistical evaluation as discussed in Chapter 2, a total of 450 questionnaires were required in the selected study location. 150 were distributed to the Mapo region (low-income area), 150 to Molete (middle-income area) and 150 to Bodija (high-income area) to obtain the data for residential electricity consumption. From the Mapo region, only 101 questionnaires were retrieved from households; in Molete, 126 questionnaires were retrieved; while in Bodija, only 88 questionnaires were retrieved. This made a total of 315 questionnaires which were used for analysis using an Excel spreadsheet.

3.1.4 Survey summary

The method used in the survey of low-, middle- and high-income groups in Ibadan city has been presented. A total of 450 questionnaires were distributed but only 315 were retrieved and used for analysis. The questionnaire was designed for household heads (HHs) to complete and it was strictly anonymous. Agreeing to complete the questionnaire was regarded as consent from the participants.

Table 3 shows the percentage of household respondent for each income category. The high-income group had a lower proportion of respondents as a result of unavailability of the HH during the survey exercise. However, the response rate from each category was compared by normalising the data set obtained.

Table 3: Survey respondent percentage

Classification	Average annual income	Respondent percentage
Low-Income	≤ ₦100,000 (US$400)	59%
Middle-Income	₦1,400,000 (US$4,000)	84%
High-Income	≥₦4,000,000 (US$13,000)	67%

3.2 Residential load profile modelling

Based on the review presented in Chapter 2, a bottom-up approach is employed to model hourly residential load profile for low-, middle- and high-income groups in Ibadan city using the survey data. With this method, three basic input items of information are required: firstly, the sociodemographic characteristics of the household; secondly, the electrical appliance duration of use; and, thirdly, the period of appliance usage.

This information is sufficient to understand the overall daily occupancy behaviour and electricity consumption pattern of households. For the purpose of this study, only income and employment sociodemographic variables were analysed. It should also be noted that this study did not separate weekday and weekend load profiles, a distinction which is beyond the scope of study.

In order to investigate the contribution of each appliance to total electricity consumption, the duration of appliance use as well as the power consumption of each appliance was determined by taking the average power rating value of four different product models obtained from the manufacturers' websites, for example Samsung, LG and Philips, as shown in Appendix F. This study proposes an improvement in the appliance power rating method studied in [7], where the authors used appliance ratings from an e-commerce website to determine the power rating of household appliances. By contrast, in this study, the appliance power ratings were obtained directly from the manufacturers' websites which is considered more accurate and reliable. The problem with the method proposed in [7] is the accuracy of the sales data collected from the e-commerce website, because sellers may not be professionals or may tend to provide misleading information.

Appliance ownership characteristics, which means the number of electric appliances owned by a household, were investigated using an Excel spreadsheet to determine the relationship to electricity consumption. However, for analysis purposes, the average quantity of appliances owned by a typical household belonging to a particular income group was presented to represent all households in that group. With this information, a realistic load profile of a typical household in the low-income, middle-income and high-income group was analysed and modelled according to the responses provided in the questionnaire.

3.3 Reliability of electricity supply in Ibadan city

In this study, the reliability of the distribution system in Ibadan city was investigated according to the reliability indices discussed in Chapter 2. The city is connected to the national grid and Ibadan Electricity Distribution Company (IBEDC) is the utility company that supplies electricity to the communities in the city and also to Ogun state, Kwara state, Kogi state, Osun state and Niger state.

To investigate the reliability indices for Ibadan city, two years of data from January to December for the years 2017 and 2018 for the city was collected from IBEDC. The data collected from the power company shows the Ibadan city interruption report for each year, including all the feeders and the areas served, the number and duration of outages on a 24-hour basis for each feeder, the number of customers interrupted, the number of customers restored, the time of restoration, the type of fault and the total number of customers served. Planned outages were not considered for this study as they are not caused by component or system failure; only emergency and system outages were considered for analysis. The results obtained in this analysis were then compared with other distribution system reliability data that has been studied in Nigeria to determine the present state of electricity supply in the city.

3.4 Method for optimal sizing of SAPVS

Closely predicted residential load profiles for low-, middle- and high-income groups as well as solar irradiation data were used as input for sizing a SAPVS, and SAM software were used for simulating the overall system performance. Economic feasibility criteria such as LCOE, discussed in Chapter 2, was used to determine the adoption feasibility of the proposed system for each income group.

Meteonorm could be used to obtain a typical meteorological year (TMY) data for any location on earth [75, 80]. This software was utilised to obtain the solar irradiation data as well as ambient temperature for the Mapo, Molete and Bodija regions because the performance of a PV system also depends on meteorological conditions such as ambient temperature and solar radiation [80].

For the sizing calculation, growth in the community was considered to be at a rate of 5%. This means that, for the PV design, the system capacity was increased by 5% to accommodate growth.

A Canadian solar PV module (CS6P-250P-EA) was selected for this study due to its availability in Nigeria and a PV module comparison [12]. The module characteristics were obtained from the manufacturer's data sheet and are shown in Table 4. This module is also available in SAM software library for simulation purpose.

Table 4: Single PV Module data

PV module information	
Type	Polycrystalline
Maximum power at STC (P_{max})	250W
Optimum operating voltage (V_{mp})	30.1V
Optimum operating current (I_{mp})	8.30A
Open circuit voltage (V_{oc})	37.2V
Short circuit current (I_{sc})	8.87A
Temperature coefficient (V_{oc})	-0.34 %/°C
Temperature coefficient (I_{sc})	0.065%/°C

As discussed in Chapter 2, the number of PV modules is determined using equation (4) and the size of the PV array is determined using equation **Error! Reference source not found.**.

The inverter capacity selected for this investigation is 20% higher than the typical household AC load demand for each income group as earlier identified in Chapter 2. Several inverter models are available in the SAM software library for simulation purposes. However, an ABB inverter was selected for analysis due to its availability in Nigeria. The equation to determine the number and capacity of inverters required is given in equation (5) The inverter is assumed to be replaced every 15 years [103].

For the battery sizing, a two-day autonomy period was applied in this study. This means that the battery must be able to supply the required energy for two days when there is no sunshine or during cloudy days. A lead-acid VRLA GEL battery was selected because lead-acid batteries are readily available in Nigeria in case of replacement needs and this specific battery model is available in the SAM software library for simulation analysis. The replacement time for the battery is assumed to be 10 years [103]. The battery's data sheet was obtained from the manufacturer and is shown in Table 5.

Table 5: Selected battery specification

Battery Information	
Type	Gel VRLA
Nominal battery bank voltage	48V
Rated capacity	150Ah
Nominal bank capacity	7.2kWh

The battery‘s self-discharge rate is assumed to be 20% [67] of the state of charge which means only 80% of the battery charge is usable. Also, it is assumed that the battery degrades to 20% over a 10-year period which means only 80% of the battery is usable during its life span [67]. Therefore, equation (9) is used to obtain the required battery bank capacity (B_{cap}). In this study, the battery voltage of 48V is used as the system voltage [12, 67, 68, 104].

For this study, only the worst-case and best-case PV performance scenarios, obtained after SAM simulation, are presented. The best-case scenario would be when the optimised system is effectively able to supply the load requirements for a typical household while the worst-case scenario would be when the system is not able to effectively supply the load demand, maybe as a result of low solar radiation or other factors.

3.4.1 Economic feasibility

Prices were evaluated based on the US solar PV system cost benchmark obtained from [75, 105]. The installation labour cost is assumed to be 2.0% [75] of the investment cost and the system is assumed to be roof mounted so there is no cost for land.

A 25-year system life span was considered for cost analysis in this study because PV modules generally have a 25-year life span [80, 103]. The system degradation rate was assumed to be 0.5% [75]. The economic feasibility of the system was determined using the LCOE, IRR, NPV and SPBP. An evaluation was done assuming 50% equity on the investment cost and the other 50% on a loan from the bank, with a loan period of five years. This is because some households, especially in the low-income and middle-income groups, may not be able to afford the full initial cost of the system installation.

The annual interest rate on bank loans in Nigeria is set at 22% by the Central Bank of Nigeria [106]. Electricity cost in Ibadan city was obtained from Nigeria Electricity Regulatory Commission (NERC) [107]. Also, a feed-in tariff system has been introduced in Nigeria [17] at a rate of $0.23/kWh which was adopted to determine the system benefit–cost ratio (BCR).

Chapter 4 Results and findings

In this chapter, the appliance ownership characteristics that have a significant positive relationship to electricity consumption in the low-, middle- and high-income group is presented in Section 5.1. Also, the duration and period of appliance use, as well as the employment status of the HH, are presented to determine their correlation. The subsequent sections show the modelled load profile result of a typical household in each income group as a representative of the entire group while Section 5.5 presents results on the reliability of electricity supply in Ibadan city. The optimal sizing result for a SAPVS using the modelled load profile and solar irradiation data as input is presented as well as the overall system performance and economic feasibility of the proposed system.

4.1 Appliance ownership characteristics

Figure 3 shows the survey result for appliance ownership characteristics in the low-income group.

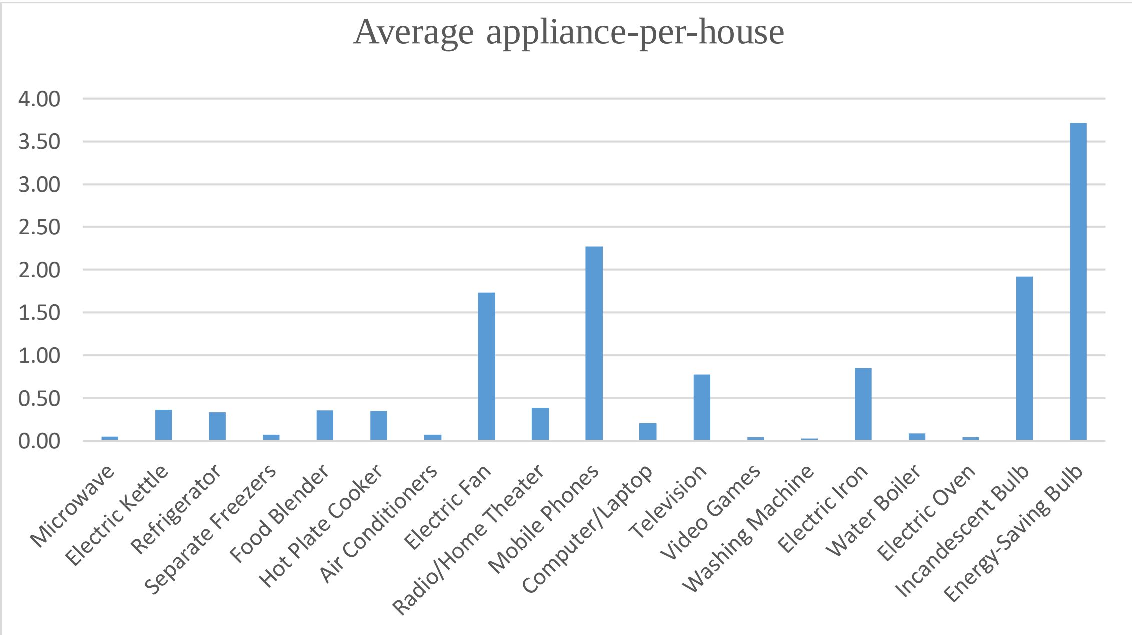


Figure 3: Average electrical appliance ownership in low-income group

From the result, it can be seen that there is a high level of ownership of energy-saving bulbs in this group. Other appliances that have a high ownership level are mobiles phones, incandescent bulbs, electric fans, electric irons and televisions. A typical household in this low-income group has an average of four energy-saving bulbs, two incandescent bulbs, one electric iron, one television, two mobile phones and two electric fans installed.

The appliance ownership characteristics of the middle-income group are shown in Figure 4 below.

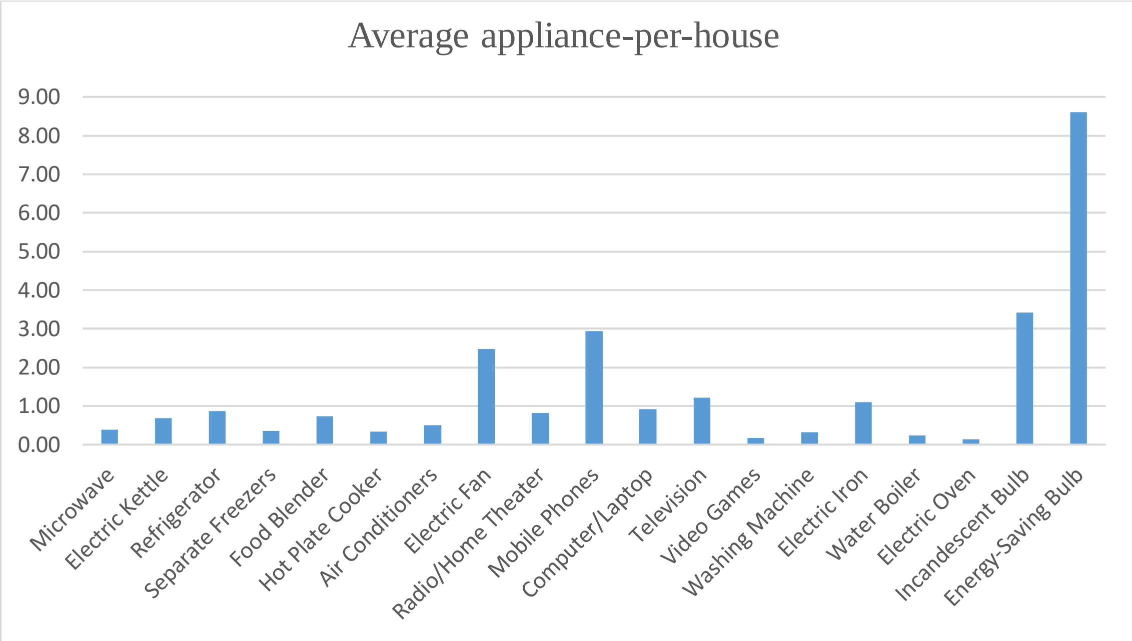


Figure 4: Average electrical appliance ownership in middle-income group

From the result shown, it can be seen that the appliance ownership level in the middle-income group is higher than in the low-income group. For example, households belonging to this group have a higher level of ownership of electric fans, bulbs and other appliances except for electric irons. Ownership of electric irons remains the same as the low-income group. A typical household belonging to this group has an average of one electric iron, nine energy-saving bulbs, four incandescent bulbs, one television, one computer, three mobile phones, three electric fans, one refrigerator, one food blender, one electric kettle and one home theatre set.

Figure 5 shows the survey result for appliance ownership level in the high-income group.

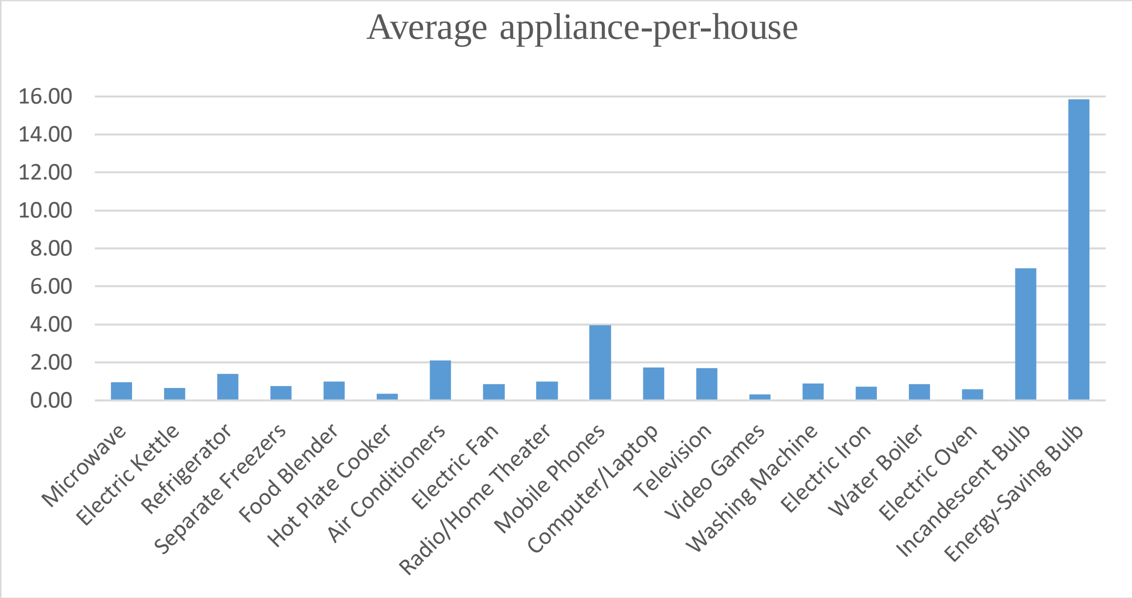


Figure 5: Average electrical appliance ownership in high-income group

From the survey result, it can be seen that a typical household belonging to the high-income group has higher ownership level of electrical appliances except for electric irons, electric fans, home theatres and food blenders, for which there is the same ownership level as the middle-income group. However, the ownership of air-conditioners, televisions, computers, washing machines, microwaves, mobile phones, electric bulbs and electric ovens is higher than the middle- and low-income groups. A typical household belonging to this group has an average of 16 energy-saving bulbs, eight incandescent bulbs, one electric oven, one water boiler, one electric iron, one washing machine, two televisions, two computers, four mobile phones, one home theatre, one electric fan, two air-conditioners, one food blender, one separate freezer, two refrigerators, one electric kettle and one microwave.

4.2 Time of appliance use

Information obtained on the duration, and time of the day these appliances are most commonly used was analysed, and Figure 6 below shows the survey results according to the responses received in the low-income group.

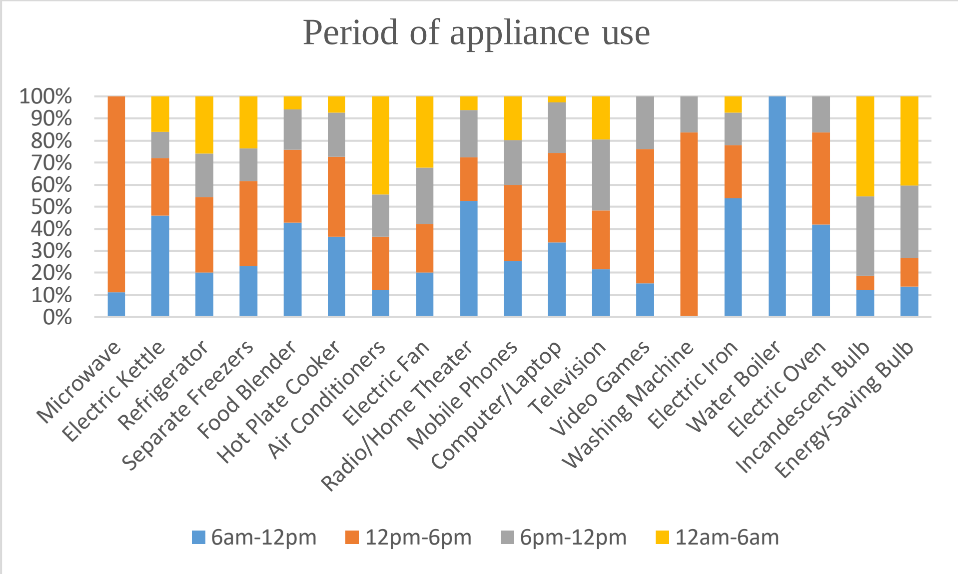


Figure 6: Percentage period of appliance use (low-income group)

According to Figure 6, microwave for example, are mostly used in the afternoon period (12pm-6pm) by the low-income group. Only 10% of the respondents make use of microwave in the morning period. A typical household belonging to this group uses electric bulbs mostly in the night and evening periods and 11% still leave their bulbs turned on in the morning period. An electric iron is mostly used in the morning and afternoon period while electric fans and televisions are used in all periods of the day, as is the charging of mobile phones.

The period of appliance use in the middle-income group is shown in Figure 7 below.

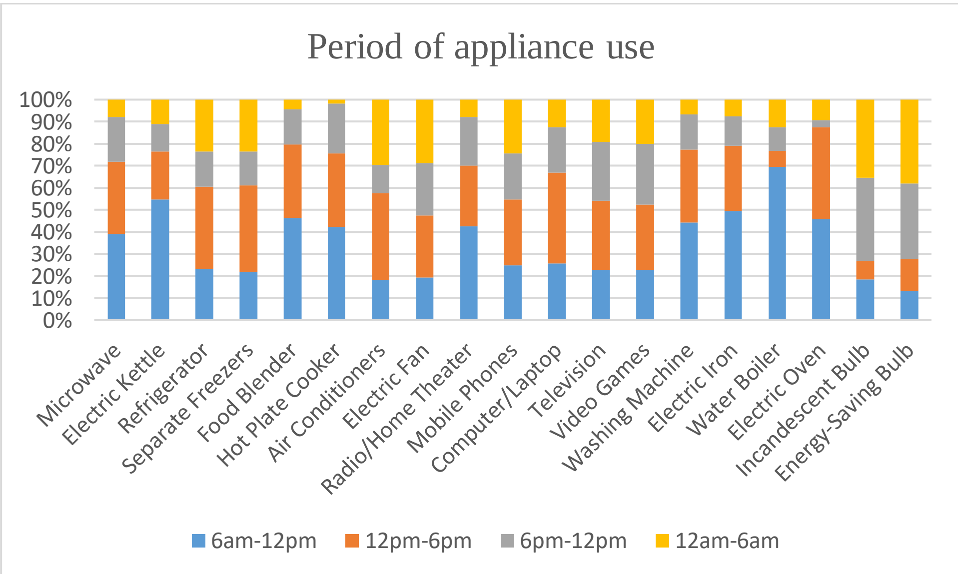


Figure 7: Percentage period of appliance use (middle-income group)

From the results as shown in Figure 7, appliances are used in morning, afternoon and evening periods. Microwave for example, are used mostly in the morning, afternoon and evening periods, while only 8% of the respondents use their microwave in the night period. Cooling and lighting appliances such as electric fans and bulbs, are used most frequently in the night period.

Figure 8 below shows the survey result in the high-income group.

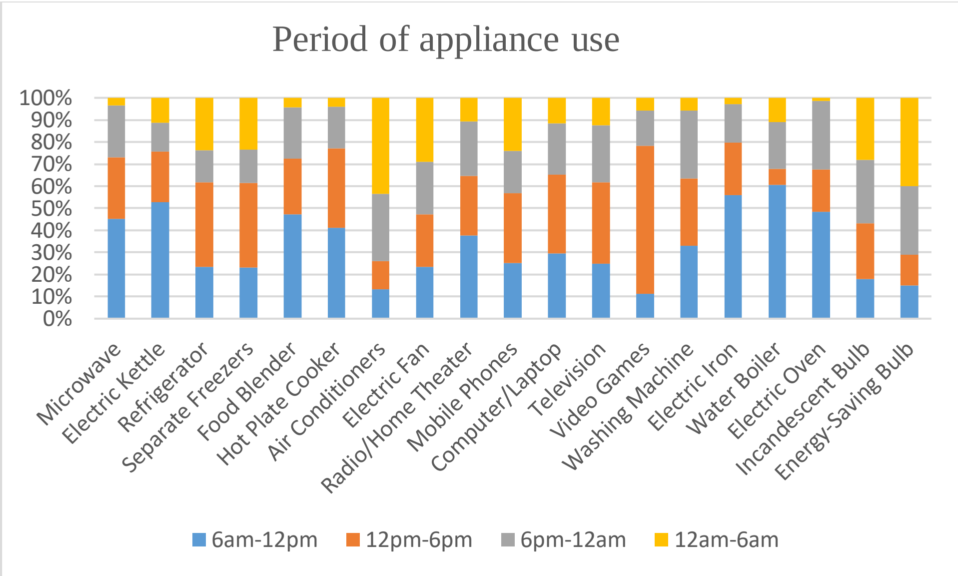


Figure 8: Percentage period of appliance usage (high-income group)

From the results shown in Figure 8, it can be seen that the period of appliance use varies from one appliance to another. Cooling and lighting appliances are mainly used in the night period while entertainment appliances, for example, video games, are used most frequently in the afternoon period with television and computer being used equally across all period of the day.

4.3 Employment level of household head (HH)

Information on the employment type of the HH was collected and analysed as full-time, part-time, unemployed or retired to determine the correlation between appliance ownership as well as period of appliance use and the employment level of the HH. It should be noted that some unemployed HHs have businesses that generate income but their income level fluctuates with time

The survey results for the relationship between appliance ownership and HH employment type for the low-income group is shown in Figure 9 below.

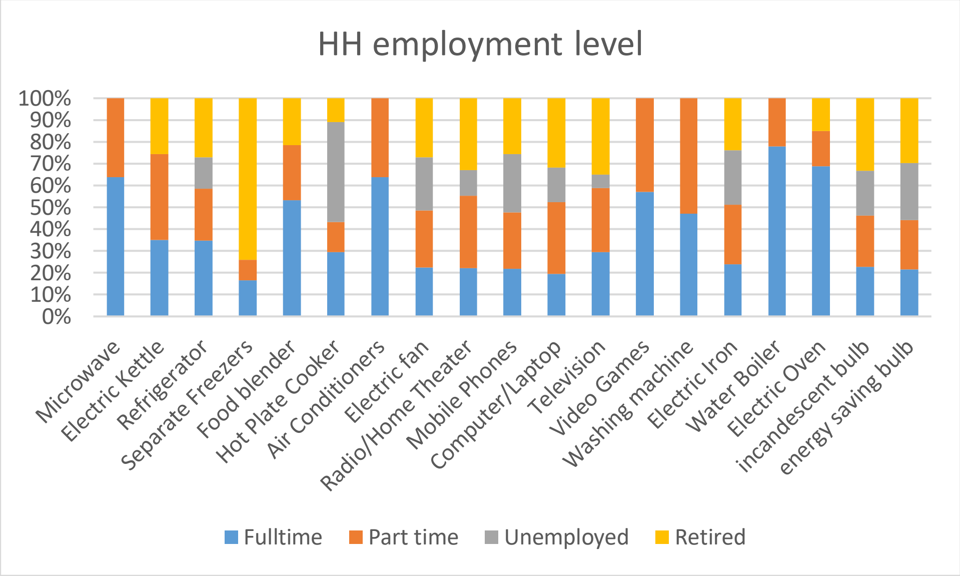


Figure 9: Appliance ownership and the employment level of HH (low-income group)

From Figure 9 above, there is a correlation between employment type of the HH and appliance ownership. Expensive appliances, for example, air conditioners, washing machines and water boilers, are mainly owned by the full-time and part-time workers. In contrast, the less expensive appliances, for example, electric fans, lighting bulbs and electric irons are owned by the full-time, part-time, unemployed and retired HHs. However, there was no correlation found between time of appliance of use and HH employment level which could be as a result of the other occupants living in the house.

Figure 10 shows the relationship between appliance ownership and the employment level of the HH in the middle-income group.

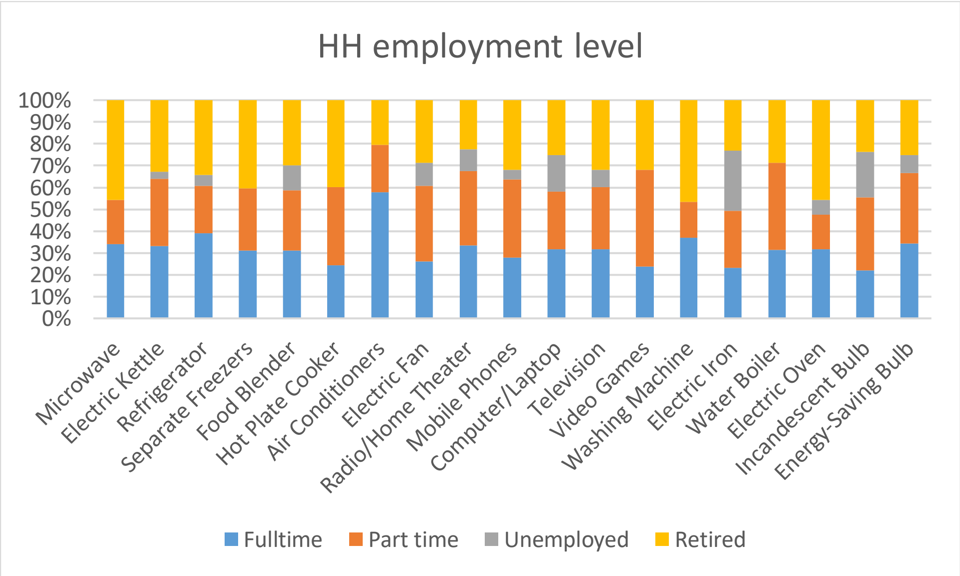


Figure 10: Appliance ownership and the employment level of HH (middle-income group)

From the results shown in Figure 10, it can be observed that fewer HHs in this group are unemployed compared to the low-income group while there are more full-time, retired and part-time workers. In this income group, expensive appliances, for example, washing machines and air conditioners, are mainly owned by the full-time, part-time and retired HHs while other, less expensive appliances, for example, electric bulbs, are owned regardless of the employment type of the HH. Again, there was no correlation found between appliance period of use and the employment level of the HH in this income group.

In Figure 11 , the relationship between appliance ownership and the employment level of the HH in the high-income group is shown.

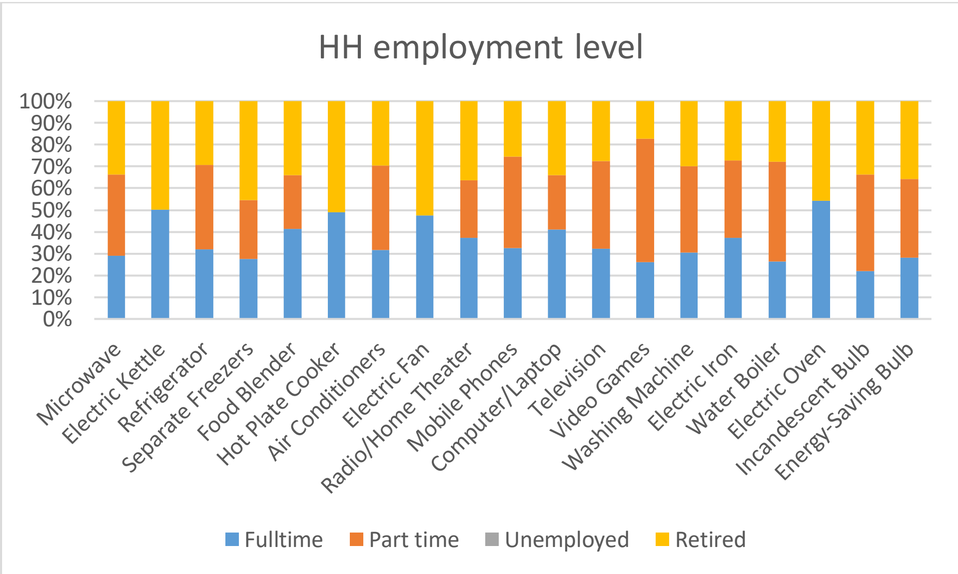


Figure 11: Relationship between appliance ownership and the employment level of HH (high-income group)

The results presented in Figure 11 show that there are no unemployed respondents in the high-income group. The group consists mainly of full-time, part-time and retired workers. Only full-time and retired HHs own electric kettles, hot plate cookers, electric fans and electric ovens. All other appliances are owned by the full-time, part-time and retired HHs. As for the low- and middle-income groups, there was no relationship found between appliance period of use and the employment level of the HH in this group.

4.4 Estimated load profile

A realistic load profile for a typical household in the low-income, middle-income and high-income groups was analysed and modelled. Figure 12 below shows the modelled load profile of a typical household in the low-income group.

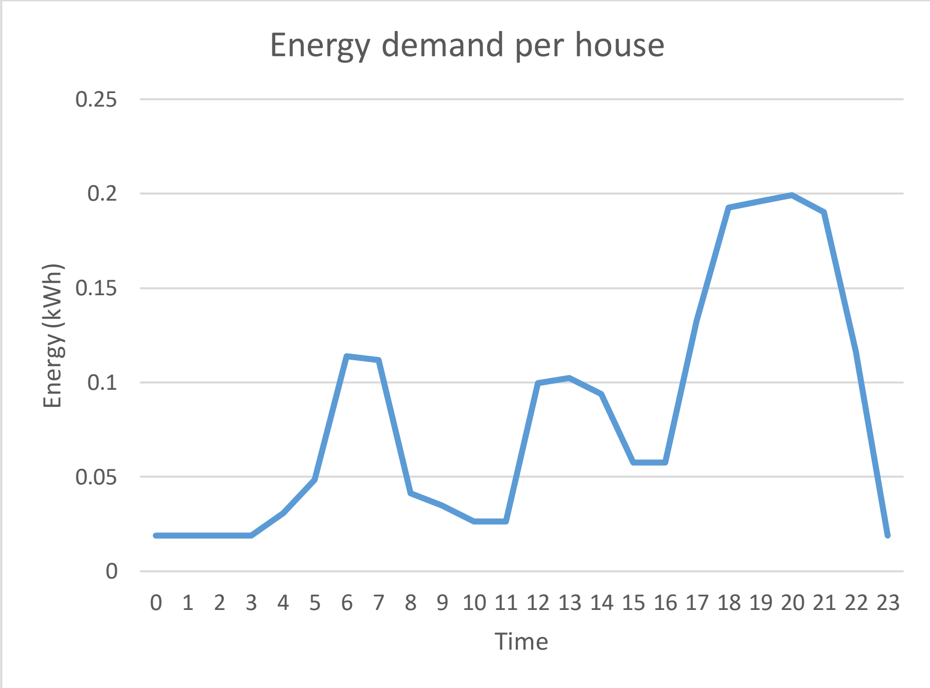


Figure 12: Modelled residential load profile for low-income group.

The results in Figure 12 show that a typical household in this income group consumes 1.97kWh of energy daily and has a maximum peak demand of 0.2kWh in the evening period. From the load profile, three distinct peaks can be identified. The first peak is in the morning period from 5am to 8am. The second peak is in the afternoon period from 12pm to 2pm. The maximum peak is observed from 6pm to 9pm.

Figure 13 shows the modelled load profile of a typical household in the middle-income group.

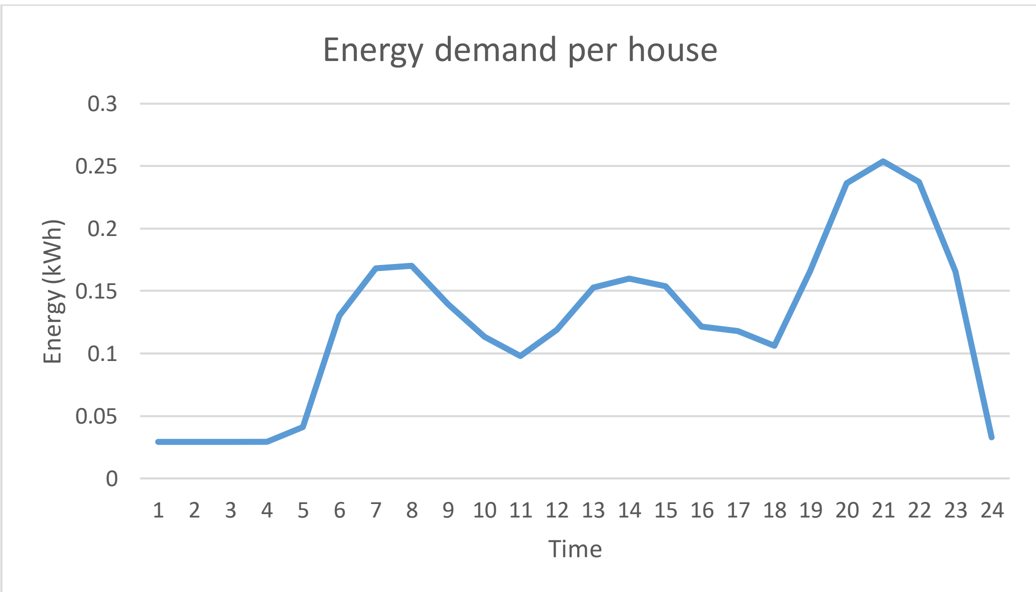


Figure 13: Modelled residential load profile for middle-income group.

The results in Figure 13 show that a typical household in this income group consumes 3.01kWh of electricity daily and has a maximum peak demand of 0.26kWh in the evening period. The load profile of the middle-income group also has three peaks. The first peak is from 5am to 8am, the second peak is from 1pm to 3pm the third peak is from 8pm to 10pm. The peaks are similar to the peak periods in the low-income group; however, the load profile for the middle-income group is flatter in the morning and afternoon periods.

Figure 14 shows the load profile result of a typical household in the high-income group.

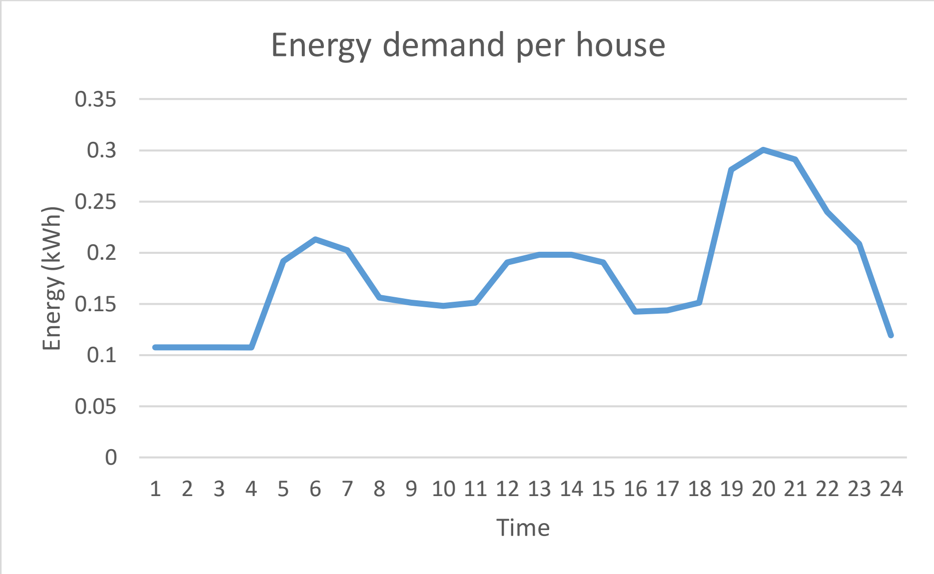


Figure 14: Modelled residential load profile for high-income group.

A typical household in this group consumes 4.3kWh of electricity daily and has a maximum peak of 0.3kWh in the evening period. The load profile in the high-income group is flatter compared to the low-income and middle-income groups and it has just one significant peak in the evening period (from 7pm to 9pm).

4.5 Reliability of electricity supply in Ibadan city

From the IBEDC data collected as discussed in Section 4.3, 21 feeders (33kV) that serve the residential regions of the city were selected for analysis to determine the customer hours interruption (CHI) for each year, number of customers interrupted, monthly CAIDI and the overall reliability using reliability indices. Figure 15 shows the monthly CHI for the years 2017 and 2018.

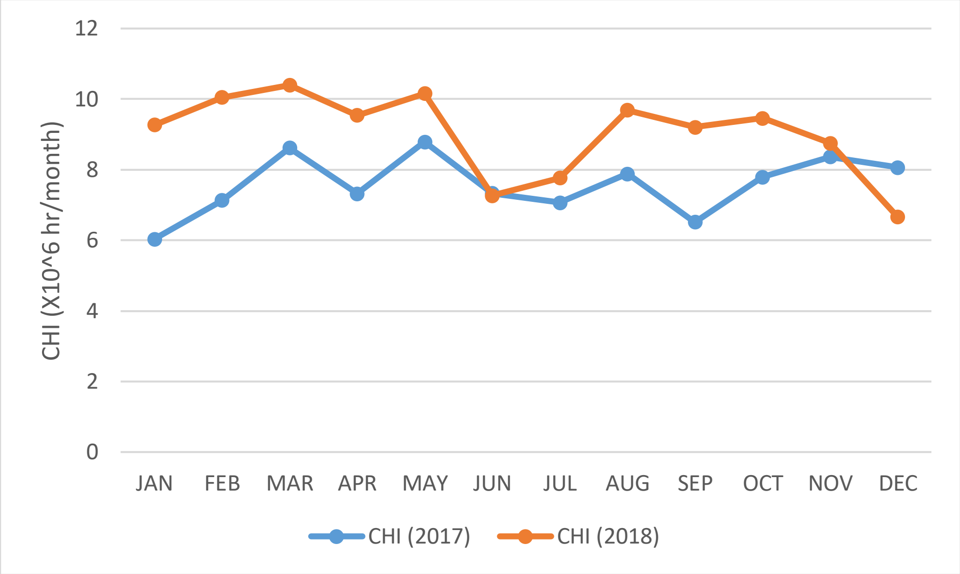


Figure 15: Monthly customer hours of interruption

From the results presented in Figure 15 above, it can be seen that there was an increase in the rate of CHI in the year 2018 compared to the year 2017. In 2017, the month of May recorded the highest CHI while in 2018, March had the highest CHI. The CHI values for 2017 and 2018 were similar in the month of November. However, in December, there were more CHI in 2017 than in 2018. This is the only month were CHI for the year 2017 is greater than in 2018. In December 2018, the duration of CHI is the lowest of any month in that year.

Figure 16 shows the monthly number of customers interrupted in the feeders considered for the years 2017 and 2018.

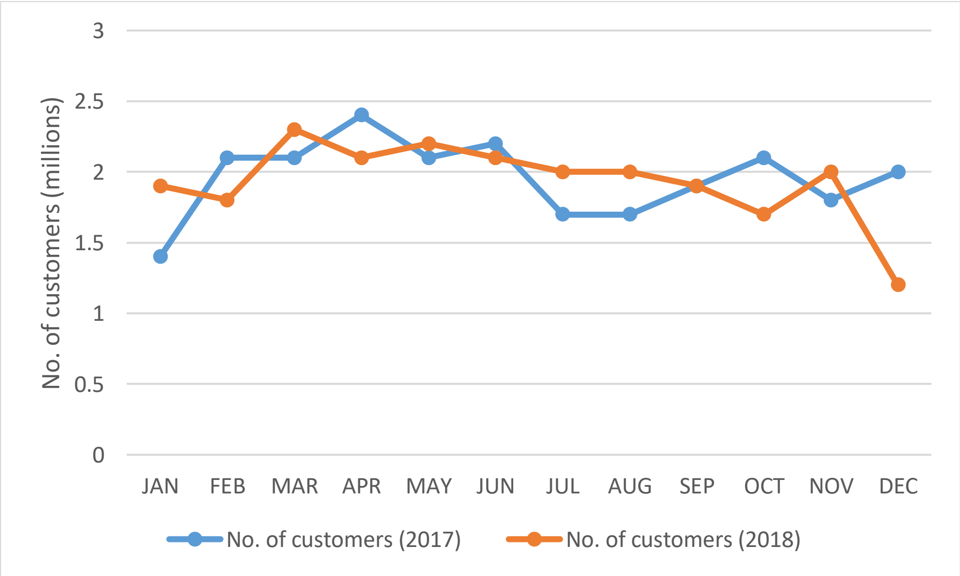


Figure 16: Number of customers affected monthly

From Figure 16 above, it can be seen that the number of customers interrupted in 2018 is higher in March, May, July, August and November when compared to the year 2017. The energy planners for the city need to put this into consideration to reduce this rate of customer interruption because, if no action is taken, this interruption rate might increase in subsequent years.

Figure 17 shows the monthly CAIDI result for the years 2017 and 2018.

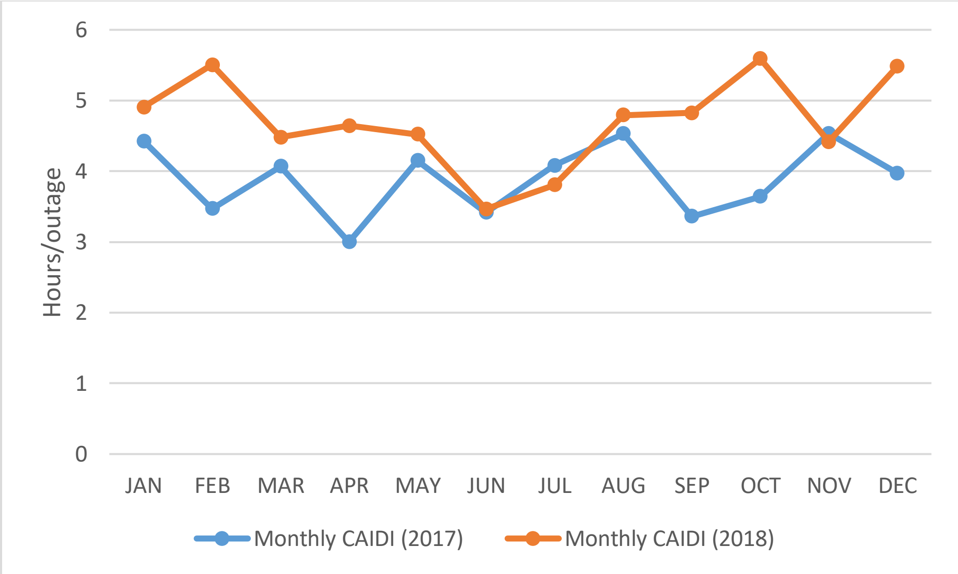


Figure 17: Monthly customer average interruption duration index

From the CAIDI results shown in Figure 17, it can be seen that the month of October has the highest number of hours of outage for every interruption in the year 2018 while in 2017, August had the highest customer outage duration.

4.5.1 Summary of reliability

The overall reliability of Ibadan city's electricity distribution system is determined using the reliability indices discussed in Chapter 2. Table 6 gives a summary of the reliability indices of the feeders considered in Ibadan city.

Table 6: System reliability indices

Year	SAIDI (hours/year)	SAIFI (f/customer/yr)	CAIDI (hours/outage)
2018	856.49	184.33	4.65
2017	782.19	203.59	3.84

From the results shown in Table 6 above, a CAIDI value of 4.65 hrs/outage in the year 2018 shows that it took an average of 4.65 hours for power to be restored in the region for each interruption experienced while in 2017 it took an average of 3.84 hours. This means that customers had a blackout duration of approximately five hours in 2018 before power was restored and approximately four hours in 2017 before power was restored for every incident.

The SAIFI index value shows the frequency of outages per customer in a year. This means that customers had a higher frequency of interruptions in 2017 than in 2018. Considering this index value alone, it could be easily assumed that the system performed better in 2018 than in 2017, but that is not the case when the system is considered across the three reliability indices.

The SAIDI index value shows the duration of outage for each customer served in a year. Customers had longer outage duration in 2018 when compared to 2017. If this is converted to days, it means that customers had 35.68 days/year of power outage in 2018 and 32.59 days/year in 2017. This could be as a result of aging infrastructure, lack of maintenance, overloading, electricity theft and other possible factors. Considering that solar energy is highly abundant in Nigeria [15], as discussed in Section 2.5, an optimised alternative source of energy in the form of SAPVS can help to supply electricity to households in the city.

4.6 Optimal sizing of SAPVS

Considering a two-day autonomy using equation (9), a DOD of 0.8 and a B_{loss} of 0.8 as discussed in Section 3.4, the required energy storage capacity of the battery bank (B_{cap}) is 6.25kWh for a typical household in the low-income group, 9.38kWh for the middle-income group and 13.44kWh for the high-income group. These values, as well as the predicted load profile, were inputted into the SAM software for optimal sizing and the sizing results are shown in Table 7 below.

Table 7: Summary of system sizing components

Income category	Daily energy consumption (kWh)	Number of inverters	Number of PV modules	Total module area (m^2)	Number of batteries
Low-income	1.97	1	4	6.2	1
Middle-income	3.01	1	6	9.3	2
High-income	4.3	1	8	12.4	2

Table 7 above, shows the daily energy required in a typical household for each income group, number of PV modules, number of inverters, total module area and the number of batteries. The sizing simulation process for low-, middle- and high-income group is shown in Appendices H, I and J respectively. For the number of PV modules, equations (2), (3), and (4) were used to verify the simulation results obtained considering a system voltage of 48V and module voltage of 30.1V. The result agreed with the SAM simulation result.

With the sizing results obtained above, the predicted load profile for each income group as well as solar radiation data were used as inputs to investigate the PV system performance on a worst-case and best-case scenario in order to determine the system adoption practicability.

4.7 PV system performance

From the simulation results shown in Appendices K, L and M, the Molete region (middle-income group) has the worst-case scenario in the month of July and the best-case scenario in the month of November. The reason for this could be that solar radiation is usually low in July, as shown in Figure 19 below. The month of July has the highest peak period of rainfall which results in cloudy days, while November is a dry season period with clearer skies and more sunshine, and consequently the system performance is highest in the month of November [102].

Figure 18 shows the hourly plane of array (POA) solar irradiance, ambient temperature and cell temperature for the Molete region.

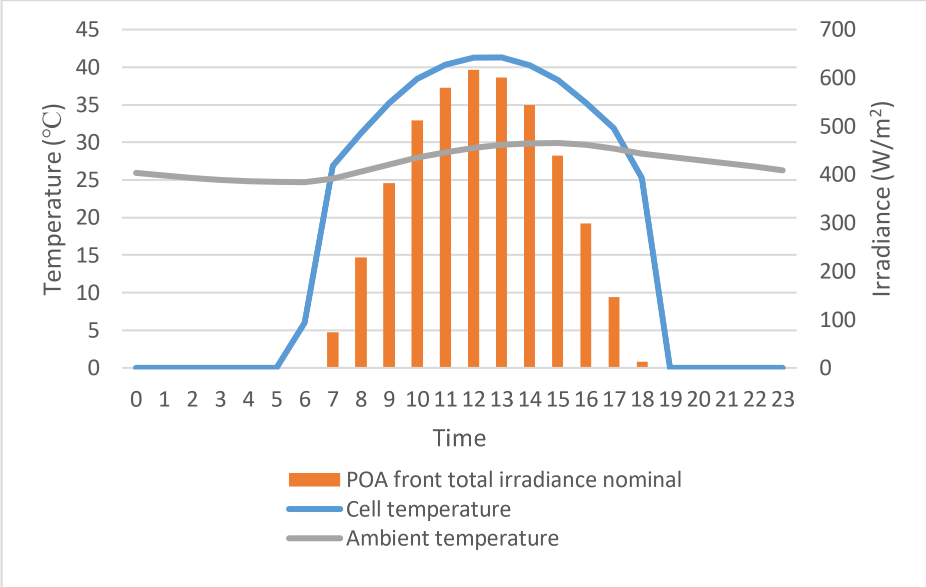


Figure 18: Hourly solar irradiance, ambient temperature and cell temperature for the Molete region

As shown in Figure 18 above, the sun rises at 7am and reaches its peak at 1pm before it sets at 6pm. The ambient temperature is seen to be relatively high and stable all through the day in this region. Figure 19 below shows the monthly solar irradiance and system AC energy for the Molete region.

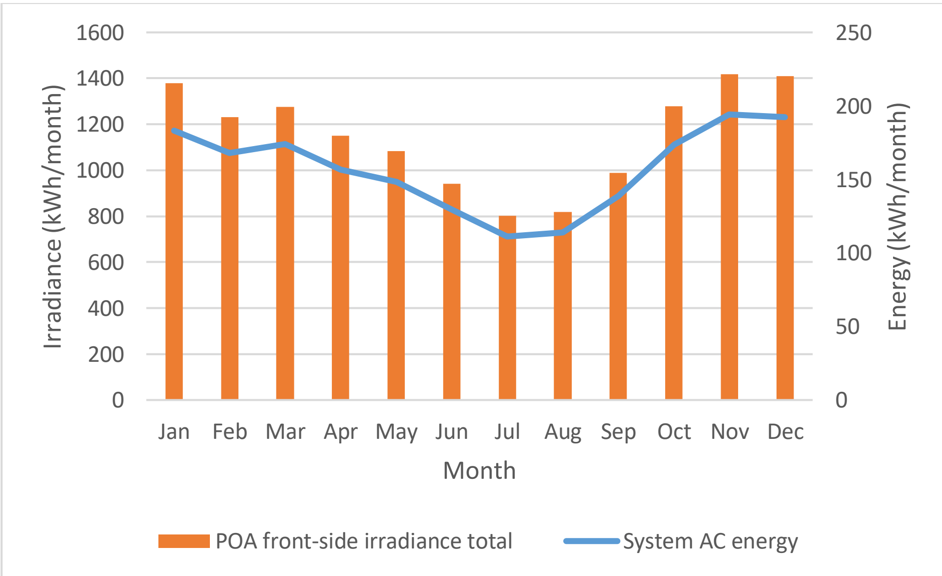


Figure 19: Monthly solar irradiance and corresponding system AC energy

From this result, November has the highest solar irradiance while July has the lowest solar irradiance. This confirms the correlation with PV system performance.

4.7.1 Worst-case scenario

Figure 20 shows the worse-case scenario of the system performance obtained from SAM simulation for the month of July across a 24-hour period.

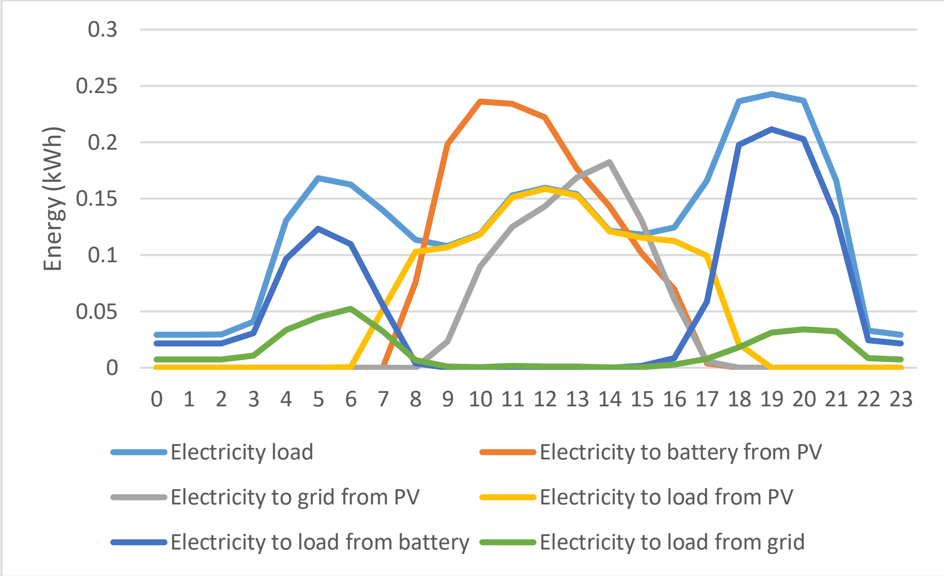


Figure 20: System performance for the month of July

From the results as shown in Figure 20 above, the designed SAPVS can only able to supply the required energy (electricity load) from 8am to 4pm (electricity to load from PV) when the sun is up. Battery backup would be needed to supply the energy (electricity to load from battery) required in the early hours of a day when there is no sunshine and at night after sunset. The optimally sized battery is unable to meet the required energy both in the early hours of the day and at night during the month. The reason is because of the low solar irradiation. The charge going to the battery during the day (electricity to battery from PV) from 8am to 5pm is not sufficient and, as such, electricity from the grid (electricity to load from grid) would be required to fill in the gap. This is the only month that the grid is needed due to the low solar irradiation. In the case of a feed-in tariff system, (electricity to grid from PV), only a very small amount of energy can be sold to the grid between the hours of 1pm and 3pm.

4.7.2 Best-case scenario

Figure 21 shows the best-case system performance result for the month of November across a 24-hour period.

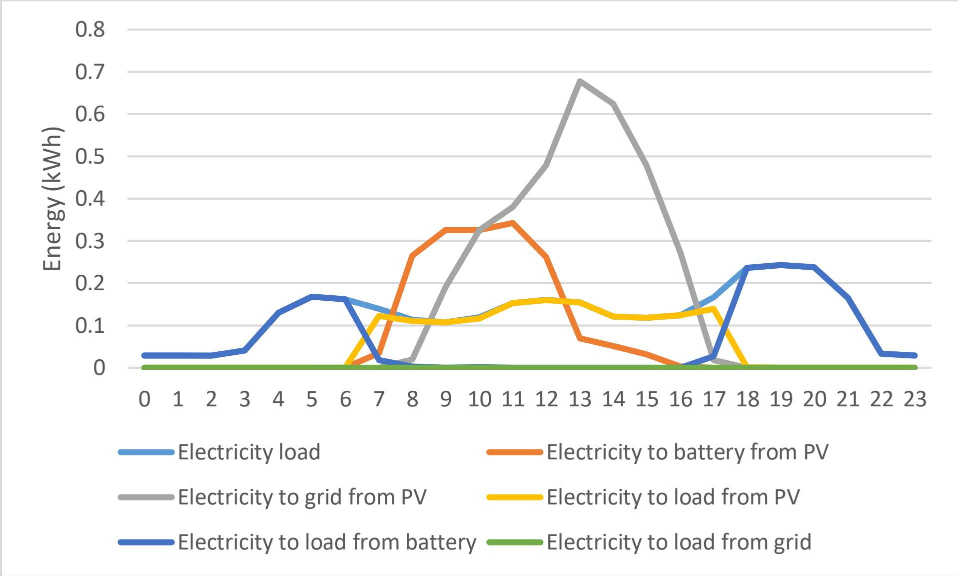


Figure 21: System performance for the month of November

From the results as shown in Figure 21 above, the optimised system is sufficient to meet the required electrical demand both in the day and at night. The PV system is able to supply the energy required during the day from 7am to 6pm which is a longer period compared to the worst-case scenario. In addition, the battery size meets the required load demand in the early hours of the morning when there is no sunshine from 12am to 7am and in the late hours of the evening after sunset, from 6pm to 12am. In the case of a feed-in tariff system, there is a sufficient amount of energy that can be sent to the grid during this month due to higher solar irradiation as shown.

In Figure 22, the result of the average annual system performance is shown.

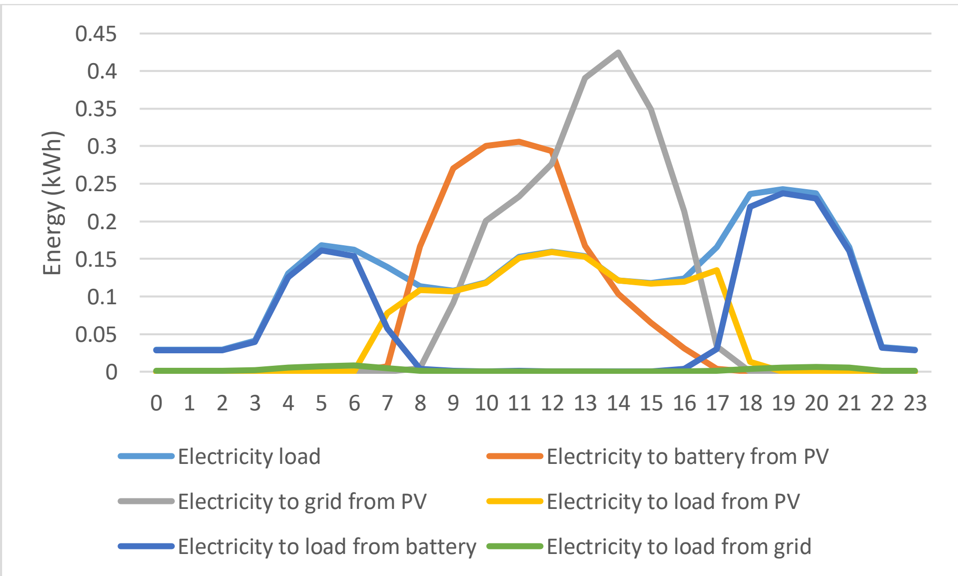


Figure 22: Average annual system performance for middle-income load profile

From the results as shown in Figure 22 above, it can be seen that the optimised system is able to meet the load demand across a 24-hour period throughout the year. The PV system effectively supplies the load demand from 7am to 5pm and also stores the excess energy generated between 8am to 2pm in the battery. Consequently, the battery is able to supply the required energy in the early morning and evening periods when there is no sunshine. There is enough energy that a surplus can be sold or stored in the grid between the hours of 12pm and 4pm. In general, the annual system performance is considered good enough to supply the energy demand throughout the year without any support from the grid.

4.7.3 Summary of annual system performance

The annual system performance for each income group in the first year is shown in Table 8. The result shows a high system performance ratio of 0.78 or 78% which measures the quality of the optimised PV system. In real life, it is impossible to obtained a PV performance ratio of 100% due to losses; therefore, the acceptable performance ratio ranges from 70 to 80% [108].

Table 8 also shows the battery efficiency, energy yield, capacity factor and the energy delivered in the first year for low-, middle- and high-income groups.

Table 8: Annual system performance

	Value		
Metric	**Low-income**	**Middle-income**	**High-income**
Annual energy (year 1)	1,257 kWh	1,884 kWh	2,522 kWh
Capacity factor (year 1)	14.40%	14.30%	14.40%
Energy yield (year 1)	1,258 kWh/kW	1,257 kWh/kW	1,262 kWh/kW
Performance ratio (year 1)	0.78	0.78	0.78
Battery efficiency (incl. converter + ancillary)	91.66%	91.57%	91.59%

From the results shown in Table 8 above, the system produces an annual energy of 1,257 kWh in the low-income group while the required annual energy in a typical household belonging to this group is only 719.05kWh. The excess 537.95kWh is stored in the battery which has a high annual efficiency of 91%. The same applies for the middle- and high-income groups. This is a good sign that the system is able to meet the load demand all year round.

4.8 Economic feasibility

Based on the US solar PV cost benchmark and using equations (15), (16), (17) and (18) discussed in Section 2.7, Table 9 shows the system component cost including inverter, batteries, electrical and structural balance of system (BOS), operation and maintenance cost (O&M) for the SAPVSs proposed for the low-, middle- and high-income groups.

Table 9: Solar PV system component cost

Solar PV System Costs							
Components	**Unit Cost (US$)**	**Quantity**			**Amount**		
		Low-income	**Middle-Income**	**High-Income**	**Low-income (US$)**	**Middle-Income (US$)**	**High-Income (US$)**
Module cost	0.65/W	1000W	1500W	2000W	650	975	1300
Inverter cost	0.17/W_{ac}	850W_{ac}	1250W_{ac}	1700W_{ac}	144.5	212.5	289
Battery cost	0.84/W	1000W	1500W	2000W	840	1260	1680
Structural BOS cost	0.11/W_{dc}	1000W	1500W	2000W	110	165	220
Electrical BOS cost	0.25/W_{dc}	1000W	1500W	2000W	250	375	500
Installation labour cost	2.0% of investment cost				39.89	59.75	79.78
	Total investment cost				2034.39	3047.25	4068.78
O&M expenses	30/kW/year	1000W	1500W	2000W	30	45	60
Inverter replacement (15 years)	0.13/W_{ac}	850W_{ac}	1250W_{ac}	1700W_{ac}	110.5	162.5	221
Battery replacement (10 years)	0.77/W	1000W	1500W	2000W	770	1155	1540
Battery replacement (20 years)	0.6/W	1000W	1500W	2000W	600	900	1200

Table 10 shows the investment cost distribution result for a 50% equity share and 50% loan share as discussed in Section 4.4.1. The annuity evaluation result for low-, middle- and high-income groups is also shown in the table.

Table 10: Annuity system evaluation

Investment cost distribution						
Category	Investment cost ($)	Equity share (%)	Loan share (%)	Equity cost ($)	Loan cost ($)	Annuity evaluation ($)
Low-Income	2034.39	50	50	1017.20	1017.20	355.21
Middle-Income	3047.25	50	50	1523.63	1523.63	532.06
High-Income	4068.78	50	50	2034.39	2034.39	710.42

Figure 23 shows the cumulative cash flow for the system. It presents the results tracking the cash inflows and outflows from investment and energy generation for a 25-year period.

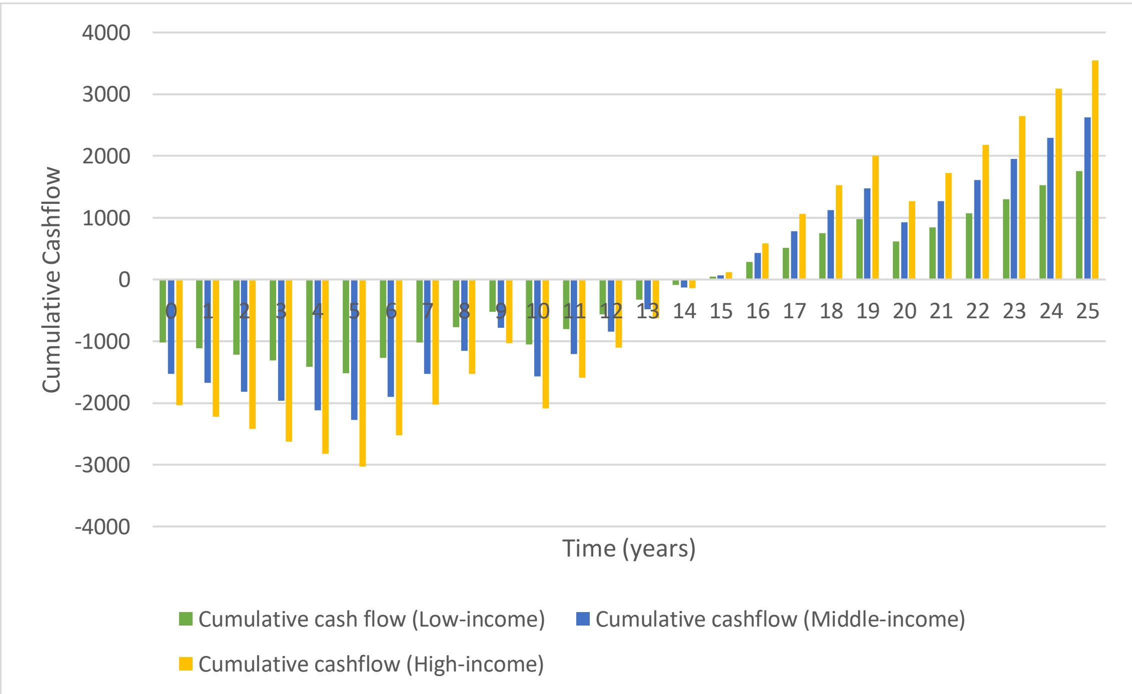


Figure 23: System cumulative cash flow

The results in Figure 23 show there is gradual increase in cash flow until the 10th, 15th, and 20th years, when the battery (10th and 20th years) and inverter (15th year) need to be replaced. After the 20th year, the cash flow began to rise continuously.

Table 11 shows the system economic feasibility with regard to the LCOE, BCR, NPV, IRR and SPBP of the system.

Table 11: System economic feasibility

Category	Energy (kWh)	LCOE ($/kWh)	BCR	NPV (US$)	IRR (%)	SPBP (Years)
Low-income	1.96	0.13	1.06	241.34	5.74	15.90
Middle-income	3.01	0.13	1.06	364.34	5.75	15.80
High-income	4.29	0.13	1.67	508.56	5.81	15.30

The results in Table 11 show that the system is economically viable for each income group and according to their energy demand. Although the initial investment cost for the high-income group is higher than the others, they earn more and as such will be able to pay a little more. However, the overall LCOE, BCR, IRR and SPBP for each income group is the same regardless of the initial investment cost.

4.9 Summary

The results obtained from modelling a realistic electricity load profile for low-, middle- and high-income households in Ibadan city, Nigeria, has been presented. There is a variation of appliance ownership characteristics for each income group. The high-income group owns more electrical appliances, which accounts for the group having higher energy demand than the low- and middle-income groups. HHs who work full-time own more expensive and high energy consuming appliances such as air conditioners. There was no correlation found between HH employment type and time of appliance use.

Ibadan city electricity reliability results show that there is a poor supply of electricity from the power company which makes the majority of households rely heavily on diesel and gasoline generators. The optimal SAPVS sizing results and the system performance results show that a SAPVS can serve as a good alternative source of electricity due to the high solar radiation in the region. The system has a high performance ratio of 0.78 which is in line with the internationally acceptable performance value [108]. The economic feasibility results show that the system can be afforded by all groups according to their load demand and income level.

Chapter 5 Discussion

This chapter presents a discussion of five major points raised in Chapter 5: appliance power rating and consumption level; the variation of appliance ownership by category; load profile variation in low-, middle- and high-income households; a comparison of electricity supply in Ibadan city with other cities in Nigeria; and the economic adoption feasibility of the optimised SAPVS.

5.1 Appliance power rating and consumption level

Although electrical appliance ownership varies between low-, middle- and high-income households, the electricity consumption of these appliances differs. Figure 24 shows the power rating and electricity consumption level of these appliances from lowest to highest power consumption.

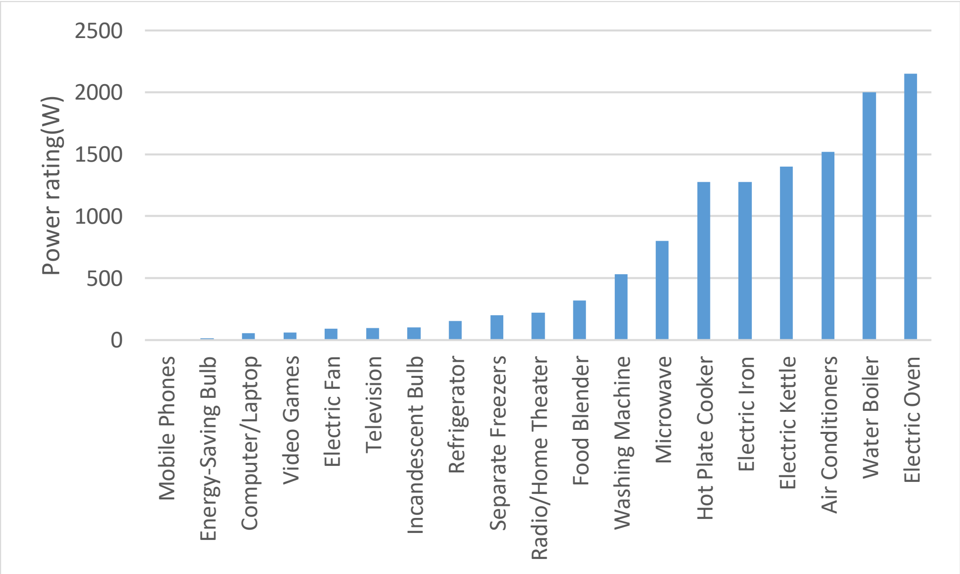


Figure 24: Average power rating of appliances

From the data presented in Figure 24 above, mobile phones have the lowest average power rating and would tend to consume the least amount of electricity. Households only use electricity to charge their phones for a short duration. Electric ovens on the other hand, have the highest average power rating of 2150W. This means that an electric oven would consume a higher amount of electricity than other appliances depending on the duration of use. Other appliances that consume high amounts of electricity are water boilers, air conditioners and electric kettles. Electric irons and hot plate cookers have the same average power consumption level of 1275W. However, hot plate cookers in most households have a longer duration of use than electric irons, thereby contributing to a higher electricity consumption. Televisions and incandescent bulbs have a similar average power rating of 98W and 100W respectively. This means that in a typical low-income household with two incandescent bulbs and one television, the incandescent bulbs would consume more electricity than the television considering the duration of use. The same applies in a typical middle-income household with four incandescent bulbs and one television. A typical high-income household with eight incandescent bulbs and two televisions, would also pay more for using incandescent bulbs considering the period of use as shown in Figure 5. Incandescent bulbs are used mostly in the night period, evening period and in the early hours of the morning period, which means they have a longer duration of use than a television, as shown in Chapter 5. Substituting incandescent bulbs with energy-saving bulbs would reduce electricity consumption for households in the low-, middle- and high-income groups. Furthermore, the variation of appliance ownership makes a significant contribution to residential electricity consumption [52] and this is in agreement with the results obtained in this study.

5.2 Variation of appliance ownership

Figure 25 shows the variation in electrical appliance ownership among the low-, middle- and high-income households while Figure 26 (a, b and c) shows the appliance ownership variation by category across the low-, middle- and high-income groups respectively.

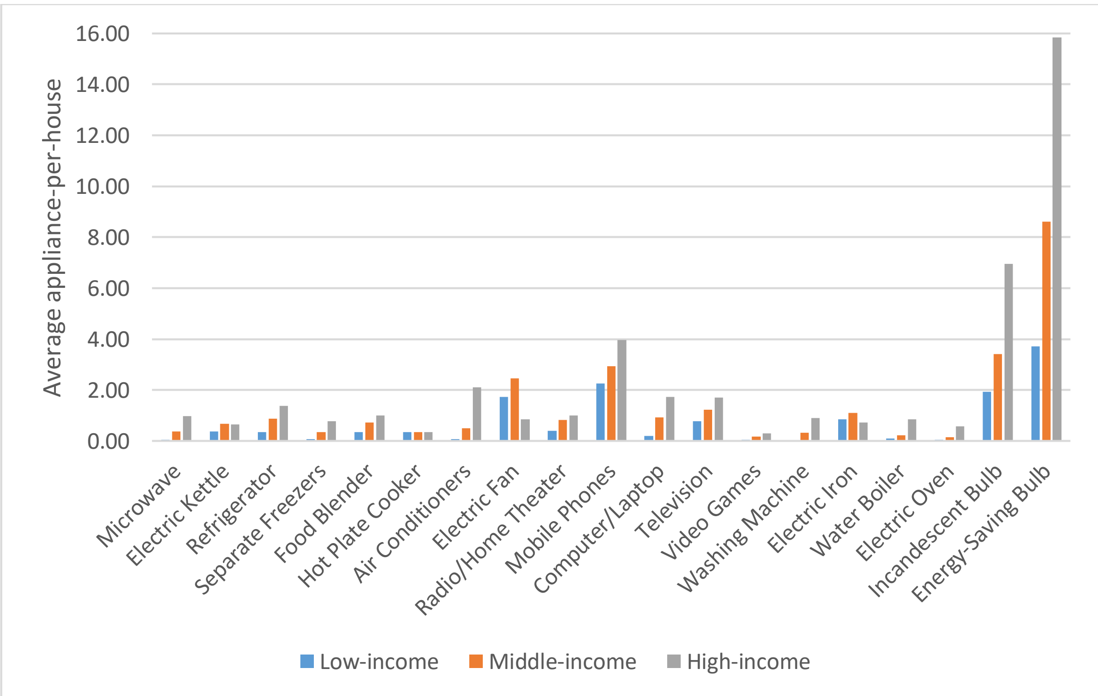
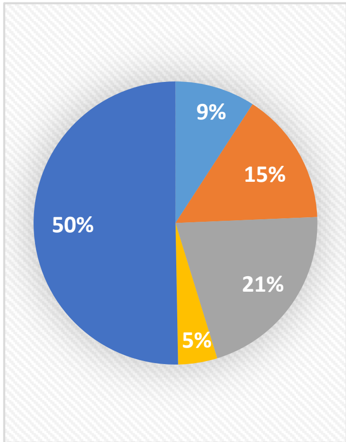
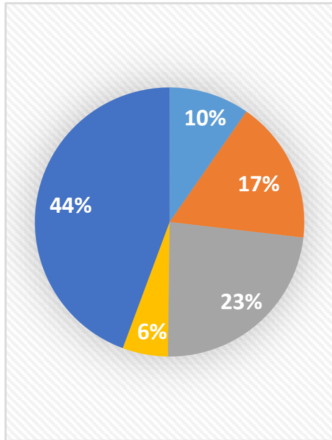


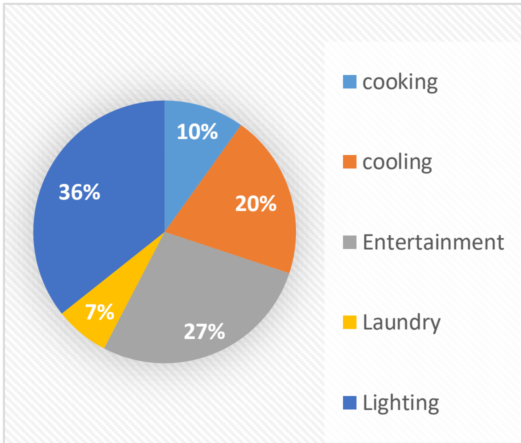
Figure 25: Electrical appliance ownership variation



(a)



(b)



(c)

Figure 26: Appliance ownership categorisation for (a) the low-income group, (b) the middle-income group, and (c) the high-income group

From the figures above, the categories of appliance ownership vary between the low-, middle- and high-income households. Cooking appliances are discussed in section 5.2.1, cooling appliances are discussed in section 5.2.2, entertainment appliances are discussed in section 5.2.3, laundry appliances are discussed in section 5.2.4 and lighting appliances are discussed in section 5.2.5. To the author's knowledge, this is the first study on electrical appliance ownership categorisation and variation in Nigeria as borne out in different sociodemographic groups.

5.2.1 Cooking appliance variation

Cooking appliances constitute 9% of the total appliances owned by households in the low-income group as shown in Figure 26(a). This means that cooking appliances can contribute some percentage to the total electricity consumption for households in this income group. The cooking appliances that have high ownership rate in this group are food blenders, electric kettles and hot plate cookers, as shown in Figure 25.

For households in the middle-income group, cooking appliances have 10% ownership rate, as shown in Figure 26(b). This is only a 1% ownership increment compared to households in the low-income group. The cooking appliances that have a high ownership rate are electric kettles, food blenders, hot plate cookers and water boilers, as shown in Figure 25. Hot plate cookers, water boilers and electric kettles have a high-power rating, as shown in Figure 24, therefore they would contribute more to electricity consumption.

In the high-income group, ownership rate of cooking appliances is also 10%, as shown in Figure 26(c). However, the appliances that are owned mostly in this group are microwaves, food blenders, water boilers, and electric ovens. which is different from the low- and middle-income groups.

The percentage ownership of cooking appliances in low-, middle- and high-income households are smaller when compared to the ownership rates of entertainment, lighting and cooling appliances; the reason could be that households prefer to purchase non-electric cooking appliances such as gas cookers or kerosene cookers, or even use firewood [4, 20], because of the unreliable electricity supply in the city [1, 2]. However, ownership of cooking appliances such as electric ovens, water boilers and hot plate cookers that have a high-power rating, as shown in Figure 24, contributes to the high electricity consumption of households in Ibadan city. Therefore, purchasing more energy-efficient cooking appliances is recommended to reduce the total electricity consumption.

5.2.2 Cooling appliance variation

Cooling appliances have a higher percentage of ownership than cooking appliances across the three income groups. A 15% cooling appliance ownership rate is recorded in the low-income household group, as shown in Figure 26(a). The results showed that households in this group own an average of two electric fans. In addition to electric fans, some households in the middle-income group also own refrigerators, air conditioners and separate freezers, resulting to a 17% cooling appliance ownership rate as shown in Figure 26(b).

In the high-income group, cooling appliance ownership is recorded at 20%, as shown in Figure 26(c). This is as a result of the higher ownership rate of air conditioners, refrigerators and separate freezers compared to the other income groups. This result is consistent with that of [109], which presented evidence that wealthier households own and uses more air conditioners in Japan.

From the results obtained, it is observed that there is a variation in cooling appliance ownership across the three income groups. Air conditioners, which are owned mainly by the high-income households, have the highest power rating, as shown in Figure 24, compared to the other cooling appliances; therefore, they would contribute more to total electricity consumption. However, it is noticeable that households in the low-income group have more electric fans than households in the high-income group. Households in the high-income group have fewer electric fans installed, but have more air conditioners which consumes more electricity.

5.2.3 Entertainment appliance variation

Households in the low-income group mainly own mobile phones and televisions, which is different from the middle- and high-income households. A few households in the low-income group also own home theatres and computers, resulting in a 21% rate of ownership, as shown in Figure 26(a). This is in line with another study that found that entertainment appliances such as computers and televisions account for 15% of electricity use in European households [110].

In this study, low-income households have the highest ownership of mobile phones, followed by televisions. However mobile phones do not consume as much energy as televisions due to their power rating, as shown in Figure 24. Therefore, households in the low-income group should place a priority on purchasing more energy-saving televisions.

In the middle-income group, entertainment appliance ownership is 23%, as shown in Figure 26(b). Mobile phone ownership is higher because every household in this income group has an average of three mobile phones. However, since mobile phones have a lower power rating, televisions, home theatres and computers have a higher contribution to total electricity consumption.

Entertainment appliances are the second highest ownership category in the high-income group which is 27%, as shown in Figure 26(c). Households in this group have an average of four mobile phones, two computers, one home theatre and two televisions. These appliance ownership levels contributed to a higher electricity consumption in a typical household belonging to this income group.

5.2.4 Laundry appliance variation

Laundry appliances have the lowest ownership level in all three income groups. Laundry appliances have a 5% ownership rate in the low-income group, a 6% ownership rate in the middle-income group and a 7% ownership rate in the high-income group as shown, in Figure 26 (a), (b) and (c) respectively.

This could mean that households do not depend much on electricity for their laundry services. For example, the majority of households in the low- and middle-income groups do not have a washing machine installed. This could mean that they either hire the services of professional dry cleaners for their laundry services or still use the traditional methods of laundry such as washing by the riverside or the use of a coal iron.

5.2.5 Lighting variation

Ownership of electric bulbs constitutes the highest level of ownership across the three income groups. This result is in agreement with a study in another developing country [52] in Tema city, Ghana, and also a study in China [111]. This means that ownership of incandescent bulbs, which inherently have a higher power rating than energy-saving bulbs, as shown in Figure 24, makes a significant contribution to the total electricity consumption of households in the low-, middle- and high-income groups.

In this study, lighting appliances constitute 50% of the ownership rate in the low-income group, 44% in the middle-income group and 36% in the high-income group, as shown in Figure 26 (a), (b) and (c) respectively. Although there are energy-saving bulbs among the three income groups, incandescent bulbs are also being used. There is need for households to reduce the ownership level of incandescent bulbs and adopt energy-saving bulbs which consume less electricity.

5.2.6 Summary

Although there is not much existing literature that links the appliance ownership categorisation to household sociodemographic groups, due to the less frequent study of appliance-related factors by other studies [6], a foundation has been established with this study. Households in the high-income group own more electrical appliances than households in other income groups. This may be because they earn more and could afford to purchase more electrical appliances. Also, the variation in the number of appliances owned could be as a result of the type of dwelling. For example, households with more rooms would tend to have more electric bulbs, fans and other appliances than households with fewer rooms, as presented in [53, 112, 113].

In addition, the employment type of the HH has a significant relationship with the number of appliances owned in the households. For example, in the high-income group, there are no unemployed respondents which means that the HHs are in a consistent paid job and, therefore, that they could afford to purchase more appliances. The group consists mainly of full-time, part-time and retired workers.

In the middle-income group, cooling appliances such as electric fans are owned in equal proportion by the unemployed, full-time, retired and part-time workers because they are cheaper to purchase. However, air conditioners are owned mainly by full-time and part-time workers in this income group.

Expensive appliances and appliances with higher electricity consumption, for example, electric ovens and air conditioners, as shown in Figure 24, are mostly owned by households in the high-income group. This means that the daily load demand in the low-middle- and high-income households would vary. Because appliance ownership is higher in the high-income group, the load demand would also be higher compared to the low- and middle-income households.

5.3 Daily load profile variation

Figure 27 shows the modelled daily load profile of a typical household in the low-, middle- and high-income groups.

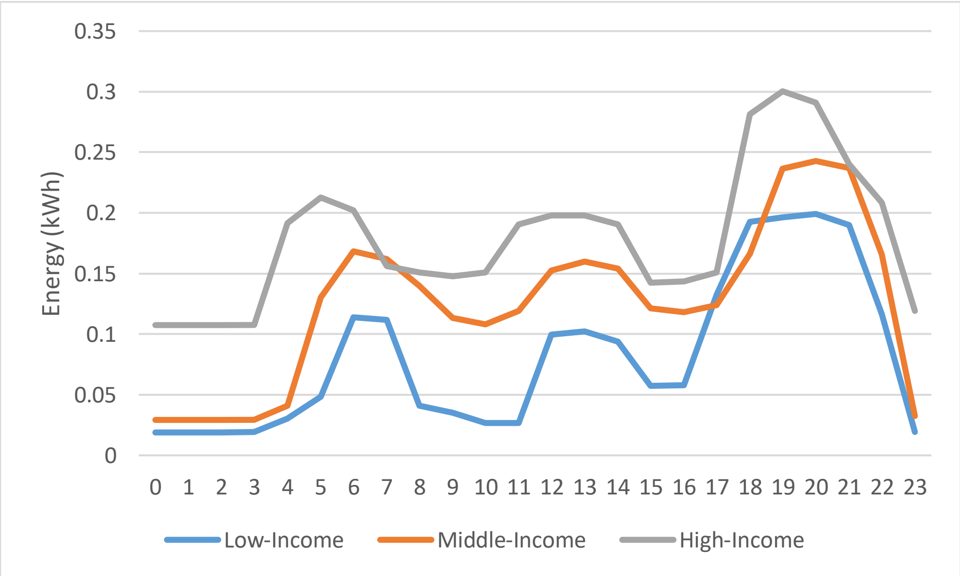


Figure 27: Comparative analysis of load profile

The low-income group has a steeper profile when compared to the middle- and high-income groups. However, three distinct peaks can be identified. The first peak is in the morning period between 5am to 8am when most occupants wake up and get ready for work. The appliances that could significantly contribute to this peak demand are incandescent bulbs and electric fans. Incandescent bulbs may have a higher contribution because, in this period of the day, lighting is needed the most. Household occupants who contribute to the first peak are probably full-time workers, school children, and part-time workers who wake up early in the morning to prepare for work or school.

The reason for the afternoon peak may also be the employment type of occupants in this group or as a result of high school children returning home from school and switching on television or playing video games. Moreover, most occupants in this group are primary school teachers and drivers who live nearby. They may return home for lunch which probably could be the cause of afternoon peak between 12pm and 2pm or the part-time workers who may be getting ready for their night shift. Appliances that could significantly contribute to this peak are televisions, for entertainment and electric fans due to the high temperature in the afternoon period.

The third peak, which is the maximum peak demand, is seen in the evening period between 6pm to 10pm. The reason for this maximum peak demand in the evening could be the full-time and part-time employees returning from work or school children returning from school and turning on the lights, television, electric fans and other appliances.

The load profile of households in high-income group is flatter compared to the other groups. This could be because of higher number of occupants living in the house and making use of appliances at all times or occupants owning their businesses and working from home. The only distinct peak for this group is noticed in the evening period between 6pm to 10pm when everyone returns from work and switches on different appliances. The daily electricity consumption in a typical household belonging to this group is higher than the rest of the other groups. The reason could be because of the ownership and usage of higher electricity consuming appliances such as air conditioners and electric ovens.

5.4 Comparison of electricity supply in Nigeria.

The average monthly power supply comparison in Ibadan city for the years 2017 and 2018 is shown in Figure 28.

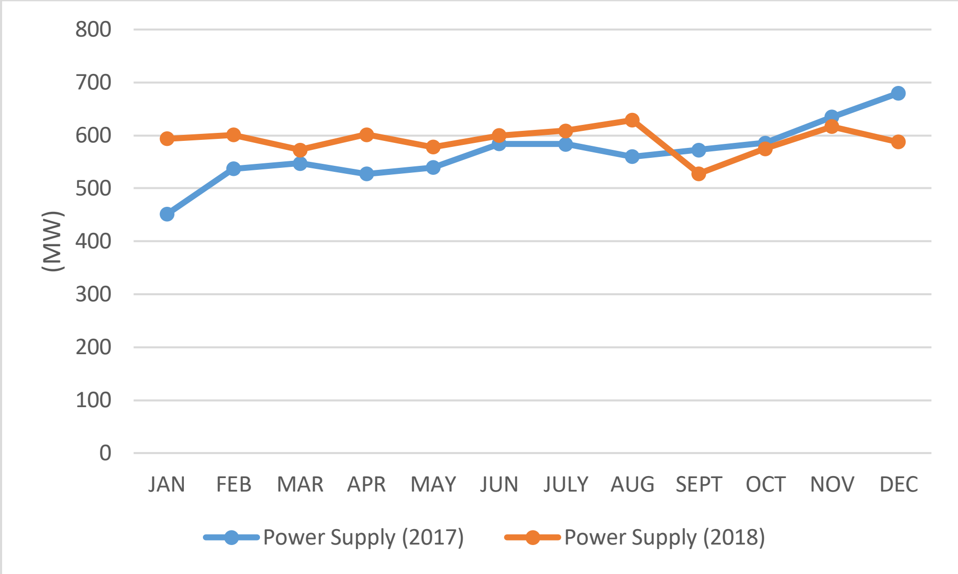


Figure 28: Power supply comparison

Comparing the results shown above indicates that the power supply in Ibadan city is deteriorating. In the year 2018 there was a higher level of electricity supply to customers until the month of October. From October, the electricity supply in the year 2017 was better and the trend result shows that the power distribution system in Ibadan city is deteriorating gradually. Comparing the reliability indices results obtained in this study with other reliability studies in Nigeria also shows that the rate of power supply in the country is very poor and unpredictable as shown in Table 12.

Table 12: Comparison of study location with previous studies

Study	**Year**	**SAIDI (hours/year)**	**SAIFI (f/customer/yr)**	**CAIDI (hours/outage)**
Osun State [63]	2017	2,470.16	695.16	3.55
Onitsha [64]	2009 to 2011	3,376.68	457.25	7.38
Ibadan city (current study)	2017	782.19	203.59	3.84
Ibadan city (current study)	2018	856.49	184.33	4.65

In Osun state, the reliability of electricity supply has been discovered to be very poor [63]. The same utility company (IBEDC) supplies power to this state. However, electricity supply in this state is worse compared to Ibadan city. Osun state is a smaller state with a smaller population [63], therefore there may be less focus on supplying electricity to this region. This could be the reason for the SAIDI value of 2,470.16 hrs/year out of 8,760 hours in a year, as shown in Table 12.

In Onitsha, Anambra state, the average SAIDI, SAIFI and CAIDI values for the years 2009 to 2011 [64] are also presented in Table 12. The results show that this state has the worst electricity supply when compared to other states in Nigeria. The average SAIFI index values for 2009, 2010 and 2011 show that customers had approximately 457 electricity interruptions in a year and 3,376 hours of electricity outages in a year. Considering the reliability indices holistically, as discussed in Chapter 5, these results mean that the reliability of the IBEDC distribution system, and Nigeria in general, is very low and far from the internationally acceptable standard values (IASV) of SAIDI 2.5hrs/year and SAIFI of 0.01 f/customer/yr [63].

5.5 SAPVS adoption feasibility

Table 13 shows a LCOE comparison after SAPVS optimisation for residential application in some developing countries.

Table 13: SAPVS economic optimisation comparison

Location	Daily load consumption (kWh)	LCOE after optimisation ($/kWh)
Busari, Nigeria [80]	5.45	0.47
New Delhi, India [79]	2.2	0.57
Malaysia [74]	1.12	0.42
Current study, Ibadan city, Nigeria.	4.29 (High-income group)	0.129

In Busari, Nigeria, an average estimated daily electricity consumption of a household was used as an input for optimisation [80]. The result showed that the LCOE after optimisation was more economically feasible compared to the cost of diesel and gasoline generators in Nigeria [15]. However, with the method used in [80], the LCOE is still higher than the result obtained in the present study. Also, the LCOEs obtained in [74, 79] after optimisation were higher than the result obtained in [80] even with a lower load demand. This is because average load demand was also used for optimisation.

In this study, a realistic load demand of a typical household in Ibadan city, Nigeria, was used for optimisation and a lower LCOE with better optimisation was obtained compared to the other studies where average load demand was used for optimisation. A comprehensive comparison of off-grid electricity cost generation in Nigeria [35] showed that LCOE for diesel generators is $0.3/kWh and for gasoline generators is $0.6/kWh. However, in this study, the LCOE of SAPVS was found to be $0.129/kWh, including storage cost. This shows that SAPVS is even cheaper and has more economic impact than diesel and gasoline generators if optimally sized. Therefore, the adoption feasibility of SAPVS for residential application in Ibadan city is high and should be encouraged.

5.6 Summary

A discussion on the five major points raised in Chapter 5 has been presented. Appliance ownership and the variation in ownership, which has been studied less frequently by other literature [6], has been discussed in Section 5.2. The appliances that contribute to the peak load profile in the low-, middle- and high-income groups have been presented and ways of reducing electricity consumption were then suggested. A comparison of electricity supply in Ibadan city with other cities in Nigeria shows that electricity supply in the country is very poor which makes households depend heavily on generators powered by fossil fuels, such as diesel and gasoline generators. Solar radiation in Nigeria has been identified as being high, as discussed in Section 2.5 and the result of this study shows that a SAPVS is a good alternative source of electricity for residential applications. Optimising a SAPVS using a realistic residential load profile gives a lower LCOE than using estimated average demand and a lower LCOE than diesel or gasoline generators. Therefore, an optimised SAPVS is a good alternative to diesel and gasoline generator use in Nigeria.

Chapter 6 Conclusion, limitation and future work

6.1 Conclusion

In this study, a bottom-up approach to modelling a realistic residential load profile for low-, middle- and high-income groups have been presented. The study has also provided an insight into the appliance ownership factors that have a significant positive effect on the residential electricity consumption of the three income groups in Ibadan city, Nigeria. The results showed that high-income households own high energy consuming appliances such as air conditioners and washing machines while households of low-income and middle-income groups own more electric fans. The employment type of the HH also contributed to the appliance ownership level in the households. However, no correlation was found between the employment type of the HH and the time of appliance use. This could be due to the fact that other occupants are living in the house and using appliances when the HH is not present.

In addition, this study shows that incandescent lighting has a significant contribution to residential electricity consumption in all these three income groups, that agrees with another study in Tema city, Ghana. In low- and middle-income households, the appliances that contributes more to the total electricity consumption are electric fans, electric irons and televisions while in high-income households, air conditioners, televisions and refrigerators have a higher contribution to the total electricity consumption. This study has provided the foundation for the implementation of energy-saving policy and ways of reducing residential electricity consumption in Ibadan city, Nigeria.

From the household survey responses, the hourly daily load profiles of typical households belonging to the low-, middle- and high-income groups were then predicted and used as inputs for optimal sizing of a SAPVS for each group to serve as an alternative source of electricity along with existing poor electricity supply in Ibadan city. The proposed optimisation method for sizing a SAPVS considering a realistic load profile proved to be practicable from the system performance results obtained using the SAM software. The annual system performance was obtained at 78% which agrees with the international acceptable standard performance value. The proposed system has a lower LCOE when compared with other study methods, as shown in Table 13. The LCOE for a system was \$0.129/kWh which is more economically feasible than using diesel and gasoline generators which have been discovered in Nigeria to have a LCOE of \$0.3/kWh and \$0.6/kWh respectively.

6.2 Limitation of study

The first limitation of this study is that the survey period was limited to the dry season only, thus the effect of seasonal factors could not be determined. Therefore, the predicted load profile was assumed to remain constant throughout the year, which may not be the case in real life as the load profile could change according to a season.

Most of the households refused to take part in the survey due to the complete lack of trust in the electricity system in Nigeria. Many households had given up on the poor electricity situation in the country and were not interested. However, the simplicity of the flyers, the use of local radio station and the distribution of information sheet proved to be very helpful in recruiting participants for this study. Also, biased responses from participants may have been encountered because some participants may have claimed ownership of appliances which they do not own to avoid shame.

6.3 Future work recommendation

This thesis has provided a good foundation on residential electricity consumption patterns and optimal sizing of SAPVS. However, there is room to improve on this study in future.

The weekday and weekend load profiles of households were not covered in this study. There is a high possibility that the load profile of households differs between weekdays and weekend, and this should be investigated further.

Secondly, electricity consumption data from the questionnaire survey could be compared with measured data where it is available, or combined with such data for a more realistic result. It will also be practicable to investigate the effect of dwelling factors and seasonal factors in sizing a SAPVS, although such investigations were beyond the scope of this study. A study on demand-side management, especially ways of trimming the peak load profile, would also be interesting.

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Publication

A publication that resulted as a proceeding of this thesis is stated below.

C. Egbon, A. Oyekola, and T.-T. Lie, "Design of stand-alone photovoltaic system in developing countries: A case study of Kano, Nigeria," in *IEEE 2018 Australasian Univs. Power Eng. Conf. (AUPEC)*, 2018, pp. 1-6.

https://ieeexplore.ieee.org/document/8757895

Appendices

Appendix A: Ethics approval

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

9 October 2018

Tek-Tjing Lie
Faculty of Design and Creative Technologies

Dear Tek-Tjing

Re Ethics Application: **18/339 Optimal sizing of standalone photovoltaic (PV) system for residential customers considering electricity consumption pattern: A case study of Ibadan City, Nigeria**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 8 October 2021.

Standard Conditions of Approval

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/research/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/research/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/research/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. If the research is undertaken outside New Zealand, you need to meet all locality legal and ethical obligations and requirements. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: onychukwu@gmail.com; adam.taylor@aut.ac.nz

Appendix B: Participant information sheet

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Participant Information Sheet

Date Information Sheet Produced:

13/08/2018

Project Title

Optimal Sizing of standalone Photovoltaic (PV) system for residential customers considering electricity consumption pattern: A case study of Ibadan City, Nigeria.

Hello,

I am a student studying Master of Engineering at Auckland University of Technology, New Zealand. I am currently conducting a research on the above titled thesis and need your input in understanding the way residents of Ibadan city use electricity in their houses and the factors that makes them use it that way. A good knowledge of this would enable us design a solar photovoltaic system (or "inverter" as it is generally called) which would be accurate and cost effective for residents in the city. A questionnaire will be issued to you to fill out in other to understand how you use electricity in your house. The result will be used for analysis and for research purposes only.

What is the purpose of this research?

The main significance of this research is to come up with a method for designing standalone photovoltaic system ("inverter" as it is generally called) for residents in the city by identifying factors that affects how people use electricity and design the systems accordingly. The current existing method which is just a way of designing PV system based on the number of appliances a customer has in their house can often make the system to be more expensive for the customers. This new method when identified would reduce cost and make the system to be affordable by almost all residents of the city. As earlier mentioned, a questionnaire has been designed to understand how you use electricity in your house and the factors that makes you use it that way. All you need to do is select the appropriate responses that relates to your household to the best of your knowledge.

This research will provide a guideline for designing a stand-alone PV system for residential customers in the future. This research is funded by New Zealand ministry of foreign affairs and trade.

How was I identified and why am I being invited to participate in this research?

Residents of Ibadan city are being sought for this research and you responded to an advertisement. Possession of a valid identity card is required to prove your eligibility as a resident of the city.

How do I agree to participate in this research?

Your participation in this research is voluntary (it is your choice) and you are able to withdraw from the study at any time. You will need to kindly go through this information sheet to understand the purpose of this research. If you still show interest after going through, kindly email consumption2@gmail.com or call Eniola on 08021462490 so that the questionnaire can be issued to you. Kindly note that this survey is strictly anonymous and the names and addresses of the respondent cannot be determined. By agreeing to fill the questionnaire you consent to take part in this survey.

What will happen in this research?

You will be asked to answer a questionnaire which would be issued to you. It will take about 30 mins to complete seeking information regarding how you use electricity in your house to the best of your knowledge.

What are the discomforts and risks?

There may be minimal discomfort when asked about appliances in your home which you do not have.

If you do not have any appliance asked in the questionnaire, kindly select No or ignore completely and move to the other appliance below. Also, Research safety protocol as attached will be strictly enforced to minimize any risk and the Olubadan has advised the research should continue.

How will these discomforts and risks be alleviated?

Kindly select No for any appliance in the questionnaire which you do not own and move to the next appliance. This survey is anonymous, so your identity cannot be identified.

Research safety protocol as attached will be strictly adhered to minimize any form of risk.

What are the benefits?

As you may be aware, there is high intensity of sunlight in Nigeria and solar photovoltaic technology ("Inverter") has been identified as a good alternative to the current epileptic power supply, but the cost of installation is still very high which sometimes is related to design of the system. This research aims to develop a method for optimal design of standalone photovoltaic systems ("Inverter") for residents of Ibadan city Nigeria which would be more cost effective and accurate in the future.

How will my privacy be protected?

Your identity card is for sighting to prove your eligibility as a resident of Ibadan city. All information provided will not be shared or distributed to any third party. The data would be stored in a secure location at Auckland University of Technology.

What are the costs of participating in this research?

There is no cost other than the estimated time required to complete the questionnaire is about thirty minutes.

What opportunity do I have to consider this invitation?

You have three to five days to think through and accept the invitation by sending an email to consumption2@gmail.com or call Eniola on 08021462490.

Will I receive feedback on the results of this research?

Because this is an anonymous survey, we are unable to provide feedback. However, findings and results would be published as a journal article.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisors,

Professor Tek Tjing Lie, tek.lie@aut.ac.nz, +64921-9428

Or

Doctor Adam Taylor, adam.taylor@aut.ac.nz, +649921-9999

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Collins Egbon, consumption2@gmail.com and Eniola, eniolaomisore17@gmail.com

Project Supervisor Contact Details:

My supervisors details are stated below;

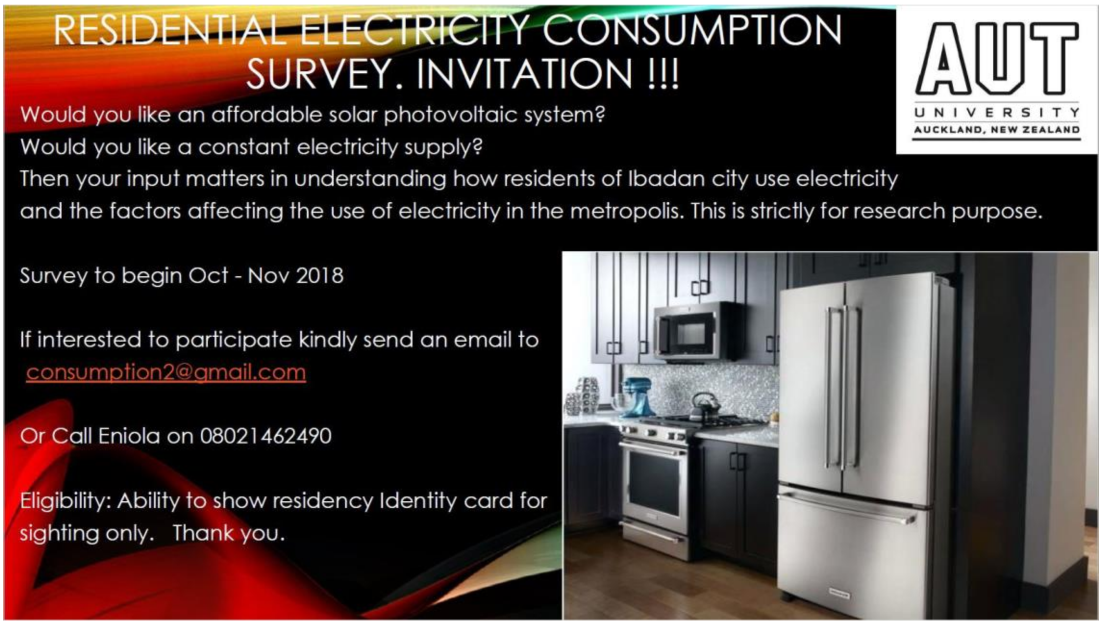
Professor Tek Tjing Lie, tek.lie@aut.ac.nz

Or

Doctor Adam Taylor, adam.taylor@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on *09/10/2018*, AUTEC Reference number *18/339*.

Appendix C: Survey flyer



Appendix D: Questionnaire

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Instruction:

Thank you for accepting to participate in this survey.
Please select the answers that gives the best representation of your house and household.
You would be asked questions about how you use electricity in your house, appliances and the building factors.
It should take approximately 15 to 25 minutes to complete.

Section 1: Please tick the box that best represent your household

VARIABLES	CATEGORIES
What type of house do you live in?	Single room ☐ Duplex ☐ BQ or Self Contained ☐ flats ☐
How many rooms are in the house?	1 ☐ 2 - 4 ☐ 5 - 6 ☐ 7 and above ☐
What is the age of the building?	Before 1980 ☐ 1980-1990 ☐ 1990-2000 ☐ After 2000 ☐
House Ownership status	Owner ☐ Rent ☐ Inherited ☐ Others ☐

Section 2: Please tick the box that best represent your household

VARIABLE	CATEGORY
How many adults live in the house?	one ☐ two ☐ three ☐ Four or more ☐
Are the occupants married?	Yes ☐ No ☐
How many children?	None ☐ 1 - 3 ☐ 4 - 6 ☐ 7 and above ☐
Age bracket of household head	18–25 years ☐ 26–45 ☐ 46 – 64 ☐ 65 above ☐
Gender of household head?	Male ☐ Female ☐
Employment status of household head	working full time ☐, working part time ☐, unemployed ☐, retired ☐

Monthly Income of household head	Below ₦18,000 ☐, ₦18,000 to ₦150,000 ☐, Above ₦150,000 ☐
Education Level of household head	None ☐, Primary ☐, Secondary ☐, University ☐, Drop out ☐

Section 3: Please tick the box that best represent your household

Type of Bulb	Total number of Bulbs	Average Number of hours used per day	What period of the day are they usually ON or used?
Incandescent or Halogen (Yellow bulb)			6am–12pm ☐ 12pm-6pm ☐ 6pm–12am ☐ 12am–6am ☐
Energy saving or Fluorescent (White)			6am–12pm ☐ 12pm-6pm ☐ 6pm–12am ☐ 12am–6am ☐
Others			6am–12pm ☐ 12pm-6pm ☐ 6pm–12am ☐ 12am–6am ☐

Section 4: Please tick the box that best represent your household

VARIABLES	**CATEGORIES**
Do you have any microwave? How many hours/mins do you use it in a day? What period of the day are they used? **(Morning, afternoon or evening time?)**	Yes ☐ No ☐ how many? ☐ ☐ Hours ☐ Minutes 6am–12pm ☐ 12pm-6pm ☐ 6pm–12am ☐ 12am–6am ☐
Do you have any Electric Kettle? How many hours/mins do you use it in a day? What period of the day are they used?	Yes ☐ No ☐ how many? ☐ ☐ Hours ☐ Minutes 6am–12pm ☐ 12pm-6pm ☐ 6pm–12am ☐ 12am–6am ☐
Do you have any Refrigerators? How many hours/mins do you use it in a day? What period of the day are they used?	Yes ☐ No ☐ how many? ☐ ☐ Hours ☐ Minutes 6am–12pm ☐ 12pm-6pm ☐ 6pm–12am ☐ 12am–6am ☐
Do you have separate freezer?	Yes ☐ No ☐ how many? ☐

How many hours/mins do you use it in a day? What period of the day are they used?	Hours Minutes 6am–12pm 12pm-6pm 6pm–12am 12am–6am
Do you have any food blender? How many hours/mins do you use it in a day? What period of the day are they used?	Yes No how many? hours Minutes 6am–12pm 12pm-6pm 6pm–12am 12am–6am
Do you have Hot plate cooker? How many hours/mins do you use it in a day? What period of the day are they used?	Yes No how many? Hours Minutes 6am–12pm 12pm-6pm 6pm–12am 12am–6am
Do you have air conditioners? How many hours/mins do you use it in a day? What period of the day are they used?	Yes No how many? Hours Minutes 6am–12pm 12pm-6pm 6pm–12am 12am–6am
Do you have Electric fans? How many hours/mins do you use it in a day? What period of the day are they used?	Yes No how many? Hours Minutes 6am–12pm 12pm-6pm 6pm–12am 12am–6am
Do you have Radio/Home theater? How many hours/mins do you use it in a day? What period of the day are they used?	Yes No how many? Hours Minutes 6am–12pm 12pm-6pm 6pm–12am 12am–6am
Do you have Mobile phones? What period of the day do you charge them?	Yes No how many? 6am–12pm 12pm-6pm 6pm–12am 12am–6am
Do you have computers/Laptops How many hours/mins do you use it in a day? What period of the day are they used?	Yes No how many? Hours Minutes 6am–12pm 12pm-6pm 6pm–12am 12am–6am
Do you have Television? How many hours/mins do you use it in a day? What period of the day are they used?	Yes No how many? Hours Minutes 6am–12pm 12pm-6pm 6pm–12am 12am–6am
Do you have Video games? How many hours/mins do you use it in a day?	Yes No how many? Hours Minutes

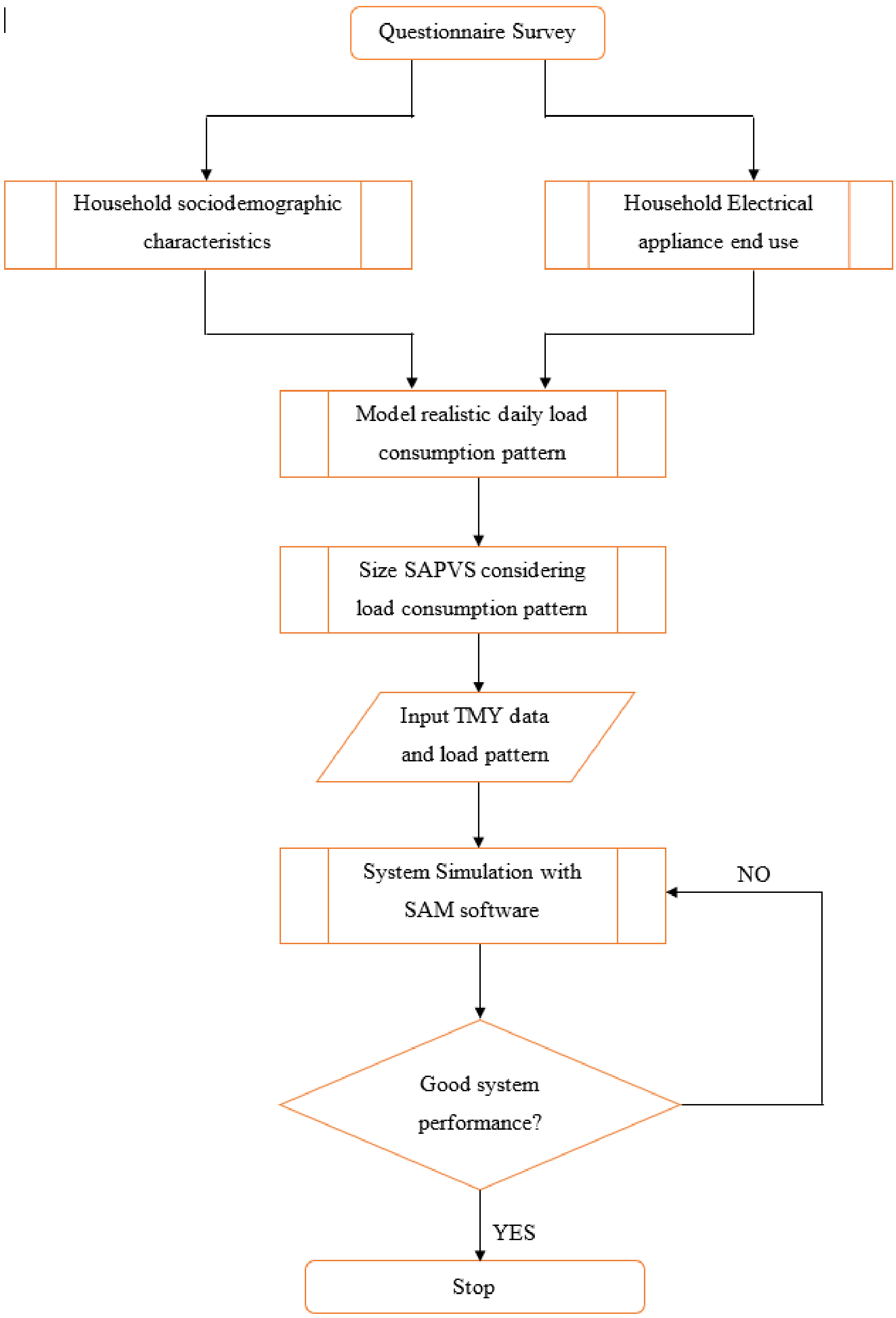
What period of the day are they used?	6am–12pm☐ 12pm-6pm☐ 6pm–12am☐ 12am–6am ☐
Do you have washing machine? How many hours/mins do you use it in a day? What period of the day are they used?	Yes ☐ No ☐ how many? ☐ ☐ Hours ☐ Minutes 6am–12pm☐ 12pm-6pm☐ 6pm–12am☐ 12am–6am☐
Do you have Iron? How many hours/mins do you use it in a day? What period of the day are they used?	Yes ☐ No ☐ how many?☐ ☐ Hours ☐ Minutes 6am–12pm☐ 12pm-6pm☐ 6pm–12am ☐ 12am–6am☐
Do you have water heater? How many hours/mins do you use it in a day? What period of the day are they used?	Yes ☐ No ☐ ☐ Hours ☐ Minutes 6am–12pm☐ 12pm-6pm☐ 6pm–12am☐ 12am–6am☐
Do you have Electric Oven? How many hours/mins do you use it in a day? What period of the day are they used?	Yes ☐ No ☐ ☐ Hours ☐ Minutes 6am–12pm☐ 12pm-6pm☐ 6pm–12am☐ 12am–6am☐

Section 5

1) How often do you have blackout? Regularly ☐ Never ☐ sometimes ☐
3) Do you have diesel/petrol generator? Yes ☐ No ☐
4) Do you have solar or inverter installed? Yes ☐ No ☐
5) If No, would you like Solar/inverter installed in your house? Yes ☐ No ☐

Thank you for completing this questionnaire

Appendix E: Research methodology flow chart

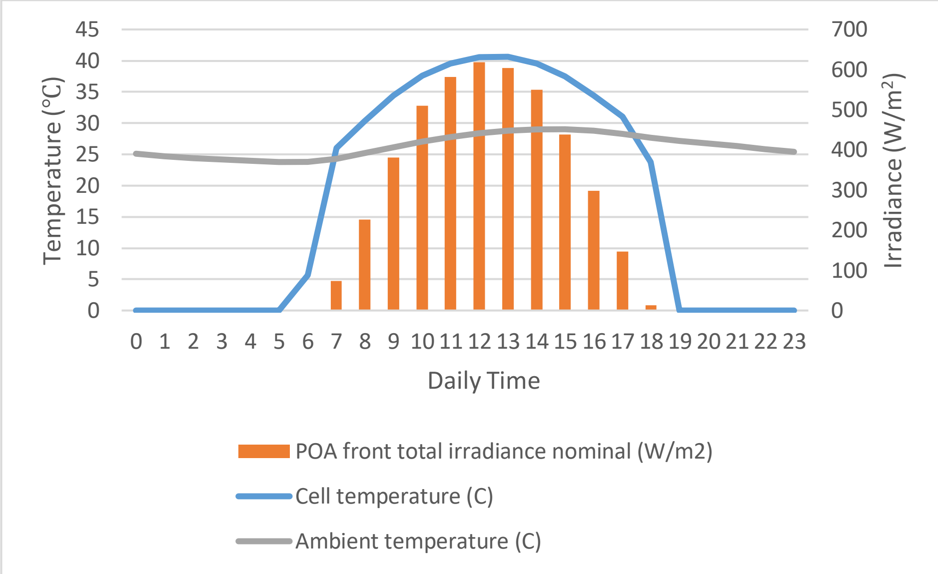


Appendix F: Appliance power rating data

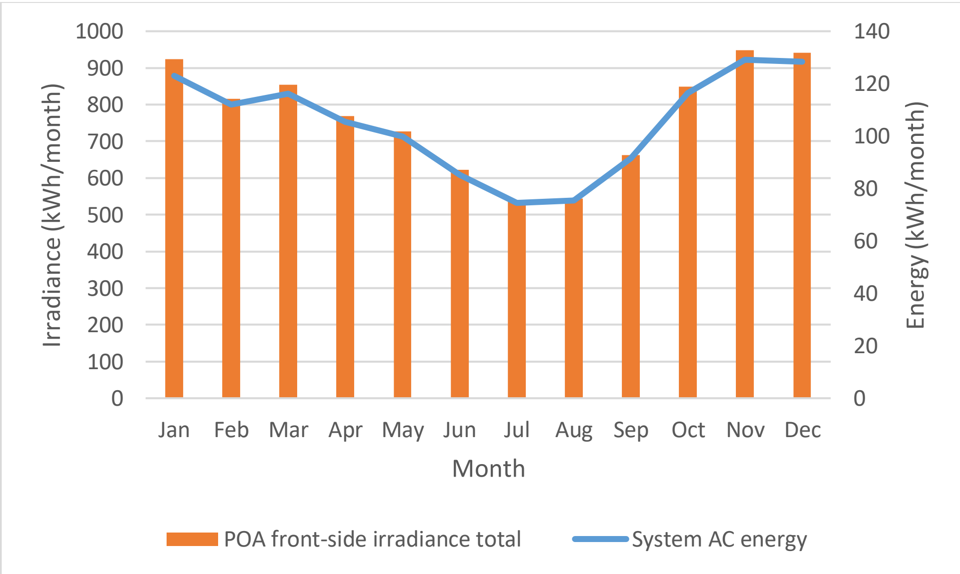
Microwave	
SAMSUNG	800W MW300G SOLO MWO 23L
LG	900W MC7887AB 28L
HISENSE	700W H20M0MMI 20L
THERMOCOOL	800W HTMO-3110EGC 31L
Average	= 800W
Electric kettle	
MASTER CHEF	1000W 2.2L
BOMEI	1850W 2.0L
SAISHO	900W 1.9L
BINATONE	1850W SSK-4006R 4L
Average	= 1400W
Refrigerator	
LG	180W GB-450UPLX 450L
NEXUS	130W NX-170
HISENSE	160W H220TWH 161L
THERMOCOOL	150 W HRF 9SEX 95L
AVERAGE	= 155W
Separate freezer	
NEXUS	200W 80L
MIDEA	220W 93L
HISENSE	200W
OMAHA	200W
Average	= 198W
Food blender	
SAMSUNG	180W 5KHB2571EOB
MASTER CHEF	300W 2L
PANASONIC	400W MX-GX1021 1.0L
NEXUS	400W NX-3011 1.5L
Average	= 320W
Hot plate cooker	
KINELCO	1000W DOUBLE BURNER
MASTER CHEF	800W MA974HL DOUBLE BURNER
BREVILLE	2400W BHP250 BSS DOUBLE BURNER
PHILIPS	900W HD4937
Average	= 1275W
Air conditioner	
LG	1095W M126JH
SAMSUNG	1500W AR12KPFNDWK/SG
THERMOCOOL HAIRER	1786W HSU-12TESN-O1
MIDEA	2000W
Average	= 1520W
Electric fans	
OX	125W 26INCHES
LONTOR	130W 16INCHES CTL-CFA001-16AC
BINATONE	65W VS 1655
PANASONIC	40W 407Y
Average	= 90W
Home theatre	
SAMSUNG	300W SC- HTB688

LG	300W LG AUD ARX542CH
HISENSE	120W BLUETOOTH SOUNDBAR
PANASONIC	160W HW-M4501
Average	= 220W
Computer	
SAMSUNG	50W
HP	55W
PHILIPS	48W
SONY	60W
Average	= 55W
Television	
SAMSUNG`	145W F9000 SERIES LED TV
LG	58.6W 55LN5700 55" CLASS 1080P LED
PANASONIC	58W LED TV VIERA TH-L32XV6M
SHARP	130W AQUOS LC-LE62OUT
Average	= 98W
Video games	
WARNER	70W
SONY	55W
XBOX	80W
PLAYSTATION	40W
Average	= 60W
Washing machine	
SAMSUNG	600W 8KG WW80H7600E
LG	400W 8.5KG SKUWTG8532WH
HISENSE	500W 8KG HWFM8012
NEXUS	620W 9.2KG NX-WM-9SASB
Average	= 530W
Iron	
BOSCON	1000W BOS EIR208
EUROSONIC	1000W
PHILIP	2100W GC2040/70 STEAM 30G/MIN
CENTURY	1000W STEAM IRON
Average	= 1275W
Water boiler	
MASTERCHEF	1800W
LINKRICH	2000W
DMWD	2500W
CROWNSTAR	1900W
Average	= 2000W
Electric Oven	
MASTERCHEF	1900W 11L
BOSCH	2200W
CROWNSTAR	2500W
CENTURY	1900W
Average	= 2150W
Incandescent bulb	
PHILIPS	400W
LONTOR	400W
SALPHA	400W
AKT	400W
Average	= 100W
Energy saving bulb	
PHILIPS	20 W Tornado
LONTOR	10W
SALPHA	16W
AKT	18W
Average	= 16W

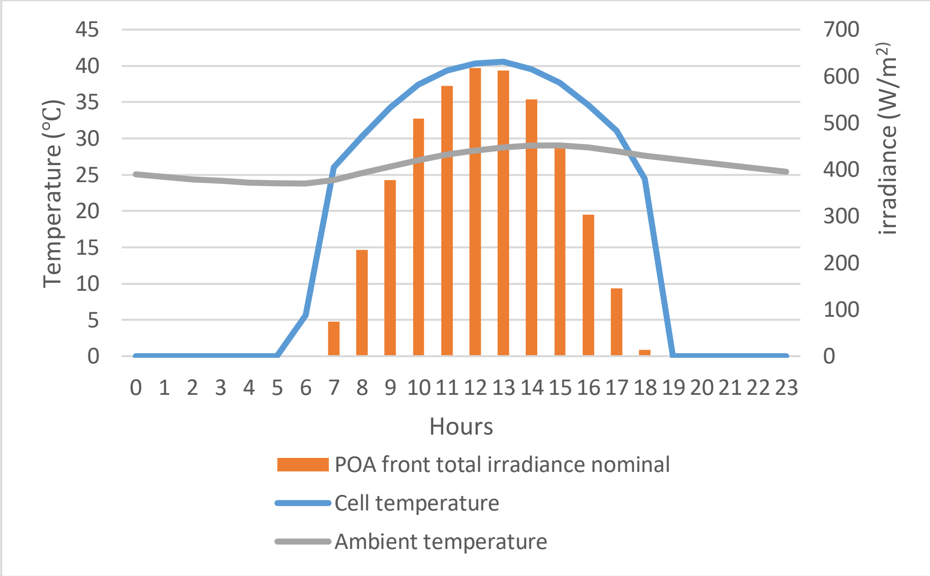
Appendix G: Site meteorological data



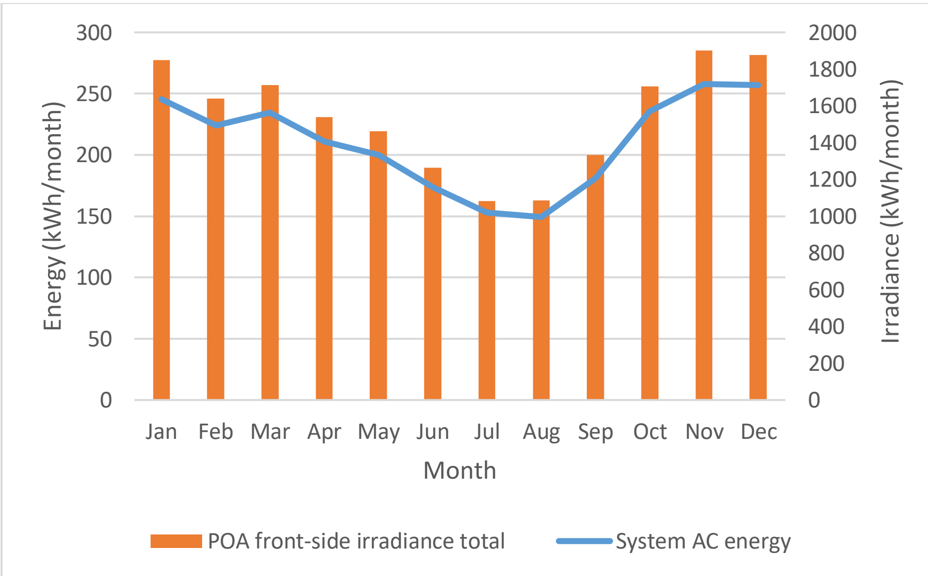
Hourly solar irradiance, ambient temperature and cell temperature for Mapo region (low-income)



Monthly solar irradiance and corresponding system AC energy for low-income group

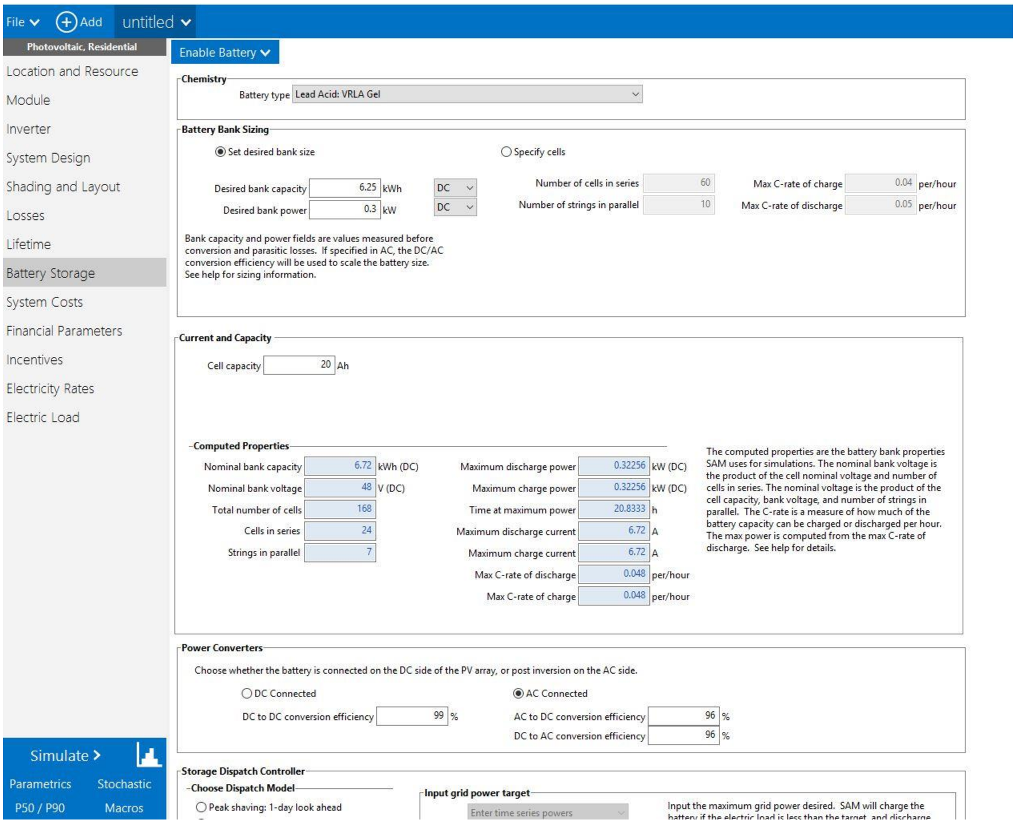


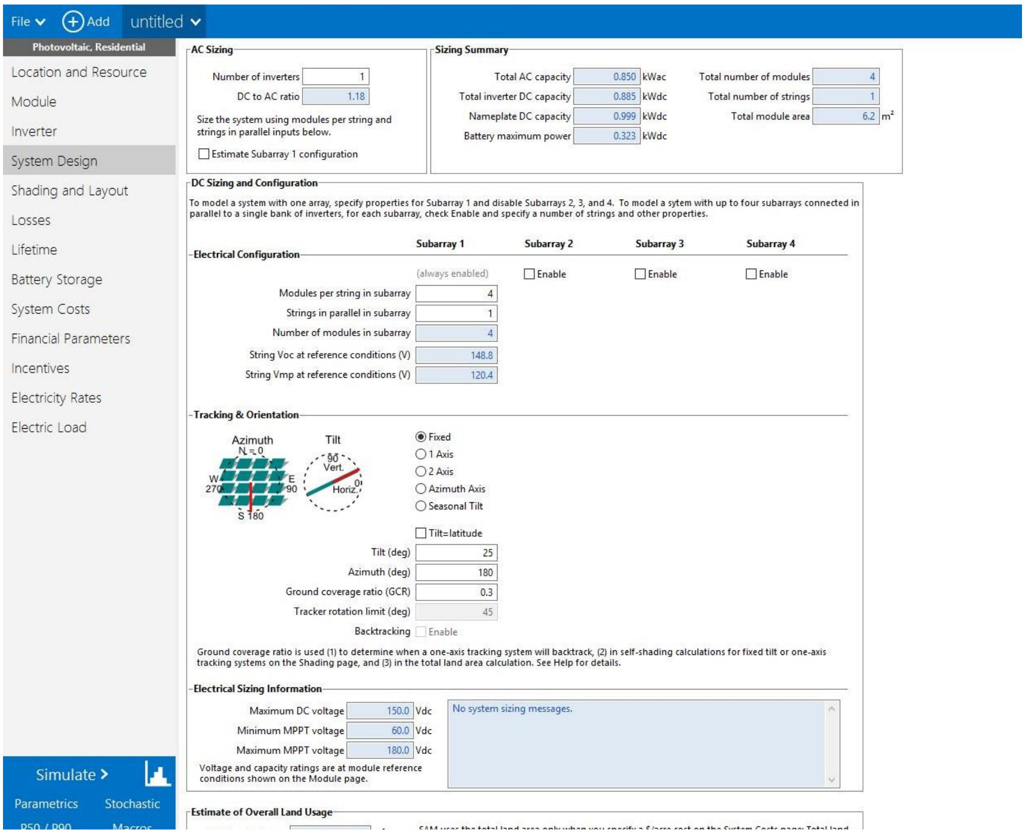
Hourly solar irradiance, ambient temperature and cell temperature for Bodija region (high-income)



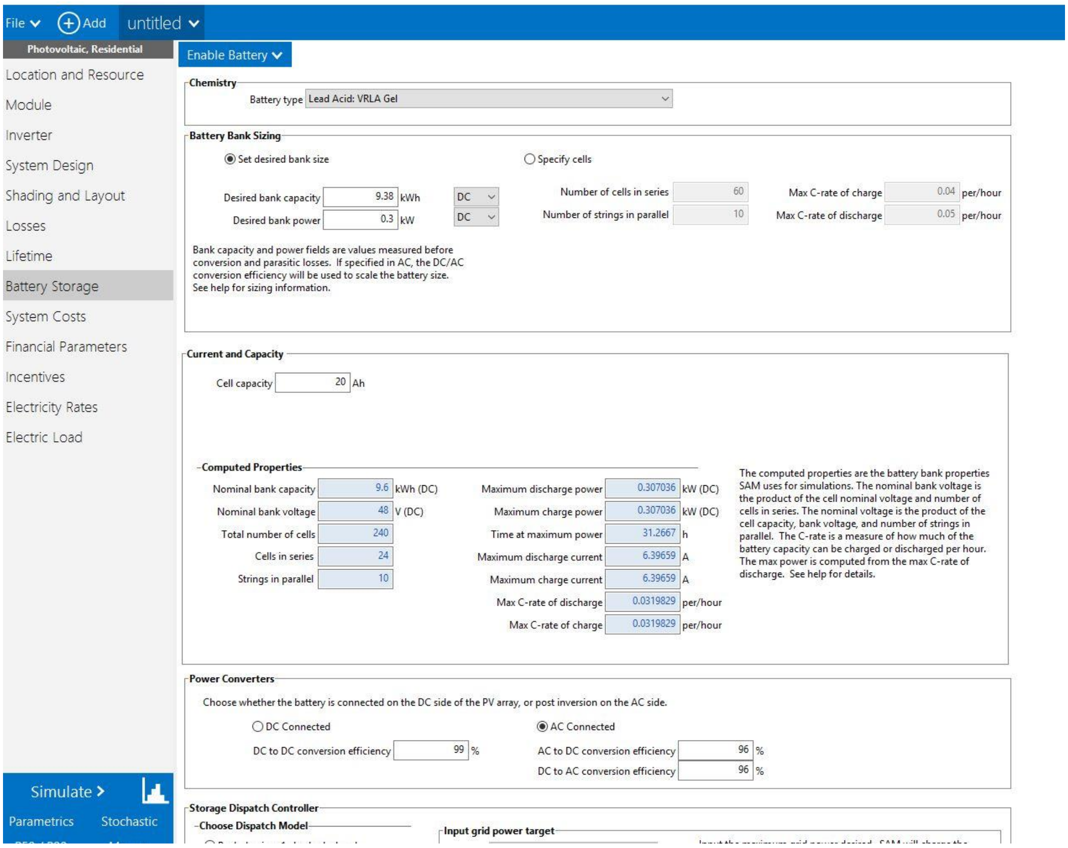
Monthly solar irradiance and corresponding system AC energy for high-income group

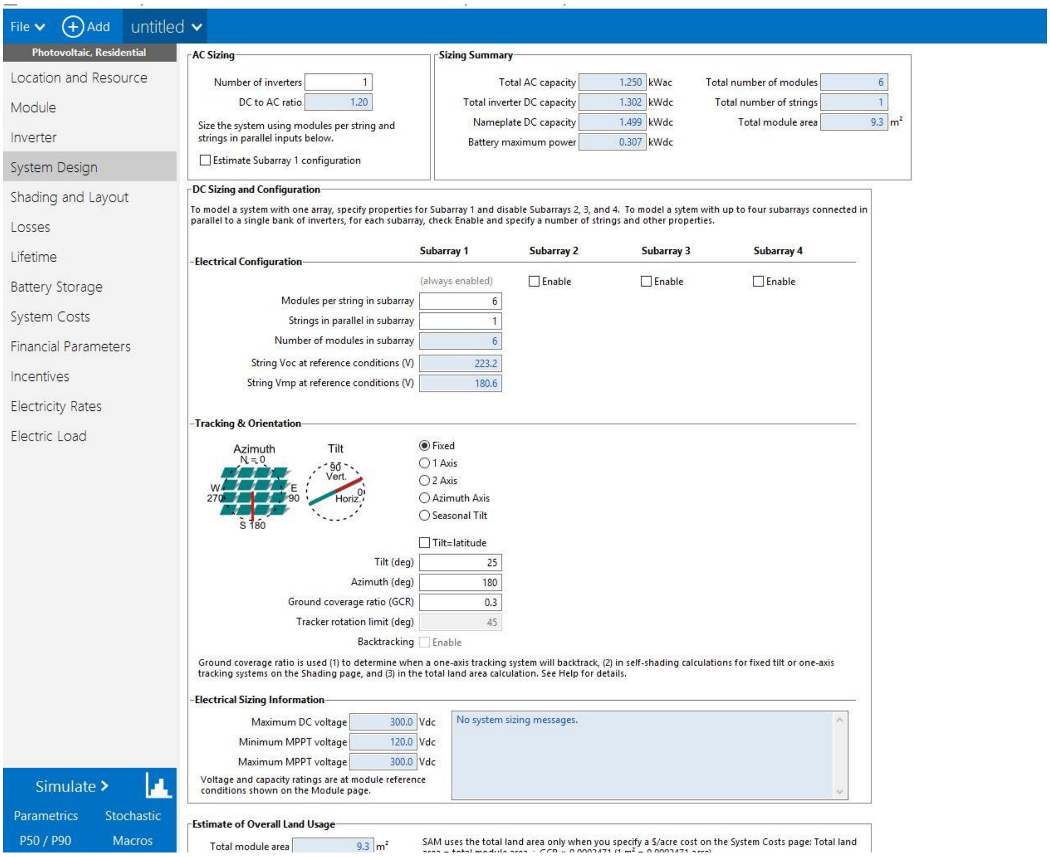
Appendix H: SAPVS simulation for low-income group



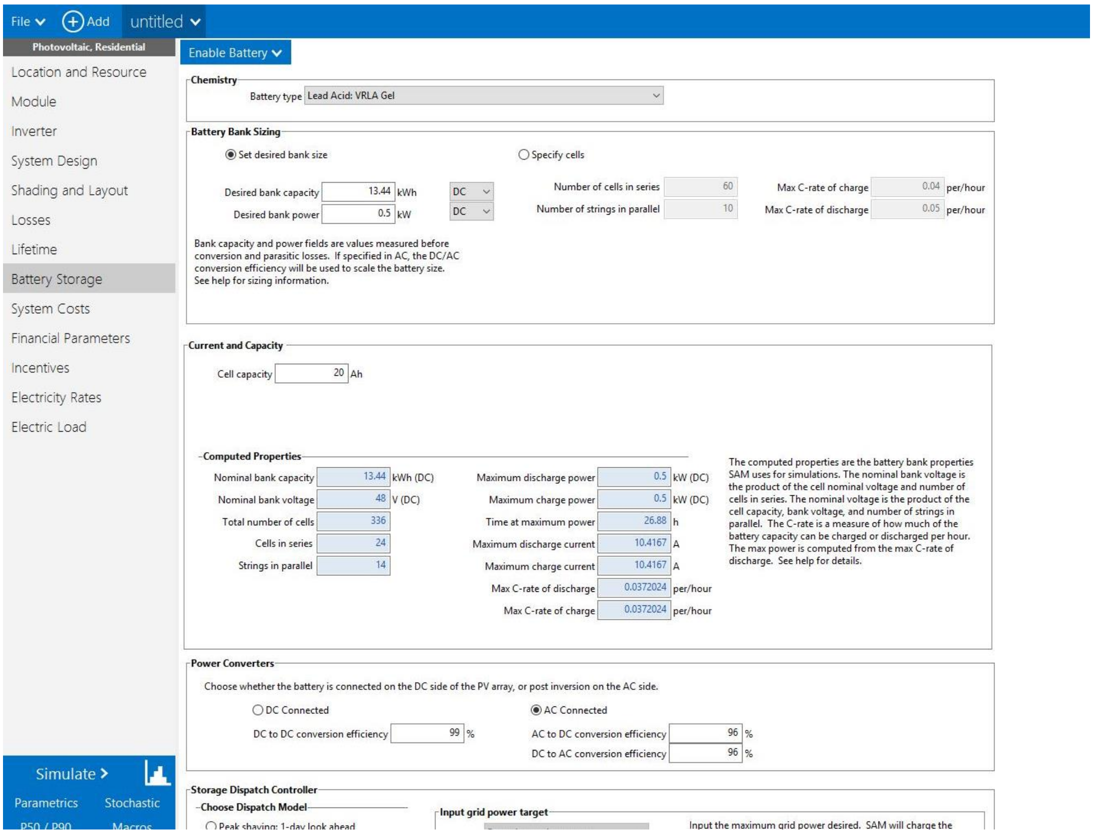


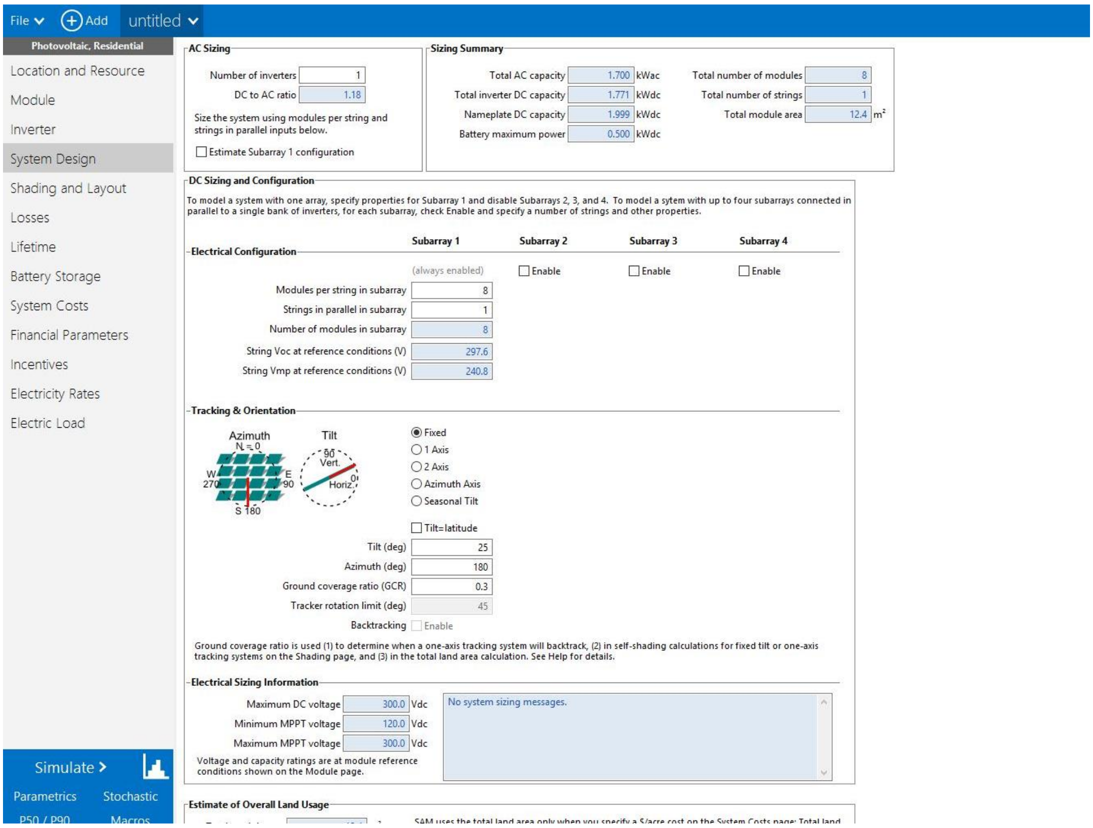
Appendix I: SAPVS simulation for middle-income group



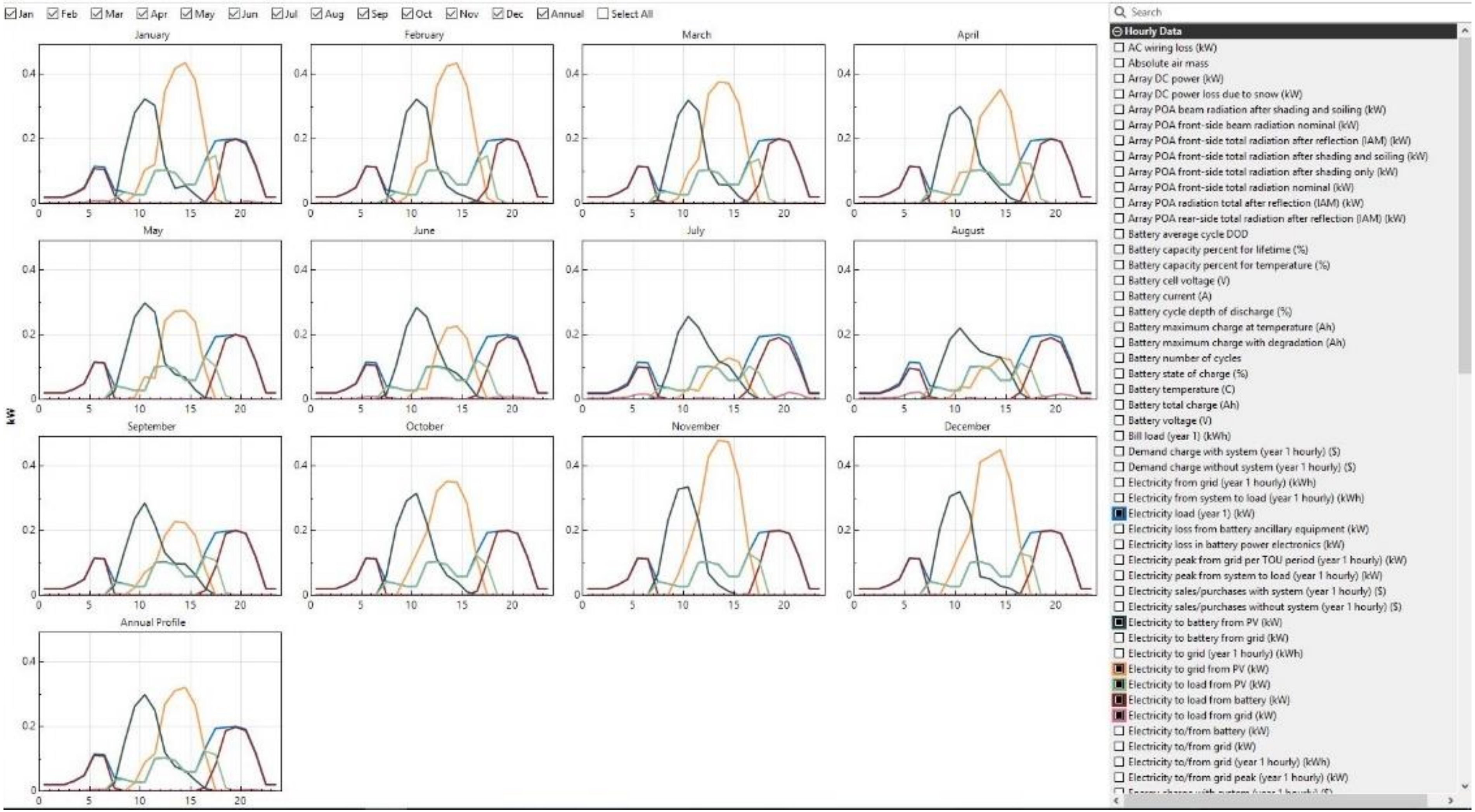


Appendix J: SAPVS simulation for high-income group

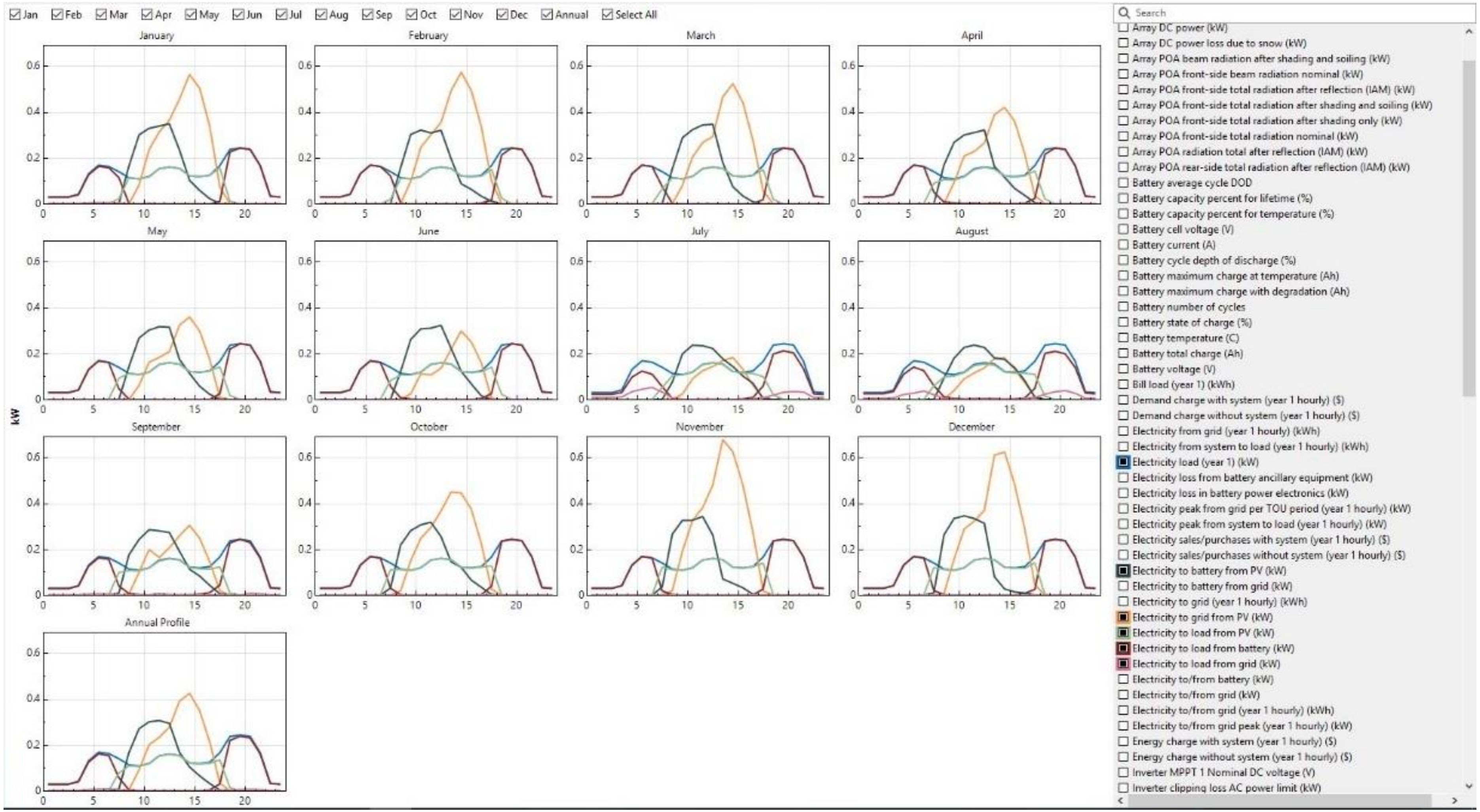




Appendix K: SAM monthly and annual system performance simulation for low-income group



Appendix L: SAM monthly and annual system performance simulation for middle-income group



Appendix M: SAM monthly and annual system performance simulation for high-income group