FEASIBILITY OF A SOLAR PHOTO-VOLTAIC SYSTEM AS AN ENERGY SOURCE FOR LIGHTING IN GRID-CONNECTED RESIDENTIAL BUILDINGS IN CAMEROON: CASE STUDY OF BUEA

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Abstract

Cameroon has the second largest hydropower potential in Africa after the Democratic Republic of Congo. However, even with this potential, electricity supply in the country is insufficient and unreliable especially in the midst of the dry season, thus the many residents affected are inconvenienced due to lack of energy for lighting. This and coupled with climate change constraints, necessitates the investigation of measures geared towards effective utilization of the available energy from the grid and the feasibility of an alternative energy source to be employed in the onsite generation of electricity in residential buildings for lighting. In this research, a total of 100 residential dwellings of different classes (T1 to T7) were surveyed in the town of Buea, Cameroon. The survey employed the use of a questionnaire designed to collect data on current lighting technologies used in dwellings and the electricity load for lighting and basic communication appliances (radios and mobile phone chargers) of the dwellings. An economic and environmental analysis for transition towards efficient lighting in the surveyed dwellings was conducted. The load profiles of the dwellings classified from the k-means algorithm in R Statistics were used in the HOMER Pro software for a techno-economic modelling of residential PV systems (stand-alone and grid back-up) to meet the load of the dwellings. The survey had a questionnaire return rate of 92%. Results of the survey revealed that artificial lighting in the dwellings is achieved through the use of the following technologies: incandescent lamps, compact fluorescent lamps (CFL) and fluorescent tubes. The economic assessment of efficient lighting transition in the dwellings for an artificial daily lighting duration of six hours revealed a net present value (NPV) that ranges from \$47 (T1 building) to \$282.02 (T5 building), a benefit cost ratio (BCR) of 1.84 and a simple payback period (PBP) of 0.17 year (2 months) for the substitution of current incandescent lamps in dwellings with CFL. The substitution of incandescent lamps with light emitting diodes (LED) revealed an NPV of the range \$89.14 (T1 building) to \$370 (T5 building), a BCR of 3.18 and a PBP of 1.92 years (23 months). The substitution of incandescent lamps with CFL and LED results to a reduction in lighting related greenhouse gas (GHG) emissions from dwellings by 66.6% and 83.3% respectively. Results from the HOMER modelling revealed a levelized cost of electricity (LCOE) of the PV system under the following parameters: 0% annual capacity shortage, 40% minimum battery state if charge (SOC), 25 years PV lifetime, 5% discount rate and 2% inflation rate to be 10 to 13 times more expensive (stand-alone system) and four to eight times more expensive (back-up system) compared to the grid electricity. The PV systems have potentials to save an annual emission of 89.17 to 527.37 kgCO_{2-e} for the stand-alone system. Favourable government policies are necessary to spur the deployment of these low carbon technologies in the residential sector of Cameroon.

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Acronyms

AC	Alternating Current
BCR	Benefit Cost Ratio
CD	Compact Disc
CFL	Compact Fluorescent Lamp
DC	Direct Current
DVD	Digital Video Disc
ESDP	Electricity Sector Development Programme
GHG	Greenhouse Gas
GWh	gigawatt-hour
HOMER	Hybrid Optimization Model for Renewable Energy
IRR	Internal Rate of Return
kW	kilowatt
kWh	kilowatt-hour
LED	Light Emitting Diode
MPPT	Maximum Power Point Tracker
MW	Mega-Watt
NPC	Net Present Cost
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PBP	Simple Payback Period
PV	Photo Voltaic
SOC	State of Charge
SONARA	National Oil Refinery of Cameroon
STC	Standard Test Conditions

Chapter 1: Introduction and background

1.1 Introduction

Greenhouse gas (GHG) emissions emanating from anthropogenic and natural activities since the onset of the industrial age have led to their increased concentration in the atmosphere. The absorption of radiations by these gases alters the amount of solar radiation reaching the earth and the amount of infrared radiation that is absorbed back into space. The result is the disruption of the earth-atmosphere energy balance leading to cooling or warming of the climate depending on the radiating forcing being negative or positive (Forster et al., 2007). The change in the global climatic parameters have in recent times raised serious global concerns and is currently one of the most worrisome problems faced by the contemporary world. Energy security is yet another issue of global concern precipitated by the unprecedented rate of consumption of oil fields and a concomitant increase in the demand of energy to drive national economies (Charman, 2010).

The built environment is recognised for its high energy use. While the building sector provides facilities for human needs and provides benefits to the society at large, it has had detrimental impacts on the environment over the last decades (Zuo & Zhao, 2014). The consumption of energy by this sector is not without environmental impacts and implications on security of energy supply. As reported by Lucon et al. (2014), the global building sector in 2010 accounted for about 32% of final energy use and over 8.8 $GtCO_2$ emissions, with energy demand from this sector projected to double by mid-century. Of the energy consumed in buildings, three quarter emanates from the residential sector (IEA, 2013). The residential sector accounts for 27% and 17% of global energy consumption and carbon dioxide emissions respectively (Nejat, Jomehzadeh, Taheri, Gohari, & Abd. Majid, 2015). The consumption of energy in the residential sector is a function of appliance duty cycle (utilization hours), appliance ownership level and the power rating of an appliance (Saidur, Masjuki, & Jamaluddin, 2007). Electrical energy remains one of the main forms of energy consumed in residential dwellings. This can be attributed to the diverse end uses of electricity of which lighting remains a basic and important end use.

Cameroon’s residential sector constitutes the second highest electric energy consumer after the industrial sector, accounting for 30% of total energy consumed (European Union Energy Initiative Partnership Dialogue Facility, 2014). This sector has grown tremendously, with strong evidence revealed through the housing boom and public construction sites observed in recent times in the country. Based on the United Nations (2015) statistics, the population of Cameroon is projected to increase from 23.34 million in 2015 to 32.94 million in 2030. Hence, this population increase will have an increased pressure on built environment services which as a consequence, will likely increase the energy demand from this sector. This is supported by the findings of Nejat at al. (2015) which shows that population, urbanization and economic growth especially in developing countries culminates in an increase in residential energy consumption. Based on the direct relationship that exists between income and appliance ownership, an envisaged increase in energy demand from the residential sector in Cameroon could as well be realised in the scenario of increasing GDP of the country considering the prediction of Kelly (2012) that an increase in GDP per capita in most developing countries will result to a major growth in appliance utilization.

In the African continent, Cameroon ranks second in terms of hydro-electricity potential after the Democratic Republic of Congo, totalling an estimated capacity of 19.7 GW (Kenfack, Fogue, Hamandjoda & Tatietse, 2011) but ironically, electricity supply in the country is inadequate. In 2012, only 7% of the country’s energy needs was met by electricity (International Energy Agency, 2015). Electricity supply, which plays an unequivocal role to the growth of any modern economy by virtue of its diverse end uses, is inadequate in the country and this can be corroborated by the frequent power cuts mostly experienced in the dry season during the months of January to June (Nfah and Ngundam, 2009). This is not unexpected owing to the fact that there is over-reliance of the nation’s electricity sector on hydro power whose output is immensely affected by the reduction of water volume in the rivers during periods of no precipitation. During this period of drought, power generated by back up thermal plants is usually insufficient to meet demand and the rationing of electricity does not guarantee the regular operation of industries. Pertaining to the electricity access situation in the country, about 3 000 out of 14 000 localities are electrified amounting to a national electrification rate of 22% while the rural electrification rate stands at 3.5% (Ayompe and Duffy, 2014).

An expected increase in electricity demand from the residential sector in Cameroon will put pressure on the energy infrastructure which currently is facing structural challenges. There is therefore need for measures to reduce energy consumption in this sector among other sectors in the country. According to Lucon et al. (2014), enhancement in energy efficiency is an immediate effective measure to reduce energy demand and carbon dioxide emissions, while providing adequate planning time for the commissioning of new power plants. A strategic area with potential for energy savings and reduction in peak power demand in the residential sector of Cameroon is lighting which is still dominated by the use of incandescent lamps (SIE, 2012). Lighting in 2007 and 2010 respectively represented 30% and 20% household electricity use in the country. In this light, the government of Cameroon has proposed to improve lighting energy efficiency through the launching of an extensive national programme for raising awareness of compact fluorescent lamps (CFLs) and light emitting diodes (LED) (SIE, 2012).

Small scale domestic sized renewable energy technologies can be used to reduce pressure on the grid. By integrating these technologies into residential buildings, the energy demand of buildings from the grid will reduce (Lucon et al., 2014). An example of a renewable energy technology that is widely integrated in residential buildings is the solar photovoltaic technology. This technology is increasingly being integrated into residential buildings as either stand-alone systems or a hybrid (grid back-up) system. In the stand-alone case, either the building goes entirely off-grid with the entire load of the building met by the PV system (Sick & Erge, 1996) or as in the hybrid case the load is either in part (as a separate DC circuit) or entirely met by both the grid and the PV system. However, the technical and economic feasibility of the integration and use of a PV system in buildings is location specific since the electricity generation potential of the system is dependent on the solar resource that varies from location to location and the energy tariff in place at domestic dwellings also varies from location to location.

The solar photovoltaic technology like other renewable energy resources does not only ensure energy access but also mitigate global climate change. There exists controversy over the environmental benefits of solar PV since some scholars consider PV as carbon free while others do not share this view. According to Nugent and Sovacool (2014), solar PV technology is unfree from emissions since it was found to have an estimated average life cycle GHG emissions of 49.81 $gCO_{2\text{-eq}}$/kWh. However, emissions from solar PV are relatively low compared to diesel (778 $gCO_{2\text{-eq}}$/kWh) and coal (960 $gCO_{2\text{-}}$

$_{eq}$/kWh). Hence, the use of electricity generated from renewable sources have a positive impact on the environment in terms of GHG emission reduction (Sapkota, Lu, Yang & Wang, 2014) since they are lower in carbon compared to conventional fuel employed in electricity generation.

1.2 Problem statement

Energy is an important and integral component that drives the development of nations. Cameroon is endowed with enormous renewable energy resources and currently possesses the second largest hydro power potential in Africa after the Democratic Republic of Congo (Nfah & Ngundam, 2009). The country also has a great solar potential with estimates of 5kWh/day/m^2 (Tansi, 2011). However, the supply of electricity in Cameroon is inadequate due to the infrastructural challenges faced by the country's electricity sector (Government of Cameroon, 2010). There is a high reliance of the electricity sector of Cameroon on hydro power, the output of which varies considerably between wet and dry seasons. During the months of January to June which coincides with the dry season in the country, the volume of water in the rivers drops considerably, reducing the output of generated power from the hydro dams which results in frequent power cuts in various parts of the networks (Nfah & Ngundam, 2009). In response to the severe blackouts, both rural and urban households in the country rely heavily on the use of kerosene lamps and candles for lighting (Lighting Africa, 2012). The use of kerosene lamps and candles do not only result to the release of GHGs and toxic substances that causes respiratory diseases (Pokhrel et al., 2010; Lam et al., 2012; Mills, 2012; Choi et al., 2015), but also poses a heightened level of risk of a fire hazard. According to Tapang (2014), a fire outbreak from a burning candle in the economic capital city of Douala, Cameroon resulted to the death of four children. With a good solar resource potential in the country, households in Cameroon could use solar PV for lighting their buildings. Earlier studies on the application PV systems in Cameroon conducted by Nfah, Ngundam, Vandenbergh, & Schmid (2008); Nfah & Ngundam (2009); and Nfah, Ngundam & Kenne (2010) focussed on hybrid applications for power generation at a whole-of-community scale. A more recent study by Ayompe & Duffy (2014) assessed the generation potential of PV systems in Cameroon but did not focus on any particular energy load of buildings. There still remains a need to understand the load demands of individual domestic dwellings and how solar PV can meet these loads. It is within this light that this study seeks to investigate the potentials of solar PV as an energy source for lighting households in Cameroon using Buea as a case study.

1.3 Aim and objectives

The aim of this study is to assess the techno-economic feasibility and associated social and environmental benefits of a solar photovoltaic as an energy system for the provision of lighting in residential buildings in Buea, Cameroon.

The objectives of the study include:

1. To determine the daily electric load for lighting and basic communication appliances for buildings in the study area.
2. To determine the technical and economic feasibility for the use of a PV system in meeting the load for lighting and basic communication appliances determined in objective 1.
3. To assess the impact of uptake of energy efficient lighting in the study area.
4. To assess the possible impact of a government policy-subsidy provision on the adoption of light emitting diode (LED) in the study area.

1.4 Limitation of the study

This study was not without limitations. The limitations associated with this study include:

1. This study was designed around fieldwork in Buea Cameroon to include a demonstration exercise with light emitting diodes (LED) bulbs in the surveyed households. However, the demonstration was not possible since many households were reluctant for the technology to be tested in their dwellings. This reluctance stemmed from the security threats in the country associated with the Boko Haram terrorist group at the time when the household survey was conducted. Hence, many households were cautious, suspicious and sensitive towards a demonstration conducted in their homes during this period.
2. Load profile data for the surveyed households was collected for a week due to time constraints. This duration is not long enough to account for monthly variations that may exist in the load.

1.5 Key assumption

In this study, it was assumed that the average time-of-use profile obtained from the surveyed dwellings was constant with no seasonal variation.

1.6 Significance of study

This study will generate information and knowledge on the technical and economic feasibility for the integration of solar photovoltaic into residential buildings in Cameroon for the provision of lighting and powering of basic communication appliances like radio and mobile phone charging. Such information will be useful in guiding households and other stakeholders to make informed decisions on the integration of solar PV into existing and future buildings. The study will develop knowledge on the factors that affects the adoption of energy efficient bulbs among households in the study area as well as the economic and environmental benefits associated with the transition towards efficient lighting in the residential sector of the country. This could inform the formulation of energy efficiency policies in the country necessary to create an enabling environment for the transition towards the use of energy efficient technologies in the residential sector.

1.7 Background of study area

Buea is a historic town in Cameroon located at latitude 4° 09' 10" N and longitude 9° 14' 28" E. In the colonial era, Buea was the capital of German Kamerun during the period (1884 – 1914) of the German rule, the capital of Southern Cameroon during the British rule (1916 – 1960) and capital of the Federated State of West Cameroon (University of Buea, 2014). Currently, Buea is the administrative capital of the South West Region and is one of two English speaking regions of Cameroon. The South West region constitutes an important economic centre consisting of the country’s lone petroleum refinery (SONARA), the lone state Anglo-Saxon University in the country, and various cocoa, rubber and banana plantations (Tansi, 2011). Buea is also a great tourist attraction centre, being close to one of the continent’s largest active volcanoes known as Mount Cameroon. The location of Buea in Cameroon is indicated in Figure 1.

1.7.1 Climate

Buea enjoys a tropical climate like other parts of the country with two distinct seasons: dry and rainy seasons. The rainy season is characterized by relatively low temperatures (about 21^{o}C) and extended periods of fog and drizzle, which could last for weeks. The dry season is marked by abundant sunshine and high temperatures that can get to 30^{o}C.

The climate of Buea differs slightly from the rest of the country by virtue of its location at the foot of Mount Cameroon (Eyong, 2007) and its proximity to the Atlantic coast of the country (University of Buea, 2014). The town enjoys a relatively cold climate with maximum temperatures that ranges from 27.1^{o}C in August to 31.6^{o}C in February (Stackhouse, 2015). Buea has humidity levels that range from 73.9% in January to 86.9% in September.

1.7.2 Socio-economic profile of Buea

Buea covers a surface area of about 866 km^2 with an estimated population of 150,000 inhabitants (Eyong, 2007). The majority of the town's population is constituted by the original indigenes of the area known as the "Bakweri". The status of Buea as a regional headquarter and as a University town since 1993 constitutes the town as an academic hub in the South West Region which has attracted a significant number of people from other ethnic groups in the country.

1.7.3 Economic Activities

Agriculture could be said to be a dominant economic activity in Buea characterized by the subsistence cultivation of food crops through the use of rudimentary tools and family labour (Eyong, 2007). Most Farming activities in Buea are concentrated in the rainy season which is the period set aside for cultivation. The common crops grown by the farmers include: maize, cassava, yams, cocoyams, plantains, potatoes and various types of vegetables. The agricultural output of the town supply not only the local market, but as well neighbouring countries like Equatorial Guinea and Gabon (University of Buea, 2014).

Outside agriculture, Buea as a regional headquarter offers some of its inhabitant's employment opportunities to hold administrative and other clerical positions in the formal (professional) sector (Eyong, 2007). A number of the town's population is employed in; public, mission and private primary and secondary schools; the state University and other private Universities; government hospitals and private clinics among others.

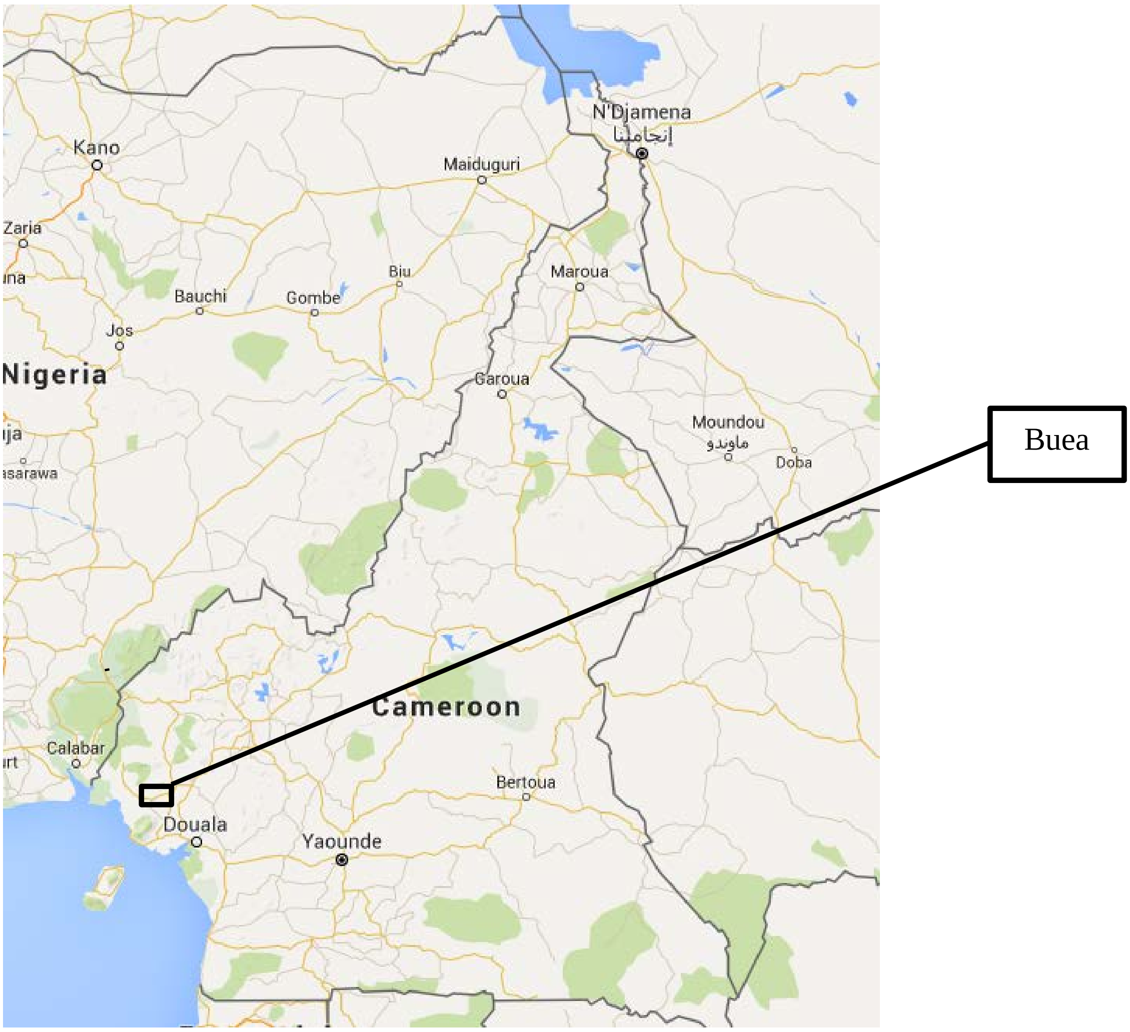

Figure 1: Map showing the location of the study area in Cameroon (Source: adapted from Google map).

1.8 Thesis outline

This thesis begins with the current chapter that provides information on the objectives and motives underlying this research work. The second chapter (page 10) is a review of related literature on the energy sector of Cameroon, lighting technologies and the solar photovoltaic technology. In the third chapter (page 55), the methodology employed in this research is outlined in detail. It gives an overview of the statistical analysis conducted and the software tool (HOMER Pro) used in designing the solar PV systems for the residential buildings. In the fourth chapter (page 70), the results of the study are presented. This chapter embodies the different classes of time-of-use electricity profiles, the different types of lighting technologies used, factors that influence on the lighting load of residential buildings, and the modelling results of the HOMER Pro software. Chapter five (page 104) dwells on the discussion of the results in relation to previously conducted studies while chapter six (page 116) provides conclusion and recommendations emanating from the study.

Chapter 2: Literature review

2.1 Introduction

This literature review covers the following topics:

- the electricity sector of Cameroon,
- the building sector of Cameroon,
- residential electricity consumption,
- energy efficient lighting technologies,
- solar energy resource in Cameroon,
- solar PV system to include design of a PV system, cost of PV system components, economic, social and environmental benefits of PV systems, case study PV projects in West Africa, and
- a review of the HOMER software for energy modelling.

2.2 Cameroon's electricity sector

2.2.1 Electricity generation capacity

Cameroon has an enormous energy potential. According to Nfah and Ngundam (2009), the country possesses the second largest hydroelectric potential (294 TWh) in Africa after the Democratic Republic of Congo estimated at 1000 TWh. However, only 5.5% of the technically-feasible capacity (115 TWh/year) has been developed.

The generation of electricity in Cameroon is open to competition. Independent power producers are authorised to generate electricity and sell to the power company under a power purchase agreement (AES SONEL, 2011). Electricity is generated in the country from three hydroelectric power stations (Edea, Song Loulou and Ladgo) as shown in Figure 2 and nine thermal power plants (Fotsing, Njomo & Tchindia, 2014). In 2010, Cameroon had an installed hydroelectric power capacity of 729 MW while it had 776 MW installed capacity of thermal power plants (diesel and natural gas) owned by both AES SONEL and independent power producers (Ayompe & Duffy, 2014).

2.2.2 Electricity supply and demand

Cameroon's electricity sector is currently poorly developed and inadequate to meet demand and this has slowed down socio-economic development in the country (Government of Cameroon, 2010). The sector faces both structural and technical challenges that can be corroborated by the low electrification rate in the country (African Development Fund, 2009). Out of over 14000 localities, only 3000 are electrified giving a national electrification rate of 22%. This low rate of electrification is a major setback for the production of goods and services since energy constitutes an important factor of production. The Cameroon electricity sector faces an annual deficit between what is produced and what is demanded. Some of this difference stems from system efficiency losses (European Union Energy Initiative Partnership Dialogue Facility, 2014).

Demand of electricity in Cameroon represents only a small proportion (about 7%) of the country's total energy consumption. The country's electricity demand in 2012 was estimated at 3710 GWh (European Union Energy Initiative Partnership Dialogue Facility, 2014). Electricity demand from low level users (defined as having a peak load below or equal to 36 kW) and medium level user (peak load above 36 kW) in Cameroon is on the rise. On an annual basis, the use of electricity by these groups of consumers increases by an average of 6% with an estimated demand of 4700 GWh and 7600 GWh in 2015 and 2025 respectively (Government of Cameroon, 2010). Conversely, the industrial demand, which is dominated by the energy requirements of the aluminium industry was estimated at 1315 GWh in 2010 with its demand estimated to triple by 2015. Based on recent studies conducted by the European Union Energy Initiative Partnership Dialogue Facility (2014), growth in electricity demand in the industry, tertiary buildings and households sectors by 2025 against the 2012 benchmark was forecasted to reach 109%, 55% and 79% respectively as shown in Table 1. This projected increase in the demand of electrical power could likely be associated to the envisage increase in the nation's population and industrialization.

Table 1: Forecast of electricity consumption growth by 2025 compared to 2012.

Sector	**2012 electricity demand**	**2025 forecasted growth in electricity demand (GWh)**	**2025 forecasted growth in electricity demand (%)**
Industry	1877	2050	109%
Tertiary buildings	720	400	55%
Household	1113	880	79%
Total	3710	3330	90%

Source: European Union Energy Initiative Partnership Dialogue Facility (2014).

Electricity supply in Cameroon is currently monopolised and the American Company AES SONEL had a 20-year concession agreement from July 2001 that gave it the exclusive rights to distribute electricity to all medium voltage (load above 36 KW) and low voltage (load below or equal to 36 kW) customers. This is with the exception of generation companies with an installed capacity of more than 1 MW who are free to negotiate bilateral agreements (AES SONEL, 2011). Thus, independent power producers of less than 1 MW capacity must sell their generated electricity to the power company with the reserved rights for distributing electricity to the consumers.

The supply of electricity in Cameroon is through a number of separate transmission networks. In 2010, the power company AES SONEL operated three different transmission grids (see Figure 2): the southern interconnected grid (SIG); the northern interconnected grid (NIG); and the eastern interconnected grid (EIG) through which all the electricity generated in the country is transmitted and distributed to the customers (Ayompe & Duffy, 2014). The southern interconnected grid covers six regions in the country: Centre (Yaounde), Littoral (Douala), West (Bafoussam), Northwest (Bamenda), Southwest (Limbe) and South (Ebolowa) while the northern interconnected grid and the eastern interconnected grid covers three (Adamawa, North and Far North) regions and one (East) region respectively (Fotsing et al., 2014).

The installed capacity and electricity demand differs between grids. In 2010, the southern interconnected grid had the highest installed capacity and the highest electrical power demand corresponding to 1321 and 654 MW respectively followed by the northern interconnected grid and the eastern interconnected grid (Ayompe & Duffy, 2014) (Figure 3). The trend of the electricity demand and installed capacity of the different grids is not unexpected since the southern interconnected grid covers the highest number of regions while the eastern interconnected grid covers the least. Also, the regions covered by the Southern interconnected grid hosts the country’s major industries and as a consequence, the reason for the high installed capacity and electricity demand from the Southern grid compared to the others.

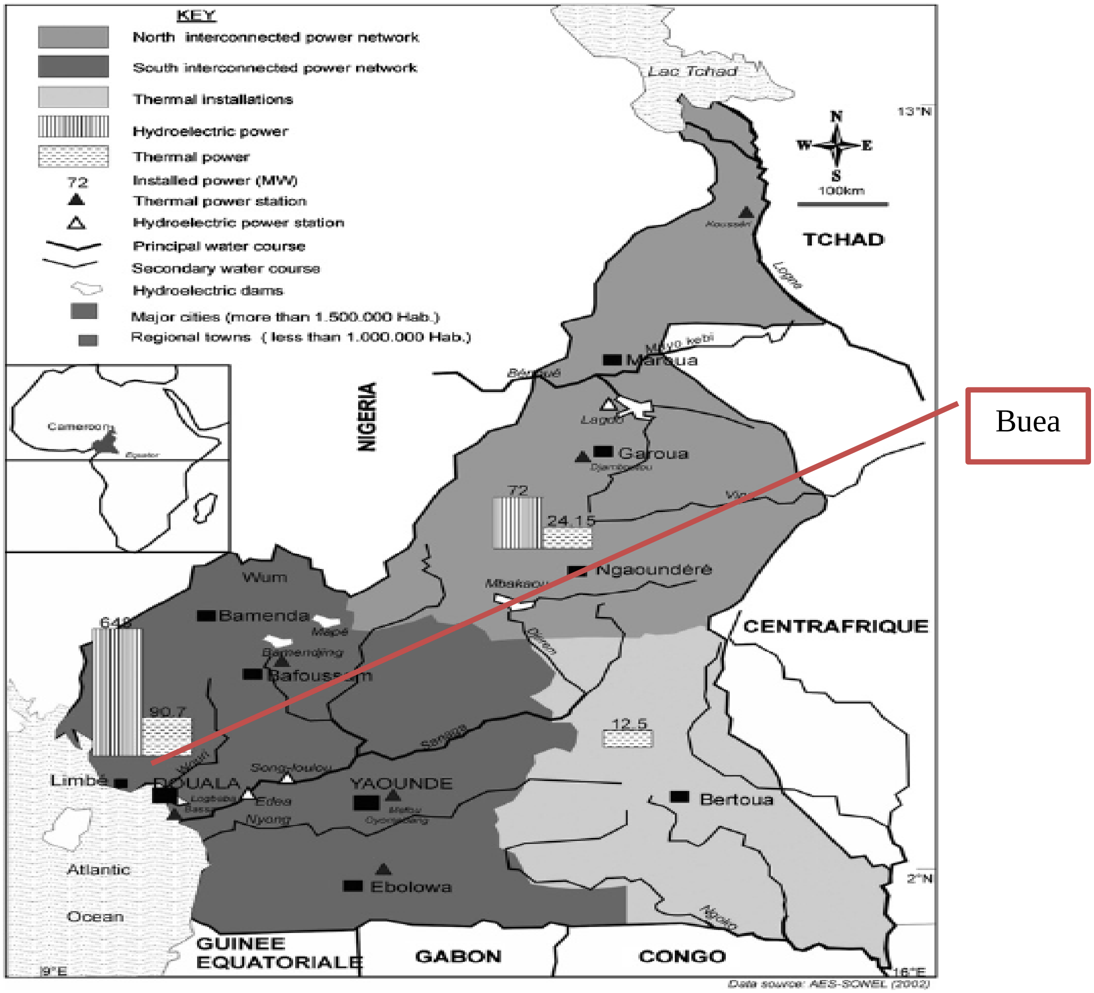

Figure 2: Map of electricity generation and transmission networks in Cameroon. Source: Nfah et al. (2008).

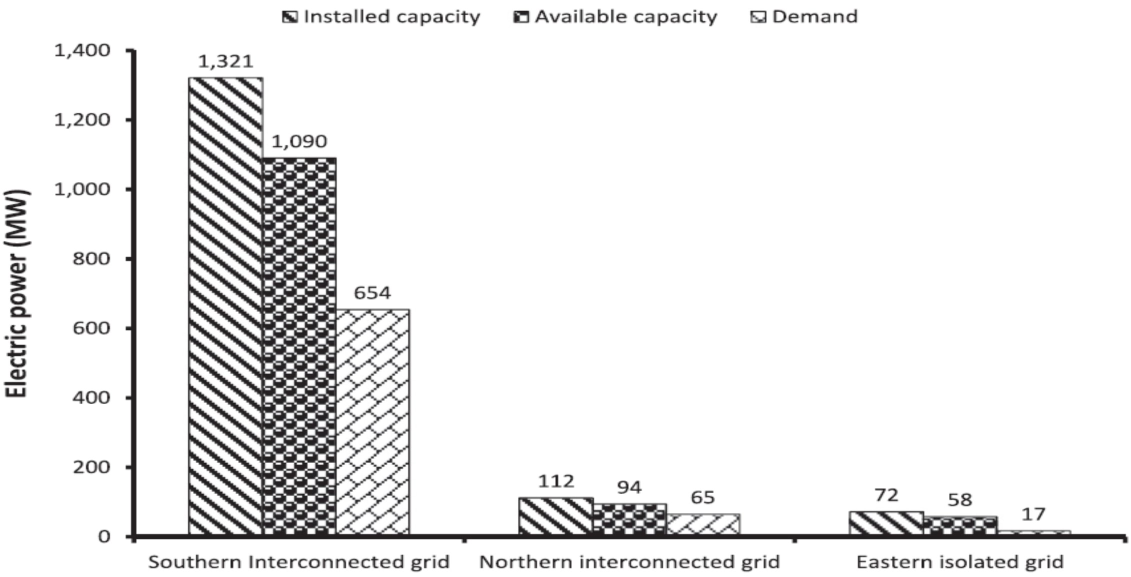

Figure 3: Installed capacity, available capacity and electric power demand in 2010 in Cameroon.

2.2.3 Reliability of electricity supply

The reliability of the supply of electricity, which plays an unequivocal role to the growth of any modern economy by virtue of its diverse end uses is poor in Cameroon. The principal source of electricity in Cameroon is the hydroelectric system which suffers from under development (European Union Energy Initiative Partnership Dialogue Facility, 2014). The absence of effective strategies that will guarantee diversification of electricity generation sources exacerbates the situation. The results are frequent power cuts mostly experienced during the drier months of January to June (Nfah & Ngundam, 2009). During this period of seasonal drought, the energy generated by back up thermal plants is usually insufficient to meet demand and the rationing of electricity does not guarantee the day-to-day operation of industries especially those connected to networks of low voltage.

The state of the existing transmission network in the country is a major cause of inefficiency. As a result of the poor maintenance and aging nature of the transmission lines, the Yaounde area (Figure 2) among others in the country is prone to significant voltage drop, heavy losses and outages (European Union Energy Initiative Partnership Dialogue Facility, 2014). The electricity distribution system is in notoriously poor conditions in both rural and urban areas, rendering the supply of electricity inconsistent, inadequate and unreliable.

2.2.4 Planned works

Electricity supply in Cameroon is projected to increase in the future so as to meet the unmet demand from the population and the energy needs of major industrial projects required to transform the economy of the country. The Cameroon government vision by 2035 is for the country to become an emerging economy and as part of this vision, the government envisages the nation to become an electricity exporter to other countries in the Central Africa sub region (Government of Cameroon, 2010). In an attempt to meet the projected increase in domestic electricity demand and those of the neighbouring countries, the Cameroon government prepared an Electricity Sector Development Plan (ESDP) (Ayompe & Duffy, 2014). This long term Electricity Sector Development Plan is to be fully developed by 2030 and prescribes new power station projects that will be need to be commissioned to close the energy deficit gap and to bolster economic growth in the country (Government of Cameroon, 2010).

Based on the provisions made in the ESDP, the plan for the development of electricity generation power plants entails the installation of over 2500MW of hydroelectric power between 2012 and 2020, and 298 MW of electricity from thermal plants between 2010 and 2013 (Ayompe & Duffy, 2014). Recently, the Cameroon government identified photovoltaics as a viable source of electricity and signed a memorandum in July 2012 with a private developer to finance, develop, build and operate over 500 MW of both stand-alone and grid connected solar PV systems between 2012 and 2020. The first phase of this project was due to commence in October 2012 and consisted of 100 MW grid connected PV systems (Ayompe & Duffy, 2014).

2.3 Cameroon dwellings

The construction of buildings in Cameroon is not well regulated and is dominated by informal practices (Pettang, Vermande & Zimmermann, 1995) which culminates in the construction of buildings of different types and characteristics. The type of building constructed will depend on the income or financial capacity of the person building. However, the Cameroon Ministry of Housing and Urban Development classifies residential buildings into six different categories (Table 2) based on the minimal area and components of the building (Manjia, Abanda & Pettang, 2015).

Table 2: Categorisation of residential buildings in Cameroon (differences between categories are in italics).

Type	Component	Quantity	Minimal area (m^2)	Entire Minimal area (m^2)
T1	Bedroom	1	12	20
	kitchen	1	3	
	Toilet	1	3	
	Corridor	1	2	
T2	*Living room + Dining room*	*1*	10	32
	bedroom	1	12	
	kitchen	1	3	
	Toilet	1	5	
	corridor	1	2	
T3	living room + Dining room	1	20	62
	bedrooms	*2*	12	
	kitchen	1	10	
	Toilet	1	5	
	corridor	1	3	
T4	living room + Dining room	1	25	89
	bedrooms	*3*	12	

Type	Component	Quantity	Minimal area (m^2)	Entire Minimal area (m^2)
	kitchen	1	10	
	Toilets	*2*	5	
	corridor	1	8	
T5	living room + Dining room	1	30	106
	bedrooms	*4*	12	
	kitchen	1	10	
	Toilets	*2*	5	
	corridor	1	8	
T6	living room + Dining room	1	35	130
	Bedrooms	*5*	12	
	kitchen	1	10	
	Toilets	*3*	5	
	Corridor	1	10	

2.4 Residential electricity consumption

2.4.1 Common household electrical appliances used in Cameroon dwellings

Limited studies exist on the electrical appliances used in Cameroon’s dwellings. Studies conducted by Manjia et al. (2015) in the capital city of Yaounde identified the following electrical appliances in dwellings:

- freezer
- fridge
- pressing iron
- DVD (CD + video player)
- simple radio
- complete radio (simple radio + DVD)
- television
- bulb
- laptop
- telephone charger
- electrical water heating coil
- computer
- fan
- vacuum cleaner
- microwave
- gas and electrical oven
- food blender/mixer
- coffee maker
- washing machine
- fluorescent bulbs and

- voltage regulator

There exists a disparity in the power rating of appliances across dwellings in Cameroon. For instance, the power rating of pressing iron for three different households surveyed was found to be 176W, 2000W and 1000W (Manjia et al., 2015). According to the authors, this disparity could be accounted for by the lack of standardisation of electrical appliances in the country. This is exacerbated by the flood of imported second handed appliances (Kenfack et al., 2011) and market forces indicating a desire for different capacities. The efficiencies of these second hand appliances are often unknown and unreliable. This could also be associated to the variation of income and or education level among households since households with higher income or education level are likely to buy more efficient appliances that consume less power while lower income households will buy less efficient and obsolete ones due to the high capital cost associated with energy efficient technologies (Kenfack et al., 2011).

The results of the studies conducted by Manjia et al. (2015) revealed the sharing of some electrical appliances among households in the country. Depending on social ties and relationships, households borrow some electrical appliances like mobile phone chargers and electrical water heating coils from their neighbours.

2.4.2 Factors that accounts for load profile of dwellings

The load profiles of dwellings differ considerably based on a number of factors. The energy consumption pattern of a dwelling during the day is influenced by a range of internal factors including but not limited to number of people in the dwelling, the pattern of work, the age of the occupants (Stoecklein, Pollard, Camilleri, Tries & Isaacs, 2001) and number of appliances owned (Nie & Kemp, 2014). From their findings, Manjia et al. (2015) revealed that the maximum energy load of buildings surveyed in the capital city of Yaounde, Cameroon occurred at 6 am while the minimum load occurred between 8 am and 11 am as indicated in Figure 4. The former coincides with the time occupants prepare to leave the house and therefore would likely have most of their appliances in use while the minimum load occurs when occupants are likely to have left the house. The occupation and working pattern of household members will influence the amount of time in a day they spend in their homes and this is likely to affect their energy consumption pattern. This is in concordance with the study of

Novoselac, Cetin & Tabares-Velasco (2014) which revealed that weekday load profile for households with members who work out of home was 2-28% less than that of households whose members work from home.

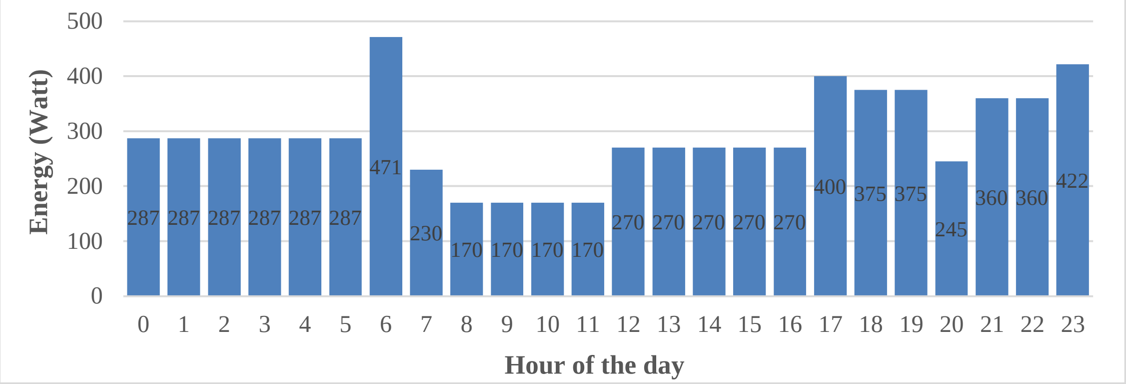

Figure 4: Electricity time-of-use profile of a dwelling in Yaounde, Cameroon (Source: Manjia et al., 2015).

The load profile of a dwelling can also exhibit variability between weekdays and weekends. Results of the study by Novoselac et al. (2014) revealed a correlation between the day of the week and energy use with an increase in energy use and changes in time of use of appliances witnessed over the weekend. The energy load profile for weekdays during business hours (9 am-5 pm) was found to be lower compared to the weekend.

Meteorological conditions are yet another important factor that influences the load of a dwelling. There is a variation in the daily electricity load between the seasons where cooling and heating loads become apparent (Novoselac et al., 2014). When temperatures become very hot during the summer, more electricity is needed for air conditioning (Aldossary, Rezgui & Kwan, 2014). A similar trend was observed in Cameroon by Fotsing et al. (2014) who reported the occurrence of the maximum and minimum load in December and August respectively, with increased use of air conditioners and fans in December (dry season) as opposed to August (rainy season) when such appliances are not used due to the cooler conditions.

2.4.3 Classification of electricity time-of-use profiles

Electricity time-of-use profiles can be classified using different approaches. According to Stoecklein et al. (2001), two approaches can be employed in profile classification: profile shape and absolute power demand. In the case of the profile shape approach, the shape of the profile is analysed while disregarding the quantitative level of consumption. This approach has as its advantage that the timing and period of the peaks determine the category more than does the absolute size of the peak. In the case of the absolute power demand, the analysis of the profile is based on the absolute power demand, leading to the grouping of high power consumers versus low power consumers and the actual use profile of the households grouped together becomes less significant.

Based on the profile shape and using the Kohonen probabilistic neural network, Stoecklein et al. (2001) classified 239 monthly average-day profiles into six main classes. The Kohonen network performs the classification task without "supervision", i.e. it defines its own criteria. The six profile classes determined by the network are shown in Figure 5. The x-axis represents the 24-hour period of the day while the thick black line represents the average profile of the class.

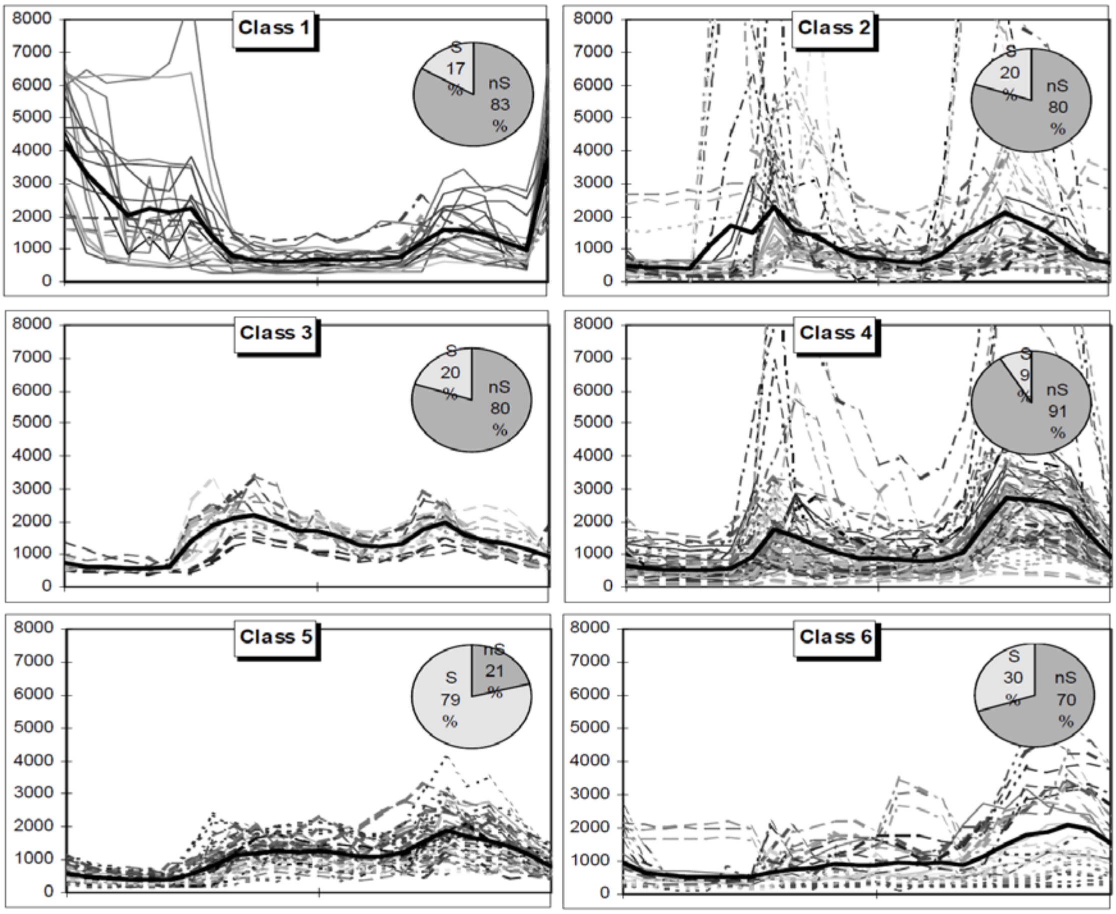

Figure 5: Classified daily electricity profiles in watts (x-axis: midnight to midnight) according to Stoecklein et al. (2001)**.**

The different classes are described (Stoecklein et al., 2001) as follows:

- Class 1: Typical night-rate profile: high night use, flat low day use and medium evening peak;
- Class 2: Morning and evening peaks about the same height. Morning peak comparatively short;
- Class 3: Flat profile with high morning peak;
- Class 4: Distinct sharp mid-morning peak, low midday and high extended evening peak;
- Class 5: No clear morning peak, medium afternoon level and early evening peak; and
- Class 6: Similar to Class 4, but later evening peak and lower overall level.

2.5 Energy efficient lighting technologies

2.5.1 Comparison of different lighting technologies

Lighting technologies can be compared based on a number of characteristics. From Pode (2010), different lighting technologies could be compared based on the following characteristics: luminous efficacy – a measure of how well a lighting technology can produce visible light; installation and operation cost; color rendering index (CRI) - an index employed for the quantification of the capacity of a light source to render color of surfaces accurately; and lamp life. LEDs possess the highest and lowest capital and operating costs respectively among the different lighting technologies (Khorasanizadeh, Parkkinen, Parthiban, & Moore, 2015) as shown in Table 3.

Table 3: Comparison of characteristics of different lighting technologies.

Lamp type	**Luminous efficacy (lm/W)**	**Lifetime of lamp (h)**	**Color rendering index**	**Installation cost**	**Operation cost**
Incandescent	12-35	2000-4000	100	Low	High
Fluorescent	50-100	10000-16000	90	Medium	Medium
CFL	40-75	6000-12000	80	Medium	Medium
LED	20-150	20000-100000	80	High	Low

Based on the comparison of the different lighting technologies presented in Table 3, it is anticipated that a shift in favour of the LED technology with lower energy consumption could yield significant energy savings that could translate into reduced operating costs for the users, and environmental impact and climate change mitigation through reduced emissions (Khorasanizadeh et al., 2015) from Cameroon’s thermal power stations. In this regard, a policy that will encourage the adoption of LED lighting will be beneficial to both the government and the population. Khorasanizadeh et al. (2015) conducted a study to determine the economic benefits of adopting LED lighting in Malaysia by comparing the LED bulb with other lighting technologies as shown in Table 4. Their results revealed that a switch from incandescent lamps to CFLs or LEDs can save 81.91% and 88.52% of annual electricity bills respectively for a household while the switch from CFLs to LEDs can generate over 36.54% savings on the annual electricity bill of a household. This is in concordance with the findings of (Chueco, López, & Bobadilla, 2015) which showed that LED technology is a cost-effective solution in some industrial and building lighting projects as a result of its low energy consumption, long lifetime and low maintenance rates.

Table 4 Data for different types of lighting technology.

Bulb type	Incandescent	CFL	LED
Power rating (W)	100	26	11
Lifetime (h)	2000	5000	50000
Lumens (lm/W)	12	70	100
Capital cost (RM)	2	20	80
Annual (8 hours daily) energy consumption (kWh)	292	75.9	32.1

The posited reduction in energy consumption for lighting associated with the adoption of energy efficient lighting is predicted based on the saturation of lighting needs, implying that the number of hours used and bulbs used in each room will remain unchanged irrespective of an increase in efficiency. The actual energy savings likely to be accrued from the use of efficient lighting technologies in buildings is questioned since the lighting duration before and after the adoption of efficient lighting is rarely the same (Tsao & Waide, 2010; Tsao et al., 2010) and this tend to affect the adoption and use of efficient lighting technology. The adoption of efficient lighting technology can influence the household to turn on the light for a longer period of time on the grounds that the lights consume less energy. This is referred to as the rebound effect (or the paradox of thrift), which holds that when an energy efficient technology is introduced and adopted, the increase in efficiency reduces the cost which stimulates increased consumption.

2.5.2 Evolution and adoption of efficient lighting technologies

Lighting technology was developed for using electricity as the energy source following the availability of electrical energy. The Incandescent style light bulb was the first lighting technology that emerged (Wen & Agogino, 2008). Incandescent lighting function is based on the flow of electric current through a metal filament of high resistance in the bulb and this resistance generates heat that causes the metal to glow and emit a yellowish light.

Fluorescent lamps on the other hand were established after the Second World War (Schanda, 2005) and function on the basis that certain gaseous materials capture radiation at one wavelength and re-emit radiation in a longer wavelength (Luo, 2011). Fluorescent lamps have further developed to compact fluorescent lamps (CFLs) which are more efficient than the former albeit they both use the same technology (Silveira & Chang, 2011).

Light emitting diodes (LED) were first fabricated in the mid-1960s using Gallium arsenide phosphide (Wen & Agogino, 2008) and the technology represents a quantum change for converting electrical energy directly into light (Sebitosi & Pillay, 2007). Unlike in the other lighting technologies, generation of light in LEDs is based on the principle of electroluminescence, in which electrons and holes recombine in a semi conductor diode releasing energy in the form of photons (Luo, 2011).

For close to a century, incandescent bulbs emerged as the main lighting technology for residential buildings due to the visual comfort. The main attempt to introduce fluorescent bulbs in residential lighting in the 1960s failed. This was despite the superior technical qualities; a lifetime 5-10 times longer than incandescent bulbs, their luminous efficiency five times greater than that of incandescent bulbs and their ability to give off very little heat (Menanteau & Lefebvre, 2000). This failure was associated with the consumer's perception of the bright light emitted by the fluorescent bulb as being cold and disappointing compared to the warm light emitted by incandescent bulbs, which was associated with visual comfort. Adding to this visual discomfort, fluorescent tubes required a change in the domestic light fittings since the fluorescent tubes were not compatible with the existing installation at the time and this served as a further disincentive for their uptake.

A number of factors influence the adoption of lighting technologies. In their Study, Min, Azevedo, Michalek, & de Bruin (2014) revealed that the five most important bulb characteristics based on which consumers make their choice include; price, energy use, color, lifetime and brightness. Both LED and CFL lighting stand out as being the more efficient lighting technologies. Compared to incandescent bulbs, they possess a longer life span and their use decreases the overall light energy consumption (Hicks, Theis &

Zellner, 2015). However, as reported by Wada, Akimoto, Sano & Homma (2012), the low capital purchase cost of incandescent bulbs acts as a disincentive for consumers to use the more expensive but more energy efficient compact fluorescent bulbs and light emitting diodes. According to the authors, this low capital cost of incandescent bulbs accounts for the reason why they are the dominant lighting technology used in many countries. From a cost perspective, it can be argued that consumers who prefer incandescent bulb to other efficient lighting technologies make their preference based on the capital cost with little or no knowledge on the operating cost of the technologies. This is confirmed by the study of Min et al. (2014) which demonstrated that a consumer was willing to spend an extra $[1]0.14 on a bulb for an increase in its lifetime and an extra $0.46 to obtain a bulb with a lower power rating. Some consumers as well have a stronger preference for incandescent bulbs over CFL on the grounds that the latter contains toxic materials like Mercury (Min et al., 2014).

The rising of energy prices globally at the end of the 20th century has led to innovation and adoption of energy efficient technologies. The innovation in the incandescent technology led to the introduction of the halogen cycle that increased the working life of the bulb and the luminous efficiency (a measure of the capacity of a light source to produce visible light) from 15 to 20lm/W (Menanteau & Lefebvre, 2000). With a luminous efficiency that exceeded 60lm/W, fluorescent lighting appeared as a better technology suited in the context of rising energy price and consequently emerged as a more competitive light energy source compared to the incandescent bulb. In Cameroon, lighting in the residential sector is dominated by the use of fluorescent and other bulb types such as incandescent lamps (Talla, Aloyem & Tchindia, 2015).

The policies of national governments can play an influential role in the uptake of efficient lighting technologies. Khorasanizadeh et al. (2015) investigated the potential impact of a government policy (subsidy provision) on the adoption of LED in Malaysia. The authors found out that the provision of subsidy on the capital cost of LED by the government will culminate in an increase in the return of investment of the consumers. Such provision of subsidy is likely to incentivize the population to adopt the efficient lighting technology.

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[1] Unless where specified, the use of $ in this thesis refers to USD.

2.6 Solar energy resource in Cameroon

Research and data on renewable energy resources (solar, wind, hydro, biomass etc.) in Cameroon is limited. According to Abanda (2012), very few studies have been conducted to evaluate the country's renewable energy resources. The limited availability of information on renewable energy resources creates an information gap for researchers, policy makers and potential investors and end-users of renewable energy technologies in Cameroon.

However, studies conducted so far on the solar resource of Cameroon using satellite derived data have revealed that the country possesses a good solar potential. Cameroon is endowed with a huge solar potential totalling about 900 trillion kWh of solar energy that reaches the land surface area per year (Ayompe & Duffy, 2014). The mean solar irradiance in most parts of the country is approximately 5.8 kWh/m^2/day (Laurea University of Applied Sciences, 2012). While SIE (2012) depicts that the solar energy potential of Cameroon ranges from 4.5 kWh/m^2/day in the Southern part of the country to 5.74 kWh/m^2/day in the Northern part, studies by Tchindia and Kaptouom (1999) estimated the solar resource of the Southern and Northern parts of the country at 4 and 5.8 kWh/m^2/day (2117 kWh/m^2/yr, see Figure 6) respectively. Studies by Tansi (2011) estimated the solar resource of the Southern part of Cameroon at 4.9 kWh/m^2/day. The variation in the solar resource potential of the country reported by various studies is likely due to the source of the data and method employed in the different studies. From Figure 6, Buea is in an area of very low relative levels of irradiance.

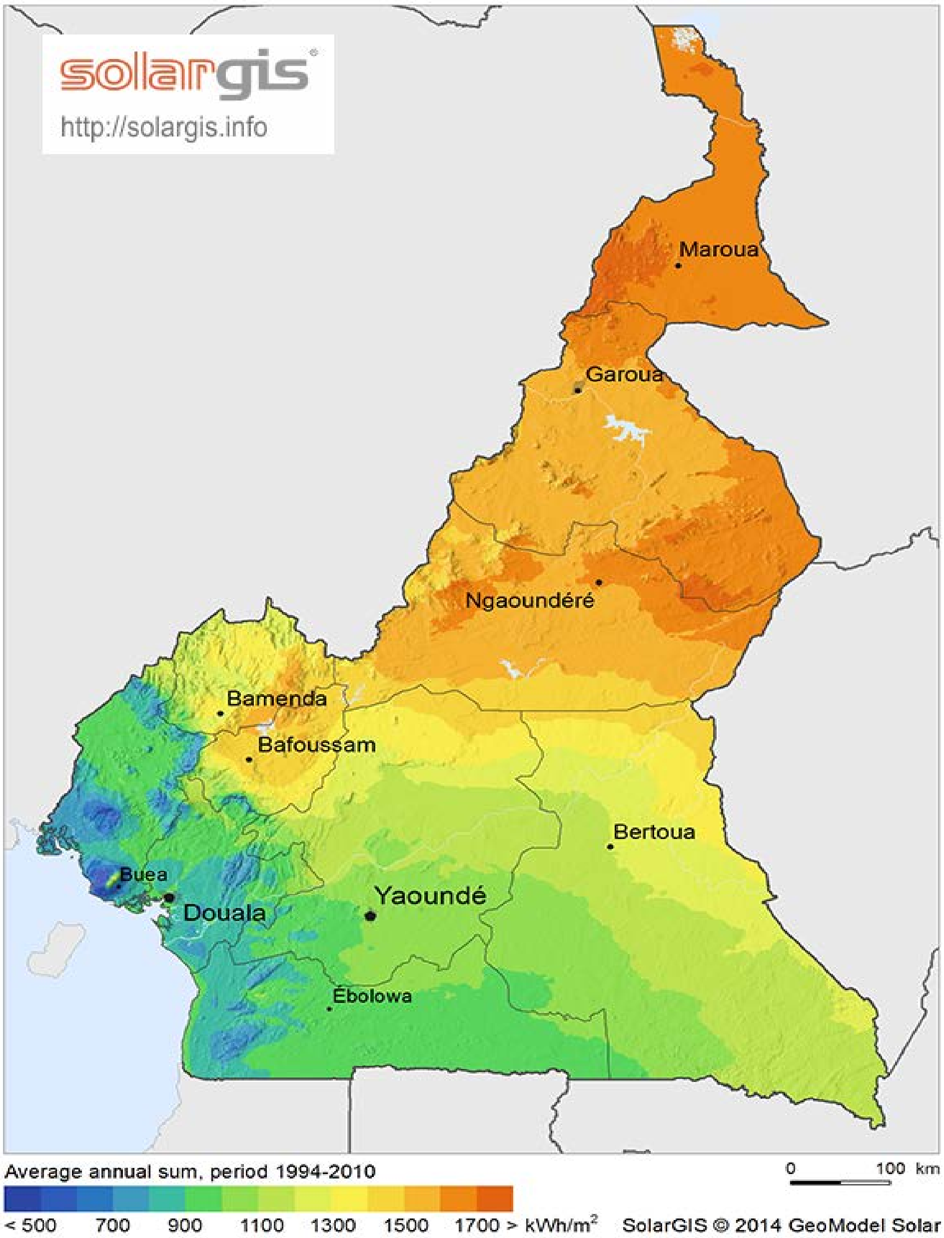


Figure 6: Direct, normal plane solar irradiation map of Cameroon (Solar GIS, 2014).

Limited research has actually been conducted to measure the solar irradiation in Cameroon. Njomo and Wald (2007) compared ground measurement solar irradiation data for Garoua and Douala to satellite derived data. Their findings revealed that the ground data was in concordance with the satellite derived data for Garoua (uniformly dry atmosphere) while there was variability in the ground data and satellite data obtained for Yaounde (forested area with persistently cloudy atmosphere). It is therefore likely that the solar irradiation reaching a particular location depends on the atmospheric characteristics. According to Ayompe and Duffy (2014), it is evident that solar irradiation data obtained from ground measurement in Cameroon is non-existent or where available, are unreliable due to the malfunctioning of devices as a result of poor maintenance. Under such circumstances, the calculation of site-specific solar data using satellite derived data sets must be the alternative.

The solar resource reaching the surface of Cameroon has potential for use in the generation of power. Tansi (2011) and Tchindia & Kaptouom (1999) reported that the solar resources reaching the surface of the country can be harnessed and employed in the generation of electricity using a solar PV system for onsite use in commercial and domestic buildings or for export to the national grid. The use of this resource is expected to yield tremendous benefits to the Cameroon Government, the population and the environment (Wirba et al., 2015) through reduction in greenhouse gas emissions and increase in the capacity of generated electricity.

So far, the solar resource has been used for some applications in Cameroon. Currently, solar power is employed in the provision of street lighting in the capital city of Yaounde and in powering base transceiver stations of mobile telephone network companies (Wirba et al., 2015). Based on the views of researchers which hold that Cameroon possesses a huge solar potential, one will expect a widespread application of the solar technology in the country. This is however not the case and Wirba et al. (2015) attributes this poor state of development of the huge solar resource of the country to the lack of commitment and dedication on the part of the government to boost this sector.

2.7 Solar PV system

2.7.1 The photovoltaic effect

The principle by which electricity is generated from solar energy is referred to as the photovoltaic effect. The cell contains a light absorbing material within its structure that absorbs photons and generates free electrons. When sunlight strikes the PV cell, it imparts enough energy on free electrons thereby exciting them to move freely (Parida, Iniyan, & Goic, 2011). An in-built potential barrier in the cell acts on these electrons producing a voltage that then drives current through a circuit.

The PV module does not make use of all the solar energy that strikes its surface. Up to 80% of the incident solar radiation available in the solar spectrum can be absorbed by the solar cell (Makki, Omer, & Sabir, 2015). Of the absorbed radiation, only a certain percentage is converted to electricity depending on the conversion efficiency of the PV cell while the unused energy is dissipated as heat which accumulates on the surface of the cells resulting in elevated panel temperature. This increased temperature then affects the performance of PV cells resulting to degradation and the shortening of their lifetime.

2.7.2 Types of solar cells

There exist a number of different solar cells employed in the PV technology and these cells contain a thin piece of semiconductor material which is silicon in most cases (Sick & Erge, 1996). Semiconductors are partially conductive for electricity since their electrical properties lies between those of metals and non-metals. The semiconductors are often doped through the addition of very small amounts of impurities which gives rise to two distinct layers referred to as the n-type and p-type layer (Sick & Erge, 1996). The n-type (typically phosphorus) material possesses an increased number of electrons while the p-type (silicon doped with boron) material has vacancies for electrons. Between the p-type and n-type is the p-n junction which plays an important role in the functioning of the solar cell since it is along the p-n junction where a built-in electrical field necessary to drive the flow of free electrons is generated.

Silicon is widely used as a solar cell in solar PV applications and the dominant PV modules used in Cameroon is composed of this solar cell. According to Bruton (2002), Silicon has been the dominant technology used as solar cells in photovoltaic applications with an increasing proportion of multi-crystalline and monocrystalline silicon being employed in the production of highly efficient solar cells while thinner wafer and ribbon technology continue to grow. Monocrystalline wafers are more expensive to produce but this process results in higher efficiency solar cells which offset the cost resulting to an equivalent final module cost like that of multicrystalline modules. The advantages in multicrystalline silicon lies in its lower capital cost for wafer production, higher utilisation of silicon and square wafers that results to higher packing density in the module compared to round or pseudo-square monocrystalline wafers. A market for high efficiency solar cells will continue to exist based on the importance of efficiency in applications where space is limited, labour cost is high and the amount of solar radiation is low. Achieving higher efficiency in multicrystalline silicon technology entails achieving a cost effective etching process which minimizes surface reflection in addition to the use of an anti-reflecting coating (Bruton, 2002).

The two types of silicon materials employed in the production of solar cells include: amorphous and crystalline silicon (Parida et al., 2011). Amorphous silicon is the most popular of the thin film technologies but it is prone to performance degradation. The different varieties of amorphous silicon includes: amorphous silicon carbide, amorphous silicon germanium, microcrystalline silicon and amorphous silicon nitride. The cell efficiencies of amorphous silicon range from 5-7%. Whereas both mono and multi crystalline silicon offers an improved efficiency. The efficiency of commercially available crystalline silicon solar cells ranges from about 14-19%. Hence, from an efficiency perspective, PV modules with crystalline silicon cells will likely be better suited for PV applications in Cameroon as a result of its higher efficiency.

Silicon leads as a dominant solar cell material as a result of its advantages over other materials. According to Bruton (2002), silicon continues to lead as a solar cell in the photovoltaic industry due to the following advantages it possesses:

- It is an abundant element in the earth's crust;
- it is non-toxic;
- an elemental semiconductor;
- passivating native oxide;
- low segregation coefficient for many metals;
- easily doped p- and n- type; and
- it is part of a $140 billion microelectronics industry.

The only major disadvantage of silicon as a solar cell lies in the fact that it is an indirect band gap semiconductor and hence requires a thick active layer of up to 1.5mm so as to absorb the full solar spectrum (Bruton, 2002). This is in contrast to thin film technologies that require only about 1 μm of material to be effective.

2.7.3 Types of PV system

Different types of PV systems exist depending on their characteristics. Based on system configuration, Zeman (2012) distinguishes three basic types of PV systems: stand-alone, grid connected and hybrid system. The stand-alone PV system rely only on PV power and can be connected directly to a load or can include batteries for the storage of the generated energy during the day to be used at night or during periods of poor weather conditions. The grid connected systems are similar in concept to power stations since the generated power is sent to the grid through grid-connect capable inverters and no battery is required for storage. Hybrid systems comprises the combination of PV modules and another means of electricity generation including but not limited to gas, wind or diesel generator and often require a more sophisticated charge control system compared to the stand-alone PV systems. In remote areas in Cameroon with no grid connection, a PV hybrid system would be a more economically viable option for electricity generation based on the findings of Mbaka, Mucho & Godpromesse (2010).

Stand-alone PV systems

In such a system, excess energy produced during periods with little or no load is stored in the battery for use subsequently during periods of low solar radiation. As a result of the variable nature of solar energy, an important and expensive aspect of stand-alone PV systems is its autonomy, required to provide reliable power supply to meet the load during unfavourable conditions which are usually periods of low radiation values and adverse weather conditions (Sick & Erge, 1996). The components of a stand-alone PV system are shown in Figure 7.

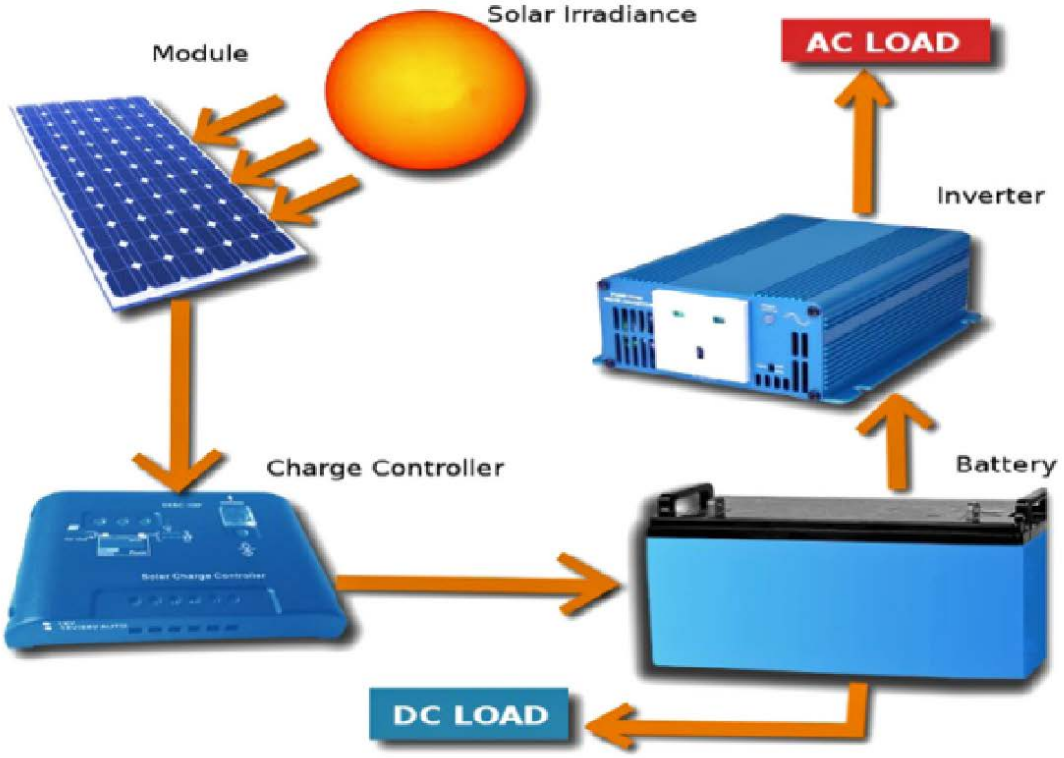


Figure 7: Components of a stand-alone PV system (Abdul and Anjum, 2015).

Grid connected systems

PV systems may be directly connected to the public grid. Such a system is cost-effective when the utility load is well matched to the solar resource profile of the location (Sick

& Erge, 1996). For instance, a grid connected system will perform well in an area with high air conditioning loads with peaks coinciding with peak sunshine hours of a summer day.

Hybrid PV system

In a hybrid system, electricity is generated from two or more systems. The combination of individual systems is proven to be adequate in the generation of power (Domenech, Ferrer-Marti & Pastor, 2015). An advantage of such a system lies in the fact that both technologies complement in each other which according to Sick & Erge (1996) increases the reliability of the system.

2.7.4 PV system components

PV module

The PV module is a very vital component of the PV system. Sick and Erge (1996) refers to the PV module as the basic element of a PV system by virtue of its role as a generator. Modules are normally connected together to form an array and the number of modules in series and parallel in the array will determine the voltage and current of the system respectively. The module's outermost layer is composed of a glass cover which protects the enclosed solar cells from damage: by gaseous substances, water and water vapour.

The functioning of a PV module is normally determined by its I-V curve. The I-V curve depicts the characteristics and performance of a module at Standard Test Conditions (STC) of $1000Wm^2$ solar irradiance, an Air Mass of 1.5 and a cell junction temperature of 25^oC (Sick & Erge, 1996). An ideal PV module’s I-V curve is shown in Figure 8. Open circuit voltage (V_{oc}) represents the voltage of the module when no current is drawn. This voltage decreases with an increase in temperature by approximately 0.4%/K for modules made out of crystalline materials while that for amorphous cells is lower. I_{sc} refers to the short circuit current of the module. This current is directly proportional to the cell temperature, increasing by 0.07%/K. Pn is the nominal power (peak power) that can be generated by the PV under STC and it is usually labelled on the module by the manufacturer.

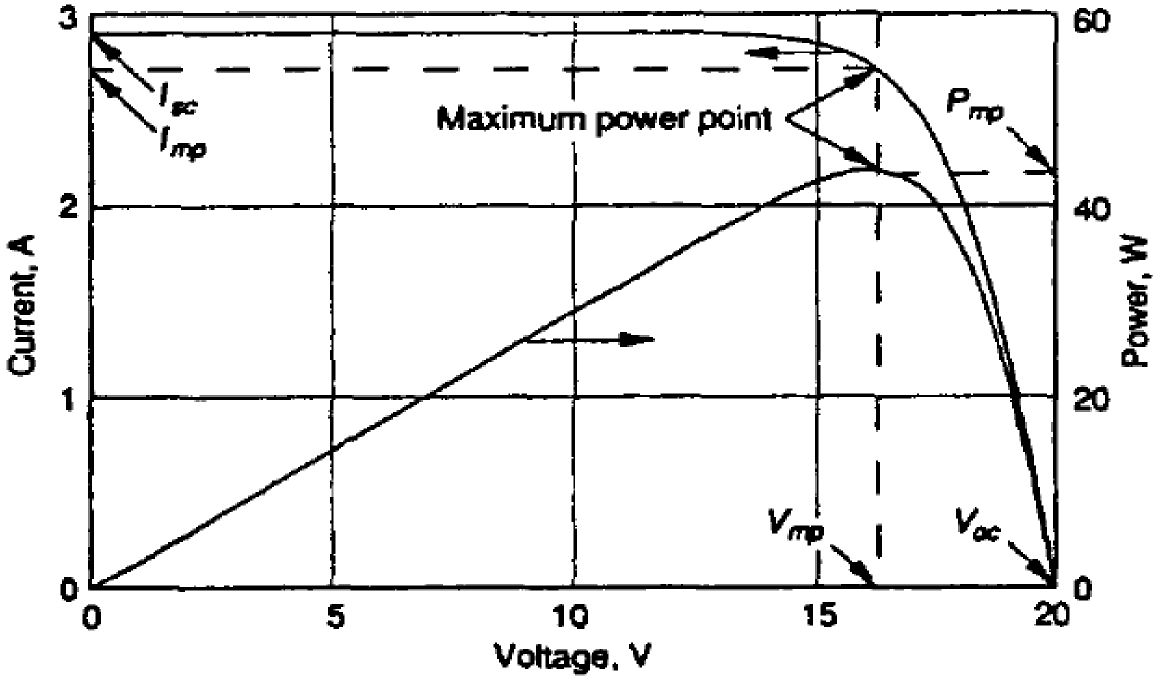


Figure 8: I-V curve and characteristics of a typical module.

Factors affecting the power generation potentials of Photovoltaics

A number of factors influence the functioning and output of PV systems. According to Makki et al. (2015), limited conversion efficiency, dust accumulation and elevated temperatures are critical factors that impact on the performance of PV cells especially in regions with sun-drenched and hot climate. While limited conversion efficiency of solar cells translate into only a small proportion of the solar energy converted into electricity, the accumulation of dust on the PV cells actually reduce their capacity to absorb the incident solar radiation, culminating to a decrease in the power generated by the system. PV cells tend to be affected most by high operating temperatures emanating from irradiance from the sun especially concentrated radiation that further increase the PV junction temperature.

Influence of temperature on photovoltaic cells

PV cells have a limit to the amount of solar irradiation they can convert into electricity. Just a small proportion of the absorbed incident solar radiation is converted into electricity depending on the cell's conversion efficiency (van Helden, van Zolingen, & Zondag, 2004) while the remainder of the absorbed energy is dissipated as heat causing the PV module to attain temperature as high as 40^0C. This is due to the fact that PV cells are able to convert only a certain wavelength of the incoming radiation into electricity.

PV modules are normally rated at STC which represents optimum conditions for their functioning. However, PV systems do not operate under optimum conditions in the field implying that the variation of the temperatures at which they operate limit their efficiency. Luque & Hegedus (2011) attributes such limited efficiency to the semiconductor material's band-gap energy.

There exist an inverse relationship between temperature increase and PV cell performance. As temperature increases, the performance of the PV cell decreases as a result of increased intrinsic carrier concentrations which consequently increases p-n junction dark saturation current and causes a decrease in the open-circuit voltage (Luque & Hegedus, 2011). According to Radziemska (2003), increase in cell temperature brings about a decrease in the mobility of charge carriers and an increase in thermal lattice vibrations which results to the deterioration of the output power of the cell. Reduction of the band-gap as a result of high doping also increases the intrinsic carrier concentration. The effect of increase temperature on the open circuit voltage as revealed by an experimental study conducted by Huang et al. (2011) is shown in Figure 9. However, the short circuit current increases slightly with an increase in cell temperature but due to the degradation of the open circuit voltage, there is a noticeable reduction in the generated electrical power.

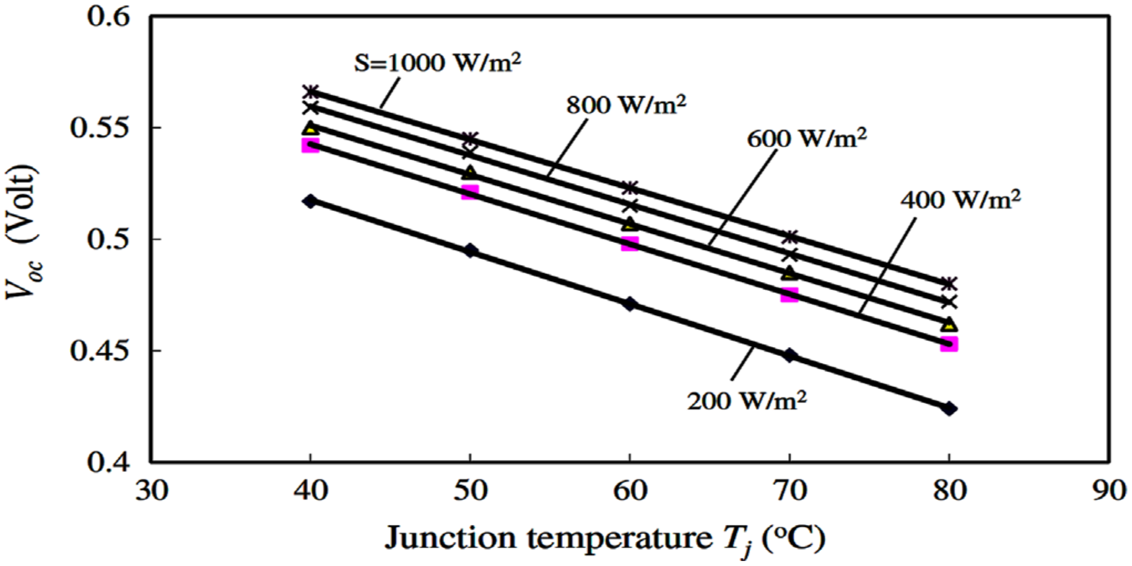


Figure 9: Influence of junction temperature of PV cell on open circuit voltage. (Source: Huang et al., 2011).

PV modules respond differently to an increase in temperature depending on the solar cell material they are composed of. Moshfegh and Sandberg (1998) reported a reduction in electrical output in the order of 0.2-0.5% for every 1^{o}C rise in temperature of the PV module for crystalline silicon, as a result of the dependence of the open circuit voltage of the cell on temperature. This property is referred to as the temperature coefficient of the PV cell.

Battery

Sunshine is highly variable on both daily and seasonal basis causing the electricity generated by PV systems to vary accordingly. Hence, there is need for energy storage capacity to manage the usual mismatch between the electrical load and electricity production for stand-alone systems (Sick & Erge, 1996). The present battery storage options available for PV building applications include; lead-acid, lithium and nickel/cadmium batteries. These batteries have their advantages and limitations. For instance, both lead-acid and nickel/cadmium batteries possess limitations with regards to energy density, cycle life, temperature of operation and toxicity. In order to design a PV system with battery storage, a good knowledge of the different battery types is needed upon which an informed choice of the battery to be used is made.

Lead acid battery

Lead-acid batteries are widely used in storage applications. These batteries have been in use and dominated the automotive market for over 150 years (Sick & Erge, 1996) due to their low cost, long and reliable service life which accounts for them being the most commonly used in PV applications (Jossen, Garche & Sauer, 2004). Batteries used in PV systems are often rated by their amp-hours, a measure of the amount of energy that can be removed from a single discharge. The amp-hour rating refers to the capacity of a battery when discharged over a specific period of time. The amp hour of a battery at C20 rate for instance represents the total amp hours produced by the battery when discharged by the load over 20 hours.

Batteries are normally produced using different designs. Most of the batteries produced are of the flooded design with the plates and separators totally immersed in the acid (Sick & Erge, 1996). Generally, all lead batteries have the same structure with the main components of a single cell comprising of positive and negative plates, terminals, separators, sulphuric acid, container, terminal sealing and a safety plug to minimise acid mist. The anode or negative plate of the lead acid battery is composed of lead and the cathode is composed of lead oxide while sulphuric acid in water solution performs the role of the electrolyte.

The battery functions by means of a chemical reaction. The electrolyte in the lead-acid battery participates in the discharge reaction as per the equation below. During charging, the reverse reaction occurs yielding sulphuric acid, lead and lead oxide (See Equation 1)

$$Pb + PbO_2 + 2H_2SO_4 \rightarrow PbSO_4 + 2H_2O$$

Equation 1

Due to the softness of lead, the grids of lead-acid batteries are specially manufactured through the addition of a variety of metals. To strengthen the grids and improve cycling characteristics, antimony is often added to the positive grid (Sick & Erge, 1996). Small amount of calcium can also be used to increase grid hardness but it does not increase the cycling performance as does antimony. For PV based applications, lead-acid battery are generally classified into antimony (deep cycle) and non-antimony (shallow cycle). An Antimony battery cannot be sealed airtight since this type of battery promotes the gassing reaction that occurs at the end of charging. Non-antimony batteries are often made with calcium alloys and the main advantage of this battery is the reduced maintenance and low self-discharge accounting for long shelf life. However, flooded battery produces gases that contain hydrogen and oxygen, which poses an explosion hazard. For this reason, such batteries always have small openings which serve as escape route for the generated gases and these batteries should always be used in ventilated areas.

Nickel/cadmium batteries

In this battery type, hydrated nickel oxide is the cathode while cadmium constitutes the anode during the discharge (Sick & Erge, 1996). The electrolyte of the battery is composed of potassium hydroxide water solution. The functioning (discharge) of the battery is represented in the chemical equation (Equation 2):

$$2NiO - OH + Cd + 2H_2O \rightarrow 2Ni(OH)_2 + Cd(OH)_2$$

Equation 2

During the charging process, the reverse reaction occurs. The nickel/cadmium batteries are mechanically rugged and have a long cycle life but have a nominal cost per Ah which is 3-5 times higher than that for lead-acid batteries.

Lithium battery

Unlike the other battery systems, the lithium battery is different in that its chemistry is not unique (Jossen et al., 2004). There exists different materials used as the electrolyte, the positive and negative electrodes. The lithium battery is advantageous in that it has a high specific energy and a long life time while its disadvantages lies in its high cost, no chemical overcharge reaction and relatively low safety (Jossen et al., 2004).

Charge controller

The Charge controller controls the charging and discharging process of the battery so as to ensure a long lifetime of the battery. The task of the controller is to ensure that battery employed in the PV system operates within the limits specified by the manufacturer (Sick & Erge, 1996). Modern charge controllers have a monitoring system that informs the user on the state of the battery and a history regarding the usage of the battery such as the number of deep discharge periods and the Ah balance. In hybrid systems, the charge controller serves as an energy management system that starts up the back-up generator automatically when the state of charge of the battery drops below a defined threshold. The principles of charge controllers include: overcharging protection and protection from deep discharge (Sick & Erge, 1996).

Overcharging protection

According to Sick and Erge (1996), three different ways are employed in ensuring overcharging protection. These include: Series controller, Parallel or shunt controller and DC/DC converters/MPPT.

For the case of the series controller, a switch is connected to the PV generator in series. When the battery voltage reaches the end-of-charge voltage, a controller opens the switch. The series controller is advantageous in that other energy sources like wind turbine can be connected to the input as well. However, its disadvantage lies in the fact that when the battery is fully depleted (0V), the charging process cannot be started since there is no energy to operate the series switch.

A Parallel or shunt controller operates on the basis that a PV generator can be operated in a short circuit mode without damage ensuing. During charging, current flows into the battery through a blocking diode and once the battery attains the end-of-charge voltage, the PV generator is short circuited by a switch. At this juncture, the blocking diode prevents the reverse flow of current form the battery into the switch as well as suppressing discharging current into the PV generator at night. Unlike the series controllers, shunt controllers will commence the charging of a fully discharged battery since the switch is only energized upon full charging of the battery.

In the case of DC/DC converters/MPPTs, both the battery and PV generator voltage vary considerably due to fluctuation in the state of charge and conditions such as temperature and insolation. This results to a mismatch between the optimum PV generator voltage and the battery voltage culminating in energy losses. DC/DC converters and MPPT prevents the loss of energy by ensuring that the PV generator operates within its maximum power point. The MPPT functions by adjusting the output voltage of the panel to a value that causes the panel to deliver the maximum energy to the load under any given condition (Garrigós, Lizán, Blanes, & Gutiérrez, 2014). DC/DC charge controllers are not relevant when the energy output of the PV system is to be maximised.

Protection of deep discharge

Deep discharge cycle and prolonged periods in partially charged conditions should be prevented in order to ensure maximum service lifetime of lead acid batteries. The load should be disconnected from the battery at a point where the battery approaches its deep discharge threshold. In PV applications, the cut-off voltage for the load should be relatively high (from 1.8-1.85 V/cell).

Inverter

Photovoltaic array can only generate direct current irrespective of its size. There exist many applications for which direct current application is suitable. However, for PV systems that supply power to the utility grid or to alternating current (AC) loads, there is need for an inverter to convert the generated direct current (DC) to AC and this is achieved by the use of an inverter (Sick & Erge, 1996).

Inverters may be classified into two main categories. According to Sick & Erge (1996), the two main categories of inverters include: stand-alone and utility-interactive. The stand-alone one is capable of functioning independently of the public utility grid with the correct timing of the 50/60 Hz output made possible by an internal frequency generator. Common stand-alone inverters often operate at 12, 24 or 48V DC. On the other hand, utility interactive inverter ensures the smooth integration with the voltage and frequency characteristics of the power on the distribution line, ensuring that the output of the PV system is fully synchronized with utility grid power. The wave form generated by the stand-alone inverter is of importance since a wave form that is not compatible with electrical appliances may damage the appliances. It is recommended for sine wave inverters to be used in stand-alone PV systems since most ac appliances are compatible to this wave form (Sick & Erge, 1996).

2.8 Design of a PV system

The entire design of a PV system is based on the size of the load. The load influences every aspect of design of the different PV system components (Bhuiyan & Asgar, 2003). Hence, its estimation must be efficient and reliable. Overestimation of the load will result to over sizing of the system which will not be cost-effective. On the other hand, an underestimation of the load will result to under sizing of the system and the generated power will not be able to power the required load.

A variety of literature exists on the design and sizing of PV systems. Authors have used different mathematical models for the sizing of the different PV system components. However, these models fall under either of the two general methods for sizing PV systems: kW method and the Ah method.

2.8.1 Sizing of array

According to Alamsyah, Sopian & Shahrir (2003), the size of a PV array can be computed using Equation 3.

$$A_{PV} = \frac{U_{el}}{H_{avg}\ x\ \eta_{PV}\ x\ \eta_{B}\ x\ \eta_{i}\ x\ T_{CF}}$$

Equation 3

Where; A_{PV} is the required PV array area in m^{2},

L_{el} is the required electric load in kW h d^{-1},

H_{avg} is the average daily irradiation of the location in kW h m^{-2} d^{-1},
$ŋ_{PV}$ is the PV panel efficiency in %, $ŋ_i$ is the efficiency of the inverter in % while
T_{CF} is the temperature correction factor.

In their study, Abdul & Anjum (2015), considered the battery and inverter efficiency to be 85% and 90% respectively. Caisheng, and Nehrir (2008) used a T_{CF} of 80% in their study.

The peak power of the PV ($P_{PVP)}$ panel under STC can be calculated using the peak solar irradiance and the efficiency of the PV panel as indicated in Equation 4 (Mahmoud and Ibrik, 2006).

$$P_{PVP} = A_{PV}\ x\ I_p\ x\ ŋ_{PV}$$

Equation 4

Where; I_p is taken as 1000 W m^{-2} (irradiance at STC).

Bhuiyan and Asgar (2003) used another method for the sizing of the PV array which entails the use of current to describe the requirement of the load. According to the authors, the PV array is sized to replace the daily load using average weather conditions. Normally, the array is sized in the design month corresponding to the month with the minimum solar insolation in order to ensure that the power generated by the array is able to reliably operate the load. The derated design current of the array (I_{DE}) is computed using Equation 5 (Bhuiyan & Asgar, 2003).

$$I_{DE} = \frac{I_{SD}}{ŋ_M}$$

Equation 5

Where; $ŋ_M$ is the module derate factor, which represents energy losses from the module due to accumulation of dust, mismatch between modules and degradation over time.

$$I_{SD} = \ (I_D)\,\max$$

Equation 6

Where; $(I_D)_{\max}$ corresponds to the largest current at the design month and selected tilt angle refers to the tilt at selected design current = β_s

$$I_{D(1-12)} = \frac{E_{c(Ah)}}{H_{ps(1-12)}}$$

Equation 7

Where: $H_{ps(1-12)}$ represents the monthly average of the peak sun hours per day for the months of January to December at a particular tilt angle (β), $E_{c(Ah)}$ refers to the Corrected Ampere-hour load calculated using Equation 8.

$$E_{c(Ah)} = \frac{E_{d(Ah)}}{\eta_w \eta_b}$$

Equation 8

Where; η_w and η_b represents wire and battery efficiency respectively. $E_{d(Ah)}$ is the Ampere-hour load calculated from Equation 9

$$E_{d(Ah)} = \frac{\sum_{i=1}^{n} N_i I_i V_i H_i}{\eta_{pce} V_{nsv}}$$

Equation 9

Where; N_i is the number of ith residential load,

I_i, and V_i refers to the current and voltage respectively that is drawn by the ith loads,

H_i is the daily duty cycle of the ith load,

V_{nsv} and η_{pce} represents the nominal voltage of the system and the power conversion efficiency.

The number of parallel PV modules in the array is obtained using Equation 10.

$$M_p = \frac{I_{DE}}{I_r}$$

Equation 10

Where; I_r is the module rated current (A).

The number of modules in series in the array is given by Equation 11.

$$M_s = \frac{V_{nbv}\ x\ B_s\ \ x\ 1.2}{V_{M,Tmax}}$$

Equation 11

Where; $V_{M,Tmax}$ is the highest temperature voltage of the module.

The total number of module is calculated using Equation 12

$$M_T = M_p \ x \ M_s$$

Equation 12

2.8.2 Battery storage

According to Wenham, Green & Watt (1994), the storage capacity of a PV system battery bank (B_{SC}) is calculated taking into consideration the battery efficiency, efficiency of the inverter, depth of discharge of the battery and the system autonomy (number of cloudy days). The formula for the determination of the battery size is shown in Equation 13.

$$B_{SC} = \frac{N_c \ x \ L_{el}}{\eta_B \ x \ D_d \ x \ \eta_i}$$

Equation 13

Where; D_d is the maximum depth of discharge of the battery and N_c refers to the system autonomy (continuous number of cloudy days).

Bhuiyan and Asgar (2003) designed the battery bank using the following equations (Equation 14, Equation 15 and Equation 16):

$$B_{rc} = \frac{E_{c(Ah)} \ x \ D_s}{(DOD)_{max} \ x \ \eta_T}$$

Equation 14

Where; D_s represents the battery autonomy while $(DOD)_{max}$ and η_T represents the maximum battery depth of discharge and temperature correction factor respectively.

The batteries in parallel is obtained using Equation 15

$$B_p = \frac{B_{rc}}{B_{SC}}$$

Equation 15

Where; B_{sc} represents the selected battery capacity.

The batteries in series is given by Equation 16

$$B_s = \frac{V_{nsv}}{V_{nbv}}$$

Equation 16

Where; V_{nbv} represents the nominal battery voltage.

The total battery in the battery bank is given by Equation 17

$$B_T = B_p \; x \; B_s$$

Equation 17

2.8.3 Controller Specification

The function of the charge controller in a system is to ensure safe charging of the battery and consequently eliminating the risk of having the batteries over charged. The controller must have the capacity to handle the maximum current generated by the PV array and its voltage compatible with the nominal voltage of the system. Hence this device must be selected carefully to ensure that it is able to carry the generated current by the array. The size of the charge controller (S_{cc}) is given by Equation 18.

$$S_{cc} = Array \; current \; x \; 1.25$$

Equation 18

The array current is multiplied by a factor of 1.25 so as to give flexibility to the charge controller to accommodate high current generated by the PV array during period of high irradiance (Sandia National Laboratories, 1995).

2.8.4 Determination of inverter size

There is need for an inverter to convert the generated dc current into ac current so as to power the ac loads in the building. The inverter should be selected in such a way that it must be able to handle the maximum expected ac power loads (Abdul & Anjum, 2015). Hence, it is recommended for the selected inverter to be 20% higher than the total rated power of the required ac loads.

2.9 Cost of PV system components in Cameroon

Literature on the cost of PV system components in Cameroon is scarce. Economic analyses of PV systems in Cameroon by Nfah et al. (2008); Nfah & Ngundam (2009) and Mbaka et al. (2010) estimated the cost of the different system components either based on studies conducted in other countries or using the cost of the components obtainable on the European market while making adjustments in either case to reflect the market price of the component in Cameroon. In their study, Mbaka et al. (2010) estimated the price of a PV module in Cameroon at €7.5/W_p. Comparing this PV module cost to that of other developing countries like India and Pakistan, the authors found out that PV module cost are relatively higher in Cameroon due to high sales taxes and custom duties. This is not uncommon since local conditions will influence the price of PV components accounting for a variation in system prices among countries (International Renewable Energy Agency, 2015). The lack of reliable cost information of PV system components in Cameroon could be likely due to the fact that the market for this renewable energy technology is yet to attain maturity.

Some information on the cost of system components exists on the websites of different solar businesses in Cameroon, such as Cameroon Solar Energy (CAMSOLAR) (Table **5**) and Haute Energy Systems Ltd (Table 6).

Table 5: Cost of PV system components in Cameroon.

System component	Specification	Cost (USD)
Module	SPWR 215W monocrystalline solar panel	$2737.05
Charge controller	PS-15M-15A-Charge controller (12V/24V, 15A)	$419.82
	PS-30M-30A-Charge controller (12V/24V, 30A)	$468.30
Battery	8G22NF-51AH @ 1.75 Gel Type Battery (12V)	$874.47
	OPzV150-150AH 1.8V C10 Gel Type Battery (12V)	$1566.54
Inverter	Suresine 300W Sinewave inverter	$697.93
	SB 3000W Inverter	$4487.95

(Source: CAMSOLAR, n.d)

Table 6: PV system component cost in Cameroon obtained from Haute Energy Systems Ltd.

System component	Cost (USD)
Module	$2/Wp
Charge controller	$9.10/A
Battery	$2.40/Ah
Inverter	$0.24/W

2.10 Installation and maintenance cost of PV systems

The installation and maintenance cost of PV systems vary considerably between individual sites. This variation in the operation and maintenance cost could be as a result of the fact that the installation and maintenance costs are often expressed or obtained as a percentage of the PV module cost, which varies from country to country. In the course of performing an economic analysis of PV systems, Mbaka et al. (2010) adopted the maintenance and installation cost of the system as 2% and 10% respectively of the initial cost of the PV modules; in their study.   Darras et al. (2015) adopted the PV installation cost as 5% of the initial module cost; while Abdul & Anjum (2015) adopted 10% of the initial PV module cost as the PV installation cost while the operation and maintenance cost of the system was adopted as 2% of the initial PV module cost.

2.11 Economic, Social and Environmental benefits of PV systems

2.11.1 Economic

The economic potential of PV systems is often obtained by conducting an economic analysis. Several economic analysis methods have been used in literature to determine the economic potential of PV systems: Abdul & Anjum (2015) used the life cycle cost analysis; Darras et el. (2015) and Bernal-Agustin & Dufo-Lopez (2006) used the net present value (NPV) economic analysis model; Ghosh, Nair & Krishnan (2015), Ayompe and Duffy, (2014) Ma, Yang, Lu & Peng (2015) and Koberle, Gernaat & van Vuuren (2015) used the levelized cost of electricity (LCOE) to demonstrate the economic potential of PV systems; Mbaka et al. (2010) used HOMER to determine the LCOE of PV systems; while Lang, Ammann & Girod (2016) used an economic model that entails cash flow dynamics for determining the economic performance of a PV system.

Life Cycle Cost (LCC) analysis

Life cycle cost (LCC) entails the analysis of the entire cost of a project over its lifetime. The LCC analysis of a PV system embodies the total fixed and operating costs over its life expressed in today’s value (Celik, 2006; Ajan, Ahmed, Ahmed, Taha & Zin, 2003, and Celik, 2007). The major cost associated with PV systems includes the capital cost of the hardware, operation and maintenance cost. Hence, the total life cycle cost of a PV system is the sum of the present worth (PW) of the PV modules, charge controllers, storage batteries, inverter, installation, operation and maintenance cost (Shaahid & Elhadidy, 2008). The PV system is assumed to have a useful service life of 20 years (Abdul and Anjum, 2015), 25 years (Ayompe & Duffy, 2014; Ma et al., 2015; IEA/NEA, 2015; and Ghosh et al., 2015) or 30 years (Kumar & Tiwari, 2009; and Koberle et al., 2015) with the exception of the storage batteries with a life span that ranges from 5 to 10 years. Therefore, the batteries need to be replaced after every five or ten years as the case may be and its cost adjusted taking into consideration inflation (i) and the discount rate (d). The present worth of the different system components is computed as follows (See Equation 21 and Equation 22):

$$Cost\ of\ PV\ Array, C_{PV} = Unit\ cost\ of\ PV\ module\ X\ Number\ of\ PV\ modules$$

Equation 19

Initial cost of batteries C_B= Unit cost of battery x Number of batteries

Equation 20

The present worth of the replacement of the battery after 5, 10, 15 and 20 years (for battery with a lifespan of 5 years) or 10 and 20 years (for battery with a lifespan of 10 years) is normally determined using Equation 21.

$$C_{B1} = C_B \left(\frac{1+i}{1+d}\right)^n$$

Equation 21

Where; n represents the year in which the battery is replaced.

The present worth of the system maintenance cost can be calculated using the annual maintenance cost and lifetime of the system as given by Equation 22

$$C_m = (M/yr)\ x\ \left(\frac{1+i}{1+d}\right)\left[\frac{1-\left(\frac{1+i}{1+d}\right)^N}{1-\left(\frac{1+i}{1+d}\right)}\right]$$

Equation 22

The life cycle cost of the PV system can then be calculated using Equation 23.

$$LCC = C_{PV} + C_B + C_{B1} + C_{B2} + C_c + C_i + C_{inst} + C_m$$

Equation 23

The annualized LCC (ALCC) of the PV system in terms of its present value can then be calculated using Equation 24.

$$ALCC = LCC\ \left[\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^N}\right]$$

Equation 24

The unit cost of the electricity generated by the PV system can be computed Equation 25.

$$UC_{el} = \frac{ALCC}{365L_{el}}$$

Equation 25

Levelised cost of electricity

The levelised cost of electricity (LCOE) is the cost per unit of electricity generated. LCOE remains the most transparent measure and widely used tool in policy discussions for comparing the unit cost of electricity generated from different technologies over their economic life (Ayompe & Duffy, 2014). LCOE corresponds to the cost of the investor using the assumptions that there is certainty of production cost and stability in electric prices over the lifetime of the project. This implies that if the levelised average lifetime cost of a power plant is equal to the electricity price, the investor will break even on the project after paying debt and equity investors, and after accounting for the required rates of return to these investors. From IEA/NEA (2010), the LCOE of a technology is given by Equation 26.

$$LCoE = \frac{CAPEX + \sum_{n=1}^{N} OPEX_n (1+d)^{-n}}{\sum_{n=1}^{N} G_n (1+d)^{-n}}$$

Equation 26

Where; CAPEX refers to the capital investment cost,
G_n is the net generation in operating year (n) (kWh),
d is the annual discount rate,
N is lifetime of the technology
while OPEX refers to the operation and maintenance cost of the technology.

Net Present Value (NPV)

In calculating the NPV of a proposal or project, the cost and benefits needs to be quantified for the expected duration (lifetime) of the project (Commonwealth of Australia, 2006). The NPV of a project or proposal is determined by discounting the cost and benefits (using an established discount rate) occurring later in the project relative to those occurring sooner. Discounting of the cost and benefits is necessary since money received now can be invested and converted into a larger amount in the future and individuals would generally prefer to receive income now than in the future. The NPV is computed as indicated in Equation 27 (Commonwealth of Australia, 2006).

Projects or programmes with a positive calculated NPV is indicative of the efficient use of the investor's resources and is a signal that the project could be economically viable.

$$NPV = \sum_{0}^{t} \frac{B_t - C_t}{(1+r)^t}$$

Equation 27

Where; B_t represents the benefit at time t,

C_t is the cost at time t, and

r is the discount rate.

The unit cost of electricity generated from solar PV systems is highly location-specific. This variation in cost is not unexpected owing to the fact that electricity generation from PV systems is determined by the strength of the sun which, varies from place to place (Schmidt, Born & Schneider, 2012) and the load to be met by the system differing from case to case. This in turn influences the number of PV modules (required to generate power to feed the required load) whose price and those of the other system components varies from country to country depending on whether they are locally manufactured or imported.

From their study using 2011 global average installation cost and late 2011 installation costs in Germany, (Ondraczek, Komendantova & Patt, 2015) revealed the PV LCOE in Kenya in the range of USD 0.29 to USD 0.51 per kWh in 2011. Studies by Schmidt et al. (2012) and Ondraczek (2014) revealed the levelised cost for Kenya as USD 0.21 and USD 0.271 per kWh respectively. Countries with rapid PV development including the United States, China, Spain and Italy exhibit relatively low PV LCOE. Medium to high income countries like South Africa, Mexico, Thailand, Malaysia, Japan, Australia, New Zealand and Chile have good prospects for future PV development (Ondraczek et al., 2015). Most parts of Africa exhibit high PV LCOE with the Democratic Republic of Congo and Zimbabwe exhibiting the highest LCOE in the continent as shown in Figure 10. This high LCOE observed for Congo and Zimbabwe could likely be due to either poor solar resource in these countries or high cost of PV system components as a result of unfavourable government policies.

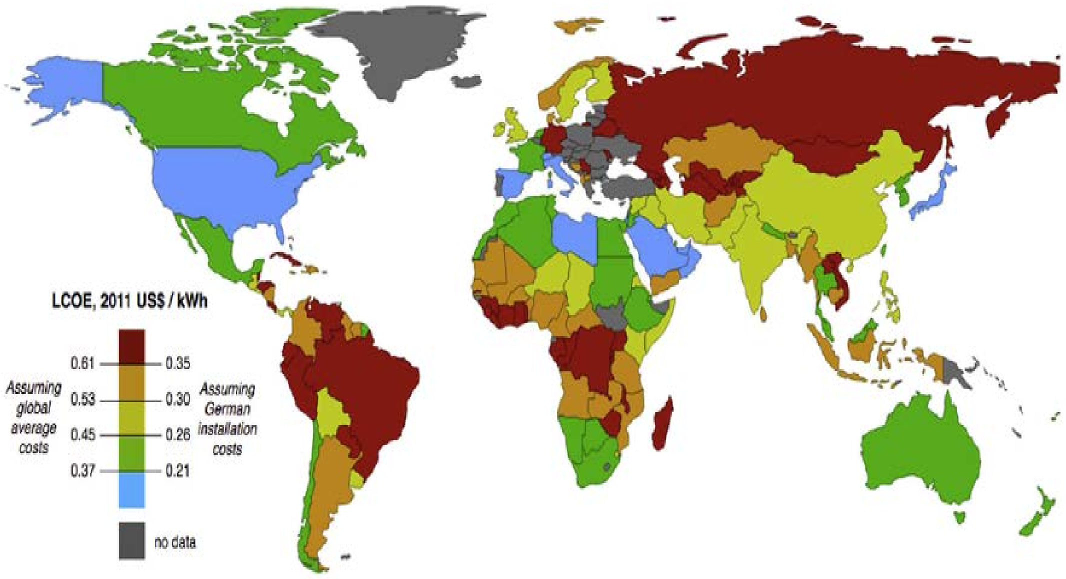


Figure 10: Global map of PV LCOE (Source: Ondraczek et al., 2015).

In Cameroon, studies conducted by Mbaka et al. (2010) in the Northern part of the country revealed the most economical cost of electricity from a photovoltaic panel to be in the order of USD 0.75 (€0.692) to USD 0.86 (€0.785)/kWh for a hybrid system (with diesel generator) and USD 0.98 (€0.896)/kWh for a stand-alone PV system. From their study, the authors concluded that small scale photovoltaic hybrid system (PVSH) is a more economically viable option for electricity generation in the country compared to a stand-alone PV system options proposed in the country's National Energy Action Plan for Poverty Reduction (Republique du Cameroun, 2007). Stand-alone PV system in most cases will require battery storage to supply power to the load after sunset. Consequently, the unit cost of electricity generated by the stand-alone PV system is expected to be higher compared to that of the hybrid system that requires lesser or no battery storage.

The cost of PV electricity in Cameroon like in other parts of the world has been on a decline. A more recent study by Ayompe & Duffy (2014) revealed a unit cost of PV generated electricity in Cameroon as USD 0.076 per kWh (using 5% discount rate and PV system capital cost of 1691 USD/kWp) and USD0.32/kWh (using a discount rate of 10% and PV system capital cost of 2819 USD/kWp). The result obtained by Ayompe & Duffy (2014) is lower compared to that obtained in 2010 by Mbaka et al. (2010) which is in agreement with the claims of IEA/NEA (2015) that the cost of solar PV among other renewable technologies have declined significantly over the last five years. This decline in the cost of the PV technology could be due to the fact that its market is attaining maturity.

2.11.2 Social benefits of PV systems

The design, installation and use of photovoltaic technology has an array of social benefits. This ranges from the creation of employment to improved health care. Studies by (del Rio & Unruh, 2007) revealed that over 4000 jobs in Spain are linked to the PV sector and this associated employment benefit renders PV attractive to local communities where acceptance of its penetration would have been difficult. The employment opportunity offered by the PV sector could take the form of direct employment of individuals in the installation and or maintenance of PV systems or could be manifest through the use of the technology for productive uses for the generation of income.

PV systems are also known for the provision of social status benefits. As opined by Rogers (2003), gain in social status is undoubtedly an important factor that motivates almost every individual to adopt an innovation. Studies conducted by Korcaj, Hahnel & Spada (2015) in Germany revealed that social status benefit of PV systems tends to influence their adoption. The authors concluded that social influence should not be underestimated as a factor in the adoption of PV systems. The benefit associated with social status is concerned with the improvement of one’s standing in the community by exceeding the existing norm which entails standing out in a positive way.

The photovoltaic technology among other renewable energy technologies improves quality of life through the provision of social benefits. According to Smith et al. (2015), access to energy emerges as one of the most important factors that play an important role in the improvement of the quality of life in disadvantaged communities globally through the provision of economic and social benefits. This is particularly true for rural areas in developing countries that are not connected to the national grid. Extending the grid to such areas is very costly and hence, the utility provider under such circumstances lacks the motivation of extending the grid to these areas. The use of PV system in such remote areas to meet the energy needs of communities have enormous social benefits including but not limited to the use of the PV generated electricity for indoor lighting after sunset which could be beneficial to children’s education (Mondal & Klein, 2011) and for the refrigeration of medical drugs in the local health centres. Individuals engaged in business in rural areas that depend on traditional fuel for lighting experience an increase in income when they switch to solar lighting as a result of extended working business hours in the evening.

Social cohesion is yet another social benefit of solar PV. According to Mondal & Klein (2011), increased social gathering was associated with the adoption of solar PV in homes in Bangladesh. People tend to come and stay up later in the evening discussing, watching television and socializing in cleaner and better illuminated environment. This tends to advance communication and increase social ties in the community.

2.11.3 Environmental benefits of PV systems

The environmental model often used to assess the environmental footprint of a product or services is the life cycle assessment (LCA). LCA is a methodology employed in the quantification of environmental burdens and impacts associated to the life cycle of a product or service, i.e. from cradle to grave (Treyer & Bauer, 2015). LCA permits the identification of environmental hotspots and unbiased comparison of product or services which meets the same needs. For instance, LCA permits the comparison of the environmental footprints of a kWh of electricity generated from different sources.

There has been controversy over the environmental benefits of renewable energy technologies since some scholars consider these technologies as carbon free while some others do not share this view. The life cycle GHG assessment for some renewable energy technologies; wind and solar photovoltaics (PV) conducted by Nugent and Sovacool (2014) revealed these technologies as unfree from emissions since both wind and solar PV were associated with an average emission of 34.11 $gCO_{2\text{-eq}}$/kWh and 49.81 $gCO_{2\text{-eq}}$/kWh respectively. However, their emissions are relatively low when compared to diesel (778 $gCO_{2\text{-eq}}$/kWh) and coal (960 $gCO_{2\text{-eq}}$/kWh). Hence, the use of electricity generated from renewable sources have a positive impact on the environment in terms of GHG emission reduction (Sapkota et al., 2014) since they are lower in carbon compared to conventional fuel employed in electricity generation.

The manufacture of photovoltaics is associated with high metal use such as iron ore, nickel, copper and silver (Treyer & Bauer, 2015). Electricity generation from photovoltaics is associated with the release of toxic substances to the environment that occurs during the mining process of the metals. However, emissions generated from PV technologies are small compared to those emanating from conventional technologies (Fthenakis, 2008). The life cycle emission of PV per GWh is far less than that of conventional technologies that generates power using fossil fuel. The life cycle emission of PV-system is influenced by the solar cell material since different materials possess different energy requirements for their manufacture. The life cycle emissions for amorphous, monocrystalline and polycrystalline solar PV systems were estimated to range from 15.6-50 g-CO_{2eq}/kWh, 44-280 g-CO_{2eq}/kWh and 9.4-104 g-CO_{2eq}/kWh respectively (Sherwani, Usmani & Varun, 2010).

Published LCA results for renewable energy technology vary significantly and this results to confusion pertaining to the actual environmental impact that ensues from the implementation of a renewable energy project (Asdrubali, Baldinelli, D'Alessandro & Scrucca, 2015). From Asdrubali et al. (2015), PV power and geothermal power emerged as the renewable energy technologies with the highest overall environmental impacts. From the life cycle assessment conducted by Treyer and Bauer (2015) on kWh of electricity generated from different sources (natural gas, natural gas combined cycle, carbon capture and storage, European pressurized reactor, photovoltaics and concentrated solar power), a kWh of electricity generated from oil is associated with the highest environmental impacts; contribution to climate change, acidification and particulate matter formation as indicated in Figure 11. The relatively high environmental impact of a kWh of electricity generated from oil is associated with the impacts that occur within the fuel supply chain coupled with the low efficiency of the power plant that culminates to high emissions of particulate matter, SO_2, NO_x and greenhouse gases. The authors also pointed that the high impact on human toxicity, ecotoxicity and metal depletion associated with a unit electricity generated from wind emanates from the mining of metals including but not limited to iron ore, nickel and copper used in the production of the turbines. The mining process of these metals results to the release of toxic substances into the environment. Greenhouse gas emissions associated to the generation of electricity in Cameroon is estimated at 0.86 tCO_2/MW (860 gCO_2/kWh) (African Development Fund, 2009). Information on the estimates of GHG emissions per KWh of electricity in the different electricity grids in Cameroon is scarce.

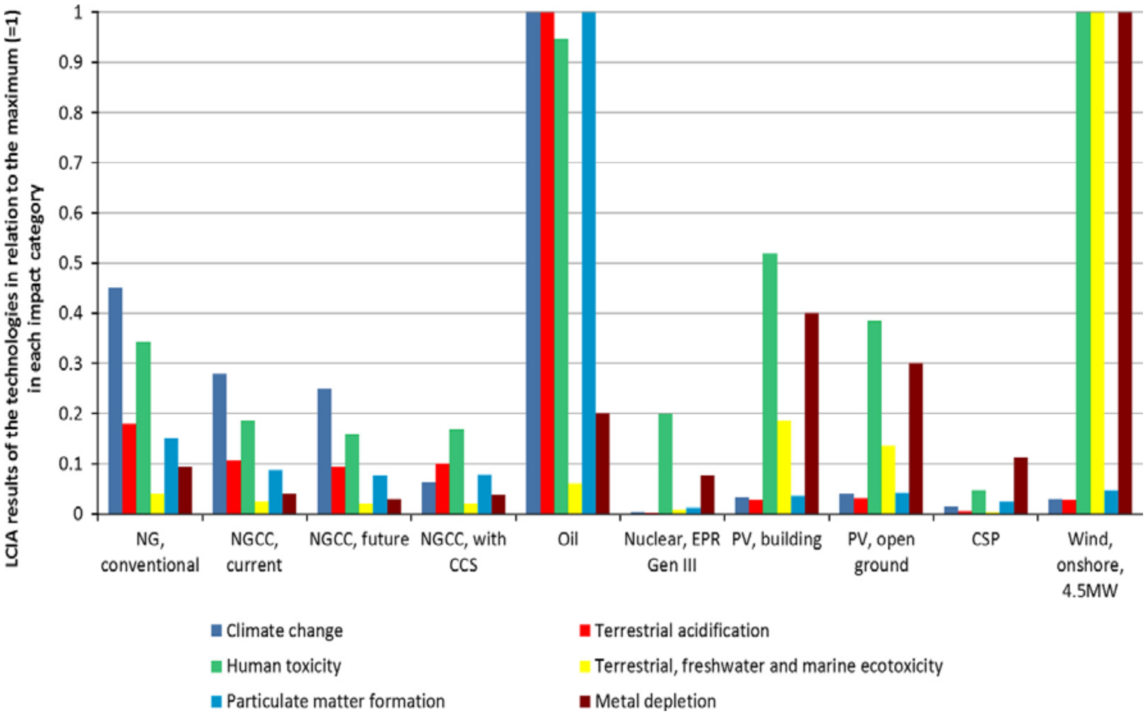


Figure 11: **Environmental impacts of electricity generation technologies for selected impact categories shown relative to the maximum (=1) in each impact category.** NG=natural gas; NGCC=natural gas combined cycle; CCS=carbon capture and storage; EPR=European pressurized reactor; PV=photovoltaics; CSP=concentrated solar power (Source: Treyer & Bauer, 2015).

2.12 Case study analysis of solar PV projects in West African Countries

There exist a number of ongoing and proposed solar PV projects in West Africa with the envisaged Nzema project in Ghana to constitute Africa’s largest photovoltaic power plant (Blue Energy, 2015). This plant will increase Ghana’s current generating capacity by 6% and will meet 20% of the Ghana government 2020 target of generating 10% of electricity from renewable resources. The project costs over $350 million and it is envisaged to go fully operational in 2017, with an operational life of 20 years. Ghana’s electricity regulators, the Energy Commission and the Public Utilities Regulatory Commission have awarded a generation licence and a feed-in-tariff to the plant’s operational lifetime.

Cameroon hosts the seventh largest PV project in West Africa. Located in the Konye sub-division of the South West Region of Cameroon, the ’51 villages’ project is geared at bringing rural electrification, 196 solar dryers and other small home systems to 51 villages (Kaboni, n.d). The population in this region have no access to electricity and are very unlikely to get connected to the national grid for several decades. Hence, this project will not only be accompanied with benefits associated with electricity such as improved lighting and education, but will provide an avenue for farmers in the region to dry their agricultural outputs (cocoa) and store it for sale at a period when the prices are favourable. A list of the top 20 largest solar PV projects in West Africa is presented in Table 7.

Table 7: Top 20 solar photovoltaic PV projects in West Africa.

No	Name of Project	Current capacity	Location	Developer	Status
1	Nzema Solar PV Park	155 MW	Awaso, Ghana	Blue Energy	Proposed
2	Tenergie Senegal PV Projects	50 MW	Taif, Darou Mousty and Merina Dakhar, Senegal	Tenergie Senegal	Proposed
3	Ivory Coast Scatec Solar PV Park	45 MW	North Ivory Coast	Scatec Solar	Preferred bidders
4	Akuo Energy Mali Solar Projects	41 MW	Kita, Kangaba, Mali	Akuo Energy	Proposed
5	Mali Scatec Solar PV Park	33 MW	South Mali	Scatec Solar	Contracting
6	Zagtouli Plant	22 MW	Ouagadougou, Burkina Faso	T.B.D	Proposed
7	Cameroon ‘51 villages’ project	21 MW	Konye, Cameroon	“Group of organisations”	Breaking ground
8	Kona dept. Solar PV plant	20 MW	Kona dept., Burkina Faso	Helios Energie	Financially closing down
9	Burkina Scatec Solar PV Park	20 MW	Center Burkina	Scatec Solar	Prefered bidders
10	Senegal Scatec Solar PV Park	20 MW	Coastal Senegal	Scatec Solar	Proposed
11	Scatec solar Ghana PV project	20 MW	Coastal Ghana	Scatec Solar	Under development
12	Gambia Solar PV project	20 MW	Birkama, The Gambia	CAMAC	Financially closing down
13	Sheikh Zayed Solar Power Plant	15 MW	Nouakchott, Mauritania	Masdar	Commissioned
14	Prosolia Solar PV projects	13 MW	Ndiare Wakhy, Coki and Barale, Senegal	Prosolia Energie Solaire	Proposed
15	Benin Solar Power Plant 1	6 MW	Kandi, Benin	Helios Energie	Commissioned
16	Mulk Solar PV Project	6 MW	Freetown, Sierra Leone	Masdar	Financially closed
17	5 MW Solar PV Project	5 MW	Djogou, Benin	CEB	Proposed
18	Mali ’30 villages’ Project	3 MW	Mali	T.B.D	Proposed
19	Zouerate 3 MW PV projects	3 MW	Zouerate, Mauritania	Power Electronics	Commissioned
20	Kolda Solar PV Project	1.5 MW	Kolda, Senegal	Isofoton	Breaking ground

(Source: Competitive Solar Solutions West Africa, n.d)

2.13 Review of the HOMER Software

The acronym HOMER represents Hybrid Optimization Model for Electric Renewable. It is a software developed in 1993 by Dr Peter Lilienthal of the United States National Renewable Energy Laboratory (NREL) and is one of the most widely used tools in the simulation, optimization and performance of sensitivity analysis of both off-grid and grid-connected renewable energy systems (Baghdadi, Mohammedi, Diaf, & Behar, 2015). In the simulation process, HOMER models the behaviour of the system configuration each hour of the year to determine its technical feasibility and life cycle cost (Lambert, Gilman & Lilienthal, 2006). The optimization process entails the simulation of many different system configurations by the software in order to search for the one that satisfies the technical constraints at the lowest life cycle cost. In the sensitivity analysis process, the HOMER software performs multiple optimizations using a range of input assumptions to determine the effects of uncertainty or changes in the input of the model. The sensitivity analysis assesses the effects of uncertainty or changes in the variables over which the designer has got no control over, including but not limited to wind speed, solar irradiance and fuel price. The relationship that exists between simulation, optimization and sensitivity analysis is illustrated in Figure 12.

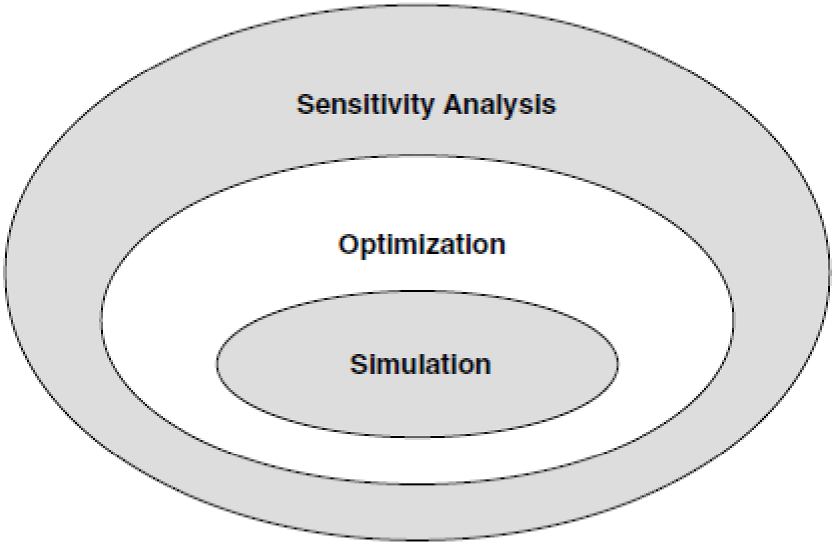


Figure 12: Conceptual relationship between simulation, optimization and sensitivity analysis. (Source: Lambert et al., 2006).

The HOMER software offers a large number of components including wind turbines, PV panels, diesel generator and batteries among others. The software simulates various hybrid renewable energy power systems and optimizes the size of their components to meet the condition of the lowest net present cost (NPC), which represents the total cost of installing and operating a system over its life time. Also, the most cost effective hybrid renewable energy system can be obtained by the software using the load profile, renewable energy potential (solar, wind, hydro, etc.), ambient conditions and the technical data of the components (Baghdadi, Mohammedi, Diaf, & Behar, 2015).

HOMER legacy is the original HOMER software version that was created at the NREL. The HOMER Pro software is the global standard employed in the optimization of micro grid design in all sectors. Originally, it was developed at the NREL but enhanced and distributed by HOMER energy.

2.14 Chapter Summary

In this chapter, existing literatures related to the topic of this thesis were reviewed and presented. The information presented in this chapter is centred on electricity sector of Cameroon and the solar resource potential of the country, lighting technologies, PV system components, cost and design, economic, social and environmental potentials of PV systems, case study PV projects in West Africa and the functioning of the HOMER software.

Chapter 3: Methods

3.1 Introduction

Research Methodology applies to how research is conducted. This research employed the collection of primary energy and socio-economic data through a survey of dwellings in Buea, Cameroon with the aid of a questionnaire supplemented by an informal interview. An economic and environmental analysis for the transition towards efficient lighting was performed using Microsoft Excel. The energy data (load profiles) for the surveyed dwellings was classified into major classes using the K-means clustering algorithm. For each of the classes, the mean load profile was used in the HOMER Pro software to design and model economic and technical performance of a specified PV system. Correlation and regression analysis were conducted to determine the factors that have an influence on the load profile of the dwellings and the adoption of LED. A simplified schematic of the methodology employed in this study is presented in Figure 13.

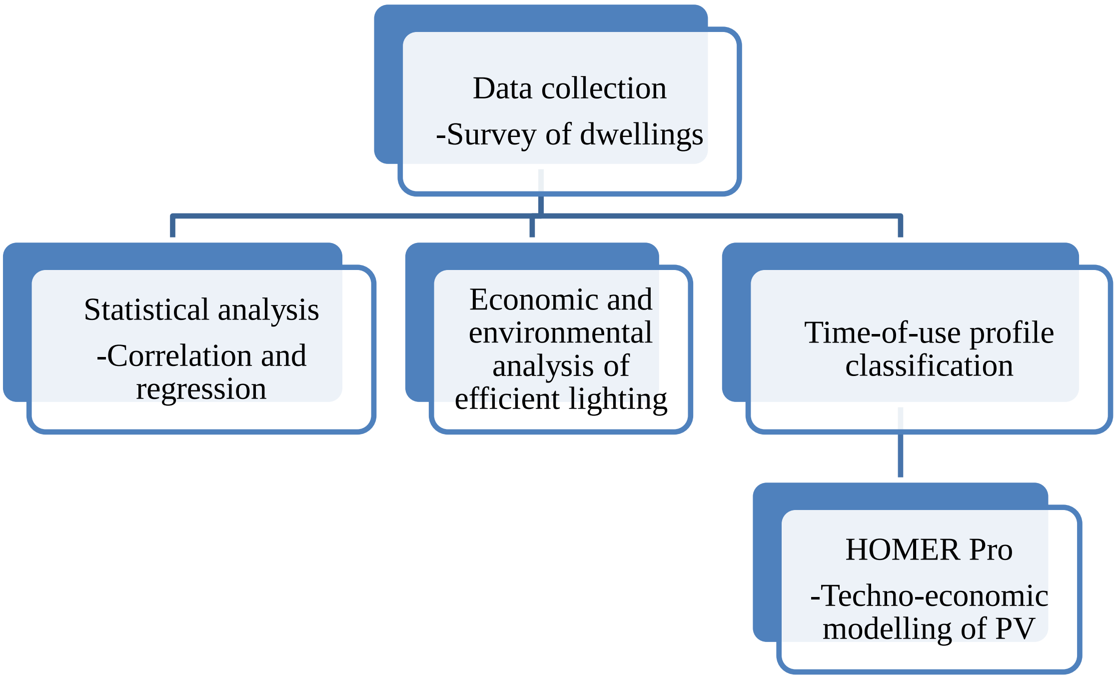


Figure 13: Schematic of research methodology.

3.2 Data collection

The sizing a residential stand-alone PV system often begins with the assessment of the existing required load to be met by the PV system (Abdul and Anjum, 2015). This preliminary step is of paramount importance since it determines the size of the different components that will constitute the stand-alone system. The required residential load considered in this study is that of lighting and basic communication appliances like radio and mobile phone chargers. Data on lighting load for residential building in Cameroon is scarce. In an attempt to overcome this shortcoming, a survey of households was conducted in the case study town of Buea, in the South West Region of the country so as to generate primary quantitative data to be employed in this study.

3.2.1 Questionnaire preparation

The questionnaire was prepared based on the required information to be collected. Upon finalization of the first draft of the questionnaire, an electronic copy was sent out for review. Based on the comments received from the first review process, the questionnaire was fine-tuned and a second draft was obtained. This second draft was submitted electronically for review and comments received from this second round review process were addressed and a third draft of the document was obtained. This version of the document was equally submitted for review. At this stage, very little comments were received from the review process. The comments were addressed and the final draft of the document was sent out electronically for pre-testing within New Zealand and in Cameroon. Based on the response from the pre-testing exercise, the questionnaire was further refined and this final version of the document was employed in the data collection process (See Appendix 1: Questionnaire employed in data collection, p130).

Structure of questionnaire

The questionnaire was structured to collect information on the electrical load for lighting and other basic communication appliances of the dwellings as well as information related to the uptake of the efficient light emitting diode (LED) technology by households. The questionnaire was composed of four different sections. Section one of the questionnaire was designed to capture socio-economic data of the surveyed household while section two was designed to obtain data on the characteristics of the family or residents under survey and their attitude and preferences towards different lighting technologies. The third section of the questionnaire was designed to collect information on current household lighting system and basic communication appliances used in the dwelling. This section captured information on the different types, number and power rating of communication appliances and bulbs used for lighting in the surveyed building. In the course of the survey, this section was completed first by the respondents with the assistance of the researcher. The respondent was briefed on the different types of light bulbs so as to enhance their capacity to match the different bulbs with their respective names. The power rating of the different appliances were read directly from them. The final section of the questionnaire was designed as a time of use diary to collect information on the daily duration of use of the different bulbs and communication appliances in the dwelling. This section was structured to obtain data for a week (Monday to Sunday) after which the questionnaires were retrieved from the respondents. The household survey exercise lasted for a duration of four weeks.

3.2.2 Household survey and questionnaire administration

A stratified random sampling approach was employed in the data collection process. The case study town, Buea was stratified into two; rural and urban settlements as was adopted by Nkwatoh, Manga, Yinda, Iyassa and Nkwatoh (2009). The urban areas considered in the study included Molyko and Bonduma while the rural areas surveyed included Muea, Bomaka and Mile 16. A total of 100 households (35 and 55 in the urban and rural settlement respectively) were randomly selected and surveyed with the aid of a questionnaire. The number of dwellings surveyed was limited to the time and financial resources accorded for the study. The survey achieved a questionnaire return rate of 92%.

In order to ensure the collection of quality data, the questionnaires were administered by the researcher to the head of the surveyed households where possible. Where the household head was unavailable, the questionnaire was administered to a household member of the age of 18 and above. This characteristic of the targeted respondents was considered to be desirable as it was believed that this group of respondents could better provide the required information which the questionnaire was intended to collect.

Data collection by the questionnaire was meant to be supplemented with a practical lighting demonstration using LED in the surveyed dwellings. The LED demonstration was orientated at providing household members with a comparison of the quality of light from the LED bulb to those of current conventional light bulbs used in their dwelling, so that they could state their preference for one lighting technology in relation to the others. In preparation for this exercise, a 9W Philips LED was purchased. The demonstration exercise was however unsuccessful due to issues related to security in the country at the time this survey was conducted (August to September, 2015). However, the data collection process with the aid of a questionnaire was supplemented by an informal interview, presentation and discussion with the respondents so as to obtain in-depth information.

The presentation was mostly centred on the quality of light (lumens) and cost associated with the LED technology in comparison to those of the conventional lighting technologies. This information provided to the respondent was directed at educating them in order to enhance their capacity to make an informed choice of the lighting technology preferred by their household.

3.3 Data analysis

3.3.1 Data inputting into excel

The collected data from the household survey were analysed using Microsoft Excel 2013 spreadsheets In order to facilitate the statistical analysis. Descriptive statistics (frequency) was performed using the Statistical Package for Social Science (SPSS) version 22 while regression analysis and electric load profile classification was performed using the R Statistical software.

3.3.2 Economic and environmental analysis for transition towards efficient lighting.

The average number of each lighting technology used in the different types of surveyed dwellings and the average daily duration (hours) for lighting was computed using Microsoft Excel spreadsheets. From the time of use dairy employed in the survey, the average required daily duration for artificial lighting for each dwelling was obtained by summing up the lighting duration of the seven days of the week and dividing the sum by seven. By summing up the average daily duration of all the buildings and dividing the sum by the total number of buildings, the average daily duty cycle for lighting in dwellings was obtained. Using the R Statistical software package version 3.0.3, regression analysis was conducted to determine the possible influence of the independent variables; household income, level of education of household head and unit type (apartment or single family detached house) on the adoption of light emitting diodes for lighting in residential dwellings. An economic and environmental analysis for the substitution of incandescent lamps in the surveyed dwellings with CFLs and LEDs was conducted using Microsoft Excel spreadsheets. The economic analysis was based on the net present value (NPV), internal rate of return (IRR), simple payback period (PBP) and benefit cost ratio (BCR). The impact of government policies pertaining to the provision of different rates of subsidy for LEDs for use in the residential sector was assessed using the return of investment for LED adoption in the first year.

3.3.3 Economic analysis of efficient lighting transition

Economic analysis was conducted to determine the benefits of substituting incandescent light bulbs in dwellings with CFL and LED. The dominant category of CFL and incandescent bulb used in dwellings were considered for the analysis alongside 10W LED bulb.

Net Present Value (NPV)

In calculating the NPV of a proposal or project, the cost and benefits needs to be quantified for the expected duration (lifetime) of the project (Commonwealth of Australia, 2006). The NPV was computed using Equation 27.

The economic benefit for the analysis represents saving through reduced electricity consumption brought about by the use of energy efficient light bulbs while the cost employed in the analysis represents the cost of electricity supply from the grid for lighting as well as the capital cost of the efficient bulbs without need to change fittings. Using T1 as an example, the NPV for substituting incandescent lamp with CFL for year one was computed using 5% discount rate and a daily lighting duration of six hours as shown in Table 8. The same steps were followed in Table 8 for computing the NPV of the LED technology and the NPV for the different years. The NPV for the entire lifetime of the project was obtained by summing up the obtained NPV from year zero to the last year. Similarly, the NPV for the different building types was obtained.

Table 8: Method employed in the computation of NPV for transition towards efficient lighting (CFL)

Number of incandescent bulb	**Power rating of incandescent bulb (PRI)**	**Number of CFL**	**Power rating of CFL (PRCFL)**	**Average daily duty cycle (ADDC)**
1	60W	1	20W	6 hours
Annual electricity consumption for incandescent (AECI) = PRI/1000 * ADDC * 365 days				
Annual electricity consumption for CFL (AECCFL) = PRCFL/1000 * ADDC * 365 days				
Annual electricity cost for incandescent-AECTI (year 1) = AECI * $0.12/kWh (electricity tariff)				

Number of incandescent bulb	**Power rating of incandescent bulb (PRI)**	**Number of CFL**	**Power rating of CFL (PRCFL)**	**Average daily duty cycle (ADDC)**
Annual electricity cost for CFL-AECTCFL (year 1) = AECCFL * $0.12/kWh (electricity tariff)				
Benefit of CFL in year 1 = AECTI – AECTCFL				
Net cash flow (NCF) = Benefit in year 1– Cost in year 1				
NPV = NCF/$(1+d)^n$, where n is equal to 1 (year 1).				

Benefit cost ratio and simple payback period

The benefit cost ratio was computed by dividing the total discounted benefits by the total discounted cost. The simple payback period represents the time required for the profits or other benefits of an investment to equal its costs. Using T1 as an example, the BCR and PBP for substituting incandescent with CFL was computed as presented in Table 9. Similarly, the BCR and PBP for the other building types and for LED were computed.

Table 9: Method employed in the computation of BCR and PBP for transition towards efficient lighting (CFL)

Benefit cost ratio		
Total discounted benefit = A		
Total discounted cost = B		
BCR = A/B		
Simple payback period		
Year	Cash flow	Net invested cost
0		-C
1	+D	0

Return on investment (ROI) and IRR

Return on investment simply measures the gain or loss of an investment relative to the money invested. The higher the ROI, the higher the profits compare favourably to the costs of the investment. The ROI was simply calculated by dividing the net benefits by the investment cost of the project. Using T1 as an example, the ROI for substituting incandescent lamp with LED in year one for six hours lighting duration with no government subsidy was computed as presented in Table 10. The IRR was calculated using the IRR formula in Microsoft Excel.

Table 10: ROI computation for substituting incandescent lamp with LED.

LED capital cost	**Annual electricity price for incandescent lighting**	**Annual electricity price for LED lighting**
$19.88	$B	$C
Benefits of LED (BLED) = $B - $C		

LED capital cost	**Annual electricity price for incandescent lighting**	**Annual electricity price for LED lighting**
Cost for operating LED (CLED) = $C		
Net benefit of LED (NBLED) = BLED - $C		
ROI = (NBLED)/ $C)*100		

3.3.4 Environmental analysis of efficient lighting transition

The environmental analysis for the GHG emissions associated with the use of the different lighting technologies in dwellings was conducted using the formula presented in Equation 28.

$$Emission\ (KgCO_{2-e}/yr) = Activity\ data\ x\ emission\ factor$$

Equation 28

Activity data in this case represents the annual energy consumption in kWh for a lighting technology obtained as a product of its power rating and its duration of use (in hours) for a period of one year. The emission factor is the quantity of GHG emitted per unit of the activity. Put differently, it is the amount of GHG emitted per kWh of electricity consumed. The emission factor considered in this study is 860g $CO_{2\text{-}e}$/kWh, which is the amount of emissions associated with the generation of a kWh of electricity in Cameroon (African Development Fund, 2009). The environmental benefits in terms of GHG emission saving associated with the switch from incandescent to CFL and LED lighting was obtained by simply subtracting the annual emissions associated with either CFL or LED from that of incandescent as presented in Equation 29.

$$Emission\ savings = E_i - E_e$$

Equation 29

Where;

E_i = emission associated with incandescent lighting and
E_e = emission associated with efficient lighting (CFL or LED).

Using the T1 building type as an example, the environmental analysis computation for substituting incandescent lamp with CFL is presented in Table 11. The same steps were followed to determine the emission saving associated with LED for T1. The environmental analysis for the other residential building types considered in this study was performed using the same approach.

Table 11: Method employed in the computation of emission savings associated with the transition towards efficient lighting (CFL)

Number of incandescent bulb	**Power rating of incandescent bulb (PRI)**	**Number of CFL**	**Power rating of CFL (PRCFL)**	**Average daily duty cycle**
1	60W	1	20W	6 hours
Annual activity data for Incandescent (AADI) = PRI/1000 kW * 6hours * 365 days				
Annual activity data for CFL (AADCFL) = PRCFL/1000 kW * 6 hours * 365 days				
Emission from incandescent (E_I) = AADI * 0.86 kg CO_{2-e}/kWh				
Emission from CFL (E_e) = AADCFL* 0.86 kg CO_{2-e}/kWh				
Emission saving =$E_I – E_e$				

Sensitivity analysis on efficient lighting transition

A sensitivity analysis for the environmental potential for transition towards efficient lighting was performed by varying the average daily lighting duration to four and eight hours. The sensitivity analysis on the economic potential for the transition towards efficient lighting (CFL and LED) was conducted based on the following sensitivity variables: an increase in the discount rate from 5% to 10%; varying the daily lighting duration to four and eight hours; and varying the lifetime of LED to 40000 hours and 60000 hours. The effect of different government subsidy rates on the return on investment on the LED technology within its first year of adoption was also investigated.

3.3.5 Load profile computation

The electric load profile for lighting and other basic communication appliances for all the buildings surveyed was computed using Excel spreadsheet. The energy load for each appliance was obtained using the formula in Equation 30 (Abdul and Anjum, 2015).

$$El = P\ X\ Dc$$

Equation 30

Where; El is the energy load in Wh,
P is the power rating (W) of the appliance and
Dc is the daily cycle of use of the appliance in hours.

The daily load profile for each dwelling was obtained as an average of the load profile for the seven days of the week for which time of use data of the appliances were obtained.

3.3.6 Load profile classification

The classification of the electricity time-of-use profiles obtained from the surveyed dwellings was done by using the profile shape approach. This approach entails the classification of the profiles based on the analysis of their shape (Stoecklein et al., 2001). Unlike the absolute power demand approach that takes into account the absolute power demand in the profiles, the profile shape approach is advantageous in that the timing and period of the peaks determine the category of the profile more than does the absolute size of the peak.

The daily average profiles were classified using the K-means clustering algorithm in R Statistics (Version 3.0.3). This algorithm classifies patterns without supervision, hence, the criteria for the classification process is determined by the algorithm. Using a plot of the total sum of squares within-groups of the data set against the number of clusters in K-means, the appropriate number of clusters to be employed in the categorization, suggested by a bend in the graph was determined to be six. Based on the appropriate number of clusters, the data set was classified into six different classes generating a mean profile for each class.

3.4 Correlation and Regression analysis

A correlation analysis (Pearson correlation) was conducted using the R Statistics software version 3.0.3 to determine the relationship that exists between the following variables at 95% confidence level ($P<0.05$): daily electric load of buildings, level of education of household head, monthly income of household head, unit type (apartment or single family detached house) and building class. A multiple linear regression analysis was performed on the data set so as to establish the influence of the independent variables (level of education of household head, monthly income of household head, unit type and building class) on the dependent variable (electric load of buildings).

3.5 Modelling of PV systems

3.5.1 Design of PV system

A PV system was designed to meet the mean load profile for each class as a stand-alone and back-up system to the grid. A total of 12 PV systems were therefore designed comprising of six stand-alone system and six grid back-up systems. The schematic of the designed PV systems is presented in Figure 14.

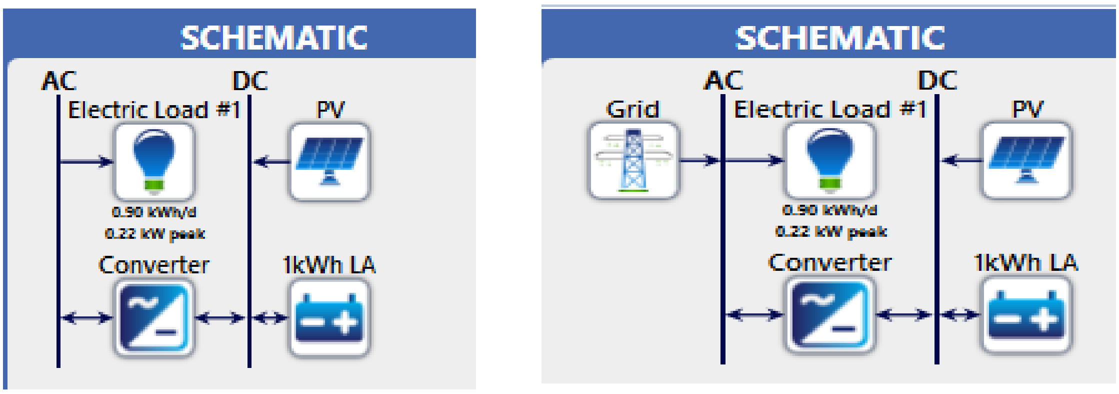
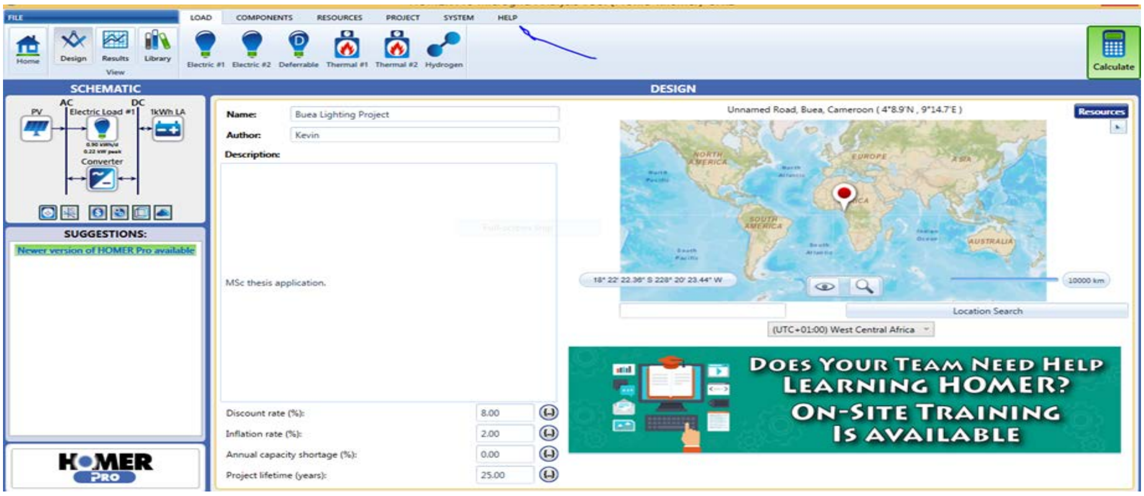


Figure 14: Schematic of stand-alone (left) and grid back-up (right) PV systems.

Step 1: Site specification

The home page of the HOMER Pro software has the world map (Figure 15) with a search box. To begin, details of the project (name and author) was provided on the home page and the location of the study area for which the PV system is designed was typed in the search box of the map and searched. HOMER Pro searches the specified location on the map and displays its geographical coordinates.



Unnamed Road, Buea, Cameroon (4°8.9'N , 9°14.7'E)

Name: Buea Lighting Project
Author: Kevin
Description: MSc thesis application.

Discount rate (%): 8.00
Inflation rate (%): 2.00
Annual capacity shortage (%): 0.00
Project lifetime (years): 25.00

(UTC+01:00) West Central Africa

Figure 15: Home page of the HOMER Pro software.

Step 2: specification of load profile and system components

The mean electric load profile for each of the six profile classes obtained from the K-means algorithm was introduced into the HOMER Pro software under the load tab (Figure 16).

Name: Electric Load #1

January Profile

Hour	Load (kW)
0	0.034
1	0.034
2	0.034
3	0.030
4	0.030
5	0.031
6	0.028
7	0.033
8	0.006
9	0.005
10	0.004

Time Step Size: **60** minutes

Random Variability

Day-to-day (%): 10

Timestep (%): 20

Metric	Baseline	Scaled
Average (kWh/d)	.9	.9
Average (kW)	.04	.04
Peak (kW)	.22	.22
Load Factor	.17	.17

Load Type: ● AC ○ DC

Scaled Annual Average (kWh/d): 0.90

☐ Efficiency (Advanced)

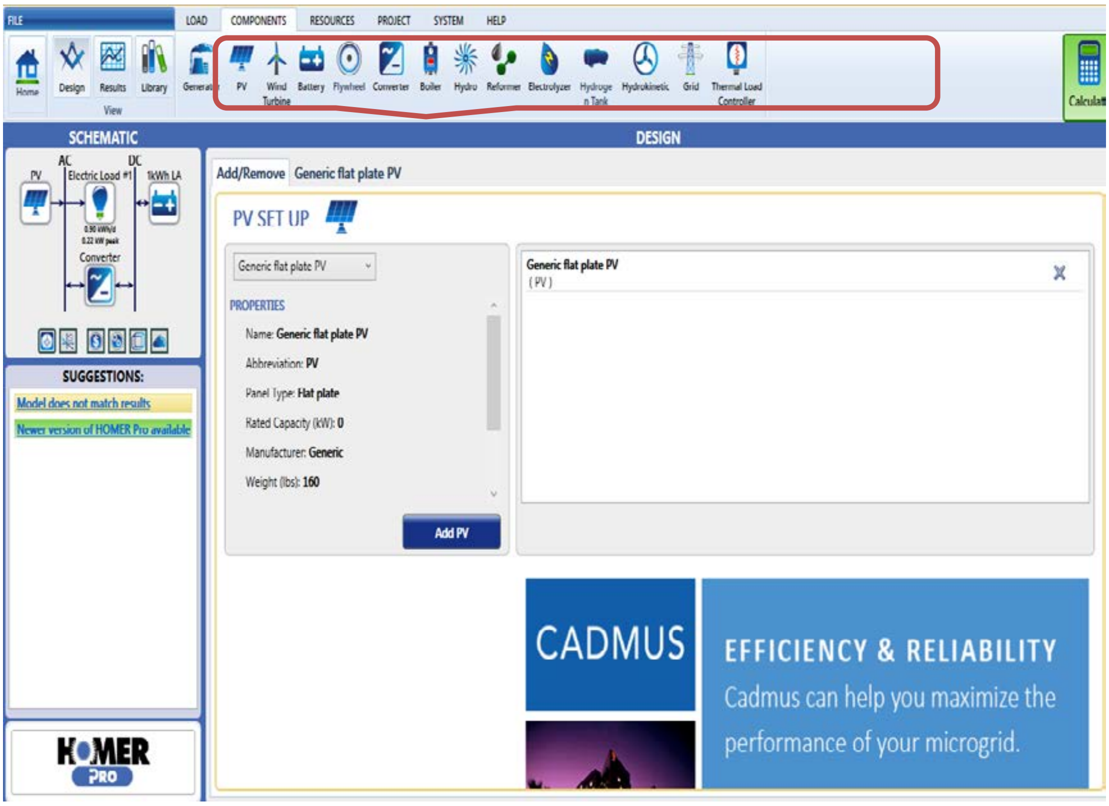
Efficiency multiplier: 1

Capital cost ($): 0

Lifetime (yr): 10

Figure 16: Screen capture of the Load tab of HOMER Pro

The different PV system components (battery, PV array and converter) were chosen under the component tab (Figure 17) and their technical and cost details were specified. In addition to the other PV components mentioned above, the advanced grid component was added for the system designed to serve as a back-up energy source during grid failure and battery charging from the grid was prohibited. Under the reliability tab of the advanced grid component (Figure 18), the period of grid outages was specified to occur from 7-9 pm daily for six months; January to June which according to Nfah and Ngundam (2009), corresponds to the period of the year when electricity supply from the grid is unreliable in Cameroon. The solar resource data (Global Horizontal Irradiation-GHI) for the study location, Buea, was imported directly into the software under the resource tab from the National Aeronautics and Space Administration (NASA) Langley Research Centre Atmospheric Science Data centre. The average daily solar radiation per month for the study area obtained from the HOMER Pro software is presented in Figure 19. The annual average daily radiation of the study area is 4.2 kWh/m^2/day as obtained from the HOMER Pro software.



Model does not match results

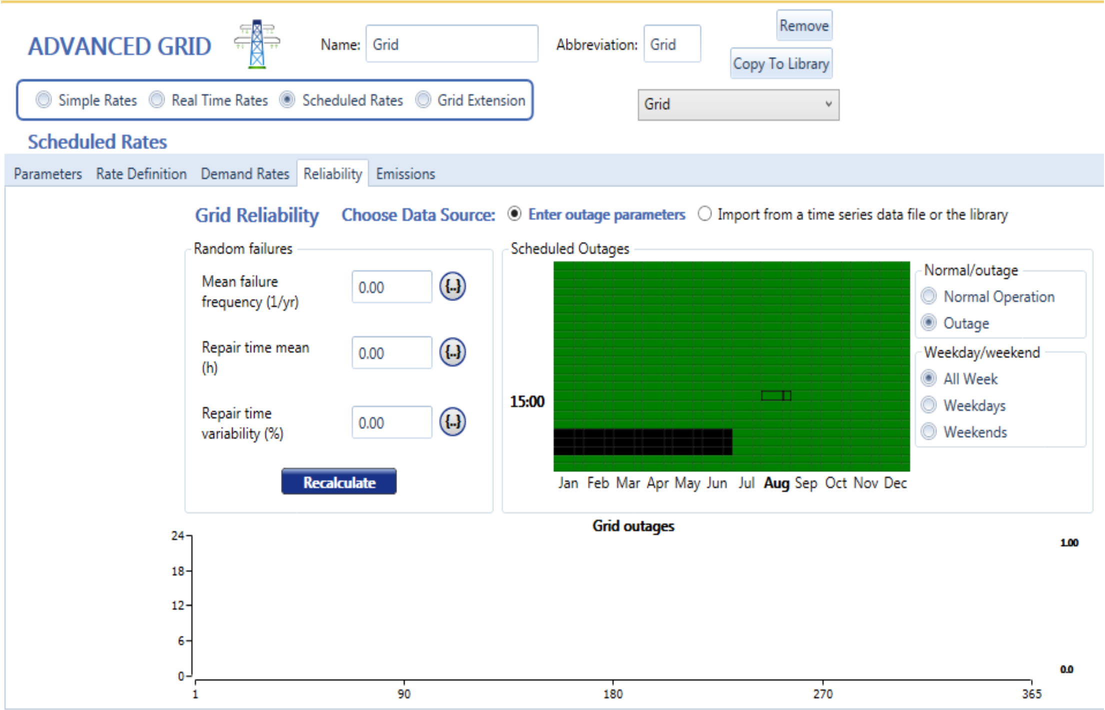
Newer version of HOMER Pro available

Generic flat plate PV

Name: Generic flat plate PV
Abbreviation: PV
Panel Type: Flat plate
Rated Capacity (kW): 0
Manufacturer: Generic
Weight (lbs): 160

Generic flat plate PV
(PV)

Figure 17: Screen capture showing the different components (in red rectangle) under the Component tab of HOMER Pro.



Name: Grid
Abbreviation: Grid

○ Simple Rates ○ Real Time Rates ● Scheduled Rates ○ Grid Extension

Grid

Choose Data Source: ● Enter outage parameters ○ Import from a time series data file or the library

Mean failure frequency (1/yr): 0.00
Repair time mean (h): 0.00
Repair time variability (%): 0.00

Normal/outage
○ Normal Operation
● Outage

Weekday/weekend
● All Week
○ Weekdays
○ Weekends

Figure 18: Reliability tab of the advanced grid component.

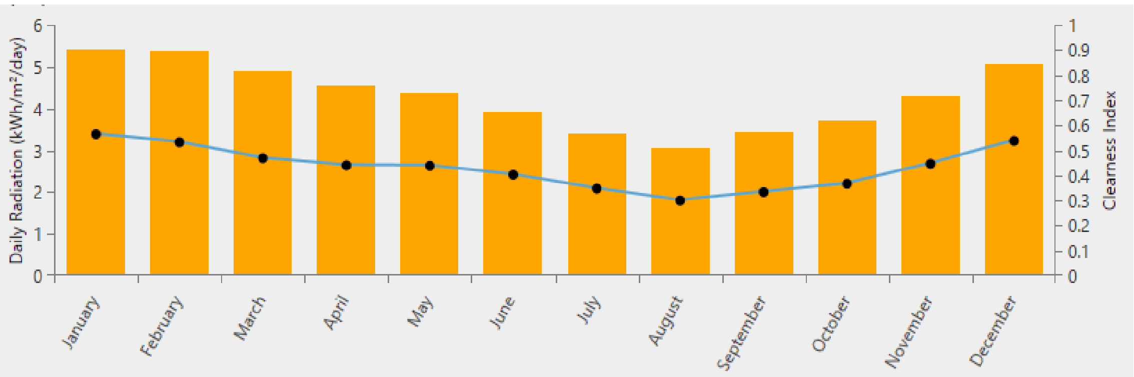


Figure 19: Average daily solar radiation for Buea obtained from HOMER Pro software.

Step 3: Calculation

The software performed the simulation process by modelling the behaviour of the system configuration each hour of the year in order to determine the system's technical feasibility and life cycle cost. HOMER Pro conducted the optimization of the system by simulating different system configurations with the objective of searching for the system that satisfies the technical constraints at the lowest life cycle cost. The calculation for the base case scenario was performed based on the following; a minimum battery SOC of 40%, 0% maximum annual capacity shortage, 5% discount rate, 2% inflation rate and a PV lifetime of 25 years.

3.5.2 Economic analysis of PV systems

The economic analysis for the PV system was conducted by HOMER. HOMER used the economic data provided to determine the net present cost (NPC) and the levelized cost of electricity generated by the system using 5% discount rate and 2% inflation rate. The cost data employed in the economic analysis is presented in Table 6. The operation and maintenance cost was considered as 2% of the initial PV module cost while the installation cost of the system was considered as 10% of the initial PV module cost.

3.5.3 Sensitivity analysis of the PV system modelling

A sensitivity analysis was performed in HOMER on five different variables: minimum battery SOC, maximum annual capacity shortage, PV lifetime, inflation and discount rate in order to determine their effect on the system's LCOE. Details of the sensitivity parameters is presented Table 12.

Table 12: Sensitivity parameters employed in the HOMER modelling.

Sensitivity variable	**Base case**	**Sensitivity case(s)**
Maximum annual capacity shortage	0%	5%, 10% and 15%
Minimum battery SOC	40%	30%
Discount rate	5%	10%
Inflation rate	2%	5%
PV lifetime	25 years	20 years and 30 years

3.5.4 Environmental analysis of the residential solar PV systems

In the environmental analysis of the PV systems, the average value (162 g-CO_{2eq}/kWh) of the emissions associated to monocrystalline PV system obtained by Sherwani et al. (2010) was adopted. Taking into consideration the estimated emission of a kWh of conventional electricity generated in Cameroon (860gCO_2), the emission savings (E_s) associated with the use of a kWh of electricity generated by the PV system was computed as follows:

$$E_s \ = \ E_c - E_{PV} = 860gCO_2 - 162gCO_2 = 698gCO_2$$

Where; E_c is the emission associated with a kWh of conventional generated electricity in Cameroon and E_{PV} represents emissions associated with a kWh of PV generated electricity.

Hence, the daily emission savings associated with the use of PV generated electricity in the residential buildings in this study was computed by simply multiplying the daily load (in kWh) of the respective buildings by 698gCO_2. In the course of a grid outage, the emissions from the grid will automatically be zero. However, it was assumed that emissions of kWh of electricity generated from a diesel generator in Cameroon is equal to that from the grid and that households decide to use generators to meet their energy needs (lighting) during an outage. It is based on this logic that the grid back-up PV system was considered for the environmental analysis. For the case of the back-up system, only the daily load from 7 to 9 pm from the month of January to June was considered in the computation. The annual emission saving is obtained by multiplying the daily emission saving by 365 days for the stand-alone systems and by 181 days for the back-up system.

3.6 Chapter summary

The methodology employed in this study has been presented in this chapter. In the first section of the chapter, the methodology used in the survey of residential buildings was described. The subsequent sections of the chapter dwelt on the methodology employed in the economic and environmental analysis of transition towards efficient lighting, statistical (regression) analysis, techno-economic modelling of the residential solar PV systems using the HOMER Pro software and an environmental analysis of the residential solar PV systems.

Chapter 4: Results

4.1 Introduction

This chapter is structured as follows: the first section of the chapter presents the socio-economic information of respondents; the second section presents the characteristics of the surveyed dwellings; in its third section, the characteristics of the different lighting technologies employed in the surveyed dwellings is presented; section four presents the economic and environmental potential of efficient lighting adoption; the time-of-use electricity profiles of the surveyed dwellings is presented in section five; and in the last section of the chapter, the results of the techno-economic modelling of the PV system is presented.

4.2 Socio-economic information of respondents

4.2.1 Gender

A greater proportion of the respondents that participated in this study were males. Of the 92 respondents, 57.6% (53 respondents) were males (Figure 20).

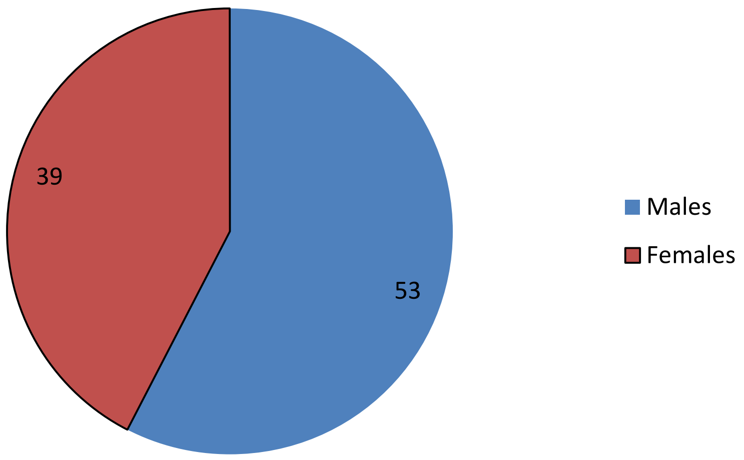


Figure 20: Gender of Respondents.

4.2.2 Marital status of respondents

Over half of the respondents for the study were married while 34.8% of the respondents were single as shown in Table 13.

Table 13: Marital status of respondents.

Marital status	Frequency	Percent
single	32	34.8
Married	57	62.0
Widow/widower	2	2.2
Divorced	1	1.1
Total	92	100.0

4.2.3 Occupation and level of education of respondents

The majority (32.6%) of respondents were holders of the secondary school certificate (Cameroon Ordinary Level General Certificate of Examination) followed by holders of Bachelor Degree (28.3%) while the Higher National Diploma (HND) emerged as the qualification with the least number of respondents corresponding to 6.5% as presented in Figure 21. Buea is a university town and hence not uncommon for over a quarter of respondents in the surveyed households to be holders of a Bachelor Degree.

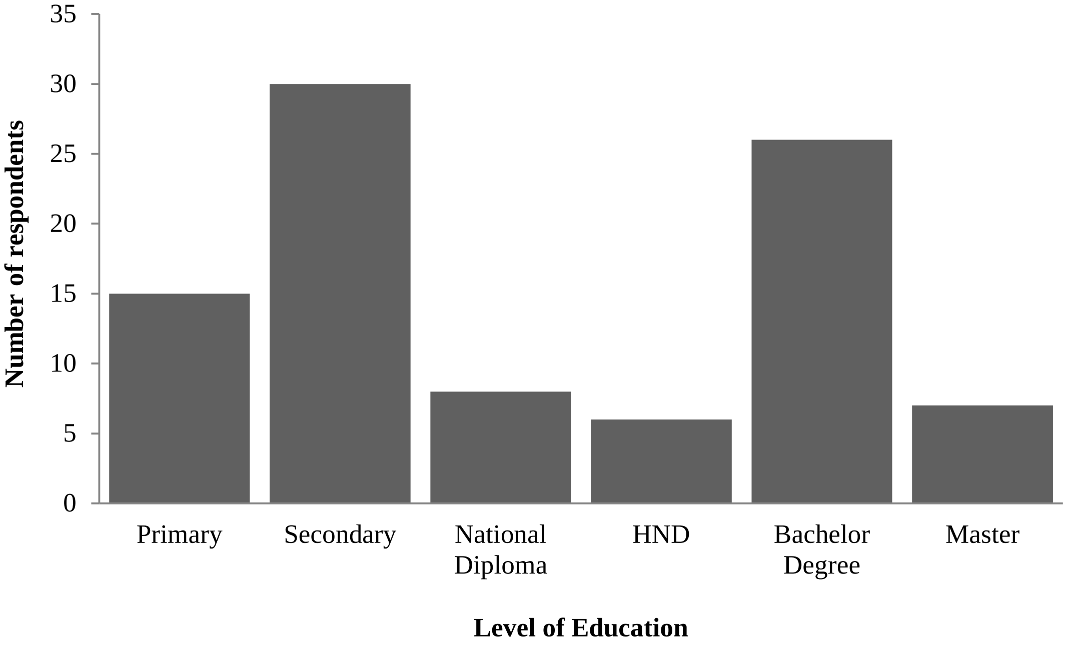


Figure 21: Level of Education of respondents.

Pertaining to the occupation of respondents, civil servants constituted the majority (32.6%, corresponding to 30 respondents) followed by businessman/woman which accounted for 23.9% of the respondents while only 1 (1.1%) of the respondents was an applicant as shown in Table 14.

Table 14: Occupation of respondents.

Occupation	**Frequency**	**Percent**
Farmer	12	13.0
businessman/woman	22	23.9
Retiree	5	5.4
Civil servant	30	32.6
student	5	5.4
Housewife	2	2.2
Private sector worker	2	2.2
Applicant	1	1.1
Technician	13	14.1
Total	92	100.0

4.2.4 Monthly income level of households

Analysis of the collected data revealed that majority of the households (47.8%) belonged to the income range of 50,000-125,000 CFA while only one household belonged to the income range of 350,001-425,000 CFA as presented in Table 15.

Table 15: Monthly income level of households.

Income (CFA)	**USD Equivalent**[2]	**NZD Equivalent**[3]	**Frequency**	**Percent**
<50,000	<82.84	<123.11	13	14.1
50,001-125,000	82.85-207.1	123.12-307.82	44	47.8
125,001-200,000	207.2-331.35	307.83-492.45	23	25.0
200,001-275,000	331.36-455.6	492.46-677.12	8	8.7
275,001-350,000	455.61-579.86	677.13-861.79	3	3.3
350,001-425,000	579.87-704.11	861.80-1,046.46	1	1.1

4.2.5 Household size and composition

Over half (53.3%) of households had five to nine residents while only one of the 92 households had 15 to 19 residents as shown in Table 16. The analysis of the collected data revealed that of the 92 households, 84 (91.3%) had either students or pupils residing therein while this was not the case for 8 households (8.7%).

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2 Currency conversion is valid as of 1:20 pm, December 20th, 2015 (1USD=603.599 CFA).

3 Currency conversion is valid as of 1:20 pm, December 20th, 2015 (1NZD=406.131 CFA).

Table 16: Household size.

Number of residents	Frequency	Percent
1-4	35	38.0
5-9	49	53.3
10-14	7	7.6
15-19	1	1.1
Total	92	100.0

4.3 Characteristics of dwellings

4.3.1 Unit type

For the purpose of this study, ‘unit type’ refers to whether the surveyed building is an apartment or a single family-detached building. Analysis of collected data revealed that over half (57.6%) of the surveyed dwellings were apartment units while the remainder of the dwellings were single family detached buildings. A characteristic of the surveyed apartment buildings is the sharing of a common electricity meter. At the end of the month, the electricity bill received from the power company is shared among the households connected to the common meter by the landlord or a designated individual.

4.3.2 Building class

A quarter of the surveyed buildings were of the T3 building class while only two buildings belonged to the T7 category as indicated in Table **17**. Buildings are officially classified into six categories (Table 2). However, two buildings emerged from the survey which did not fall into any of the six categories. For the purpose of this study, the two buildings were classified under the seventh category denoted as T7 (Table 17) and T7 differs from the T6 category in that it contains an additional bedroom.

Table 17: Building class of surveyed building.

Building class	Frequency	Percent
T1	13	14.1
T2	11	12.0
T3	23	25.0
T4	20	21.7
T5	16	17.4
T6	7	7.6
T7	2	2.2
Total	92	100.0

4.4 Current lighting technologies employed in households

4.4.1 Preference to lighting technologies

The analysis of the data revealed that 59 households preferred CFL, followed by LED which was preferred by 31 households while only two households preferred incandescent bulb for lighting. After information on energy savings and energy cost reduction associated with the use of efficient lighting technologies was disclosed to the respondents, there was a change in the preference for the different lighting technologies. While the number of households with preference for CFL dropped from 59 to 48, those with preference for LED increased from 31 to 39 while households with preference for incandescent witnessed an increase from two to five as shown in Figure 22.

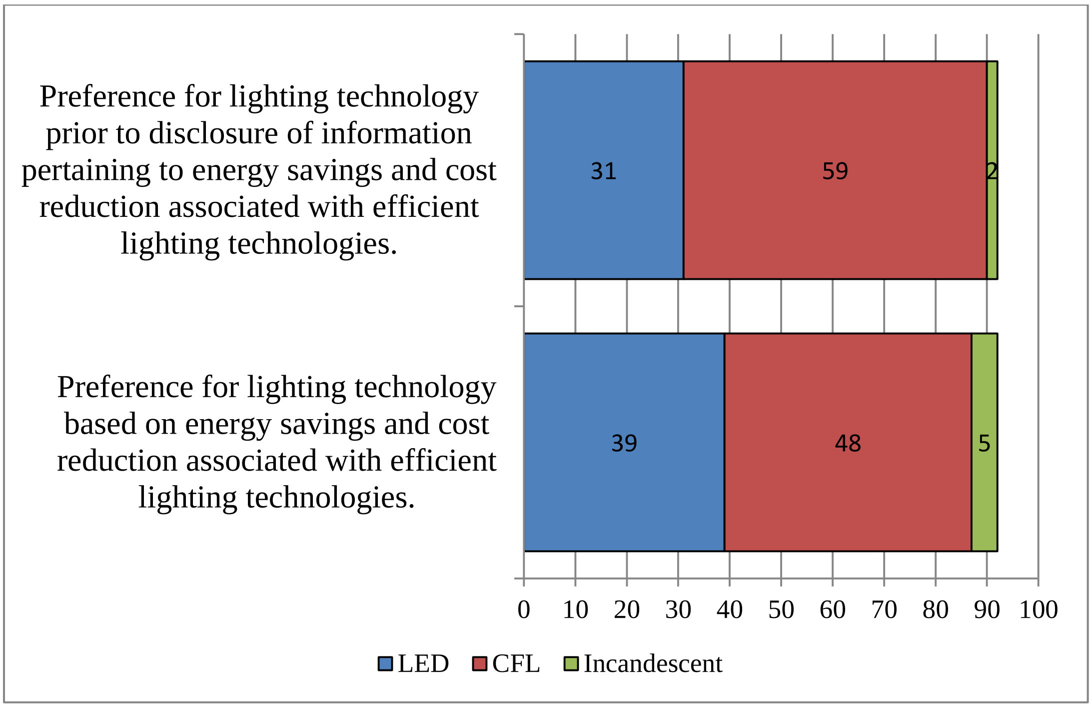

Figure 22: Households preference for lighting technologies based on knowledge of associated energy savings.

4.4.2 Current bulbs used in dwellings

The results of the survey revealed that three different types of light bulbs are used in dwellings. These include: incandescent, CFL and fluorescent tubes. LED was not used in any of the surveyed dwellings. Majority (15.2%) of the surveyed households used CFL only for lighting while 12% and 10.9% used only incandescent and fluorescent tube respectively for lighting. Over 60% of surveyed dwellings use a combination of two or all three of the technologies for lighting as indicated in Figure 23.

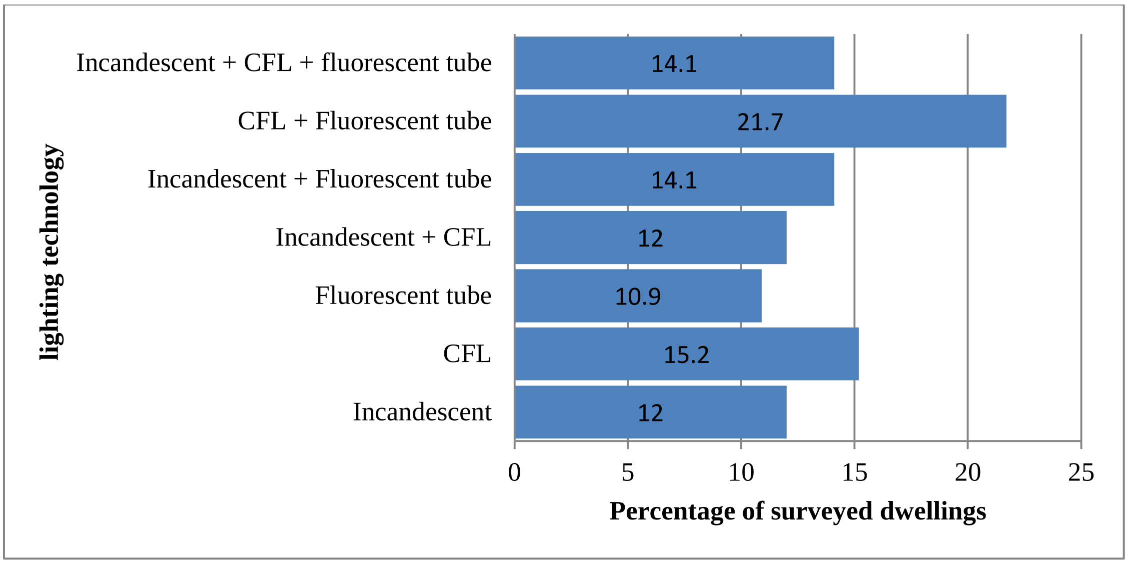

Figure 23: Current lighting technologies used in dwellings.

Incandescent

Analysis of the results revealed that incandescent lighting in the surveyed dwellings is accomplished by bulbs of four main power rating: 40W, 60W, 75W and 100W. Incandescent lighting is dominated by the 60W bulb category which is used in 36 of the surveyed dwellings while the 40W was found to be the least used of the incandescent bulbs as indicated in Figure 24. A 60W incandescent lamp used in dwellings is presented in Figure 25.

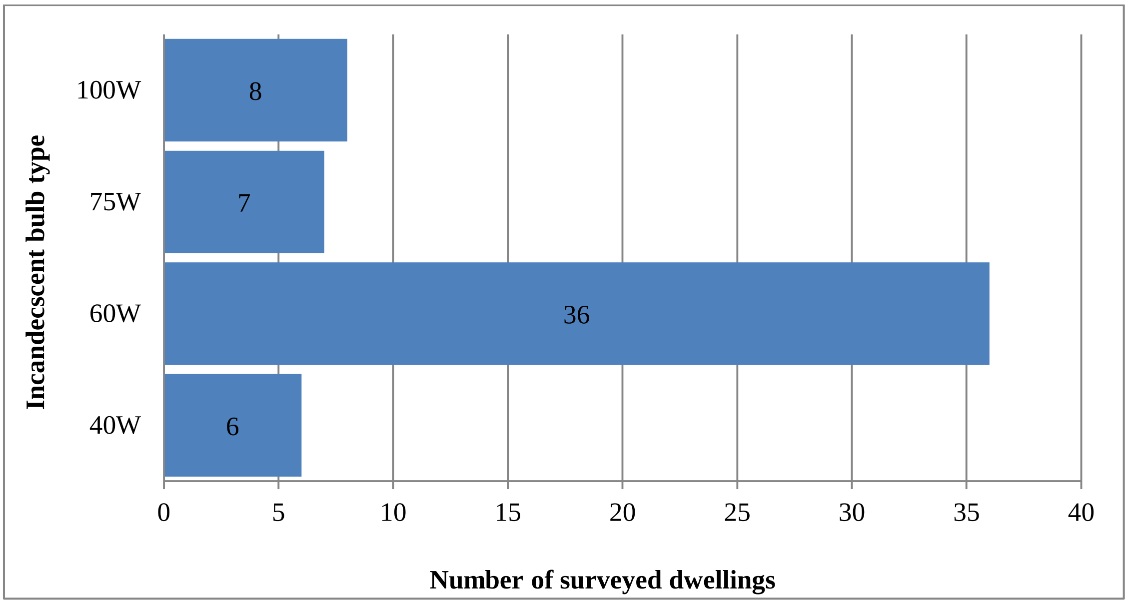

Figure 24: power rating and numbers of incandescent bulbs used in dwellings.

Figure 25: 60W incandescent lamp used in dwellings.

Compact fluorescent lamp

Results of the survey revealed that CFLs used in dwellings are of the following power rating: 11W, 18W, 20W, 22W, 26W, 30W, 36W, 40W, 60W, 75W, 80W and 85W. Figure 26 presents a 20W CFL used in residential dwellings in the study area.

Figure 26: 20W compact fluorescent lamp used in residential dwellings.

CFL lighting is dominated by the 20W bulb category which was found to be used in 33 dwellings while the 11W, 26W and 36W categories were used in only one dwelling respectively as shown in Figure 27.

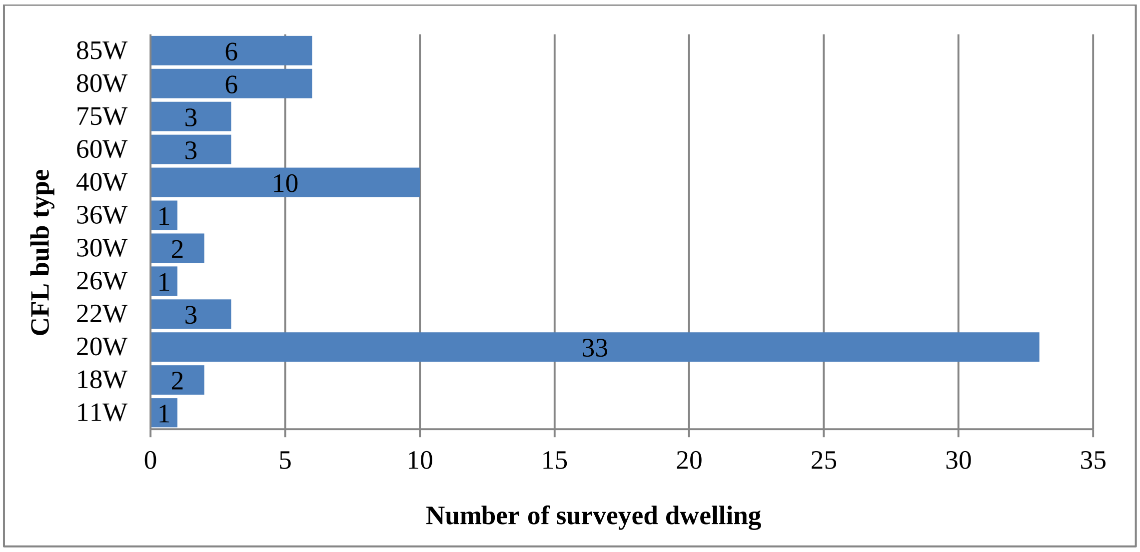

Figure 27: Power rating of CFLs used in dwellings.

Fluorescent tube

Lighting of dwellings using fluorescent tube is through the use of two main bulbs; 40W and 60W. Fluorescent tube lighting is dominated by the 40W category which was found to be used in 43 dwellings while the 60W fluorescent tube was used in 21 dwellings. Figure 28 represents a 60W fluorescent tube used in dwellings.

Figure 28: A 60W fluorescent tube used in dwellings.

4.4.3 Alternative lighting technologies used by households during grid failure

A number of alternative technologies are used by households for lighting during a power outage. These include: kerosene lamp, rechargeable lantern, solar lantern and candle. Households that use candle during a power outage do so because they find it relatively inexpensive and affordable while households that employ the use of rechargeable lantern and solar lantern do so for safety reasons since they do not pose a fire hazard unlike a candle and kerosene lamp. A greater proportion of the surveyed dwellings (38%) use candles only for lighting during a power outage while 22.8%, 7.6% and 2.2% of surveyed households used only rechargeable lanterns, kerosene lamps and solar lanterns respectively. Over 29% of the households surveyed use a combination of two or more of the technologies for lighting during a power outage as shown in Figure 29.

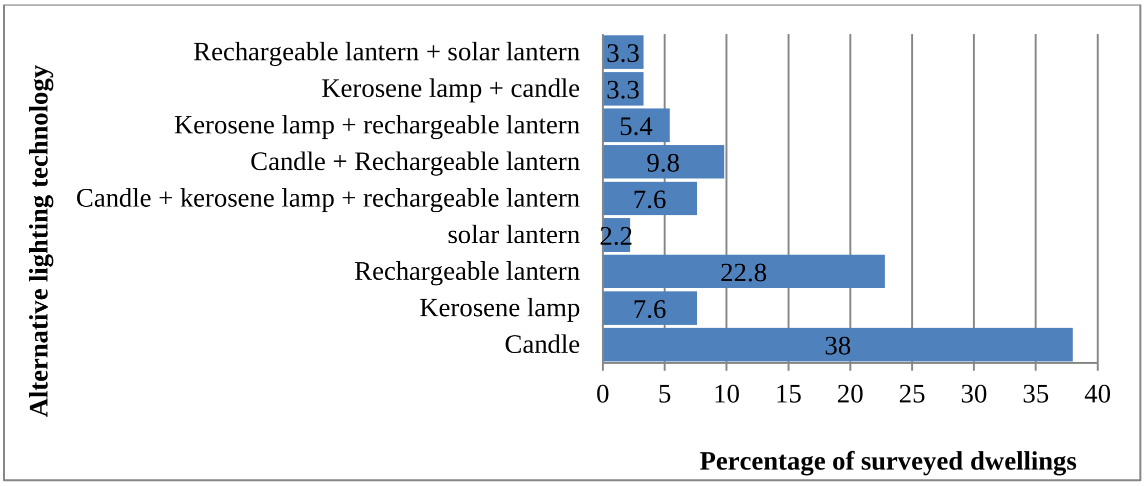

Figure 29: Alternative lighting technologies used in dwellings.

4.5 Economic and environmental potential of efficient lighting adoption

4.5.1 Factors predicting the adoption of LED bulbs

Multiple regression analysis was conducted to predict the adoption of LED from the independent variables; level of education of household head, income and unit type. All the independent variables had a positive effect on the dependent variables. However, results of the regression model revealed that neither of the independent variables statistically significantly predicted the dependent variable (LED adoption) at $p < 0.05$ as shown in

.

Table 18: Summary of multiple regression analysis for LED adoption.

Variable	B[4]	SE_B[5]	β[6]	T values	P values
Intercept	2.027	.227		8.915	.000
Income	.043	.067	.075	.641	.523
Level of education	.047	.043	.135	1.094	.277
Unit type	.033	.164	.023	.203	.840

4.5.2 Economic potential of efficient lighting adoption

Economic analysis was conducted to determine the benefits of substituting incandescent light bulbs in dwellings with CFL and LED. The 20W CFL and 60W incandescent bulb were considered for the analysis since they constitute the dominant lamps used in the surveyed dwellings for the CFL and incandescent category respectively. From the survey, the average daily duration where artificial lighting was required in dwellings was determined to be six hours. A sensitivity analysis was conducted by varying: the daily duration of lighting from 6 hours to 4 hours and 8 hours; and the discount rate from 5 to 10%. The average number of incandescent light bulbs used in the surveyed dwellings is presented in Table 19. Incandescent light bulbs were not used in either of the two T7 buildings surveyed and for this reason, T7 was not considered in the economic and environmental analysis for the transition towards efficient lighting. The input data employed in the economic analysis is presented in Table 20. From Table 20, the expected lifetime of the LED bulb is 50,000h which corresponds to 22.83 years at a daily usage of 6 h while the CFL with an expectant lifetime of 5,000h corresponds to 2.28 years and incandescent bulb is expected to last for 2,000h (0.91 year). Put differently, in 22 years for which a single LED could be used for lighting, incandescent lamps must be replaced 25 times and CFLs 10 times. The duration of the project was obtained by dividing the lifetime of the LED bulb by the product of the average daily lighting duration and the number of days (365) in a year. The project duration

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[4] Unstandardized regression coefficient

[5] Standard error of the coefficient

[6] Standardized coefficient

corresponds to 22, 34 and 17 years for the daily lighting duration of six, four and eight hours respectively.

Table 19: Average number of incandescent bulbs used in dwellings.

Building class	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
Average number of incandescent bulbs	1	3	4	5	6	4

Table 20: Input data for the different bulb types.

Bulb type	**Incandescent**	**CFL**	**LED**
Power rating	60	20	10
Lifetime (h)[7]	2000	5000	50000
Cost price (in USD)[8]	0.58 (CFA350)	0.83 (CFA500)	19.88 (CFA12000)
Average daily duty cycle (hrs)	6	6	6
Lifetime (years)	0.91	2.28	22.83
Number of bulbs required for 22 years	25	10	1

Energy consumption of each lighting technology

The annual energy consumption for each lamp type based on a daily lighting duration of 6 hours for the different building classes is presented in Table 21. The energy consumption of each lamp type increases from T1 through to T5 and decreases to T6. The results of the sensitivity analysis revealed an increase in the energy consumption for all the lighting technologies with an increase in the lighting duration as shown in Figure 30.

Table 21: Quantity of energy consumed (kWh/year) by each lighting technology at six hours of use daily.

Building class	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
Number of bulbs required	1	3	4	5	6	4
Incandescent (60W)	131.4	394.2	525.6	657	788.4	525.6
CFL (20W)	43.8	131.4	175.2	219	262.8	175.2
LED (10W)	21.9	65.7	87.6	109.5	131.4	87.6

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[7] Based on manufacturers' specification

[8] Based on local commercial prices during the research period.

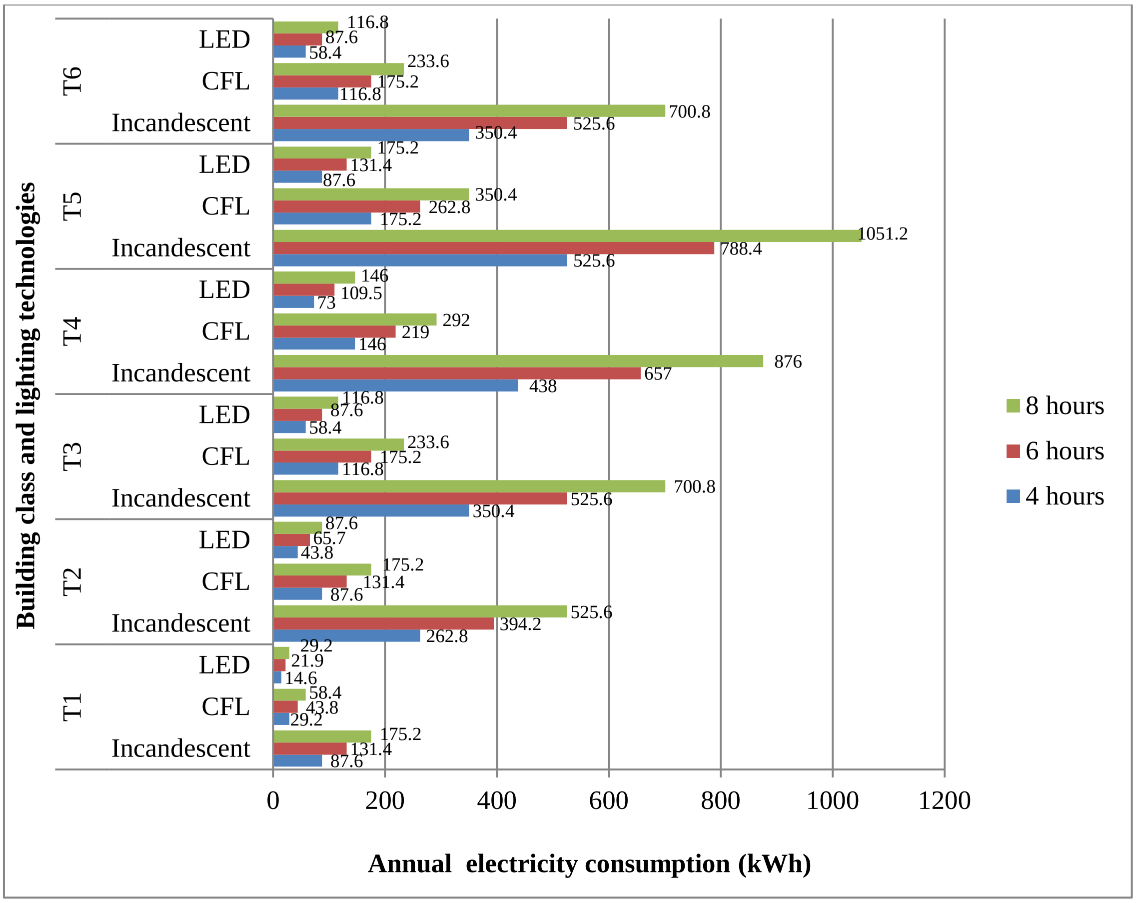

Figure 30: Variation of energy consumption with number of lighting hours for different lighting technologies per category of building class surveyed.

Annual electricity cost for lighting using different lamps

The annual electricity cost for lighting for the different lighting technologies and for different building classes based on the current electricity tariff in Cameroon (USD$0.12/kWh[9]) is presented in Table 22. The electricity cost followed the same trend like the energy consumption, increasing from T1 through to T5 and decreasing to T6.

Table 22: Annual electricity cost (USD) for lighting of different lamps per category of building class for the base case (six hours of lighting).

Building class	T1	T2	T3	T4	T5	T6
Incandescent	15.77	47.30	63.07	78.84	94.608	63.072
CFL	5.23	15.77	21.02	26.28	31.54	21.02
LED	2.63	7.88	10.51	13.14	15.77	10.51

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[9] Equivalent to CFA 75/kWh. Currency conversion is valid as of 1:20 pm, December 20th, 2015.

Investment profitability

The results of the economic analysis for the substitution of incandescent bulbs with CFLs and LEDs in the different residential buildings using the average daily artificial lighting duration of six hours is presented in Table 23. The economic benefit for the analysis represents saving through reduced electricity consumption brought about by the use of energy efficient light bulbs. The cost employed in the analysis represents the cost of electricity supply from the power company for lighting as well as the capital cost of the efficient bulbs without need to change fittings. The NPV for CFL ranges from $60.02 to $360.14 while that for LED ranges from $112.85 to $677.08. The simple payback period for CFL and LED were obtained as 0.17 year (two months) and 1.92 years (23 months) respectively, the benefit cost ratio (BCR) for CFL and LED were obtained as 1.84 and 3.18 respectively while the internal rate of returns (IRR) for CFL and LED were respectively obtained as 621% and 53%.

Table 23: Results of economic analysis for substitution incandescent lamps with efficient lighting based on six hours lighting duration over the 22-year project duration.

Building class		**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
NPV	CFL	$60.02	$180.07	$240.10	$300.12	$360.14	$240.10
	LED	$112.85	$338.54	$451.39	$564.24	$677.08	$451.39
IRR	CFL	621%	621%	621%	621%	621%	621%
	LED	53%	53%	53%	53%	53%	53%
BCR	CFL	1.84	1.84	1.84	1.84	1.84	1.84
	LED	3.18	3.18	3.18	3.18	3.18	3.18
PBP	CFL	0.17 year*	0.17 year	0.17 year	0.17 year	0.17 year	0.17 year
	LED	1.92 years**	1.92 years	1.92 years	1.92 years	1.92 years	1.92 years

* 0.17 year = 2 months, ** 1.92 years = 23 months

Effect of lighting duration on the economic benefits of efficient lighting

The results of the sensitivity analysis performed on the average daily artificial lighting duration are presented on Table 24 and Table 25.

Table 24: Results of economic analysis based on daily lighting duration of four hours over the 34-year project duration.

Building class		**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
NPV	CFL	$47	$141.01	$188.01	$235.02	$282.02	$188.01
	LED	$89.14	$267.43	$356.57	$445.71	$370.37	$356.57
IRR	CFL	406%	406%	406%	406%	406%	406%
	LED	35%	35%	35%	35%	35%	35%
BCR	CFL	1.77	1.77	1.77	1.77	1.77	1.77
	LED	2.58	2.58	2.58	2.58	2.58	2.58

Building class		T1	T2	T3	T4	T5	T6
PBP	CFL	0.25 year*	0.25 year	0.25 year	0.25 year	0.25 year	0.25 year
	LED	2.83 years**	2.83 years	2.83 years	2.83 years	2.83 years	2.83 years

*0.25 year = 3 months and ** 2.83 years = 34 months

Table 25: Results of economic analysis based on daily lighting duration of 8 hours over the 17-year project duration.

Building class		T1	T2	T3	T4	T5	T6
NPV	CFL	$70.28	$210.83	$281.11	$351.38	$421.66	$281.11
	LED	$131.56	$394.68	$526.24	$657.80	$789.36	$526.24
IRR	CFL	835%	835%	835%	835%	835%	835%
	LED	70%	70%	70%	70%	70%	70%
BCR	CFL	1.88	1.88	1.88	1.88	1.88	1.88
	LED	3.33	3.33	3.33	3.33	3.33	3.33
PBP	CFL	0.13 year*	0.13 year	0.13 year	0.13 year	0.13 year	0.13 year
	LED	1.5 years**	1.5 years	1.5 years	1.5 years	1.5 years	1.5 years

* 0.13 year = 1.5 months and **1.5 years = 18 months

The NPV of CFL and LED increases with an increase in the duration of artificial lighting as shown in Figure 31. The IRR and the BCR for both CFL and LED increases with increase in the lighting duration (See Figure 32 and Figure 33) while the PBP for both lighting technologies decreases with an increase in the daily duration of artificial lighting as shown in Figure 34.

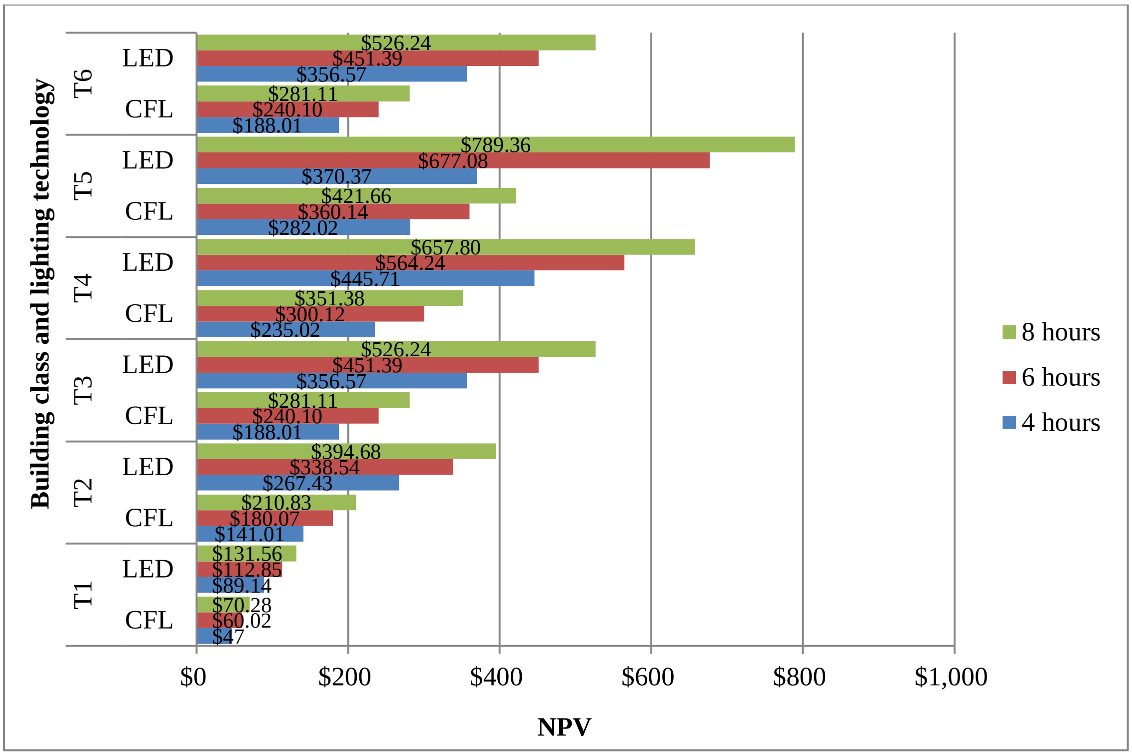

Figure 31: Variation of NPV with daily lighting duration.

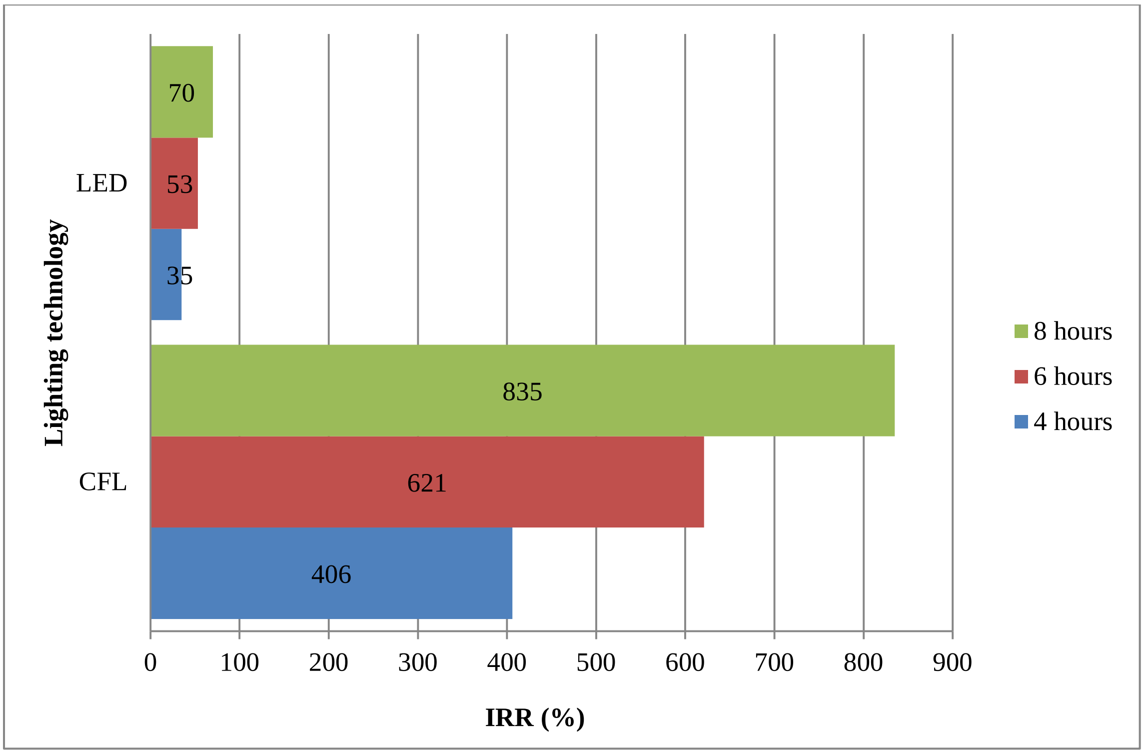

Figure 32: IRR of CFL and LED for different lighting durations.

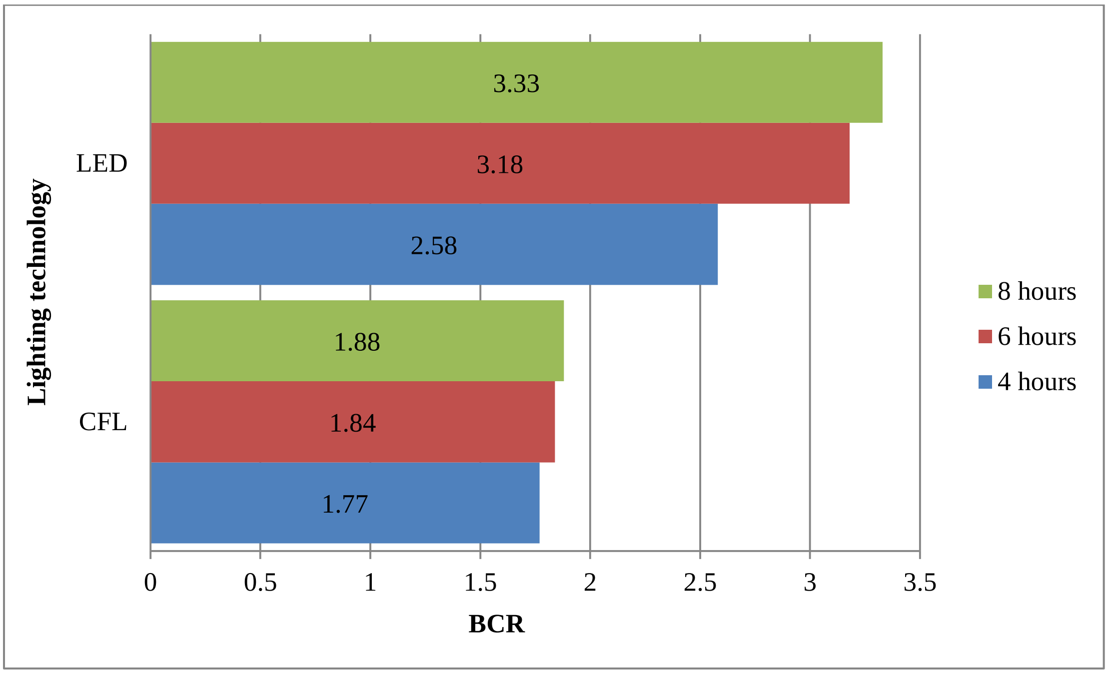

Figure 33: BCR of CFL and LED for different lighting durations.

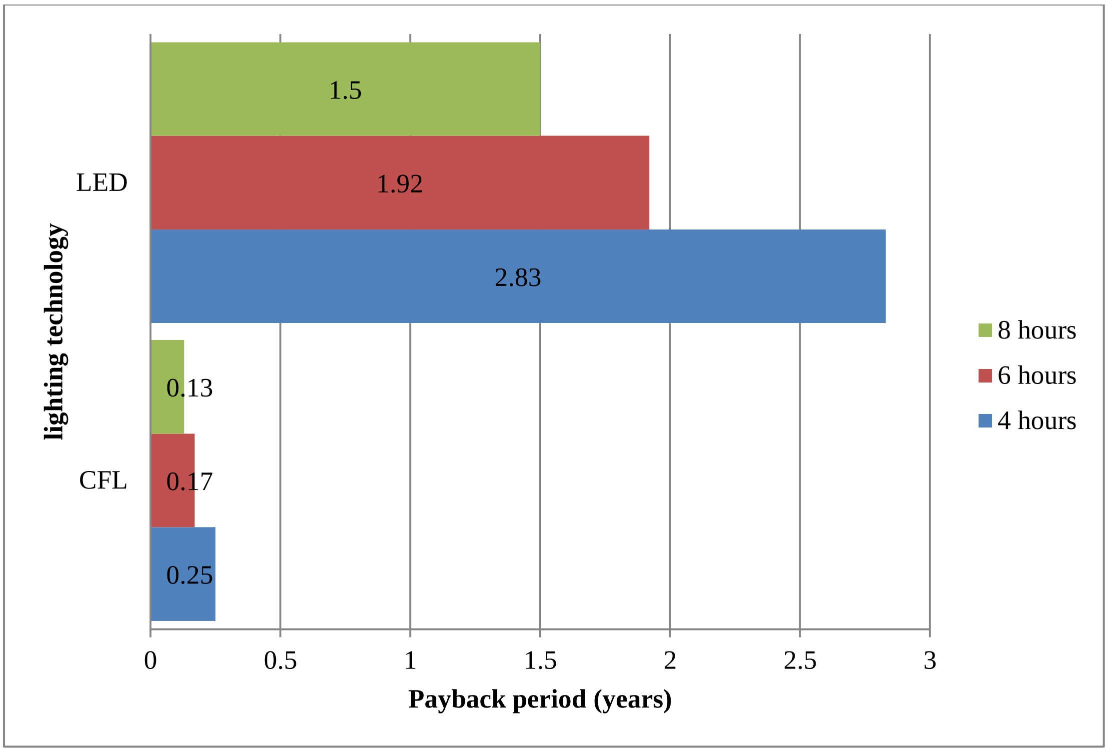

Figure 34: Payback period of CFL and LED for different lighting durations.

Effect of discount rate on the economic benefit of efficient lighting

The result of the sensitivity analysis using 10% discount rate is presented in Table 26. The NPV and CBR for both CFL and LED witnessed a decrease with an increase in the discount rate from 5 to 10 % (See Figure 35 and Figure 36) while both IRR and PBP witnessed no change with an increase in the discount rate.

Table 26: Result of sensitivity analysis using 10% discount rate.

Building class		**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
NPV	CFL	$38.01	$114.02	$152.02	$190.03	$228.03	$152.02
	LED	$65.75	$197.25	$263.01	$328.76	$394.51	$263.01
IRR	CFL	621%	621%	621%	621%	621%	621%
	LED	53%	53%	53%	53%	53%	53%
BCR	CFL	1.83	1.83	1.83	1.83	1.83	1.83
	LED	2.68	2.68	2.68	2.68	2.68	2.68
PBP	CFL	0.17 year	0.17 year	0.17 year	0.17 year	0.17 year	0.17 year
	LED	1.92 years	1.92 years	1.92 years	1.92 years	1.92 years	1.92 years

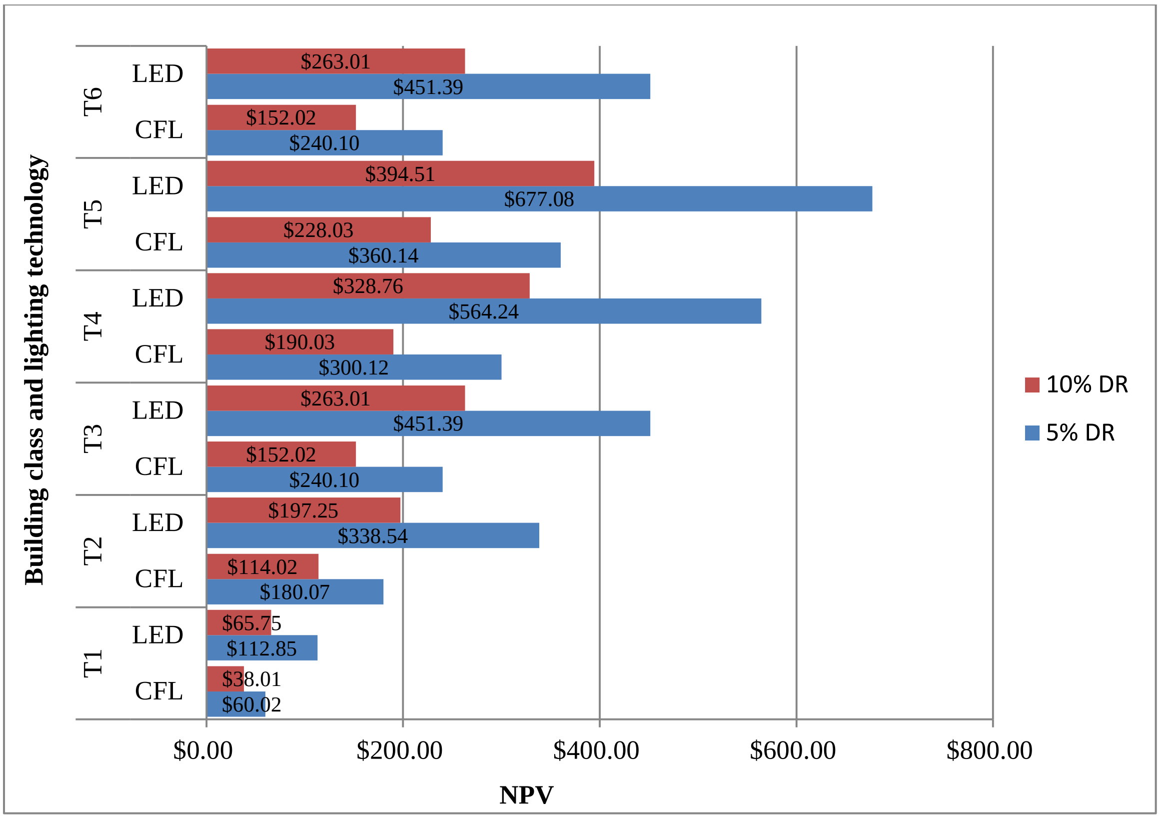

Figure 35: NPV of CFL and LED at 5 and 10% discount rate.

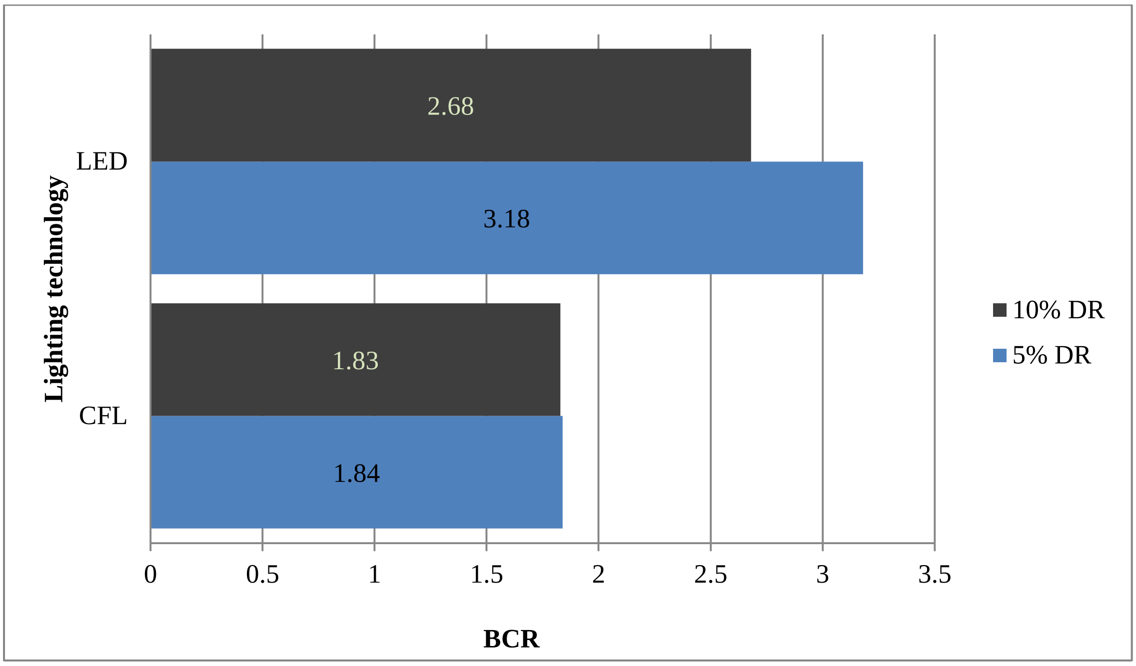

Figure 36: BCR of CFL and LED at 5 and 10% discount rate.

Effect of lifetime on the economic benefit of LED

A sensitivity analysis was also performed on the lifetime of the LED. While the IRR and PBP remained constant, the BCR and the NPV increased with an increase in the lifetime of the LED lamp. The BCR of the LED for 40000, 50000 and 60000 hours lifetime is 3.11, 3.18 and 3.35 respectively. The effect of the lifetime of LED lamp on the NPV is presented in Figure 37.

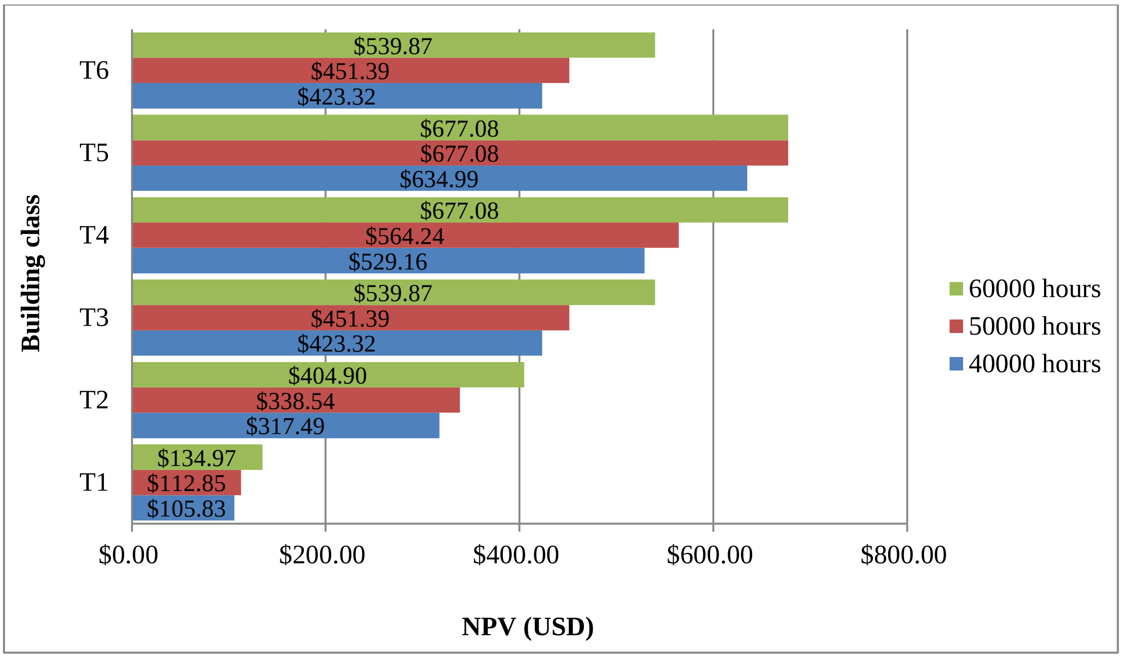

Figure 37: Effect of lifetime of LED on NPV.

Possible effect of subsidy by the Cameroon government on the return of investment of LED

The potential effect of different rates of government subsidy (on LED purchase cost) on the return of investment of LED in the first year of adoption is presented in Figure 38. The return of investment increases with an increase in the subsidy rate by the government for all three daily artificial lighting durations. The return on investment as well increases with an increase in the lighting duration. A return of investment that exceeds one depicts that the investment or project is profitable and worthwhile.

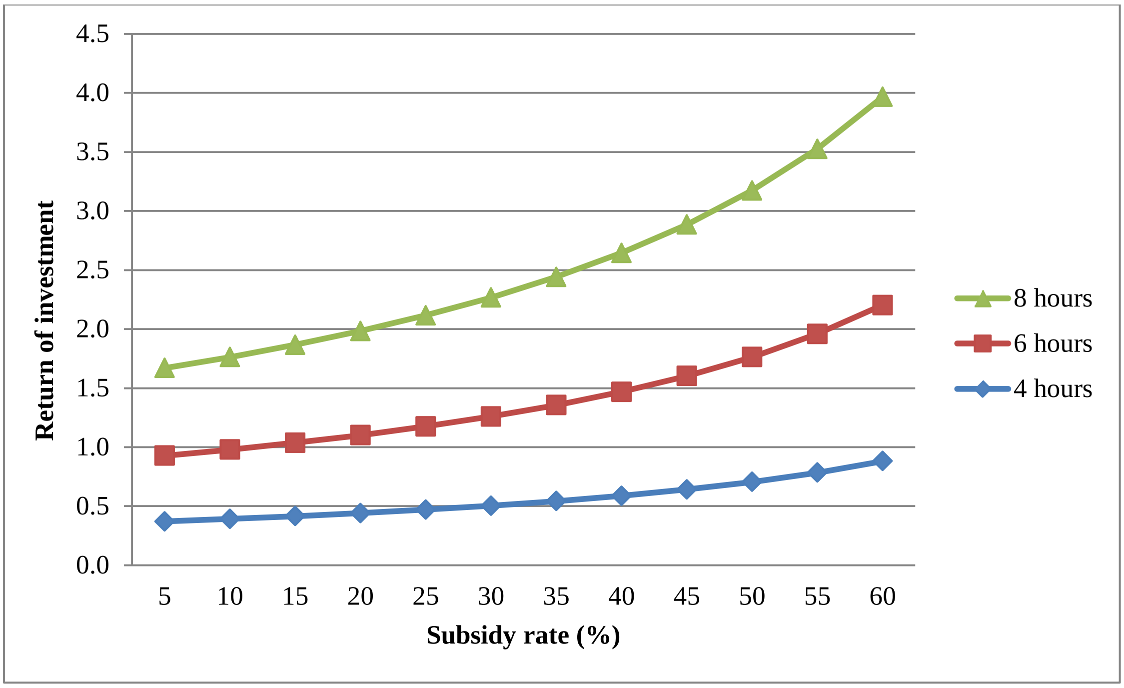

Figure 38: Return of investment for different subsidy rate and lighting durations by substituting incandescent lamps with LEDs in the first year.

4.5.3 Environmental Potential of efficient lighting adoption

The results of the environmental benefits in terms of greenhouse gas emission savings for replacing incandescent lamps with CFLs and LEDs in residential buildings at an average daily duration of 6 hours is presented in Table 27. The GHG emission savings increases from T1 to T5 and decreases to T6. The GHG emission savings was computed using the emission factor of 0.86 kgCO$_{2\text{-e}}$/kWh, which corresponds to the emission associated with the generation of a kWh of electricity in Cameroon (African Development Fund, 2009).

Table 27: Greenhouse gas emission savings (kgCO$_{2\text{-e}}$) for replacing incandescent lamp by CFL and LED.

Building class	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
CFL emission saving	75.34	226.01	301.34	376.68	452.02	301.34
LED Emission saving	94.17	282.51	376.68	470.85	565.02	376.68

The environmental potentials of both lighting technologies increased with an increase in the daily duration of artificial lighting in dwellings. The results of the sensitivity analysis on the environmental benefits of replacing incandescent lamps with CFLs and LEDs are presented in Figure 39.

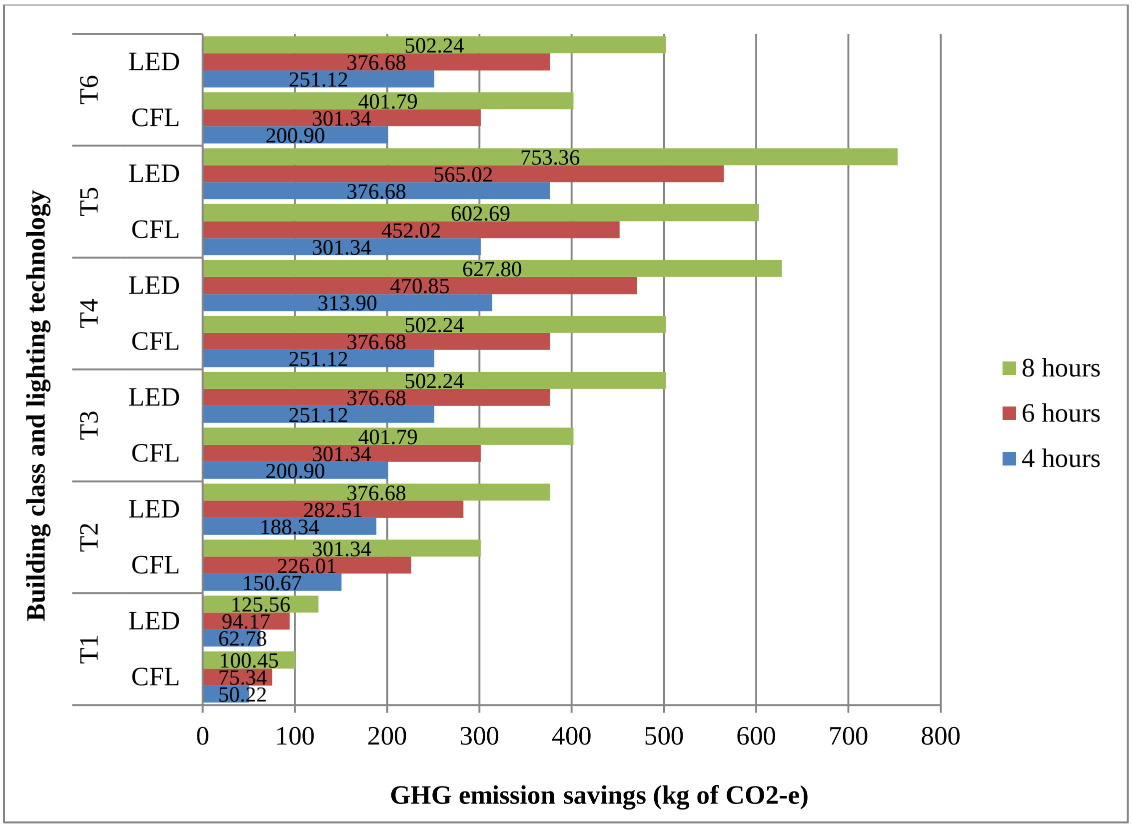

Figure 39: Results of sensitivity analysis on the environmental benefits of replacing incandescent lamps by CFLs and LEDs.

4.6 Time-of-use profile of dwellings

4.6.1 Factors affecting load of dwellings

A multiple regression analysis was conducted to predict the dependent variable (electric load of buildings) from the independent variables; level of education of household head, income of household head, unit type and building class. The independent variables statistically predict the dependent variable, F(4, 87)=14.475, p <0.0005, with an adjusted R^2 value of 0.372 which signifies that the independent variables explain 37.2% of the variability of the dependent variable, electric load of buildings. With the exception of one variable (unit type), the independent variables have a positive effect on the dependent variable. However, only one (building class) of the four independent variables statistically significantly predicted the dependent variable at $p < 0.05$ as presented in Table 28.

Table 28: Multiple regression analysis summary for electrical load of dwellings.

Variable	B[10]	SE_B[11]	β[12]	T values	P values
Intercept	49.861	238.192		.209	.835*
Level of education	68.293	36.718	.184	1.860	.066*
Income	47.571	59.888	.078	.794	.429*
Unit type	-178.150	142.404	-.116	-1.251	.214*
Building class	228.265	36.047	.569	6.332	.000*

* denotes the probability level (95% confidence interval).

4.6.2 Classes of time-of-use profiles

The six profile classes determined by the k-means algorithm are shown in Figure 40. Each line represents the daily electricity profile for a single dwelling averaged over one week and the thick red line shows the average electricity profile for a particular class.

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[10] Unstandardized regression coefficient

[11] Standard error of the coefficient

[12] Standardized coefficient

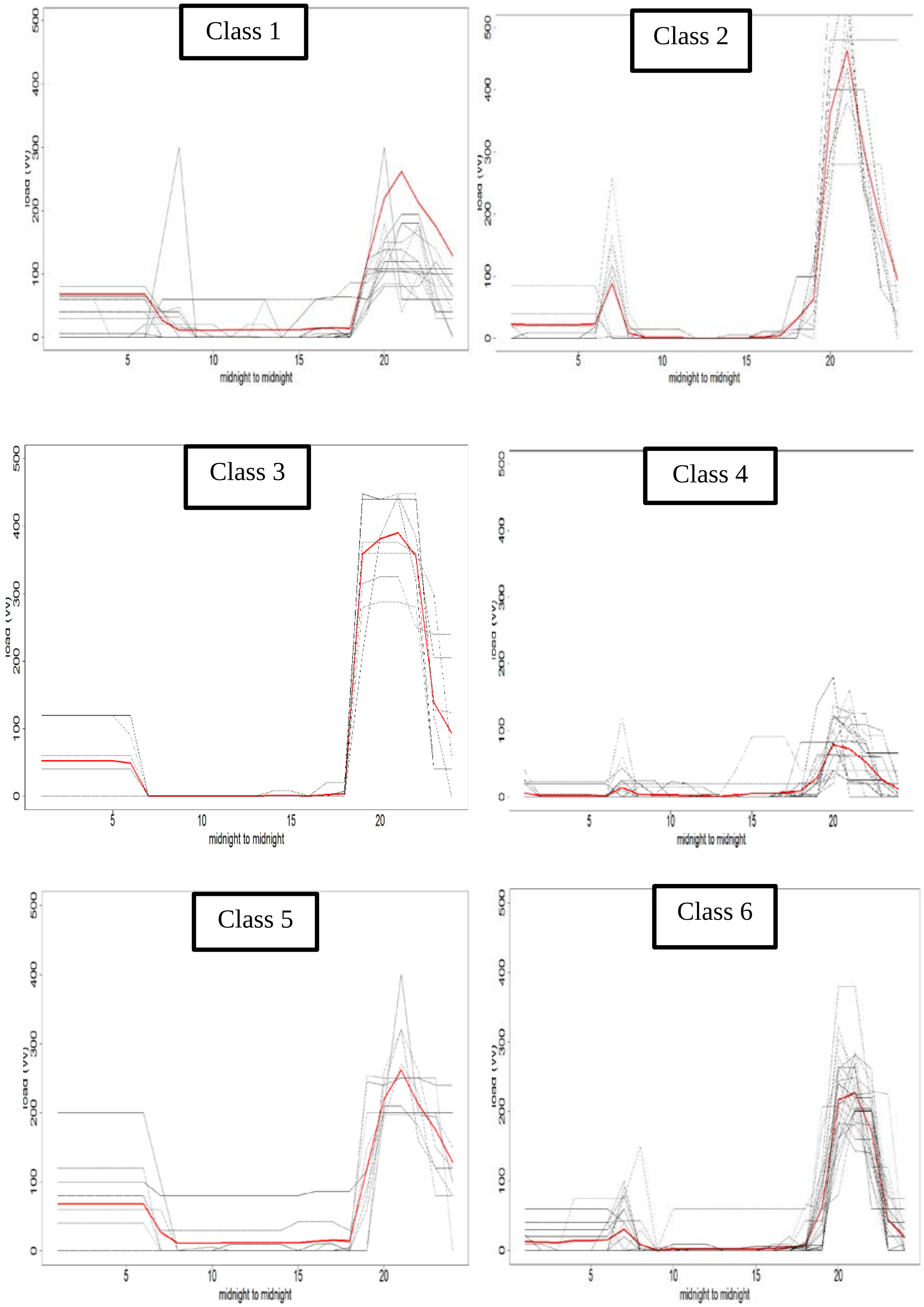

Figure 40: Daily electricity profile classes in watts (x-axis: midnight-to-midnight, y-axis: watts) obtained from the k-means algorithm.

From Figure 40, the following electricity profile classes can be distinguished:

- Class 1: Low early morning peak, flat afternoon use and high evening peak.
- Class 2: Fairly flat profile in the early morning and high evening peak.
- Class 3: Similar to class 2, but has a lower morning peak and a higher afternoon peak.
- Class 4: Low morning use, flat afternoon use and high evening peak
- Class 5: Similar to class 4, but higher morning and afternoon use and sharp evening peak.
- Class 6: low morning peak, low afternoon use and high evening peak.

Average electricity profile per class

The average electricity profile for lighting and basic communication appliances for each class is presented in Table 29. The mean profiles are characterised by high energy use in the evening (from 7-10 pm), low morning electricity use (from 00:00 – 7am) while electricity use is at its lowest between 8 am and 4 pm.

Table 29: Average daily electricity profile (in watt-hour) for each profile class as depicted in Figure 40.

Time of day	class 1	class 2	class 3	class 4	class 5	class 6
0	33.81	22.78	52.50	5.86	68.00	12.63
1	33.81	21.56	52.50	2.14	68.00	11.81
2	33.81	21.56	52.50	2.14	68.00	11.48
3	30.06	21.56	52.50	2.14	68.00	14.26
4	30.06	21.56	52.50	2.14	68.00	14.26
5	31.31	23.56	48.75	1.95	68.00	15.74
6	27.63	88.44	0.00	13.82	27.00	30.67
7	33.38	8.67	0.00	4.77	11.00	8.37
8	6.00	1.67	0.00	3.05	11.40	0.15
9	5.13	1.67	0.00	2.82	11.60	2.70
10	3.88	1.67	0.00	2.64	11.90	2.67
11	5.13	0.00	0.00	1.77	11.90	2.67
12	8.75	0.00	0.00	1.09	11.90	2.33
13	3.75	0.67	1.00	2.73	11.90	2.33
14	5.63	0.67	1.00	5.27	12.20	2.44
15	8.75	2.33	0.00	5.27	13.80	3.00
16	9.38	4.67	2.50	6.23	15.40	4.15
17	10.75	30.44	3.50	9.50	14.10	8.11
18	75.38	63.00	358.75	29.36	119.50	61.78
19	133.00	363.33	381.75	78.50	219.10	216.74
20	118.13	463.00	390.25	72.55	261.70	226.70
21	118.50	302.56	355.38	52.27	212.70	171.04
22	75.81	186.33	139.13	26.73	175.40	44.22
23	55.19	93.67	93.63	11.73	129.00	19.11

Time of day	class 1	class 2	class 3	class 4	class 5	class 6
Total (kWh/day)	0.90	1.68	2.07	0.35	1.69	0.83

4.6.3 Residential buildings per class of electricity time-of-use profile

The number of building(s) of a particular building class per electricity TOU profile class is presented in Table 30. The majority of T1, T2, T3, T4, T5, T6, and T7 buildings belong to class 4, class 4, class 6, class 1, class 2, class 3 and class 5 TOU profile class respectively.

Table 30: Number of each building class per electricity time-of-use profile.

Building class	Electricity time-of-use profile class						
	class 1	class 2	class 3	class 4	class 5	class 6	Total
T1	3	0	0	8*	0	2	13
T2	2	0	0	6*	1	2	11
T3	3	1	0	6	4	9*	23
T4	7*	1	3	1	2	6	20
T5	2	6*	3	1	0	4	16
T6	0	1	3*	0	2	1	7
T7	0	0	0	0	2*	0	2

* denotes the TOU profile class to which the majority of buildings of a particular building class (across a row) belongs to.

4.7 Techno-economic modelling of a residential solar photovoltaic system using HOMER Pro.

4.7.1 Stand-alone PV system

System components specification

Based on the modelling process of the stand-alone residential PV system for meeting the load presented in Table 29, the result of the technical specifications of the systems is shown in Table 31. The result presented in Table 31 is based on the maximum annual capacity shortage and the minimum battery state of charge of the base scenario which corresponds to 0% and 40% respectively. The monthly average electricity production of the PV system designed for each profile class is presented in Figure 41.

Table 31: Results of technical specification of system components for stand-alone system.

Profile class	PV array (kW)	1 kWh Lead acid battery	Converter (kW)	PV power output (kWh/year)	Unmet load (kWh/yr)
Class 1	0.8	5	0.3	1005.0	0.2
Class 2	1.6	9	0.9	2010.0	0.3
Class 3	1.9	12	0.7	2387.0	0.4

Profile class	PV array (kW)	1 kWh Lead acid battery	Converter (kW)	PV power output (kWh/year)	Unmet load (kWh/yr)
Class 4	0.3	2	0.2	376.84	0.0
Class 5	1.6	9	0.5	2009.79	0.1
Class 6	0.7	5	0.5	879.28	0.1

Figure 41: Monthly average electricity production for stand-alone PV system for different profile classes as obtained from modelling in HOMER Pro.

A sensitivity analysis was conducted on the maximum annual capacity shortage and the minimum battery state of charge. The effect of the annual capacity shortage and minimum battery state of charge on the specification of the system components is presented in Table 32. From Table 32, increase in the maximum annual capacity shortage from 0 to 15% decreases the size of the PV array and/or the battery while a decrease in the minimum battery state of charge from 40% to 30% decreases the PV array size and/or battery size.

Table 32: Effect of maximum annual capacity shortage and battery state on charge on system components.

Profile class	Sensitivity variable	Sensitivity value (%)	PV array (kWh)	1 kWh Lead acid battery	PV power output (kWh/year)
Class 1	Maximum annual capacity shortage	0	0.8	5	1004.9
		5	0.5	4	628.1
		10	0.4	4	502.5
		15	0.5	2	628.1
Class 2		0	1.6	9	2010
		5	0.9	8	1130.5
		10	0.8	7	1004.9
		15	0.7	6	879.3
Class 3		0	1.9	12	2387.0
		5	1.0	8	1256.1
		10	1.0	8	1256.1
		15	0.9	7	1130.5
Class 4		0	0.3	2	376.8
		5	0.3	1	376.8
		10	0.2	1	251.2
		15	0.2	1	251.2
Class 5		0	1.6	9	2009.8
		5	0.9	7	1130.5
		10	0.8	6	1004.9
		15	0.7	6	879.3
Class 6		0	0.7	5	879.3
		5	0.5	4	628.1
		10	0.4	3	502.5
		15	0.4	3	502.5
Class 1	Minimum battery state of charge	30%	0.7	5	897.3
Class 2			1.4	9	1759.0
Class 3			1.7	11	2135.0
Class 4			0.3	2	376.8
Class 5			1.5	8	1884.1
Class 6			0.8	4	1004.9

Economic analysis

The results of the economic analysis assessed by the LCOE and the net present cost (NPC) of the system is presented in Table 33.

Table 33: Results of economic analysis of the stand-alone system for the base case.

Profile class	Initial capital	LCOE	NPC
Class 1	$3772	$1.22	$6984
Class 2	$7316	$1.24	$13329
Class 3	$9017	$1.27	$16717
Class 4	$3772	$1.25	$2749
Class 5	$7220	$1.22	$13137
Class 6	$6692	$1.26	$6692

The effect of the discount rate and inflation rate on the LCOE is presented in Figure 42. Using profile 1 as an example, an increase in the discount rate from 5% to 10% increases the LCOE from $1.22/kWh to $1.61/kWh while an increase in the inflation rate from 2% to 5% decreases the LCOE from $1.22/kWh to $1.02/kWh as shown in Figure 42.

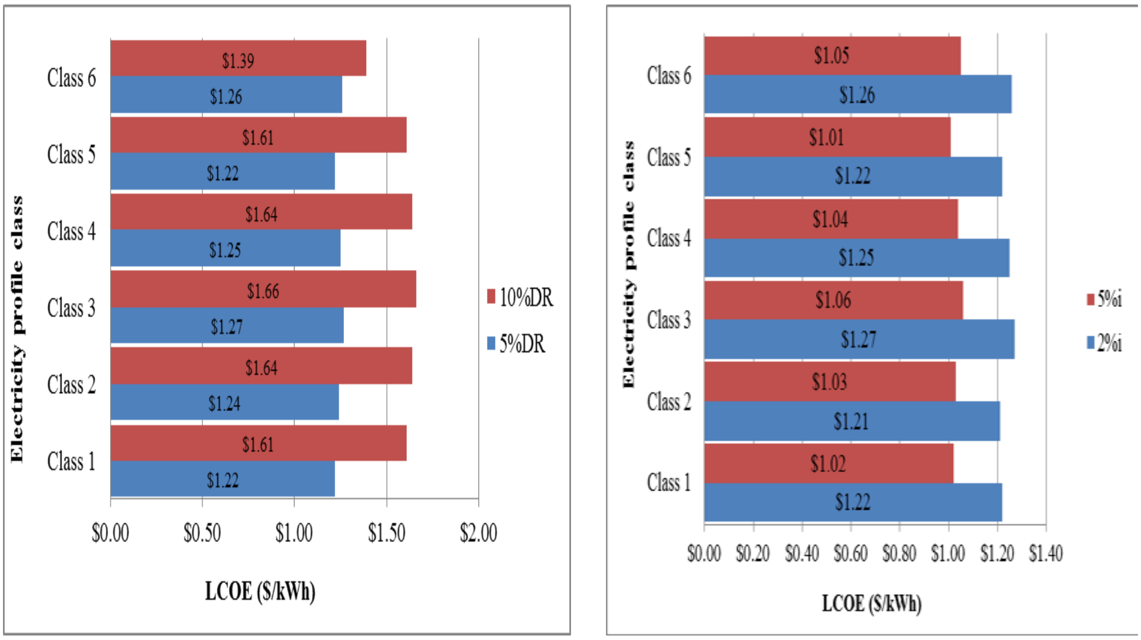

Figure 42: Effect of discount rate (Left) and inflation rate (Right) on the LCOE of the stand-alone PV system.

From Figure 43, an increase in the maximum annual capacity shortage from 0 to 15% results to a decrease in the LCOE while the LCOE of all profile classes decreased with increasing PV lifetime.

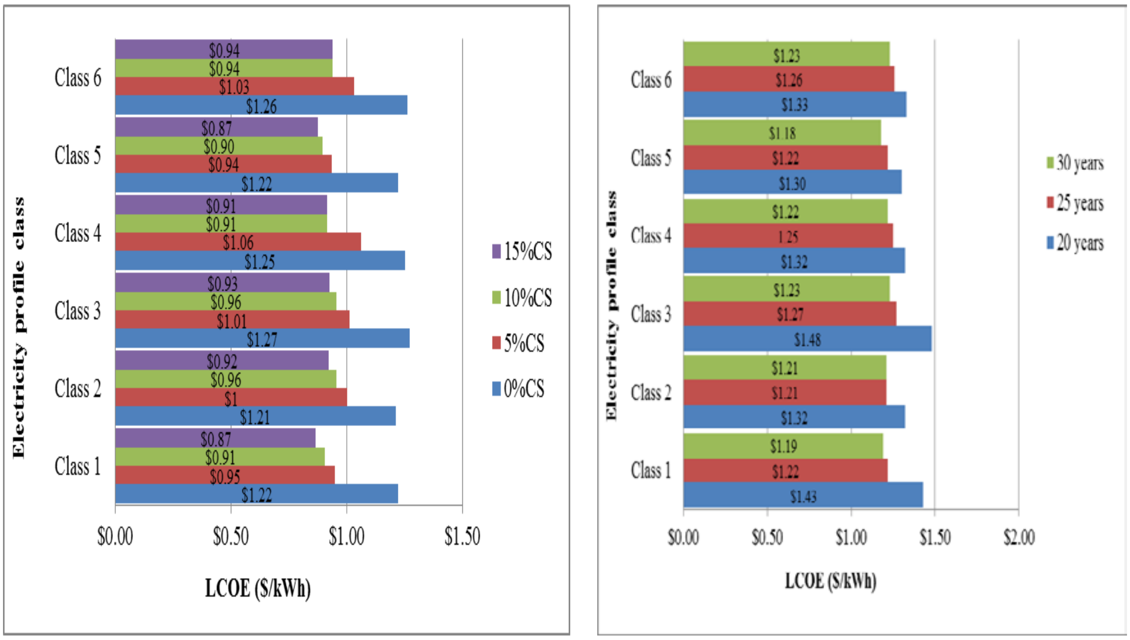

Figure 43: Effect of maximum annual capacity shortage (Left) and PV lifetime (Right) on the LCOE for stand-alone PV system.

The LCOE of the stand-alone PV system for all the six profile classes decreased with a reduction in the minimum battery state of charge as shown in Figure 44.

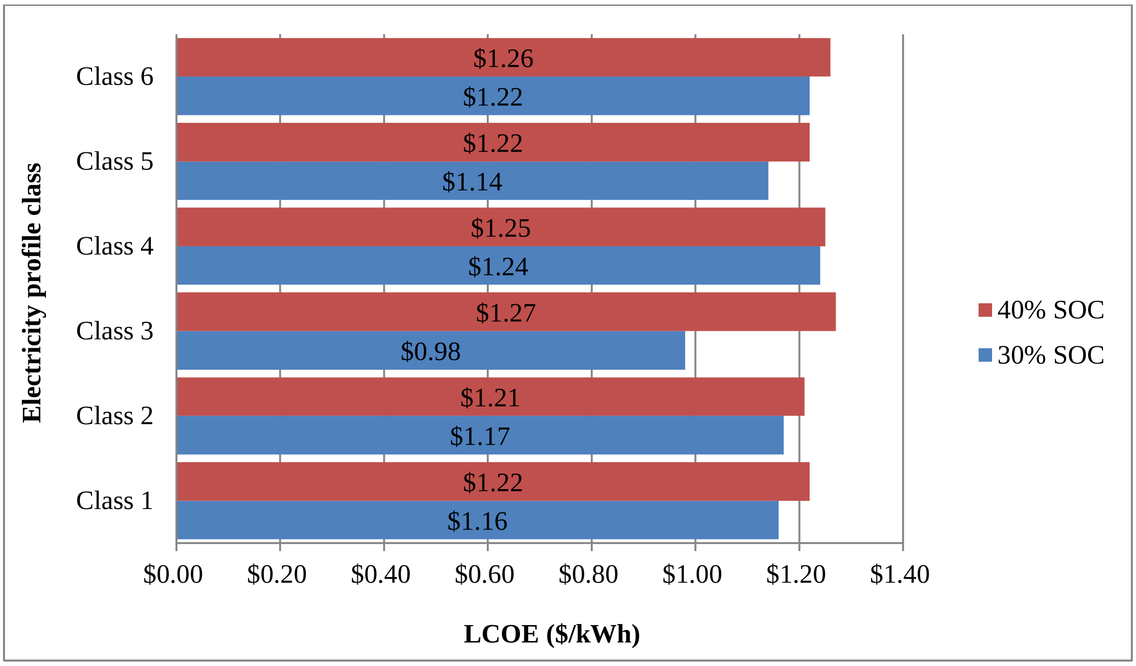

Figure 44: Effect of the minimum battery state of charge on the LCOE for stand-alone PV system.

4.7.2 Solar PV-grid system

This system was designed to operate as a back-up electricity supply to meet the load of the buildings (in Table 29) during a power outage (from 7-9 pm in the months of January to June).

4.7.3 System components specification

The result of the technical specifications of the system components is presented in Table 34.

Table 34: Result of system component specification for back-up PV system for the base case.

Profile class	PV array (kWh)	1 kWh Lead acid battery	Converter (kW)	PV power output (kWh/year)	Unmet load
Class 1	0.3	2	0.5	376.84	0.2
Class 2	1.0	5	0.9	1256.12	0.3
Class 3	0.9	5	0.8	1130.51	0.6
Class 4	0.2	1	0.3	251.22	0.0
Class 5	0.7	3	0.5	879.28	0.4
Class 6	0.5	3	0.5	628.06	0.2

The effect of the maximum annual capacity shortage and minimum battery state of charge on the system components (PV array size and the number of battery) is presented in Figure 45 and Figure 46 respectively.

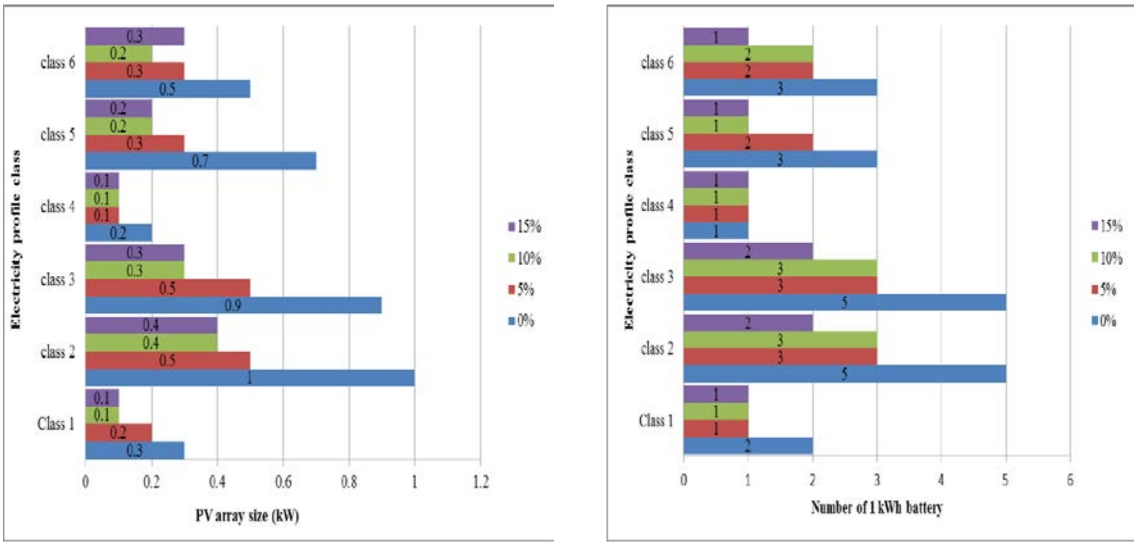

Figure 45: Effect of maximum annual capacity shortage in 5% increments against PV array size (Left) and number of battery (Right) for back-up PV system.

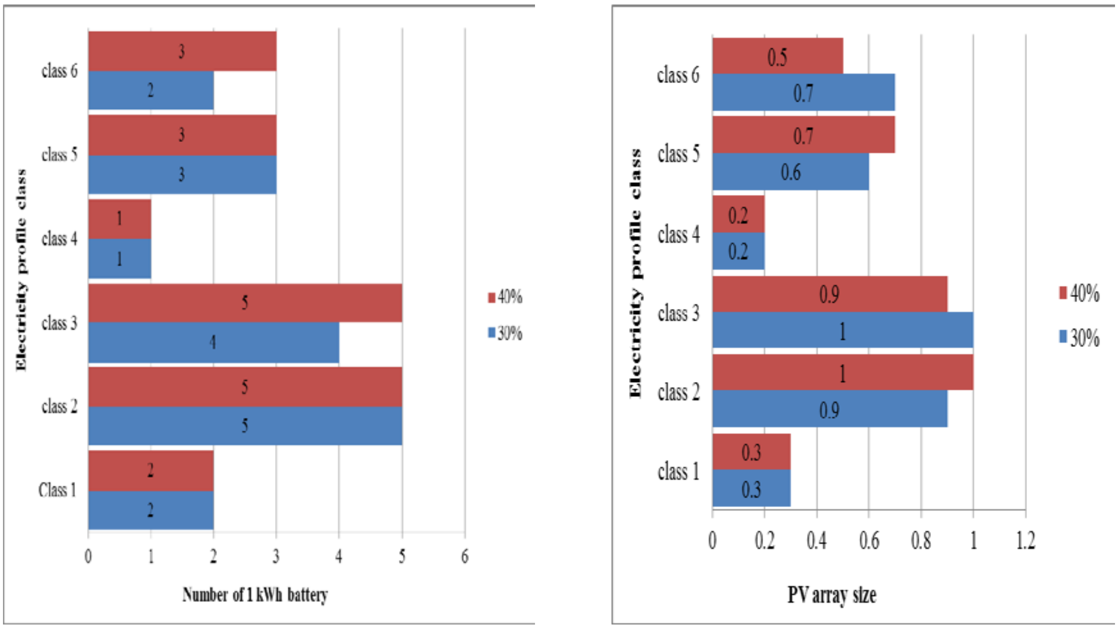

Figure 46: Effect of minimum battery state of charge on battery size (Left) and PV array size (Right) for the back-up PV system.

The monthly electrical output of the system designed for the different electricity profile classes is presented in Figure 47.

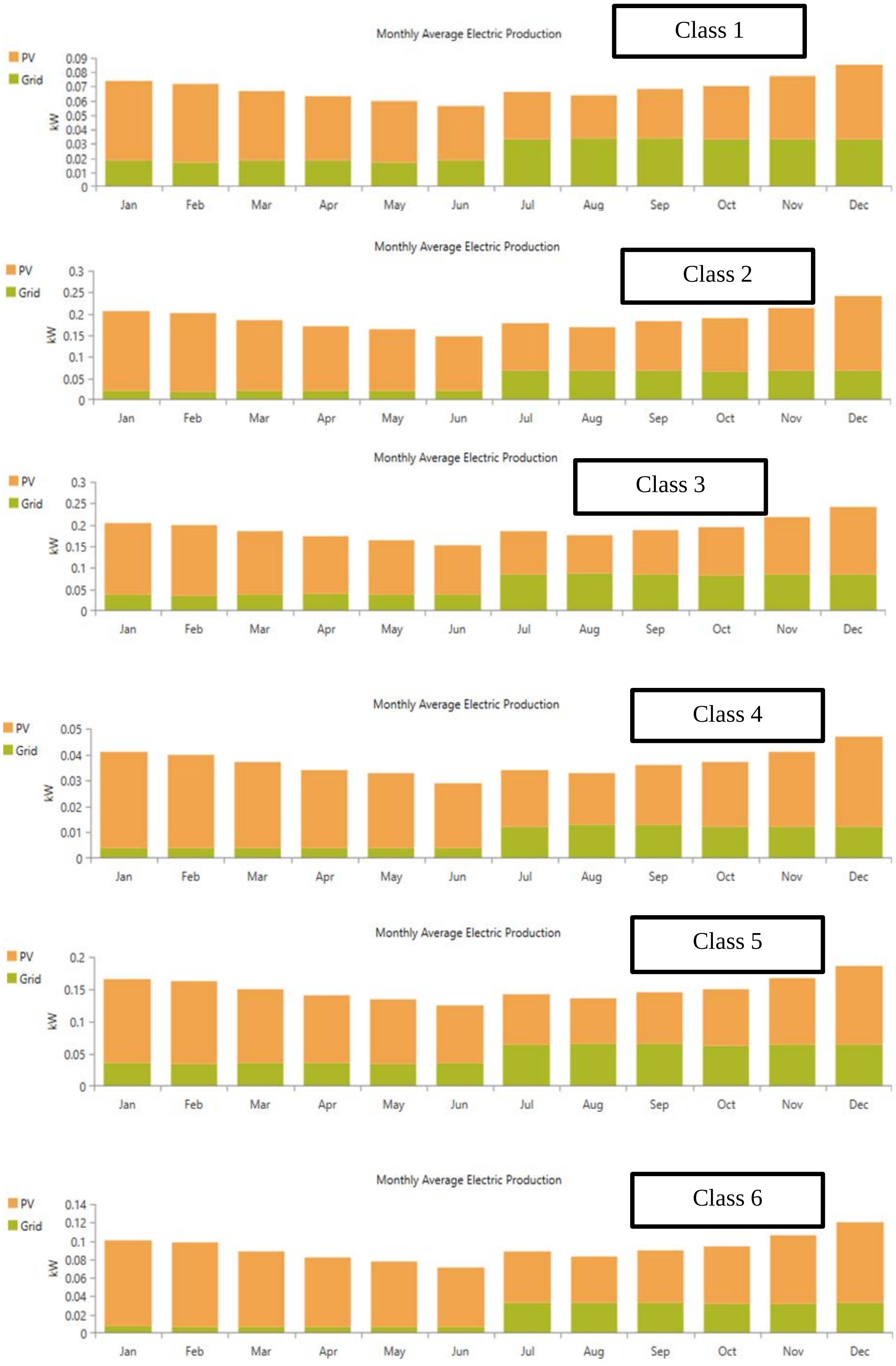

Figure 47: Monthly electricity production of back-up PV system for the different electricity profile classes with the grid outage period shown (from January to June).

Economic analysis

The result of the economic analysis of the base case (5% discount rate, 2% inflation rate, 40% minimum battery state of charge, PV lifetime of 25 years and maximum annual capacity shortage of 0%) for the back-up PV system is presented in Table 35.

Table 35: Economic analysis of grid connected PV system over a 25-year lifetime.

Profile class	Initial capital	LCOE	NPC
Class 1	$1545	$0.58	$3330
Class 2	$4466	$0.81	$8733
Class 3	$4194	$0.658	$8694
Class 4	$922	$0.806	$1779
Class 5	$2945	$0.557	$6022
Class 6	$2395	$0.891	$4747

The effect of the discount rate and inflation rate on the LCOE of the back-up PV system is presented in Figure 48. From Figure 48, increase in the discount rate increases the LCOE of the system while an increase in the inflation rate decreases the system's LCOE. An increase in the maximum annual capacity shortage and lifetime of the PV module reduces the LCOE of the grid back-up PV system for the respective electricity profile classes as shown in Figure 49.

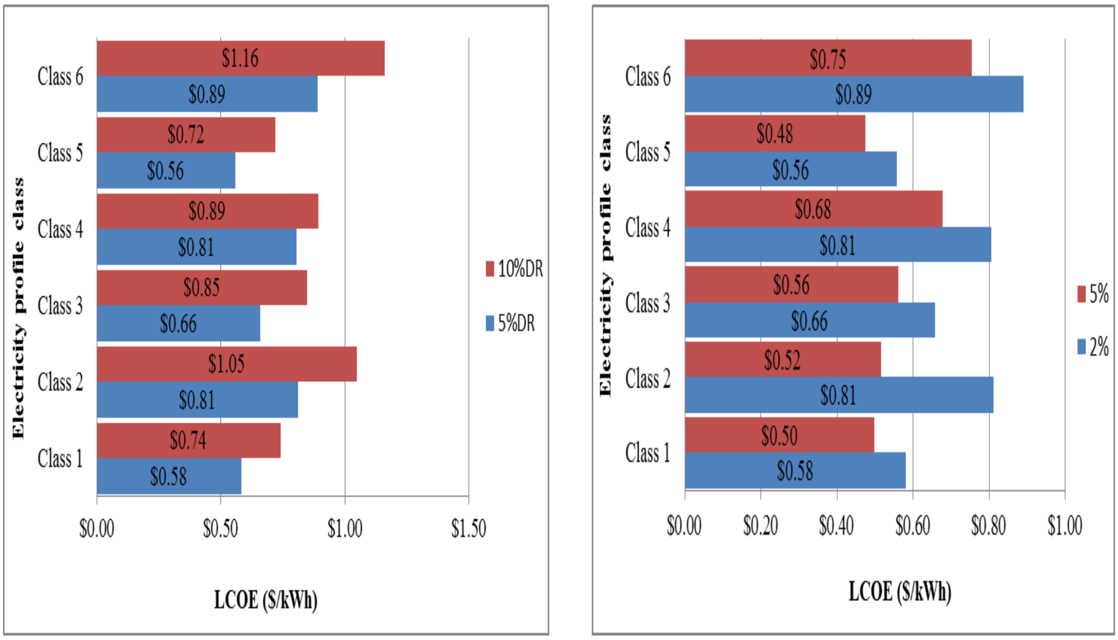

Figure 48: Effect of discount rate (Left) and inflation rate (Right) on the LCOE of the grid back-up PV system.

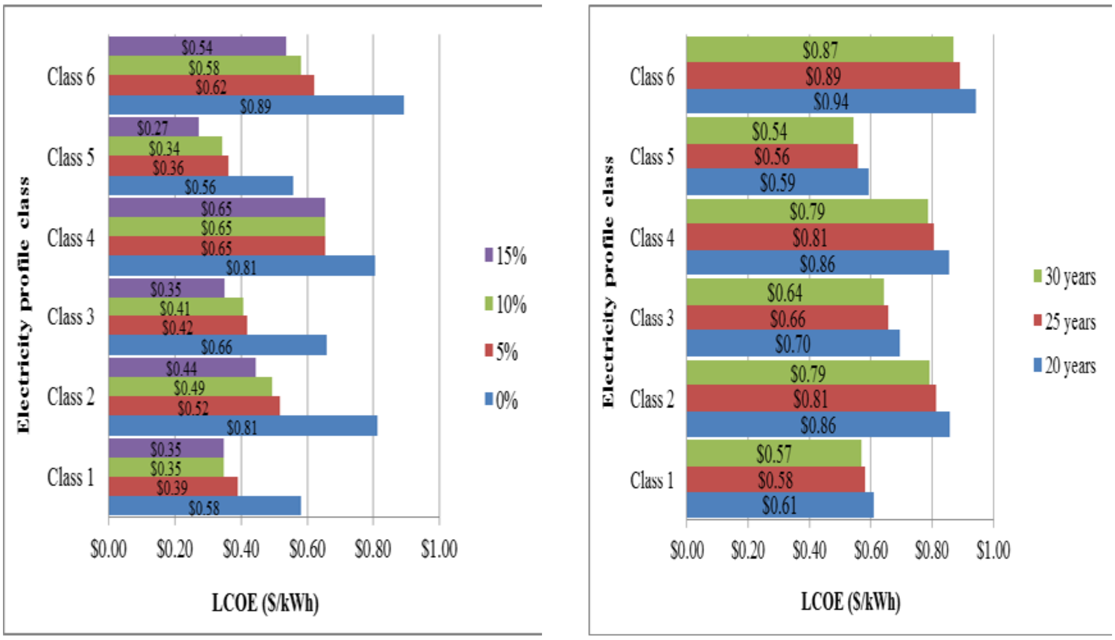

Figure 49: Effect of maximum annual capacity shortage (Left) and PV module lifetime (Right) on the LCOE of the grid back-up PV system.

A decrease in the minimum battery state of charge from 40% to 30% results to decrease in the LCOE of the system for all the classes with the exceptions of class 1 and 4 as shown in Figure 50.

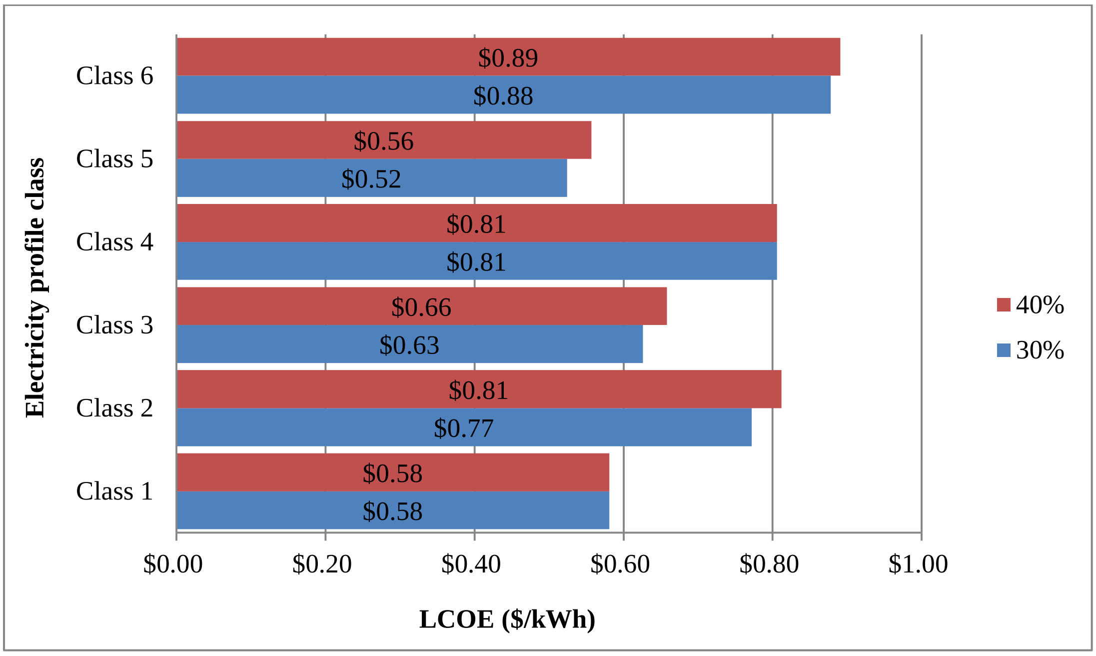

Figure 50: Effect of battery minimum state on the LCOE of grid back-up PV system.

Environmental analysis

The results of the environmental analysis for the use of PV generated electricity for lighting and powering of basic communication appliances in dwellings is presented in Table 36. The annual emission saving per electricity profile class associated with the stand-alone system is higher compared to that of the back-up system.

Table 36: Annual emission reductions (kgCO$_{2\text{-e}}$) associated with the use of PV systems in dwellings.

Profile class	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Stand-alone system	229.29	428.01	527.37	89.17	430.56	211.46
Grid back-up system	46.69	142.62	142.43	25.68	87.61	77.63

4.8 Chapter summary

The outcomes of this study were presented in this chapter. The following results were presented: socio-economic data of respondents, characteristics of the surveyed dwellings, current lighting technologies used in dwellings, economic and environmental potentials of a transition towards efficient lighting in residential buildings including the effect of government policies, electricity time-of-use profiles and the techno-economic modelling of the residential solar PV and its associated environmental benefits.

Chapter 5: Discussion

5.1 Introduction

The first part of the chapter discusses: the lighting technologies employed in households for artificial lighting; factors that influence the adoption of LED; the economic and environmental potential of efficient lighting; factors affecting the load of the surveyed dwellings; and the electricity time-of-use profiles of dwellings. In the second part of the chapter, the results of the techno-economic modelling of the PV systems are discussed. The potential environmental and social benefits of the systems are also discussed in this part of the chapter.

5.2 Lighting technologies employed in households

Pertaining to households' preference to lighting technologies prior to the disclosure of the economic benefits of efficient lighting (Figure 22), a majority of the households preferred CFL followed by LED while incandescent light bulbs were the least preferred. Preference for LED lighting increased among households following a disclosure of information (see Appendix 1: Questionnaire employed in data collection, page 138) on the capital cost of the different lighting technologies and the energy savings and cost reduction associated with LED lighting. In a similar study conducted by Zhou and Bukenya (2016), the authors reported that energy savings information of a technology significantly impacts the willingness of the consumer to pay for that technology. However, only three different types of bulbs: incandescent, CFL and fluorescent tube were employed for lighting in the surveyed buildings. Albeit LED was preferred by more households compared to incandescent bulbs, the former was not used for lighting in any of the surveyed buildings and this could be as a result of the high capital cost of LED which stands as a disincentive for their adoption by dwellings.

The existence of a variation in the use of lighting technologies across the surveyed dwellings as depicted in Figure 23 and their power rating (Figure 24 and Figure 27) is evident that human choice influences the selection and use of a lighting technology in a dwelling. The variation in the use of the lighting technologies and their power rating is supported by the claim of Richardson, Thomson, Infield & Delahunty (2009) which holds that, the number of installed lighting units, the lighting technologies used and their power ratings varies from dwelling to dwelling with the variation accounted by human choice. The fittings could also influence the bulb type used in a dwelling. Tenants in rented apartments with fittings for fluorescent tubes for instance are limited to use just fluorescent tubes for lighting their dwellings. Over 60% of surveyed dwellings use a combination of two or all three of the technologies for lighting as indicated in Figure 23 and this agrees with studies by Enongene, Murray, Holland, Abanda & Manjia (2016) who found out that residential dwellings in Cameroon use a mixture of different lighting technologies for artificial lighting.

In the event of a grid failure, households employ the use of alternative lighting technologies for lighting including: candles, rechargeable lantern, kerosene lamps and solar lanterns as presented in Figure 29. While some households use only a particular alternative lighting source for lighting their dwellings during grid failure, others use a combination of two or more. It is evident that the two main factors based on which households make their choice on a particular alternative lighting technology to use are cost (affordability) and safety. Households that use candles and kerosene lamps do so since they are relatively cheaper and can be purchased in retailed quantities whereas those that employ only the use of cleaner technologies like solar and rechargeable lanterns do so due to safety concerns over fire hazard associated with the use of candle and kerosene lamp. Concern on the safety of candle in particular is not unexpected owing to the casualties on lives and property in the country associated with its use (Tapang, 2014).

5.3 Factors predicting LED adoption

5.3.1 Income and level of education of households

From the regression model (Table 18), all the independent variables had a positive effect on the dependent variables albeit neither of the independent variables statistically significantly predicted the dependent variable (LED adoption) at $p < 0.05$. From the positive relationship that exists between the dependent and the independent variables, it is likely that the higher the income of a household the more financially viable and likelihood of the household to invest in LED lighting. The same trend is expected for the level of education of the household head. The higher the educational level of a household, the greater the likelihood of LED adoption since such individuals are likely to understand the benefits in terms of cost reduction associated with the transition towards efficient lighting. This agrees with studies by Mills and Schleich (2012) who reported that income and education levels are determinants of energy-efficient technology adoption with higher levels of income and education associated with energy-efficient technology adoption.

5.3.2 Market distortions associated with unit type of dwellings

Pertaining to unit type, the regression analysis revealed that single-family detached dwellings are more likely to adopt LED lighting compared to apartment dwellings. This is not unexpected due to the sharing of a common electricity meter which is common among apartment dwellings in the study area unlike single-family detached houses with their own respective electricity meters. Hence, apartment dwellings with a shared electricity meter are not motivated to invest in LED lighting since the monthly electricity bills from the power company is shared among households who tend to be dissatisfied with the amount they are charged to pay. Under such a scenario, dwellings will prefer to use incandescent lamps with low capital but high operating cost for lighting. The sharing of electricity meters therefore stands out as a disincentive for the adoption of LED lighting in dwellings since energy savings which translate into cost reduction is an incentive for household occupants to invest in energy efficient technologies (Stephan & Stephan, 2016).

5.4 Economic potential of efficient lighting adoption

The annual energy consumption of each lamp type based on a daily lighting duration of six hours increases from T1 through to T5 due to an increase in the number of bulbs and decreases to T6. The energy consumption decreases from T5 to T6 because the latter uses less number of incandescent bulbs for lighting than the former. Consequently, the annual electricity cost for lighting associated with each technology follows the same trend as the energy consumption. The use of a lesser number of incandescent lamp for lighting in the T6 households compared to T5 could be attributed to human choice as depicted by Richardson et al. (2009).

A switch from incandescent lighting to CFL and LED would reduce the annual electricity bill by 66.8% and 83% respectively (Table 22). This reduction in power consumption and consequently electricity bills corresponds with the findings of Aman, Jasmon, Mokhlis & Bakar (2013) which holds that the use of LED is not only beneficial for utility, but for consumers as well. The transition towards LED yields the greatest energy cost reduction since the wattage of the LED bulb is lower than that of CFL and incandescent.

The NPV of LED is higher than that of CFL per building class (Table 23), implying that transition to LED appears to be a more profitable option. However, transition towards LED lighting will be profitable to single-detached family dwellings who pays their electricity bills directly to the power company and is unlikely to be the case for apartment dwellings that share a common electricity meter and pay their bills to the landlord or a designated individual. The IRR for CFL and LED both exceeded the discount rate employed in the calculation of the NPV which according to the Commonwealth of Australia (2006) depicts that both projects are efficient. The simple payback period for CFL (two months) is lower than that of LED (23 months), implying that it will take a relatively short time for the investment cost of CFL to be recovered. The lower payback period of CFL compared to LED could be explained by the fact that the former has a lower capital cost (Khorasanizadeh et al., 2015) compared to the latter. The benefit cost ratio (BCR) for CFL and LED were obtained as 1.84 and 3.18 respectively. The higher BCR of LED implies that it yields greater benefits irrespective of its higher capital cost. According to Chueco et al. (2015), these benefits of LED are associated with its low energy consumption and long useful lifetime.

5.4.1 Effect of lighting duration, discount rate and lifetime of lamp on the economic potential of efficient lighting

The NPV of CFL and LED increases with an increase in the duration of artificial lighting as presented in Figure 35 and Figure 36. This is expected since more energy savings are accrued when efficient lighting technologies are used for a longer duration than for a shorter one. An increase in the BCR and a decrease in the PBP of CFL and LED associated with an increase in the lighting duration (Figure 33) implies that, transition from incandescent to more efficient lighting technologies is more beneficial for longer lighting durations. Hence, it would be more beneficial for instance, for dwellings to replace an incandescent lamp used for longer durations such as security light, with LED.

The NPV and BCR associated with transition from incandescent to CFL and LED lighting decreased with an increase in the discount rate (Figure 35 and Figure 36). This is not uncommon since the discount rate is inversely proportional to the NPV, implying that a higher discount rate will reduce the present value of future cash flows. Increase in the discount rate results in the benefits of efficient lighting which occurs over the 22-year period (Starting from year one) to be more heavily discounted, culminating in a reduction in the present worth of the benefits. Outside the operating cost of both CFL and LED, which is discounted, their first capital investment occurs in year zero, which remains undiscounted. This implies that an increase in the discount rate has a relatively smaller influence on the costs of CFL and LED over the lifetime of the project compared to the benefits. Hence, this explains why an increase in the discount rate culminates in a decrease in the BCR. From Figure 36, increase in the discount rate has a greater effect on LED compared to CFL. Again, this is explained by the fact that the capital investment cost for LED occurs once (year zero) over the entire project lifetime which is undiscounted whereas for CFL with a shorter lifetime, after the investment in year zero, the technology is purchased 11 more times during the 22-year period for which the cost is discounted. This discounting reduces the present value of the cost associated with the CFL compared to LED. Hence, both the benefits and costs of the CFL are heavily discounted resulting to only a slight decrease in the BCR with an increase in the discount rate unlike LED. The IRR and the payback period remained unchanged with an increase in the discount rate since they both do not depend on the discount rate. As revealed by the sensitivity analysis performed on the lighting duration (Table 24 and Table 25), an increase in the daily lighting duration decreases the payback period and increases the NPV, IRR and BCR implying that an increase in the daily lighting duration increases the economic benefit associated with a transition towards efficient lighting.

The NPV of substituting incandescent lighting with LED per building class is directly proportional to the lifetime of the LED lamp. An increase in the lifetime of the LED technology implies that more benefits will be accrued to the technology since it will last longer and hence, an increase in its NPV (Figure 37). The BCR of replacing incandescent lamp with LED also increased with an increase in the lifetime of the technology. Again, this is because more benefits will be obtained for a longer lifetime of the technology for the same capital cost of the technology which occurs once at the start of the project (year zero). The IRR and the payback period are not influenced by the lifetime of technology and for this reason, they remain unchanged.

5.4.2 Effect of government subsidy on return on investment of LED

Despite the long term economic benefits associated with the use of the LED technology in residential dwellings, the high capital cost of the technology could stand as a disincentive for its adoption. The potential outcome of different rates of government subsidy (on LED purchase cost) on the return of investment of LED in the first year of adoption revealed an increase in the return on investment with an increase in the subsidy rate by the government for all three daily artificial lighting durations (four, six and eight hours). This is expected since an increase in the subsidy rate on the LED technology by the government implies that households will spend less to purchase the technology to achieve the same energy saving and hence, a higher return. The return on investment as well increases with an increase in the lighting duration since LED lighting is more profitable for longer lighting durations than for shorter ones. A return on investment that exceeds one depicts that the investment or project is profitable and worthwhile. For the six and eight hours lighting duration scenarios, with a government subsidy of 10% and 5% respectively on the LED capital cost within the first year (Figure 38), consumers would experience a return on their investment since the ROI is equal to one for the six hours duration and greater than one for the 8 hours duration . For the four hours lighting scenario, consumers would be able to experience a return within the first year if the government of Cameroon could subsidize the capital cost of LED by 30%. This subsidy to be paid by the government would translate into reduced electricity consumption in the residential sector and GHG emission savings (Khorasanizadeh et al., 2015).

5.5 Environmental Potential of Efficient lighting adoption

The GHG emission savings associated with the transition towards efficient lighting increased from T1 to T5 and decreased to T6 (Table 27). This trend is observed because the number of incandescent bulbs employed in lighting and consequently, energy consumption increases from T1 through to T5 and decreases to T6. The environmental benefits associated with LED is greater than that of CFL and this is in agreement with the study of Principi and Fioretti (2014) who assessed the life cycle environmental burden of CFL and LED and concluded that LED has a significant impact on reducing carbon footprints as a result of its higher energy efficiency during its operational phase.

5.6 Factors affecting the load of surveyed dwellings

The regression model adjusted R^2 value of 0.372 implies that the independent variables (unit type, building class, income of household head and level of education of household head) explains 37.2% of the variability that exists in the dependent variable (load of building). With the exception of the unit type, all the independent variables had a positive relationship with the dependent variables (Table 28). This implies that an increase in the independent variable results to an increase in the electric load of the building. For the case of the unit type, electric load of apartment dwellings is higher compared to those of single detached family dwelling. This could be explained by the fact that apartment dwellings share a common electricity metre with the electricity bill at the end of each month being shared among the tenants which in most cases does not reflect their actual consumption. Hence, there is no rationale for apartment dwellings to engage in energy saving measures which culminates in their high electric load as opposed to single family detached dwellings with their own respective electricity meters.

Statistically, the independent variables did not significantly predict the dependent variable at $P < 0.05$ with the exception of the building class whose influence on the electric load of the dwellings was statistically significant. Hence, the electric load increases with an increase in the building class - a determinant of the size of buildings. This finding is consistent with that of Li, Hong & Yan (2014) who found that building size is a determinant factor that influences the energy performance of buildings.

5.7 Time-of-use electricity profile classes

The time-of-use electricity profiles of the dwellings were classified into six major classes based on the shape of the profiles (Figure 40). The grouping of the electricity profiles of the dwellings in this study agrees with the approach used by Stoecklein et al. (2001) in the classification of 239 profiles into six main classes. The mean electricity profile per class is characterised by variation within the day; with high energy use in the evening (7-10 pm) and low energy use in the morning (midnight to 7 am). The high energy use in the evening could be explained by the fact that lights are turned on during this period (after sunset) for artificial lighting. From midnight to 7 am, most lights in the dwellings are likely to be turned off while household members are asleep and this could explain why electricity usage is low during this period. Electricity use was lowest between 8 am and 4 pm and this is in consistent with the findings of Manjia et al. (2015) who found out that electricity load of residential buildings in Yaounde, Cameroon was at its lowest between 8 am and 11 am. This period during which electricity use is lowest coincides with the time household occupants are likely to have left their respective homes.

Pertaining to the prominent electricity TOU profile class to which the different building class belongs, the below list indicates the different TOU electricity profile class to which the majority of each building class occur. The majority of:

- T1 and T2 buildings belong to class 4 electricity TOU profile class;
- T3 buildings belong to class 6 electricity TOU profile class;
- T4 buildings belong to class 1 electricity TOU profile class;
- T5 buildings belong to class 2 electricity TOU profile class;
- T6 buildings belong to class 3 electricity TOU profile class; and
- T7 buildings belong class 5 electricity TOU profile class (Table 30).

T1 and T2 belong to the same TOU profile (class 4) and this could be explained by the fact that both building classes do not differ a lot in terms of building characteristics. Hence, they are likely to have similar types and number of appliances. The daily load (in kWh) increases in the order:

- Class 4 (T1 and T2) < class 6 (T3);
- Class 6 (T3) < class 1 (T4);
- Class 1 (T4) < class 2 (T5);
- Class 2 (T5) < class 5 (T7); and
- Class 5 (T7) < class 3 (T6).

With the exception of T7, the increasing trend observed in the daily load of the electricity TOU profile class corroborates that the electricity load of buildings increases with increase in building size (from T1 to T5). The lower daily load observed for T7 compared to T6 could be likely due to the fact that the two T7 buildings surveyed used more efficient lighting technologies that consumed lesser energy compared to those employed in the T6 buildings.

5.8 Techno-economic modelling of residential photo-voltaic system

5.8.1 Stand-alone and back-up PV system

The technical specification of the components for the designed stand-alone PV system and back-up PV system varies among the different profile classes (Table 31 and Table 34). This variation is expected since the electricity load for the different profile classes are not the same. The variation in the system components also explains the difference in the monthly average output of the systems designed for the different electricity profile classes.

An increase in the maximum annual capacity shortage decreases the size of the PV array and/or battery bank for the stand-alone and PV-grid back-up system. This is as a result of the fact that increasing the capacity shortage increases the acceptable amount of the load that can be unmet by the system and hence, lesser energy is required from the system to meet the load. Conversely, a decrease in the minimum battery state of charge reduces the size of the PV array and/or battery. This effect of decreasing minimum battery state of charge on the system components can be explained by the fact that more energy from the battery bank is made available for use as the minimum battery state of charge decreases.

The initial capital of the systems ranged from \$3772 to \$9017 for the stand-alone system and from \$922 to \$4466 for the PV back-up system. Comparing the systems with the lowest capital costs (\$3772 and \$922) to the monthly income of the surveyed households (Table 15), implies that households with the lowest monthly income (<\$82.84) will require 45.5 and 11 months of their income in order to possess the capital cost of the stand-alone and PV back-up system respectively. Similarly, surveyed households in the highest income class will require: 5 to 6.5 months of their income so as to afford the initial capital of the stand-alone system; and 1.3 to 1.5 months of their income to afford the initial capital of the PV-grid back-up system. The LCOE generated by the systems (Table 33 and Table 35) ranges from \$1.22 to \$1.66/kWh for the stand-alone system and from \$0.58 to \$0.981/kWh for the back-up system. These values are quite high compared to the cost of electricity (\$0.12/kWh) supplied from the national grid in Cameroon. Hence, the PV electricity generated from the systems designed for meeting the lighting and basic communication appliances load of residential buildings is not competitive to that from the national grid as it is 10 to 13 times more expensive (for stand-alone system) and four to eight times more expensive for the designed back-up system. The range of the LCOE of the PV systems obtained in this study is high compared to:

- $0.27/kWh obtained by Ondraczek (2014) for Kenya;
- $0.14/kWh (PKR 14.8 kWh^{-1}) obtained for Pakistan (Abdul and Anjum, 2015);
- $0.17 (0.7 R$) to $0.23 /kWh (R$ 0.94) obtained for Brazil (Miranda, Szklo & Schaeffer, 2015); and
- $0.14/kWh (Rs. 9.56 kWh^{-1}) obtained for Bangalore, India (Ghosh et al., 2015).

It is therefore evident that the LCOE generated from solar PV is location specific. As opined by Mbaka et al. (2010), the high unit cost of PV generated electricity in Cameroon could be associated to the high cost of solar PV modules.

5.8.2 Sensitivity analysis

An increase in the discount rate from 5 to 10% increased the LCOE of all the systems (Figure 21 and Figure 29). This could be explained by the fact that, the present value of future cash flows of the project is decreased as the discount rate increases. The same increasing trend of the LCOE was observed for an increase in the discount rate in the study of Ayompe and Duffy (2014). Conversely, an increase in the inflation rate from 2 to 5% decreases the LCOE of the systems. This is because as the inflation rate increases, the present value of the future cash flows increases. Also, an increase in the maximum annual capacity shortage (Figure 43 and Figure 49) reduces the LCOE since the accepted amount of load to be unmet by the system increases with increasing capacity shortage, translating into a PV array and battery bank of lower capacity. From Figure 43 and Figure 49, increase in PV lifetime reduces the LCOE of the systems. This is expected since increase in the PV lifetime implies that more energy will be generated by the system for the same initial capital cost and this explains a decrease in the LCOE. A decrease in the minimum battery state of charge as well decreases the LCOE of the systems (Figure 44 and Figure 50). This is explained as a result of a decrease in the minimum battery state of charge which implies that the batteries in the battery bank can be discharged to a greater depth and hence less number of batteries will be needed to supply the required energy to the load. However, the LCOE for profile class one and four of the system designed as a back-up to the grid (Figure 50) remained unchanged with a decrease in the minimum battery state of charge. This is as a result of the fact that a change in the minimum battery state of charge did not change the size of the PV system components for profile class one and four. It is likely that the batteries in the systems designed for class one and four were not discharged as low as 40% in the base case scenario and hence decreasing the minimum SOC to 30% will not make any difference.

5.8.3 Comparison of stand-alone PV system and PV-grid system

The size of the system components (with the exception of the converter) for the stand-alone system is greater than that of the designed back-up PV system per class of electricity profile. This is explained by the fact that unlike the stand-alone system, the back-up system is designed to meet the load of the buildings only during periods of grid outages (7-9 pm) from the month of January to June which coincides with the period of the year with regular power outages in Cameroon (Nfah & Ngundam, 2009). Thus, the reason why the initial capital and the LCOE of the back-up system per profile class are lower compared to that of the stand-alone system.

5.8.4 Potential environmental and social benefits of the PV system

The annual GHG emission saving associated with the integration and use of PV systems in residential dwellings for lighting and powering of basic communication appliances (Table 36) ranges from: 89.17 to 527.37 $kgCO_{2\text{-}e}$ for the stand-alone system; and from 46.69 to 142.62 $kgCO_{2\text{-}e}$ for the system designed as a back-up to the grid. The avoided emission for the stand-alone system is higher than that obtained for the back-up system. This is not uncommon since as opposed to the stand-alone system designed as the sole source of energy to the buildings, the back-up system was designed to meet the daily load of the dwellings only from 7 to 9 pm for a duration of six months (January to June) while the dwellings were meant to rely on electricity from the grid for the rest of the day.

The majority of the surveyed dwellings had students and or pupils as part of their inhabitants. Hence, it is likely that these students/pupils engage in studies after sunset. During periods of grid outages which is regular in the course of the dry season in the country, the use of alternative lighting sources like candles and/or kerosene lamp for performing night tasks is a common practice in dwellings. Using electricity generated from the PV system will enable students/pupils to be able to conduct evening studies under favourable conditions in the event of an outage. Also, activities of other household members like food preparation by women will as well be uninterrupted during grid outage after sunset as the energy generated by the PV system will be used to provide lighting.

The use of PV generated electricity instead of kerosene lamps and candles will mitigate the fire hazard associated with the use of kerosene lamps and candles which does not only culminate in the loss of property but human lives as well (Tapang, 2014). Also, the use of electricity generated from the PV for lighting will likely yield health benefits to the inhabitants of the dwellings since candles and kerosene lamps are known to release toxic substances that causes respiratory diseases (Choi et al., 2015; Lam, Smith, Gauthier & Bates (2012); Mills, 2012; & Pokhrel et al., 2010).

5.9 Chapter summary

The results of the study were discussed in this chapter. The first part of the discussion focussed on lighting in dwellings including the current technologies used, adoption of efficient lighting and its associated economic and environmental potentials, and the factors that affects the load of dwellings. The second part of the discussion dwelled on the techno-economic modelling of the residential PV system for meeting the load of the dwellings and the associated environmental and social benefits.

Chapter 6: Conclusion and Recommendations

6.1 Introduction

This is the concluding chapter of this study. The first part of the chapter is focused on the conclusion of the research findings while the second part is focused on the recommendations emanating from the study.

6.2 Conclusion

- The average daily load for lighting and basic communication appliances for dwellings in Buea ranges from 0.35 to 2.07 kWh.

The time-of-use electricity profiles of the dwellings were classified into six major classes. The mean electricity profile per class is characterised by variation within the day; with high energy use in the evening (7-10 pm) and low energy use in the morning (midnight to 7 am) while electricity use is lowest between 8 am and 11 am. The electric load (dependent variable) of dwellings is positively influenced by the building class, income on household head and level of education of household head while it is negatively influenced by the unit type (apartment or detached building). All the dependent variables put together influences 37.2% of the variability that exists in the dependent variable. Of the independent variables, only the building class statistically significantly predicts the dependent variable at $P < 0.05$.

- The technical specification of the components designed to meet the load of the dwellings at 0% capacity shortage and 40% minimum battery SOC are in the order of the following range: 0.3 to 1.9 kW of PV array, 2 to 12 one kWh of lead acid battery and 0.2 to 0.9 kW converter for the stand-alone system; and 0.2 to 0.9 kW of PV array, 1 to 5 one kWh lead acid battery, and 0.3 to 0.9 kW converter for the system designed as a back-up. The initial capital of the systems ranges from \$3772 to \$9017 for the stand-alone system and from \$922 to \$4466 for the back-up system while the LCOE generated by the systems ranges from \$1.22 to \$1.66/kWh for the stand-alone system and from \$0.58 to \$0.981/kWh for the back-up system.

The back-up system is a more economically viable option with a lower initial capital and LCOE compared to the stand-alone option. The sensitivity analysis revealed an increase in the LCOE of the systems with an increase in the discount rate while the LCOE decreased with an increase in the annual capacity shortage and inflation rate and a decrease in the minimum battery SOC. From a technical perspective, PV systems are viable for providing energy to residential buildings in Buea, Cameroon for lighting and powering of basic communication appliances like radio and mobile phone charging. Conversely, the use of PV systems as an energy source to residential dwellings in Buea is not economically viable. The LCOE generated from the systems designed for meeting the lighting and basic communication appliances load of residential buildings is not competitive to that from the national grid as it is 10 to 13 times more expensive (for stand-alone system) and four to eight times more expensive for the designed back-up system. Albeit the economic unviability of the systems, the integration and use of PV systems in residential dwellings in Buea during grid outages presents potential social benefits through its role in: enabling students/pupils to study under conducive conditions; reduction of risks of respiratory diseases associated with indoor air pollution caused by the use of candles and kerosene lamps; and mitigating fire hazards in dwellings which is posed by the use of alternative lighting technologies like candles and kerosene lamps. The use of PV generated electricity for basic communication appliances and lighting in residential dwellings in Buea, Cameroon has potential of mitigating climate change through the avoidance of an annual emission (per building) in the range of 89.17 to 527.37 kgCO_{2-e} for the stand-alone system and 46.69 to 142.62 kgCO_{2-e} for the system designed as a back-up to the grid.

- A transition from incandescent lighting to CFL and LED have potential of culminating in a reduction of dwellings’ annual electricity bill for lighting by 66.8% and 83% respectively which is a win-win situation for both the utility and the consumers.

The sharing of a common electricity meter among apartment dwellings is a disincentive for households to adopt LED for lighting. Single detached family dwellings are more likely to adopt LED lighting compared to apartment dwellings. The NPV for substituting incandescent bulbs with LED is higher per building class compared to CFL and the BCR for transition towards efficient lighting for a daily lighting duration of six hours is 1.84 and 3.18 for CFL and LED respectively, corroborating that a transition to LED yield greater benefits. However, the simple payback period for CFL is lower than that of LED. The environmental benefits in terms of avoided emissions associated with the transition towards efficient lighting in dwellings depends on the number and wattage of incandescent lamps replaced by more efficient lighting technologies. The annual avoided GHG emission associated with a switch from incandescent bulbs to CFL for a daily lighting duration of six hours ranges from 75.34 (T1 building class) to 452.02 $kgCO_{2-e}$ (T5 building class) while that associated with a switch from incandescent to LED lighting ranges from 94.11 (T1 building class) to 562.02 $kgCO_{2-e}$ (T5 building class). Hence, transition towards efficient lighting in the residential sector has potential for climate change mitigation.

An increase in the discount rate from 5% to 10% decreased the NPV and BCR associated with the transition from incandescent to CFL and LED lighting per building class. The NPV and BCR of switching from incandescent lamp to LED is directly proportional to the lifetime of the LED technology. More benefits will be generated from the LED technology with an increase in its lifetime. The NPV for the four, six and eight hours daily lighting duration ranges from $47 to $282.02, $60.02 to $360.14, and $70.28 to $421.66 respectively for CFL. The NPV for the LED ranges from $89.14 to $370.37, $112.85 to $677.08, and $131.56 to $789.36 for the four, six and eight hours daily lighting duration respectively. The BCR for four, six and eight hours daily lighting duration is: 1.77, 1.84 and 1.88 respectively for CFL; and 2.58, 3.18 and 3.33 respectively for LED. The PBP for four, six and eight hours daily lighting duration is: three months, two months and one and a half months respectively for CFL; and 34 months, 23 months and 18 months respectively for LED. The IRR for CFL is 406%, 621% and 835% for the four, six and eight hours of daily lighting duration respectively while that for LED is 35%, 53% and 70% for the four, six and eight hours lighting duration respectively. Hence, the transition towards efficient lighting is more economically beneficial for longer duration of lighting than for shorter ones.

- The implementation of favourable policies (subsidy provision) by the government of Cameroon has potential to positively influence the adoption of LED in the residential sector of the country.

The introduction of a subsidy on the capital cost of LED by the government will affect the return on investment of the technology. An increase in the rate of government subsidy on LED capital cost increases the return on investment of LED in its first year of adoption. A government subsidy of 30%, 10% and 5% on LED will enable consumers to experience a return on their investment within the first year of adoption if the LED is used daily for four hours, six hours or eight hours respectively.

6.3 Recommendations

Based on the outcome of this study, the following recommendations are made:

1. Further investigations should be carried out to determine a mechanism or framework that will generate incentives for the adoption of efficient lighting among households with a shared electricity meter, since apartment dwellings with a common electricity meter lack the motivation and economic incentives that constitutes a prerequisite for the adoption of energy efficient technologies.

2. The government of Cameroon alongside other stakeholders in the electricity sector like the power company among others should consider organizing a nationwide campaign and sensitization on the economic benefits associated with the transition towards efficient lighting particularly LED. Such campaigns could take the form of adverts over the national and local radio and television stations. This will likely go a long way to inform dwellings' adoption of LED for lighting.

3. The formulation and implementation of appropriate policies by the government of Cameroon pertaining to renewable and energy efficient technologies will create an enabling environment that could spur their deployment and uptake within the nation. Such policies could be in the form of reduction of import duties or the provision of subsidy on solar PV and LED among other technologies.

4. Further research on the adoption of efficient lighting (LED) in residential dwellings that entails a lighting demonstration exercise using LED light bulbs should be conducted in the country.

6.4 Chapter summary

This is the concluding chapter of this thesis. The first part of this chapter draws conclusion from the findings of the study while the second part of the chapter proposes recommendations and the way forward.

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APPENDICES

Appendix 1: Questionnaire employed in data collection

MASSEY
UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

Questionnaire for inventory of energy appliances (bulbs and other communication appliances) used in dwellings in Buea.

Introduction

I am Kevin Enongene studying a Master’s degree in Environmental Management at Massey University, New Zealand. I am currently carrying out a research on the technical feasibility for the use of solar photo-voltaic system in providing energy for residential lighting and powering of basic communication appliances (radio, mobile phone chargers, etc.) in Buea. You are humbly invited to participate in this research by providing your views by completing this questionnaire. Your contribution is significant and will assist in completion of this research. Any information provided will only be used for academic purposes. Participation in this study is voluntary and personal information of participants will not be published. All materials will be deposited at Massey University, Palmerston North.

Section 1: Socio-economic characteristics of Household

1. Name of Respondent (Optional):
2. Street and House address:
3. Sex:

☐ Male

☐ Female

4. Marital status:

☐ Single

☐ Married

☐ Widow/widower

☐ Divorced

5. Occupation/profession of household head :

☐ Farmer

☐ Business woman/man

☐ Retiree

☐ Civil servant

☐ Others……………………………………

6. Level of education of household head :

☐ No formal education

☐ Primary

☐Secondary

☐ National Diploma

☐ Higher National Diploma

☐ Bachelor Degree

☐ Masters

☐ PhD

☐ Professor

7. Monthly income (CFA) of household :

☐ Less than 50,000

☐ 50,001-125,000

☐ 125,001-200,000

☐200,001-275,000

☐275,001-350,000

☐ 350,001- 425,000

☐ < 425,001

8. Household size:
   Number of Males _________, Number of females_____________
9. Please provide the number of your household member(s) that falls within the following age ranges:
   Under 15 ________
   16-25_______
   26-35_______
   36-45_______
   Over 46_________

Section 2: Household Characteristics (please tick a box as appropriate)

10. Is there a student(s)/pupil(s) in your household?

☐ Yes

☐ No

11. Is there any member(s) of your household who stays at home during weekdays between 8am-5pm?

☐ Yes

☐ No

12. Which of the two categories below best describes your dwelling? (Please tick the appropriate box)

i. ☐ Apartment

Number of bedrooms:_____

Number of lounge:_______

Number of toilets ______

Number of dining room:_____

Number of Kitchen____

ii. ☐Single family house

Number of bedrooms:_____

Number of lounge:____

Number of toilets ______

Number of dining room:_________

Number of Kitchen________

13. Taking into consideration the quality of light produced, which of the following lighting technology will you prefer for your household?

i. Light emitting diode (LED) ☐

ii. Compact fluorescent lamp ☐

iii. Incandescent bulb ☐

14. Taking into consideration the cost (see appendix 1 on page 8), which of the following lighting technology will you prefer for your household?

i. Light emitting diode (LED) ☐

ii. Compact fluorescent lamp ☐

iii. Incandescent bulb ☐

15. Which of the following does your household use for lighting during a power outage?

i. Candle ☐

ii. Kerosene lamps ☐

iii. Rechargeable lanterns ☐

iv. Others:_______________________________

16. For each of the substitutes to electric lighting applicable to your household in question 12 , what is the average weekly quantity consumed by your household?

i. Candle**:** average weekly quantity (number of candles) consumed ___

ii. Kerosene Lamps: average weekly quantity of kerosene (in litres) consumed ____

17. Would your household consider the use of a solar PV as a backup for lighting during power outage?

☐ Yes

☐ No

18. In the event of a power outage, which will you prefer for lighting your household?

☐ 12V light bulbs

☐ 240V light bulbs

Section 3: Household current lighting system

Please provide information on the existing bulbs used for lighting in your household alongside other basic communication appliances (like radios and mobile phone chargers)

Appliance (radio, mobile phone chargers, bulbs e.g. fluorescent, incandescent, etc.)	**Power rating (W)**	**Quantity (Number)**	**Model (if power rating is unavailable)**

Section 4: Household energy consumption pattern

For each of the appliance used in your household (in section 3) and for the different days of the week, please provide information on the duration of hours used and the period of the day during which it is used. Please see the example below

Example: Last Monday, Jonathan’s security light (fluorescent bulb) was on from 6 pm to midnight and he charged his mobile phone from 8 pm to 10 pm.

Appliance	**Duration of use (hours)**	**Time of the day**																							
		6am	**7**	**8**	**9**	**10**	**11**	**12**	**1pm**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**00**	**1am**	**2**	**3**	**4**	**5**
Fluorescent bulb	6													◄						►					
Mobile phone charger	**2**															◄		►							

Monday

Appliance	**Duration of use (hours)**	**Time of the day**																							
		6am	**7**	**8**	**9**	**10**	**11**	**12**	**1pm**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**00**	**1am**	**2**	**3**	**4**	**5**

Tuesday

Appliance	**Duration of use (hours)**	**Time of the day**																							
		6am	**7**	**8**	**9**	**10**	**11**	**12**	**1pm**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**00**	**1am**	**2**	**3**	**4**	**5**

Appliance	Duration of use (hours)	Time of the day																							
		6am	7	8	9	10	11	12	1pm	2	3	4	5	6	7	8	9	10	11	00	1am	2	3	4	5

Wednesday

Appliance	Duration of use (hours)	Time of the day																							
		6am	7	8	9	10	11	12	1pm	2	3	4	5	6	7	8	9	10	11	00	1am	2	3	4	5

Thursday

Appliance	Duration of use (hours)	Time of the day																							
		6am	7	8	9	10	11	12	1pm	2	3	4	5	6	7	8	9	10	11	00	1am	2	3	4	5

Friday

Appliance	Duration of use (hours)	Time of the day																							
		6am	7	8	9	10	11	12	1pm	2	3	4	5	6	7	8	9	10	11	00	1am	2	3	4	5

Saturday

Appliance	Duration of use (hours)	Time of the day																							
		6am	7	8	9	10	11	12	1pm	2	3	4	5	6	7	8	9	10	11	00	1am	2	3	4	5

Sunday

Appliance	Duration of use (hours)	Time of the day																							
		6am	7	8	9	10	11	12	1pm	2	3	4	5	6	7	8	9	10	11	00	1am	2	3	4	5

Appliance	**Duration of use (hours)**	**Time of the day**																							
		6am	**7**	**8**	**9**	**10**	**11**	**12**	**1pm**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**00**	**1am**	**2**	**3**	**4**	**5**

Appendix 1

Table 37: Lifetime, power rating, energy consumption and Cost comparison of different lighting technologies.

	Light emitting diode	**Compact fluorescent lamp**	**Incandescent light bulb**
Projected lifespan (in hours)[1]	50,000	5,000	2,000
Power rating (W)	11	26	100
Cost per bulb (in CFA)[13]	11,523	2,884.58	288.48
kWh of electricity consumed for 50,000 hours	550	1,300	5,000
Cost of electricity (at CFA 75/kWh)	41,250	97,500	375,000
Bulbs needed for 50,000 hours of use	1	10	25
Bulb expense for 50,000 hours	11,523	28,845.8	7,212
Total cost (in CFA) for 50,000 hours	52,773	126,345.8	382,212

THANK YOU FOR YOUR COOPERATION

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[13] Khorasanizadeh, H., Parkinen, J., Parthiban, R. & David Moore, J. (2015). Energy and economic benefits of LED adoption in Malaysia. *Renewable and Sustainable Energy Reviews* 49, 629-637.
Exchange Rate: 1MYR=144.240

Appendix 2: Computation of the economic and environmental potentials of transition towards efficient lighting

Table 38: Computation of NPV for transition from incandescent lighting to CFL.

Number of incandescent bulb	**Power rating of incandescent bulb**	**Number of CFL**	**Power rating of CFL**	**Average daily duty cycle**
1	60W	1	20W	6 hours
Annual electricity consumption for incandescent = 0.06kW * 6hours * 365 days = 131.4 kWh/year				
Annual electricity consumption for CFL = 0.02kW * 6 hours * 365 days = 43.8 kWh/year				
Annual electricity cost for incandescent (year 1) = 131.4 kWh * $0.12/kWh = $15.77				
Annual electricity cost for CFL (year 1) = 43.8 kWh/year * $0.12/kWh = $5.26				
Benefit of CFL in year 1 = 15.77 – 5.26 = $10.51				
Net cash flow (NCF) = $B_t – C_t$ = 10.51 – 5.26 = $5.25				
NPV = 5.25/$(1+0.05)^1$ = $5				

Table 39: Computation of benefit cost ratio and simple payback period for transition from incandescent lighting to CFL.

Benefit cost ratio		
Total discounted benefit = $138.37		
Total discounted cost = $75.34		
BCR = $138.37/$75.34 = 1.84		
Simple payback period		
Year	Cash flow	Net invested cost
0		-$0.83
1	+5.26	0

Table 40: Computation of return on investment for substituting incandescent lamp with LED.

LED capital cost	**Annual electricity price for incandescent lighting**	**Annual electricity price for LED lighting**
$19.88	$15.77	$2.63
Benefits of LED = $15.77 - $2.63 = $ 13.14		
Cost for operating LED = $2.63		
Net benefit of LED = $13.14 - $2.63 = $10.51		
ROI = (10.51/19.88)*100 = 52.87%		

Table 41: Environmental analysis computation for substituting incandescent lamp with CFL.

Number of incandescent bulb	Power rating of incandescent bulb	Number of CFL	Power rating of CFL	Average daily duty cycle
1	60W	1	20W	6 hours
ADI = 0.06kW * 6hours * 365 days = 131.4 kWh/year				
ADCFL = 0.02kW * 6 hours * 365 days = 43.8 kWh/year				
Emission from incandescent = 131.4 kWh/year * 0.86 kg $CO_{2\text{-}e}$/kWh = 113 kg $CO_{2\text{-}e}$/year				
Emission from CFL = 43.8 kWh/year * 0.86 kg $CO_{2\text{-}e}$/kWh = 37.67 kg $CO_{2\text{-}e}$/year				
Emission saving = 113 – 37.67 = 75.33 kg $CO_{2\text{-}e}$/year				

Where;
ADI = activity data for incandescent lamp
ADCFL = activity data for CFL