Botswana Electricity Sector Planning and CO_2 Emissions Reduction through Solar PV in Office Buildings

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ABSTRACT

Coal is the most abundant energy resource in Botswana, with a total reserve of about 212 billion tones. Currently 600 MW of electricity is generated from coal and 160 MW is generated from imported diesel fuel. With rising electricity demand in the future it is planned that the extra generation will come from coal, however there is mounting pressure to reduce CO_2 emissions during electricity generation. The main challenge Botswana is facing, from an electricity generation point of view, is to find alternate and economic clean energy technologies for electricity generation in order to reduce CO_2 emissions. With little natural renewable energy resources other than the sun, the most obvious alternative to coal generation is solar generation. Botswana is blessed with about 21MJ/m^2/day of average solar radiation with over 3200 hours of sunshine per year.

In order to reduce emissions Botswana has set targets of 15 percent and 25 percent electricity generation from renewables (most likely solar) by 2025 and 2030 respectively, as well as replacing planned coal generation expansion with Coal Bed Methane (CBM) in future. Furthermore, the government is also considering using Carbon Capture Storage (CCS) to reducing CO_2 emissions from coal generation, as an alternative to widespread solar.

With these thoughts in mind this study investigates; (1) generation options for reducing CO_2 emission in the electricity sector of Botswana through to 2030, (2) the economic feasibility of using solar PV in Botswana office buildings, and (3) the amount of CO_2 emissions reduction that can be achieved if the solar PV generation was rolled out to many office buildings in Botswana, both commercial and government buildings.

From the electricity sector planning study compared to business as usual, a 44.6 percent CO_2 emission reduction in Botswana is possible through uptake of 25 percent solar PV and replacing diesel with CBM. With additional application of CCS to coal, emissions can be reduced further to 82.1 percent. However, the additional 37.5 percent emissions reduction relies heavily on CCS a developing technology with high system costs.

From the solar PV study, two DC solar PV systems were determined to be the most economical system with Net Present Costs (NPC) of US$ 1,840,105.75 and US$ 473,394.53, compared to two AC solar PV systems with NPC of US$ 2,068,279.31 and US$ 587,673.24. The levelized costs for DC solar PV system without inverter and batteries is 0.47 US$/kWh which is 14.9% less than the AC solar PV system with inverter without batteries at 0.54 US$/kWh. Similarly,

the DC solar PV system with batteries is 1.82 US$/kWh, 3.8% lower as compared to levelized costs for AC solar PV system with batteries and inverter at 1.89 US$/kWh.

Lastly, it is estimated that between 12 percent and 39 percent CO_2 emissions reduction is possible in Botswana by rolling out installation of DC solar PV systems in 11564 commercial and government office buildings throughout Botswana.

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NOMENCLATURE

BPC	Botswana Power Corporation
BEWRA	Botswana Energy and Water Regulator Authority
BOL	Botswana Oil Limited
CEPA	Carbon Emission Pinch Analysis
CCGT	Combined Cycle Gas Turbine
CO2	Carbon Dioxide
CBM	Coal Bed Methane
CCS	Carbon Capture Storage
CSTP	Concentrated Solar Thermal Power
CSP	Concentrated Solar Power
DRC	Democratic Republic of Congo
EROI	Energy Return on Investment
GDP	Gross Domestic Product
GW	Gega Watt
GWh	Gega Watt Hour
GEF	Gross Emission Factor
IPP	Independent Power Producers
ktoe	Kilo Tons of Oil Equivalent

kWh	Kilo Watt Hour
kt	Kilo Tons
MMGE	Ministry of Mineral Resources, Green Technology and Energy Resources
MW	Mega Watt
Mt	Mega Tons
NZ	New Zealand
NG	Natural Gas
OCGT	Open Cycle Gas Turbine
PV	Photovoltaic
RPS	Renewable Portfolio Standard
SADC	Southern African Development Community
SAPP	Southern Africa Power Pool
TWh	Tera Watt Hour
toe	Tons of Oil Equivalent
WECC	Western Electricity Coordinating Council

CHAPTER 1: INTRODUCTION

1.1 Overview

Botswana is still a developing country under the organization of Southern African Development Community (SADC) of countries. The electricity generation and supply issue in SADC region is mandatory to the Southern Africa Power Pool (SAPP). SAPP was established under SADC countries, and is comprised of the members states of; Botswana, South Africa, Namibia, Zambia, Zimbabwe, Lesotho, Swaziland, Angola, Tanzania, Malawi, Mozambique and Democratic Republic of Congo. SAPP's primary objectives are to provide; 1) reliable and economical electricity supply to the SAPP members and 2) manage utilization of natural resources and the effect on the environment (SAPP, 2013). Among the SAPP members, Botswana have experienced electricity crisis in previous years before 2015.

Botswana is currently generating 600 MW of electricity from the abundance of coal in the country (reserves 212 Billion tonnes) and 160 MW from imported oil as diesel (Mothebe, 2013; Paya, 2012). The electricity demand in Botswana continues to increase because of the increase in electricity connections of both rural and some developing businesses. Nevertheless, Botswana is facing a challenge of employing cleaner coal technologies in order to reduce carbon emissions in the electricity generation sector.

The country is blessed with high potential of solar energy. Botswana receives over 3200hrs of sunshine a year at an average daily radiation between 21- 28MJ (equivalent to 5.83 – 7.78 kWh) per meter square on a horizontal surface (UNDP, 2012). Currently, the contribution of solar to the electricity generation is less than one percent towards the targets of 15 percent and 25 percent renewables by 2020 and 2030 respectively. There are only small installations of some solar energy initiatives carried out such as; 1.3 MW solar PV system and 485 Solar Home Systems installed in rural community areas. Solar energy remains as an opportunity where further research on solar technology should be carried out, in order to maximize the utilization of the available energy resources of the country.

HOMER Pro software was selected as a technological tool to help with this study. The software is helpful for quantifying the parameters of a solar energy system in terms of geographical location and solar panel area size. HOMER Pro is software that was established by the United States National Renewable Energy Laboratory for the purpose of designing renewable energy systems that are both technically and economically feasible from a cost of energy and net present value point of view (NREL, 2016). The software has previously been used to identify the most economical system among a range of alternatives. A study in Bangladash used the HOMER Pro software to analyse Solar PV, Solar thermal and Hydro power systems to find the lowest cost system for irrigation in Sandip-para area (Deb, Bhuiyan, & Nasir, 2013). The solar PV system was found to be the most cost effective system due to its reasonable cost of energy and net present value.

Carbon Emissions Pinch Analysis (CEPA) was also used to estimate the level of carbon emissions reduction when increasing renewable electricity generation in the electricity sector. It is a useful method which is capable of integrating the supply and demand of energy production of several systems in order to estimate their carbon emissions produced. Energy Return on Investment (EROI) method was also used together with CEPA to determine the level of economic trade off involved with specific renewable energy changes. These methods enable the evaluation of possible energy mixes for a country to invest in, if carbon emission reduction is the important factor.

CEPA and EROI methods were used in the analysis of the electricity sectors of New Zealand and California. The evaluations were similar and focused on reducing carbon emissions within a designed target and time by increasing the renewable energy in the electricity generation sector. The results of the study showed that a target of 90% renewable electricity generation by 2050 was achievable in New Zealand even with the introduction of 50% plug in hybrid electric vehicles in the light passenger transport fleet (Michael R.W Walmsley, Walmsley, Atkins, Kamp, & Neale, 2014). In California, the 33% renewables target of electricity generation from renewable (excluding large hydro) by 2020 was on track to be achieved with the large scale adoption of solar PV and wind (M.R.W Walmsley, Walmsley, & Atkins, 2014).

1.2 The Aim of the Study

This study proposes to reduce carbon emissions in Botswana electricity generation through the adoption of an efficient solar PV system for office buildings preferably for commercial and government office buildings. The study focuses on finding the most cost effective solar PV system in terms of energy cost and net present value using HOMER Pro software. Four types of solar PV systems are assessed, these are (1) DC solar PV system with battery storage, (2) DC solar PV system with inverter only, (3) AC solar PV system with inverter and battery storage, (4) AC solar PV system with inverter only.

The carbon emission reduction by increasing renewable electricity production in the electricity sector of Botswana by year 2020 and 2030 respectively was also estimated using CEPA method and the change in EROI was also estimated.

The specific objectives of the research are as follows;

i) To identify economically viable options for Botswana to reduce the dependency on fossil fuels (coal and oil) for AC electricity generation.
ii) To estimate the carbon emissions reduction potential in Botswana with solar PV and the estimated increase in costs when increasing renewable energy in the electricity generation sector by using CEPA and EROI methods.
iii) To show the potential of reducing carbon emissions in Botswana through promoting the use of solar PV energy as electricity supply in office buildings.
iv) To find the most economic system between AC or DC Solar PV system by comparing the solar PV system with battery storage to systems without battery storage but uses the grid for storage.
v) To minimize the cost of solar PV technology through reducing the number of solar panels required for the system design.
vi) To assist policy makers and decision takers in Botswana, in terms of the development of standards to support DC building infrastructures.

The approach used to demonstrate the potential for the PV systems was to undertake a case study of one of the office buildings in Gaborone city, Botswana. The data of the case study was used as the baseline to design an optimal DC solar PV system, in terms of quantifying the system cost effectiveness and the potential of CO_2 emissions reduction. In addition, the results of this work will be made public to policy makers in Botswana so useful national renewable energy policies can be developed that give useful guidance to building services decision makers.

1.3 The Framework of the Study

This study is composed of seven chapters with different sub topic headings in each chapter. Chapter 1 defines the electricity situation in Botswana and why there is a need to carrying out this study. It also outlines the purpose of the study, and resolution of the problem in order to mitigate the challenges. A literature review to support the research of this study is covered in chapter 2. Findings of related studies using the same methods or techniques, such as CEPA, EROI and HOMER Pro software, are also reviewed. The advantages and disadvantages of solar PV either as a DC system or a AC system are highlighted. Chapter 3 describes the methodologies used in this study and the spreadsheet tools developed. The current energy resources used for electricity generation in Botswana and SADC counties are analysed in chapter 4. It is shown that Botswana faces a significant economic challenge to reduce the carbon emissions generated from large scale fossil fuel electricity generation. Options for reducing carbon emissions in the future are proposed.

Chapter 5 outlines the results of a solar PV case study carried out on one of the government office buildings in Botswana. The analysis was performed using HOMER Pro software. Both electricity supply and electricity demand from the single building were analysed and options for maximizing electricity generation through battery storage or minimizing electricity generation costs through minimal battery storage were considered. The benefit of using the solar DC power directly in the building for DC powered devices versus converting solar power to AC power and keeping all devices on AC power was also considered. In chapter 6 the scaling up of the successful solar PV model to all office buildings in Botswana is discussed and the overall carbon emissions reduction potential and energy expended of the system are estimated. The energy storage challenge in renewable energy is also discussed in this chapter by means of finding suitable solar energy storage for Botswana. Chapter 7 summarizes the findings and the corresponding way forward from the results of the study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The best opportunity for Botswana to reduce carbon emissions is through widespread use of Solar PV. However, to do so the levelized costs of solar PV needs to be as competitive with coal generation as possible otherwise uptake in Botswana will be minimal. The aim of this study is therefore to investigate the benefits of combining solar PV directly with commercial and government office buildings in Botswana. As part of this investigation the option of supplying DC power directly to devices that can potentially run off DC power e.g. LED lights, Computers, Refrigerators etc. is also considered, knowing that such an approach can save on the cost of the DC to AC invertor. The assumption will be made that DC powered devices will be able to be sourced at similar cost to AC powered devices in the future.

Using solar PV power directly in DC mode is not new and there are numerous applications where this concept has been modelled and studied. To give background to this topic in this chapter the initial development of DC and AC systems in the 1800's is first discussed and the merits of either system are reviewed. This is followed by a review of solar PV technology and how this electricity generation approach has numerous methods that have reduced dramatically in costs in the last 20 years. The need for storage, either through batteries, or thermal storage either hot water when solar in excess or refrigeration when in excess is then discussed. Lastly use of solar PV to commercial and government office buildings and the pros and cons of using DC versus AC power are discussed.

2.2 Historical Background DC versus AC Systems

One of the key factors of this research is to reduce CO_2 in the electricity generation in Botswana through supplying solar power directly to office buildings. This is because solar energy was found as the highest opportunity in Botswana through the abundance of the resources. It is in this background that the complications of the direct current (DC) and alternative current (AC) supply in buildings were revealed to suggest a better application of solar power supply. In general, DC can be defined as a one way directional flow of electric charges, which results in a constant flow of electric current. This makes it differ with AC, which possess directional change in current flow for about 50-60 times (50-60Hz) per second depending on the operated amount of voltage. Figure 1, illustrates the behaviour of both DC and AC in terms of current flow, when either one of the two is subjected to voltage and time.

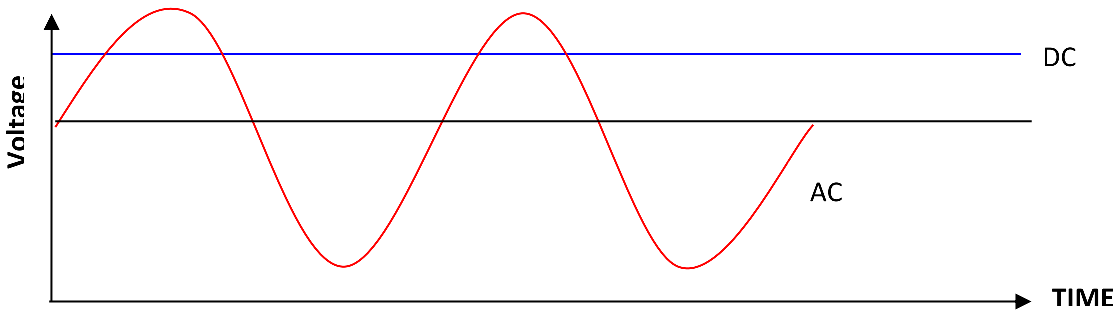


Figure 1: Difference between DC and AC Systems in terms of Current Flow

In review of the history it states that the ideas of AC and DC flow of current were discovered by Tesla and Thomas respectively. According to their debates around 1880's, the AC got an advantage over DC in terms of; easy voltage transforming into different levels of applications, transmission of power over a long distance and as well as having better characteristics to support the fossil energy driven generators (Justo, Mwasilu, Lee, & Jung, 2013). This enabled AC to dominate over DC up until 1954 when the first commercial high voltage direct current (HVDC) transmission line rating 20MW, 200A and 100kV was established between the mainland of Sweden and Gotland Island. The HVDC transmission system transmits a large amount of energy between two points with very minimal losses. The disadvantageous of the HVDC is the losses which are incurred through convertors at the start point of transmission where electrical current is converted from AC to DC and at the receiving terminal point where the same current is converted from DC to AC. Apart from that HVDC made DC into a more effective and cost-efficient technology than AC on transmission of high voltage power. This is due to the concept which states that using higher voltage maximizes efficiency on power transmission. In this regard, the HVDC transmission becomes more favourable than AC transmission system because of some of the following reasons;

i) Losses from HVDC system which are involved at both the start and end terminals are high whereas in HVAC system the line transmission losses become even much higher because the losses increase with distance.
ii) As for the same transmission capacity, all costs such as transmission lines, land acquisition and operation-maintenance are low in favour of HVDC than HVAC.
iii) At synchronization connection points, there are some difficulties faced with system stability in the AC network, whereas for the HVDC network it is controllable and possible to synchronize with no change in system stability.

Other researches indicate that the AC system is becoming less cost-effective because of the limited fossil fuels long-term and due to increasing need for more power plants and more distribution lines. Consequently, there are much more energy losses and elements faults potentials encountered in the transmission lines. These are caused by the alternating current process and the energy conversion process from AC to DC, especially when powering the DC electric appliances (Foss, 2014; Justo et al., 2013; Larruskain, Abarrategui, Zamora, & Aginako, 2011). Despite all the arguments between DC and AC electricity supply, it is estimated that about 5-10% of energy is wasted during electrical conversion processes and much more is wasted on multiple AC-DC conversions (Sinopoli, 2012).

2.3 Some Controversial Issues between DC and AC Systems Efficiencies in Buildings Worldwide

The data collected and recorded in 2011 by US Energy Information Administration (EIA) states that commercial buildings consume about 12% of the total world electricity use including losses (EIA, 2011). The Navigant research report on a comprehensive review of DC power technologies for commercial buildings which was conducted in 2013 outlines that DC is vigorously gaining the world confidence due to energy efficient and clean technologies, as compared to AC system (Eckard & Gohn, 2013; Mokhatari, Nourbakhsh, Zare, & Ghosh, 2013). The global market for DC building technologies is rapidly growing. In 2013 the North America and Europe accounted for about 76% of the global market. Whereas, the market shares for Africa, Middle East and Latin America remain limited. To increase uptakes of DC in Africa government interference and support is going to be needed, and this should be considered before the cost of energy escalates function. In addition, most of electronic technologies for both commercial and industrial application are advancing in DC electricity supply system (Eckard & Gohn, 2013; Mokhatari et al., 2013). DC electronic technology is more advancing in devices such as; LED lights, computers, televisions and IT data server centres, and is used already in automotive, marine, banks and manufacturing industries (Justo et al., 2013).

The research on “Reviving the War of Currents for the Opportunity to Save Energy with DC Distribution System in Commercial Building” outlines some important factors for comparison between the AC and DC electricity distributions systems (Porter, Mercier, May-Ostendorp, Denkenberger, & Turnbull, 2014). These factors include the market benefits and barriers of deploying the DC distribution systems, which is an interesting topic when considering the DC technology in buildings. It outlines benefits which include;

i) reduction of energy waste in electronic devices through elimination of bulk numbers of AC-DC power supply (adaptors), since the DC devices can be supplied by the DC power supply,
ii) provision of an ease/reconfiguration of overhead lighting system to support the DC ceiling grid, such that the overhead lighting can be supplied by the DC power at low voltage,
iii) improvement of power quality through elimination of high demand charges, which results from the high spikes of larger power conversion devices in buildings such as motor drives (VSD), central air conditioners compressors and server power supply.

There are also some barriers which can be a challenge to the breakthrough of the DC technology and these include:

i) Inadequate expertise of the trades and consumers on the wiring and use of DC technology respectively,
ii) High cost of DC products because of their availability in the market is very low.

The study by Porter et al. also revealed some energy savings and cost effectiveness on energy end use through a conducted case study in a 50 000ft^2 (4645.152m^2) commercial building in the USA. The case study compared the energy savings of both AC and DC distribution systems under two scenarios: Code-compliant (existing buildings built under California's Title 24 code) and Zero Net Energy (ZNE) buildings (the building supplied by on-site PV power system). As a result, it emphasized that 8% of the total energy use in ZNE buildings was saved through deploying the DC distribution system due to eliminations of energy conversions (Porter et al., 2014). The research also mentioned that standards of DC technology in buildings are needed to move the technology forward. These include the Emerge Alliance Data/Telecom Standard developed under an open industry association called Emerge Alliance. The Emerge Alliance is focused on promoting the DC power technology in commercial buildings with regard to safety, low voltage power distribution and use (Porter et al., 2014; Ziegenbein, 2009). This research, gives a good overview to the DC technology in terms of energy savings and cost effectiveness on energy end use in buildings. This can assist the decision takers and policy makers in order to promote the DC technology in office buildings. In contrast, the study did not link the energy savings with the carbon emissions that can be reduced when considering the DC distribution system in ZNE buildings. In addition, the set up cost effectiveness of the DC solar PV system of the ZNE buildings in terms of components cost, was not emphasized in the research.

Energy Efficient Low-Voltage DC-Grids for Commercial Buildings study conducted by the European ENIAC R&D project consortium DC Components and Grid (DCC+G) demonstrated the efficiency between AC and DC grids with regard to a three phase AC and two phase DC power supply system to a commercial building (Weiss, Ott, & Boeke, 2015). A two phase 380V DC system was developed and installed along side a conventional three phase 400/230V AC distribution system at an office building of the Fraunhofer Institute in Erlangen, Germany. An equivalent load power, local source power (PV and Conventional Grid) and wiring system were applied for comparison between the two distribution systems. The study revealed that there are less energy conversion losses achieved from the 380V DC compared to the 400/230V AC distribution system. In this regard, 2.7% energy efficiency was realized in favor of DC system when operating on a normal day. The efficiency increased to 5.5% on an operation cycle when a vast amount of energy from local source power were provided. Other energy efficiencies advantages to the 380V DC systems were also realized (Weiss et al., 2015):

i) The efficiency can be even further increased when supplying high power loads like central air conditioning systems. This is because high power loads create spikes for high demand in the AC system, which requires power factor corrections,
ii) The DC system can reduce the electronic scraps because some gadgets like AC/DC power supply will be not required,
iii) The DC approach can reduce the complexity of the current traditional system through eliminations of some components in the system eg an inverter.

In contrast to the previous study, where the scope of work was concentrated more on energy conversion losses and the cost effectiveness of the system set up is not fully explored, and nothing is mentioned about CO_2 emissions issues. The master research conducted at Norwegian University of Science and Technology in Trondheim city, Norway on DC Supply in Buildings (Foss, 2014). The purpose of the study was to simulate a system solution for a modern building in order to compare the AC and DC systems with respective to their energy end use loads. This is because the realistic shows that most of the existing buildings are installed with 230V AC while their loads are DC power design. Therefore, two analysis were performed: analyzing the efficiency of the existing AC system supplying the DC loads and analyzing the efficiency of the DC system supplying the DC loads.

Physical measurements of the selected building for the case study were also considered as an important factor, in order to give an accuracy design of the size of the DC system. The study compared the two different systems with regard to energy losses, efficiencies, safety and possible economic aspects. The selection of the voltage level is found to be a critical factor when designing the DC distribution. In the previously mentioned study it was proven that a 230V DC standard voltage level can be sufficient for office loads, only if it is designed with a cable length not exceeding 80m. In the case of higher power loads limited to 6.5kW, the voltage level has to be increased to 326V DC with a reduced cable length of 47m. On the economic side, the results show that Low Voltage Direct Current (LVDC) is beneficial when supplying DC loads at a voltage level of 230V DC, due to the reduced power losses. LVDC is defined by the European Union Directive Standard 2006/95/EC as DC voltages ranging between 75-1500V DC and for LVAC as AC voltages ranging between 50-1000V AC. The standard also outlines that low voltages systems can power equipment that include; induction heaters, washing machines, refrigerators, microwave ovens and electrical heaters. The study also revealed that in future, the realistic LVDC system size to supply a floor in a building with DC loads is approximately 20kW. This capacity is advantageous to the invention of the smart grids system, which can make it possible to connect different distributed generators from renewable energy sources such as wind, solar and fuel cells. Though there are some challenges with energy storage technology which needs improvement in order to sustain the renewable energy technology. It is emphasized that the growing technology of electrical vehicles can also be used as storage for excess energy generated by simple connecting the car battery bank to the smart grids. Therefore, it was concluded that an efficiency of 95% was possible in a DC/DC converter, whereas 90% efficiency was likely in an AC/DC converter. Further calculations stressed that an efficiency of 95% was obtained from appliances with DC/DC convertor, whereas 85% was obtained from the appliances with AC/DC convertor. Therefore, the results summarised that the LVDC distribution system has potential benefits when compared to LVAC distribution system (Foss, 2014). In contrast, this study outlined good results the energy losses between LVAC and LVDC systems but it does not emphasizing more on the comparison of the cost effectiveness and CO_2 reduction in buildings between the two systems even though it is part of on the broader scope of the study.

2.4 Solar PV Technologies

2.4.1 General Information

In general, solar PV energy can be described as a generation of electricity using photovoltaic energy from the sun light rays. The system consists of a set of different components such as solar panels, inverter, batteries and other electrical accessories like charge controllers, DC isolators, meters, tracking devices, cabling and mountings. The functionality of these components is illustrated in Figure 2, whereby the solar panels form a solar array of which its number of panels depends on the required size of the PV system plant. These panels absorb sun light rays and convert it into DC electricity. The inverter converts the DC electricity from solar panels to AC. The cabling and other accessories connect these major components in order to have a full PV working system (Dolphin, 2012; Dunlop, 1998).

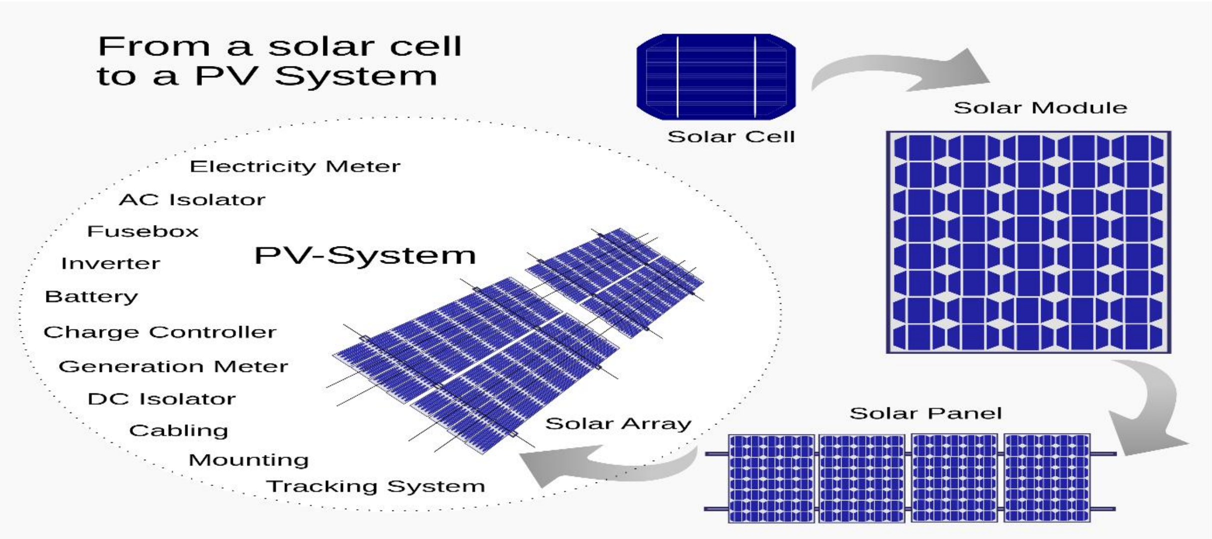


Figure 2:- Components of a Solar PV System

In order to improve on the performance of the system, tracking devices are installed together with the solar panels to track the availability of the sun light rays through tilting the panels to the best possible angles. Batteries also are connected to the system for the purpose of storing the excess energy produced by the system such that it can be used during peak times or when required (Jayapragash, Baskshi, & Kumar, 2017).

2.4.2 DC solar PV and Conventional AC Solar PV Systems

DC and AC solar PV systems use similar operational mechanisms to generate DC electricity from sun light. The only difference is that the AC solar PV system involves an installed inverter and rectifier for conversional processes: DC to AC then AC to DC when supplying DC devices. Actually, this system is designed to supply the AC electricity driven devices.

The DC solar PV system involves elimination of other components in the system, such as the inverter. The system is designed to supply DC electricity directly to DC driven electronic devices (Fregosi, Ravula, Brhlik, & Saussele, 2015; King, Gonzalez, Galbraith, & Boyson, 2007). The differences of the two systems are illustrated in Figures 3a and 3b respectively.

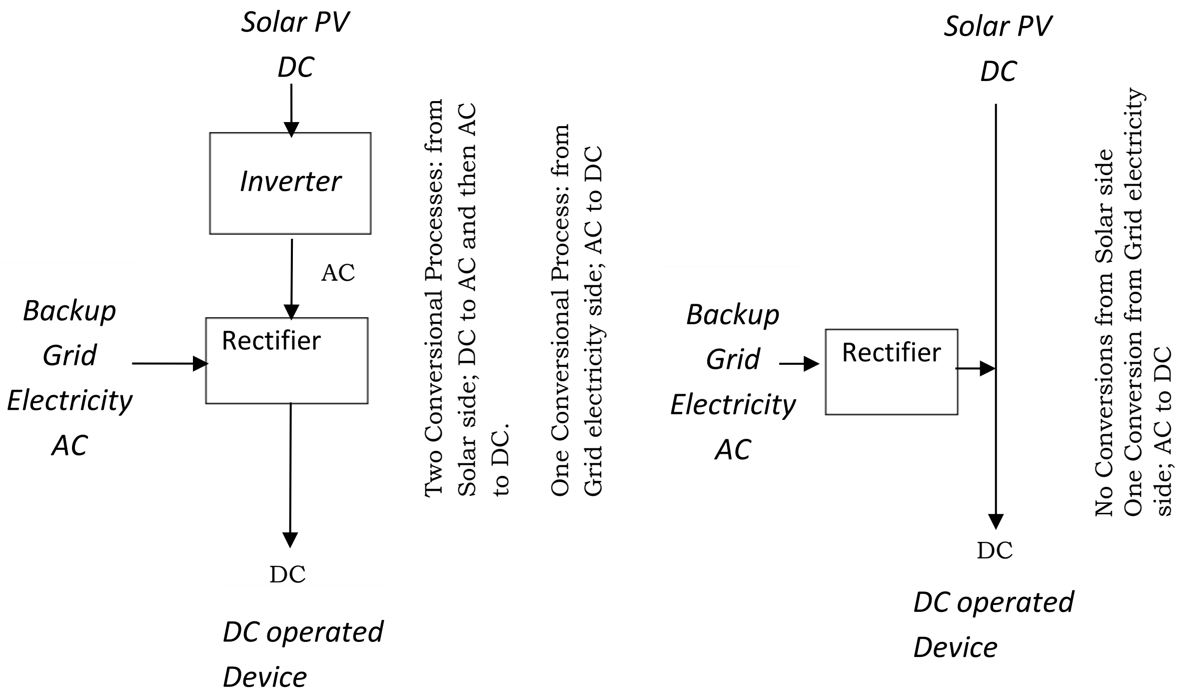


Figure 3:- Schematic Diagrams of an AC and DC Solar PV Systems

Most of the debates between these two systems, interrogate the issues of energy efficiency and conservation on solar electricity generation system. This involves issues of the system capital costs, maintenance costs, energy losses, reliability and safety. Robert Bosch LLC and National Renewable Energy Laboratory presented a conference report in the 2015 IEEE First International conference on DC microgrids. The report was successful and it demonstrated an efficient solar PV energy DC microgrid as compared to a traditional AC solar PV system. A scale of 15-20% lower capital cost in favour of DC system was achieved compared to AC system. In addition, energy losses and maintenance costs were reduced due to eliminations of AC-DC rectifier and DC-AC inverter (Fregosi et al., 2015). DC supply still remains a key factor for further research as far as solar technology is concerned, in terms of electricity supply from source to end use, as well as smart grid integrations.

2.4.3 Solar PV Systems and Maintenance

Solar PV systems are just like any other operational plant as they also require operation and maintenance in order to sustain good performance over their lifetime period. They are also installed with a remote monitoring system which is connected to internet. The remote monitoring system is required for monitoring the system data logging operations. The monitoring system assists in raising an alarm to fault functioning of some components of the plant. In this regard, the diagnose and rectifying the problems becomes easier to achieve in a timely manner (Haiti & Sanz-Bobi, 2014). It is estimated that an efficient operation and maintenance (O&M) practice can increase the performance of the solar PV system and reduce the operation cost from $0 to $40/kW/year. Thus means that the system's average performance ratio could be improved from 88% to 94% due to a well-planned O&M schedule. It also highlighted that with reduced downtimes and increased performance, the system can extend its lifetime from 25 to 40 years (NREL, 2015).

One of the studies carried out in Germany aimed at finding an alternative economic and reliable maintenance strategy for different solar PV plant sizes. In this case, three sizes: 1, 10 and 100MW (nominal power) of fixed-tilt ground-mounted solar PV plant types were modelled. The plants set up were configured with a central inverter with respect to AC/DC switch, circuit breaker and an inverter. The analysis ran the comparison of corrective maintenance against the maintenance strategies monitored in different periodic times. The test also took an account of system running spot prices/costs and spare parts inventory in the operation services of the solar PV plants. As a result the corrective maintenance was found to be the most cost effective maintenance strategy in terms of lower total running costs and plant downtimes (Camilo, Castro, Almeida, & Pires, 2017; Peters & Madlener, 2017).

In the USA, the Electricity Power Research Institute conducted a study on budgeting for solar PV Plant Operating and Maintenance: Practices and Pricing. It is stated that solar PV systems needs a steady operations and maintenance service which can sustain the system for over 20-30 years life-time frame. The study also outline the possible estimates of O&M solar PV components and costs as follows; overall budgets (US dollar 10-45/kw year), general site maintenance (US dollar 0.20-3/kw year), wiring/ electrical inspection (US dollar 1.40-5.00/kw-year), panel washing (US dollar 0.80-1.30/kw-year), vegetation maintenance (US dollar 0.50-1.80/kw-year), inverter maintenance (US dollar 3.00-7.50/kw-year), inverter replacement (US dollar 6.00-10.00/kw-year) and spares (US dollar 2.00-20.00/kw-year (Nadav, Dean, & Geoff, 2015). Furthermore, it has been discovered that the maintenance improves the efficiency of solar systems due to the system technology set up and material used, which includes the following four things.

2.4.2.1 Nano-grids

A nano grid may be defined as a single power source connected to a single load, e.g. a single building or machine. A micro grid on the other hand comprises of the connection of multiple loads to multiple power sources e.g. a power supply network connected to a few buildings. Therefore, a solar PV nano-grid comprises of a solar PV array, batteries, power supply cables and a load. Typically, solar PV micro-grids consists of an array of solar PV modules (which produce DC electricity) as well as supply cables linking the solar PV array to the inverter and from the inverter to the load. The small loads on a nano-grid make it feasible to use only battery power such that it does not include an inverter/rectifier. A case study was conducted on houses in India, for the purpose of observing the impact of nano grids on net-zero energy homes. It was found that while the efficiency for DC-powered equipment was reduced with increasing load, an example that the efficiency dropped by 3% as the load was doubled from 115W to 235W. The AC control efficiency showed an increasing trend by 1% as the load was doubled from 315W to 649W. However, the total efficiency of the AC loaded system ranged from a third to half of that of the DC system, demonstrating the effectiveness of DC systems for small loads (Muthuvel, Daniel, & Yazhini, 2016).

However, the batteries needed to be maintained appropriately in order to avoid the reduction in efficiency performance of the system and maintain the lifespan of the system. The nano-grid's effectiveness can be improved further by the eventual installation of a smart metering system (Goulden, Bedwell, Rennick-Egglestone, Rodden, & Spence, 2014). Nano grids will likely be easier to test and restore than micro grids due to their small scale and simplicity. Hence their implementation should be the most effective solution to the high cost and price volatility of solar PV technology (Candelise, Winskel, & Gross, 2013).

2.4.3.2 Nanotechnology

Nanotechnology has applications for improved maintenance, improved operational efficiencies and potentially cost reduction in the form of reduced material usage i.e. the conducting material is nano particles. The use of TiO_2 (Titanium IV oxide) nano particles makes the transparent solar possible allowing for greater effectiveness of the Trombe Wall by providing three energy benefits from the insolation such as natural light, DC electric power and environment assisted natural heating/cooling through the fluid (Chau, Chen, Hwang, Tsai, & Lin, 2009). The use of carbon nanotubes in modules to give them an anti-reflective and self-cleaning property is an example of the application of nanotechnology for efficiency performance and maintenance (Beard, Luther, & Nozik, 2014; Hanaei, Assadi, & Saidur, 2016).

Nanotechnology cells are designed to achieve increased operational efficiency and/or reduce maintenance costs compared to the conventional solar PV cells. For example, the hydrophobic, self-cleaning, anti-reflective coating eliminates the labor cost required for manual cleaning of conventiaonal solar PV technologies. The micro-scale design of the solar PV panels prevents dirt that collects on the panels from sticking to their surface. When water is poured onto their surface, it sinks below any dirt forming a layer of flowing water between the dirt and the panel surface. The dirt particles suspended in the water are then carried away leaving the solar panel surface clean. However, for the ordinary solar PV systems all the cleaning is labor intense (Hanaei et al., 2016).

2.4.3.3 Solar PhotoVoltaic - Trombe Wall

A Trombe wall is a hollow, composite wall comprising of either two layers of glazing or one layer of glazing and a solid wall surface. The hollow is filled by an inert fluid (e.g. argon gas) or air to insulate the building's interior, by absorbing excess heat from solar insolation and preventing excess heat loss from the building) for the purpose of reducing heating loads in winter and cooling loads in summer. When double-glazing is used, the wall doubles-up as a source of natural light (Özbalta, 2010). The inner glazing layer may be replaced by a solar PV panel, to increase the efficiency of the use of sunlight by converting some of it into electric power (Irshada, Habiba, & Thirumalaiswamya, 2014).

The life cycle cost savings of the gas filled Trombe wall was found to be up to 22.18%. In the case of the conventional Trombe wall, the typical maintenance expenses incurred are the cost of occasionally repainting the black exterior coating and labor cost of cleaning the glazing. This may be negated by using transparent self-cleaning nanotechnology solar PV cells and installing them on the exterior rather than the interior. Conversely, the conventional solar PV panels would have mounting bolts/screws, which would have to be checked and changed at regular intervals, requiring labor costs to maintain each panel mounting and potentially recurring costs due to the mountings being on the exterior of the building, and therefore exposed to weather variations (Irshada et al., 2014).

2.4.3.4 Other material technologies

The other way to minimize costs while improving efficiencies of the solar PV panels is to use improved processing technologies such as ion-doping of cells using plasma immersion and chemical vapor deposition (Huang, Lin, Shen, Shieh, & Dai, 2011; Young et al., 2016). These methods improve the operational efficiency of the solar PV cells and provide the potential for development of more complex technologies. An example is the potential use of dye sensitized cells to improve the operational efficiency of the solar PV system (Guo, Sun, Gao, & Liu, 2015).

2.4.3.5 Energy Storage and Solar PV

The intermittency problems of renewable energy sources mostly solar PV can be offset by the use of energy storage. Energy storage technologies have the potential of storing the generated intermittent energy and using it upon demand. Ideas of making energy storage systems more cost effectively have been proposed by different researchers and these include; hybrid energy storage and load shifting (Yang, Cheng, & Chunya, 2014). The idea of hybrid energy storage involves the combination of supercapacitors and batteries. The supercapacitors have high power density with low energy density, which make them charge very fast and quickly discharge the electricity. Vice-versa, the conventional batteries have low power density with high energy density, which make them charge and discharge the electricity slowly. The idea is to combine the advantages of the two for purposes of boosting the storage system. In case of the solar PV system, the fast charging of power from generation source (PV panels) to storage will improve the overall efficiency of the solar PV system during fluctuating cloudy weather. The same principle can work well in electric cars because they require to be charged very quickly on fuel service stations or even at home. Secondly, the hybrid storage system will last longer by effectively performing the charge and discharge cycles, which the conventional batteries alone are not effective on these tasks. Thirdly, the hybrid storage system will have much more storing capacity in the same amount of space. Batteries alone have a large capacity to store charge but require a lot of space, whereas supercapacitors have less capacity to store charge and do so with less space. The combined battery-capacitor storage option will therefore have a more compact area size due to the reduced number of batteries required for the same amount of storage as well as reduced cost of the storage system (El-Kadya et al., 2015; Luca, Ohlckers, & Xuyuan, 2013)

Load shifting is another idea which has been proposed to improve energy efficiency and it involves, moving the demand of a device to a time when energy is available, called demand responses (Wimmler, Hejazi, de Oliveira Fernandes, Moreira, & Connors, 2017). This kind of approach enables the system to have less energy storage to be effective. For example a little capacity for powering lights and computers during the day in office buildings when using a solar PV system is a good match. This is because the energy consumption in an office follows the power generation trend of solar PV during the day, such that at mid-day the building loads and solar power generation will be at power peaks. Similarly, at early morning and late afternoon the load and power demand can be lower. Also in this case, some loads of the buildings can be shifted to operate during the time of solar power generation peaks. The loads such office refrigerators can be operated during power peak time. This power peak can also be used on the operations of heating water and storing it as thermal energy which is later used during solar off-peak times like in the morning and evening times. Figure 4 illustrates the principle of load shifting such that the peaks of the internal load consumptions of the building has been shifted to mid-day, so that it is covered by the peak power generation from the solar PV system. Therefore, the loads powered at night are taken care of by the power generated from the grid (Dolphin, 2012; Lin, Deng, Liu, & Chen, 2017).

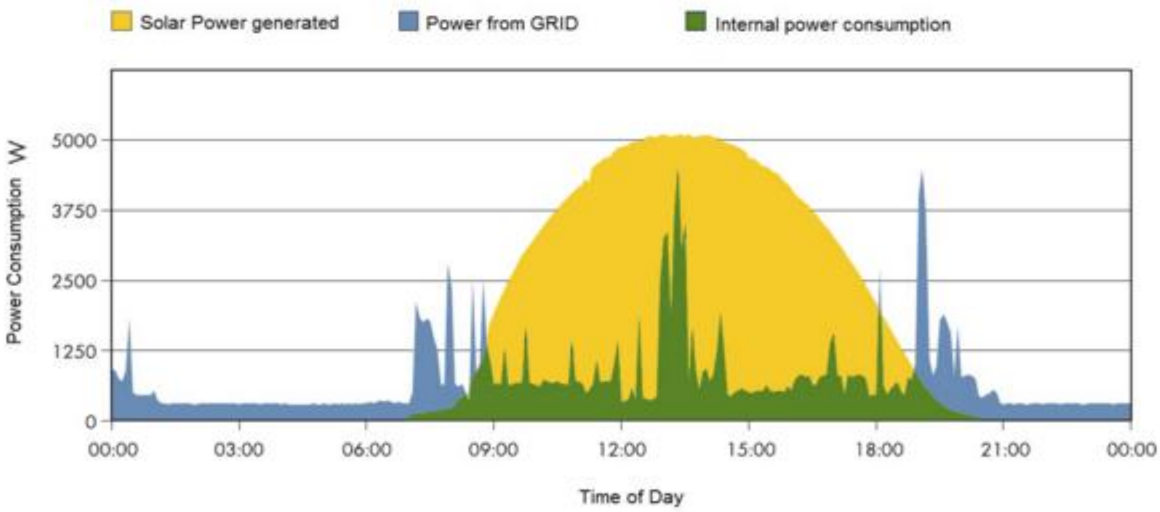


Figure 4:- Illustration on the shifting of internal load power consumption to the solar power generation peaks (Dolphin, 2012)

2.4.3.6 Solar PV applied to Commercial Buildings

There is a great potential for solar power harnessing within the urban areas; skyscrapers and other commercial buildings have greatly untapped power generation possibilities. The rooftops and the widows seem to offer a great deal of these possibilities. The incentives for considering such new thinking for commercial infrastructure include, reduced carbon emissions, an offset in the amount of electricity bought form the grid and putting roof tops to good use through roof mounted solar technology (Arora, 2016). Already, countries like the UK, Germany and China among others, have demonstrated real life applications of solar in commercial office buildings. Financially it has to make sense for one to opt for using solar in any building. Building-Integrated Photovoltaics (BIPV) is a concept of using solar technology seamlessly integrated into the structure and facade of buildings to provide power to the building as an alternative/supplement to grid power. These solar technology fittings can also provide extra functionality to buildings such as shading, cladding, and insulation. If commercial buildings where to be fitted with a solar façade, for instance, they would function to provide electricity to the buildings thus reducing electricity bills (Talal Salema, 2015). It goes without saying that this would translate into monetary saving and CO_2 emissions.

There are case-studies abound with research on commercial buildings that have utilized solar energy technology for their benefit. One such research is of Muller Precision Engineering in the UK. Their rooftop mounted solar system generates around 163,260 kWh per annum, which led to a 26% reduction in their electricity purchase from the grid (Arora, 2016). Another example of a commercial building benefiting from solar is the Cambridge Regional College which uses rooftop solar cells to generate around 182,125 kWh and to achieve a reduction of over 74 tonnes of CO_2 emissions annually (Arora, 2016). For good measure here is a third case-study, Lyreco, also in the UK. Lyreco with its roof mounted solar cells achieves savings of more than Euro53, 000 annually on electricity and at the same time achieves a 1,700 tonnes reduction in CO2 emissions (Arora, 2016). When applying new technologies such as BIPV to a building one has to weigh the benefits against the cost and a good tool in gauging this is efficiency; as there is a relationship between efficiency and savings made. To maximize the benefits of using solar technology systems in a building one must first reduce their overall load, this means deploying energy saving measures and techniques and adopting good energy habits. Therefore when purchasing the solar technologies one would save money by not catering for unnecessary wastage thus reducing the initial investment costs. Windows fitted with solar cells can be a great asset in helping to provide electricity for the building. Photo-voltaic- ventilated glazing helps to make the air conditioning more efficient at cooling and heating the building (Arora, 2016; Chow, 2007).

A lot of the appliances used in the offices operate on DC power such as printers, computers, scanners and others and function by converting AC from the mains into DC through rectifying circuits. Each appliance would have its own rectifier and there could be tens or hundreds of them across a building. Solar cells produce DC current directly and by connecting them directly to these appliances one circumvents the rectifiers and the losses inherent in them. This would make the building more efficient at utilizing its energy and bringing concomitant improvements in the energy bill and CO_2 footprint (Glasgo, 2016).

National grids such as in Botswana obtain a great amount of their electricity from fossil fuels like coal and as this is the epoch of climate-change consciousness such fuels are becoming unpopular. Some nations in the world have taken up pledges to reduce their carbon-footprint and commercial buildings will have a part to play. By integrating renewable energy technologies into buildings, this will allow them to produce some of their own energy needs and in so doing relieving pressure on the grid. The less the load on the grid the less the fossil fuels burned for power generation and so less carbon-dioxide is released into the atmosphere. This reduces dependence on the grid, and in countries with a carbon-tax on CO_2 emissions solar PV electricity generation translates to savings for whole country. One way to achieve a smaller carbon-footprint is through BIPV (Building-Integrated Photovoltaics) which when producing power for the building leads to a reduced dependence of the building on the grid.

2.4.3.7 Smart Grid Applications and Solar PV

Some research show promising advancement of intelligent system technology for smart grids in electricity generations and supply. Smart grid systems are designed to incorporate the existing AC and DC distribution systems together with solar PV systems. The techniques and economics behind the smart grids is focused more on cost effectiveness, efficiency and reducing CO_2 emissions in the electricity power supply and distribution systems. Therefore, the support and investment in developing DC supply and distribution system technology in conjunction with the exploitation of renewable energy sources is required. The technology around renewable energy can be more advanced than fossil fuel related energy supply technologies, especially for generating power to supply electricity for commercial, office and residential buildings (Foss, 2014). The importance of sustainable, low carbon and efficient energy production has become clear to all, as the use of renewable energy has been a prerequisite for many energy production projects. Smart grid technology is therefore becoming a key driver for renewable energy use.

Smart grid can be defined as an electric supply network that uses digital communications technology to detect and react to local changes in usage. Basically the smart grid provides bidirectional interchange, where information and electricity can be relayed between the final consumer and the energy provider. Information from meters and sensors can flow to and from distributed controls through telecommunication. This two way motion also applies to the electricity flowing in the grid. The Smart grid was created to enhance the power system structure, to make the grid more efficient, reliable, secure and greener. It also allows the integration of sustainable power generation technologies like hydro, wind and solar energy to the grid, as well as voltage regulation leading to reduced operation cost based on marginal production costs (Energy, 2016; Olivieri & Rocha, 2013; Phuangpornpitak & Tia, 2012).

The smart grid is composed of; smart meters with features for controlling losses, alarm recording, mass storage, Management of Advanced Metering Infrastructure (AMI) as well as management systems such as Measurements Management System and Distribution Management System. The Measurement Management System collects the meter data of the customer and energy balances. It acts as an interface to the operations by generating and maintaining database management in order to provide information such as customers' bills, and customer behavior to the energy provider (Olivieri & Rocha, 2013). One of the major benefits of the smart grid is the integration of renewable energy generation technologies. In this case, the energy produced is easily scalable such that it can be produced and conveyed within a few kilowatts for residential and commercial use. Large sums of kilowatts can only be considered at utility scale. The modern power generation technology from solar PV is more advanced than the past generation methods. The technology is grid compatible and requires a power electronics interface to convert the format of the generation (Bottaccioli, Estebsari, & Patti, 2016; Phuangpornpitak & Tia, 2012). The performance of a solar PV plant can be monitored and evaluated by a remote monitoring system. The database is obtained from smart meter readings of the solar PV plant in the grid interface, as well as notification of weather conditions through the data capturing system. The use of software can reveal from the hardware and sensors the actual and expected trends of power generation (Olivieri, Rocha, & de, 2013). Integration of renewable energy into the grid can be a great challenge considering present situations across the world. This is due to the reason that technological support like transmission infrastructure is expensive to implement and absence of a regulatory frame work makes the situation even worse. This is discussed in studies carried out in India, where implementation of smart grid projects are hindered by the electricity (amendment) bill 2014 which stated that no electricity from domestic renewable energy source can be downloaded to the grid (Akhil, 2015). In this regard, the implementation of the smart grid with solar PV was theoretically tested in a number of places like Puducherry in India. The study showed that if 5000 consumers installed rooftop solar it could provide 5 MW of power generation support to the Puducherry Electricity Department. This potentially would yield a reduction in transmission losses due to use and generation occurring locally. The study stated that the Renewable Power Obligation (RPO) of 5 MW can be made from the system and the Puducherry Electric Department would have to pay Rs 5.50 per unit of solar power generated when inject it into the grid. This was made on the assumption that the consumers continued paying their consumption charges to the utility as per the existing tariff. This was made possible by the net metering feature of the smart meters enabling the utility to read the import, export and net energy transactions (Kappagantu & Daniel, 2015).

Another case study on smart grid systems was piloted in two residential: PowerMatching City, Groningen (Netherlands) and Pecan Street, Austin Texas (USA) by comparing their energy performance and user experiences. The data were based on 2013 and 2014 consumptions of the households. It was discovered that PowerMatching City consumed on average 2.6 GW h, while Pecan Street consumed 10.1 GW h. Households in Pecan Street generated about 6.8 GW h of electricity, while PowerMatching City generated 1.14 GW h. It was further noticed that households in Pecan Street consumed 8% less electricity with respect to the USA average household domestic electricity consumption of 10.9 GW h; while households in PowerMatching City consumed 19% less with respect to the Dutch average household domestic electricity consumption of 3.1 GW h. It appeared that households in PowerMatching City had a higher potential to contribute to demand and supply balancing in electricity network because of their large reduction in consumption from the grid with self-generation. It was finally concluded that household electricity generation and consumption in smart grid pilot projects and contribution to peak load balancing is highly influenced by the smart grid set-up, local climate and related needs of heating and cooling (Obinna, Joore, Wauben, & Reinders, 2016).

In the state of Oklahoma in USA, a case study was carried out for the purpose of determining the annual cost of electricity for five households, as well as the economics of grid-tied solar panels. In this regard, it was identified that the average annual cost of electricity from the grid with traditional meter was estimated to be $1075 and for similar grid with the smart meter, $1024. On average it cost $65,000 for a 12 kW system, and to be economically competitive with grid electricity provision, the grid prices would have to increase by 420% for the grid with traditional meters and 444% for the grid with smart meters. Similarly for a 4 kW system costs $32,000, the grid price would have to increases by 254% for the grid with traditional meter and 257% for the grid with smart meter rates. It was also noticed that the economic consequences of grid-tied household solar systems differ considerably among locations and that the annual use estimates for households with similar characteristics may differ significantly. Location also matters in electricity generation, as the total annual generation from an identical 4 kW system is estimated to be 18% greater at Boise City in USA than at Miami in USA. The proportion of electricity produced by the 4 kW system that is produced at a time when it can be used by the household ranges from 78% at Idabel in USA to 52% at Boise City. A grid-tied 4 kW system at Boise City would provide 3616 kW h annually to the grid, but an identical system at Idabel would provide only 1412 kW h annually to the grid. The utility providing grid electricity to the households with operating 4 kW solar systems without net metering could expect to receive from $284 to $355 per household annual less gross revenue (Ghaith, Epplin, & Frazier, 2016).

2.4.3.8 HOMER Software Applications

Hybrid Optimization Model for Electric Renewable (HOMER Pro) software is one of the worldwide analyses tools which was found useful to this study. The software was used previously for optimization of a solar PV system in a research study on Prospects of Solar Energy in Bangladesh. The study was carried out by Chittagong University of Engineering and Technology under Department of Electrical and Electronic Engineering (Deb et al., 2013). The study discusses solar PV, solar thermal energy technologies and hydroelectric power as the possible opportunities to implement in Bangladesh, apart from other renewable energy technologies. The optimum capacity, costs, storage system, environmental and economic aspects are outlined as the objectives of the study. The study focused on solar PV system applications for generating power to;

i) drive the easy-bike and two-seated rickshaw vehicles which are designed to run on electric batteries,
ii) water pumps, for irrigation at Sandip-para rural area in Bangladesh.

The first application was designing a solar PV system to charge the two mentioned modes of transport which are commonly used in Bangladesh. The designs were sized using an excel spread sheet tool which calculated the rooftop solar panel capacity required to be installed on the roofs of the filling stations to supply power to the station chargers. It was estimated that the system required 10kW to charge 10 electric vehicles at a time. Therefore, the design estimated the maximum power supply capacity as 15kW and the minimum as 8kW. The minimum solar PV power generation was calculated by considering the average hours with sunshine per month from January to December. These hours were multiplied by 8kW to give minimum power generation per day and again multiplied by number of days in each month to give the monthly power generation. The monthly and yearly income generation of the system were obtained by multiplying the estimated power generations with cost of electricity ($/kWh). The total capital cost of the solar PV components which include installation and operational maintenance were also obtained from local market prices. Finally, the payback period were calculated by considering three estimated charges of electricity costs (low, medium and high).

For the second application, HOMER Pro software was used on the simulation of an irrigation system to be powered by solar PV located in Sandip-para, Bangladesh. In this regard, the geographical locations of Sandip-para area in terms of latitude (22^{o} 28' North), longitude (91^{o} 58' East) and time zone (GMT + 06:00) were provided and used by the software to upload the solar resources input for Sandip-para area. However, the software then generated the averages for clearness index and daily radiations of each month (January to December) in Sandip-para area. In addition, the costs of the system from local markets for the solar panels and storage devices were also provided to the software. These costs are solar panels and storage devices respectively; capital cost ($2250 and $125), replacement cost ($2000 and $100), operational-maintenance cost ($0.25/yr and $2.50/yr) and the size of the PV modules as 1000W. This data was used in the software to simulate the required system and the results presented an optimum system of a total energy demand of 14kWh/day, up to loads of 2.9 kW. Nevertheless, the system net present cost and the levelized cost of energy of the system are not indicated in the study.

A study on designing an optimized solar powered aeration system for a fish pond at Yogyakarta in Sleman District of Indonesia, was also conducted using the HOMER Pro software (Prasetyaningsari, Setiawan, & Setiawan, 2013). The study outlines that one of the problems in fish farming to ensure good fish production is to maintain the quality of the water. Therefore, the aeration process is referred as a necessary technology in order to maintain the water quality. Consequently, the study proposed to design an aeration system for the fish pond which is powered by an off-grid solar electricity system, since it is stated that the pond is located away from power grid lines. It is stated that the Indonesia has an annual solar radiation of 4.5kWh/m^2/day. HOMER Pro software was used to size an economically optimum system. The design process first involved the collection of aeration power data from the project site (Yogyakarta). The software used the power demand data to size a solar PV powered system that meets the total demand load of 1692Wh/day at the lowest levelized cost. The four main components of the solar PV system are shown in Figure 5. The optimum system was a 1kW solar PV system, 8 batteries of 200Ah total storage and a 0.2kW inventor for a levelized cost of $0.769/kWh (Prasetyaningsari et al., 2013).

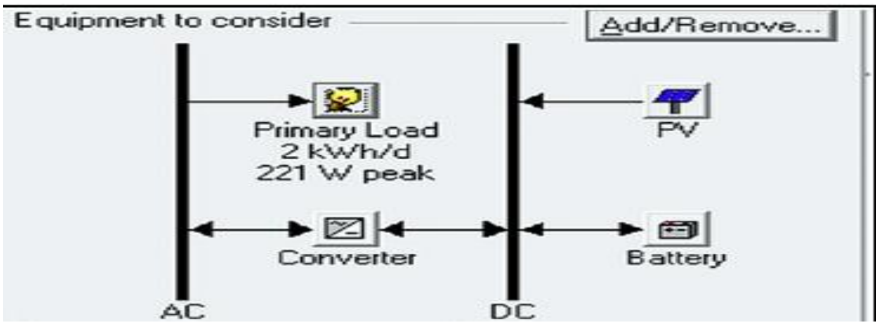


Figure 5:- Schematic diagram of components for an optimum aeration solar PV powered system (Prasetyaningsari et al., 2013)

The same software was used to analyze, compare and contrast several options the lowest life-cycle cost of PV power system for health clinics located in rural areas of southern Iraq (Al-Karaghouli &Kazmerski, 2010). The study outlined that solar PV systems can be suitable to power institutions such as clinics, schools and other social places. The clinic was the preferable institution in this study and its capacity involves; three administration rooms, a nurse’s room, a waiting room, two treatment rooms, a doctor’s room, two rest rooms and a small pharmacy. The clinic rooms are equipped with devices such as a refrigerator (80W), a vaporizer (50W), a water pump (80W), a electric sterilizer (1500W), a freezer (80W), TV set (130W) three evaporative coolers (500W each), fifteen fluorescent lamps (20W each) and seven ceiling fans

(60W each). The power data for the electric devices was collected and the average total electricity load demand per day of the clinic was found to be 31.6kWh/day. The geographical locations of the clinic was latitude (30^{o} 57 North) and longitude (46^{o} 51' East). It is stated that the site solar radiation data, in terms of monthly average solar radiation and clearness index were both obtained from NASA surface metrology and solar energy web site, whereby the yearly average solar radiation of the site was found to be 5.65kW/^{m2}/day.

The optimal system successful meet the total demand (31.6kWh) of the clinic load with the following; 6kW PV modules, 80 batteries with capacity of 225Ah and 6V, and a 3kW inverter. The costs breakdown of the solar PV system was as follows; capital cost US$50,700, produced electricity cost US$0.238/kWh and net present cost US$63,375. The comparative cost of using a diesel generator to meet the same load ie; capital cost US$4500, produced electricity cost US$1.332/kWh and net present cost US$352,303. Therefore, when the interest rate is applied to both systems of solar PV is significantly cheaper than a diesel generator the levelized electricity prices for solar PV was US$0.444/kWh and the levelized cost of diesel generator is US$1.367/kWh respectively. In addition, the analysis shows that when the solar PV system is used instead of the diesel generator, carbon emissions are reduced by of about 15604.88kg/year (Al-Karaghouli & Kazmerski, 2010).

The HOMER software was again used in India to find the cost optimized off-grid renewable oriented hybrid system suitable for generating electricity and for remote rural areas (Sen & Bhattacharyya, 2014). The renewable resources considered were for the hybrid electricity generation system consisting of solar PV, biodiesel generators, wind turbine and small hydro power. The proposed hybrid system was simulated based on data from the case study conducted in Palari village, India. The study highlights that India is facing a significant energy challenge of supplying the reliable power to its large population of about 1.3 billion people. An alternative to tradition power system is to develop the off-grid mixed renewable sources of power generation to supply the remote areas. This was proposed for the reason of avoiding the expensive of extending the grid. Cost data for the grid extension was incorporated in the study for the purpose of making a cost effective comparison to the proposed renewable hybrid electricity generation system. The configured simulation reflected an optimal hybrid system model of renewable sources such as; 30kW small hydro power, 20kW solar PV-array, 10kW biodiesel grid, convertors as 20kW rectifier and 20kW inverter. The cost optimized system did not include wind turbine generation. The cost-effectiveness of the system resulted in a capital cost ($238,000), net present cost ($673,147) and a levelized cost of electricity of as $0.420/kWh. This was cheaper than $0.44/kWh of the grid extension option. In addition, it is also stated that the optimal hybrid system can reduce annual/CO2 emissions by about 33,832kg/yr (Sen & Bhattacharyya, 2014).

The role of gen-set small solar power hybrid systems in Sri Lanka, were investigated for two combination systems and the cost-effectiveness of the systems were compared by using HOMER Pro software. Two systems studied are; simple solar PV-battery system and solar PV-diesel generator-battery system (Givler & Lilienthal, 2005). A case study for data collection was conducted in one of the village in the remote areas to establish demand. The study highlights that solar PV systems are more favorable to rural areas in terms cost-effectiveness compared to extending the electricity grid. This is because most rural loads are minimal and basically dominated by domestic equipment which just requires a minimum electricity supply capacity. In this regard, an off-grid solar PV system has lower cost compared to the stand alone on grid extension option diesel generator system. This is due to the high operation, maintenance and fuel costs of the diesel generator, The combination hybrid of solar PV, batteries + diesel generator the two systems is even more cost-effective and reliable than either a stand alone solar PV system or a diesel generator, as well as grid extension. For the optimal case power peaks in cloudy weather will be sustained by power generated by the diesel generator and the battery bank rather than solar PV. This was proved by the model is illustrated in Figure 6 which directly taken from the HOMER Pro software display.

The HOMER pro analysis indicated that the stand alone solar PV system can only be cost effective with a levelized energy cost of $0.85kWh when supplying the minimal loads up to 3.5kWh/day. At any point where the load is higher than 3.5kWh, the solar PV-diesel generator-battery bank hybrid system is required and the effective with very low levelized cost of energy is 0.302 KWH up to loads of 0.07KW (Givler & Lilienthal, 2005).

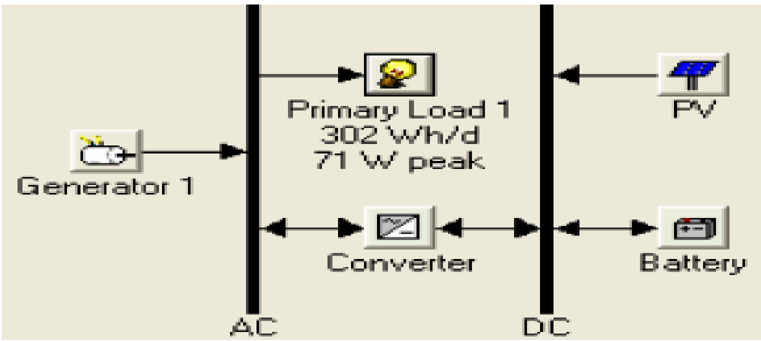


Figure 6:- HOMER Pro simulated combined model of simple solar PV-battery system and solar PV-diesel generator-battery system (Givler & Lilienthal, 2005)

2.5 Studies on Regional Planning for Clean Energy

2.5.1 General Information on CEPA and EROI Methods

Carbon Emission Pinch Analysis (CEPA) and Energy Return on Investment (EROI) methods have been useful tools to be used for the clean energy planning in the electricity and transport sector. In general, CEPA and EROI are methods that are used in the planning phase for determining a viable clean energy solution, not only in terms of reduction of greenhouse gases but also in terms of the cost of implementing and operating the clean energy solution. CEPA utilizes the use of composite curves in order to determine the optimal conditions needed to satisfy the desired outcomes. EROI on the other hand shows whether the ratio of the energy used and the energy produced by the system is economical viable. In most of the existing modern methods, the Pinch analysis is typically applied to heat integration analysis in processing plants. It has an 'intuitive appeal' and is excellent in visually communicating energy data and research results to the 'decision makers and stake holders. The idea of presenting process streams to be heated (demand) versus process streams to be cooled (supply) as temperature - enthalpy composite curves was developed in the 1980s (Berry & Linoff, 1980). This method, uses a graphical style of determining the pinch point or constraint between the energy supply and demand (Tan & Foo, 2007).

Table 1 and Figure 7(a) and (b) outline the example case scenario on how the CEPA method can be used to estimate and construct the composite curves of electricity demand and supply together with carbon emission reduction. In this case, Table 1 summaries the data for the electricity demands & supply, emissions and emission factors of the case scenario. The same data is plotted in Figure 7(a) which illustrates the supplies of electricity energy generated from renewables (300 GWh), fuel A (400 GWh) and fuel B (300 GWh). These fuel energies are used to supply an energy demand of the industrial (350 GWh) and residential & commercial (650 GWh) which produce a total emissions of 1000 $ktCO_2$-e. Therefore, Figure 7(b) indicates the reduction of the emissions from 1000 ktCO2-e to 400 ktCO2-e through the application of CEPA on fuel B by keeping the same electricity generations of fuels supply. Table 2 and Figure 9 illustrate CEPA and EROI applications which emphasizes on whether the projected new energy generation can be economical viable (M.R.W Walmsley et al., 2014).

Table 1: Example case scenario of electricity supply and demand as well as carbon emissions reduction of fuel A and B (M.R.W Walmsley et al., 2014)

	Quantity (GWh)	Emissions ($ktCO_2$-e)	Emissions Factor ($ktCO_2$-e/GWh)
Demand			
Industrial	350	350	1
Residential & Commercial	650	650	1
Total Demand	**1000**	**650**	
Supply			
Renewables	300	0	0
Fuel A	400	200	0.5
Fuel B	300	800	2.67
Total Supply	**1000**	**1000**	

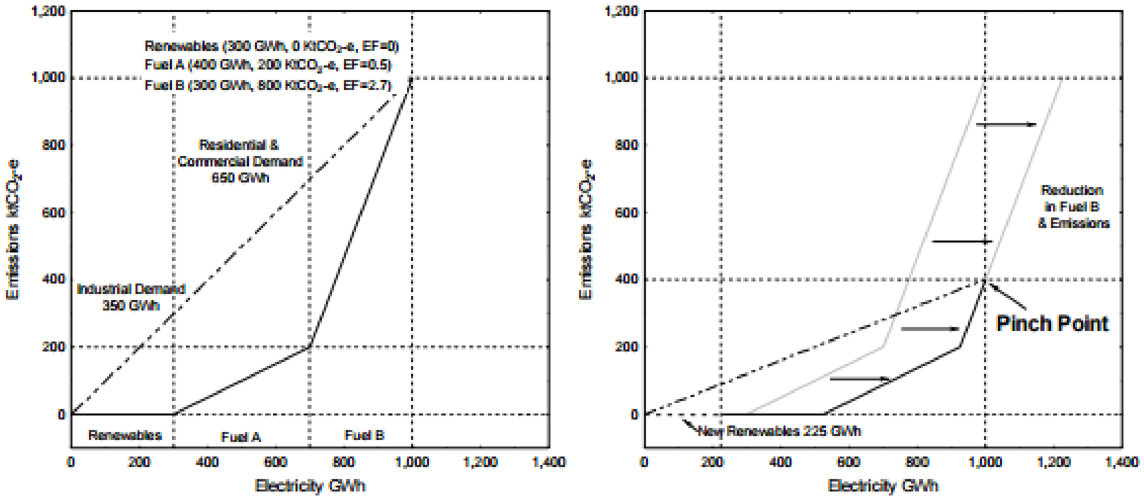


Figure 7: - Example case scenario of electricity supply and demand composite curves as well as carbon emissions reduction of fuel A and B (M.R.W Walmsley et al., 2014)

2.5.2 Case Studies on the Application of CEPA and EROI Methods in regard to Clean Energy Sector Planning

The graphical method of CEPA was used in study that was conducted on the production of phytochemical extracts and bulk chemicals. The application of the CEPA method was aimed at finding possible areas where the carbon footprints were reduced in a more economically viable way. The study focused on two industrial case studies in which one involved the production of a Tongkat Ali extract process and the other chlor-alkali chemicals (Tjan, Tan, & Foo, 2009). The Tongkat Ali extract process case study was carried out at the Chemical Engineering Pilot Plant (CEPP), Universiti Teknologi Malaysia, Jahor, Malaysia whilst the chlor-alkali case study was taken from a company based also in Malaysia. For the Tongkat extraction process, the total carbon footprint for the material was determined to be 13.7 t CO_2/month. The set goal was to reduce the footprint by 10% which corresponds to a reduction of about 1.4 t CO_2/month. The CEPA method showed that in order to achieve this a cleaner electricity source should be used¬ like biomass. However the economic feasibility of switching to such a fuel is questionable. It was then suggested that, an oil fired boiler could be used as an alternative but it only allowed up to an 8.8% reduction in emissions (Tjan et al., 2009).

The second case study which involved the analysis of the chlor-alkali production plant showed that the total carbon footprint of this plant was 4115 CO_2/month. It too had a goal of reducing the emissions by 10%. To achieve this, it was suggested to use a cleaner energy source like biomass in steam generation. Another alternative was to replace the electrolytic cells of the plant which were the largest consumers of power. Using Biomass as a clean energy source and replacing the cells helped the plant meet the 10% reduction in greenhouse gas emissions (Tjan et al., 2009).

CEPA and EROI methods were also used in a study conducted in California. California is part of the members coordinated by Western Electricity Coordinating Council (WECC) in the United States of America. The aim of the study was to successfully reach the Renewable Portfolio Standard (RPS) target by 2020. The study showed a successful reduction of carbon emissions through an estimated implementation of 33% of renewable energy to their electricity energy mix. The challenge to maintain their high EROI levels of electricity generation is also indicated in Figure 9. In this regard, CEPA and EROI methods estimated the needed solar and wind resources in order to meet the target of RPS in California. Figure 8 shows CEPA method applied to construct a composite curve which indicates that 80Mt CO_2-e (29.4% decrease) can be achievable by switching the use of coal energy to natural gas.

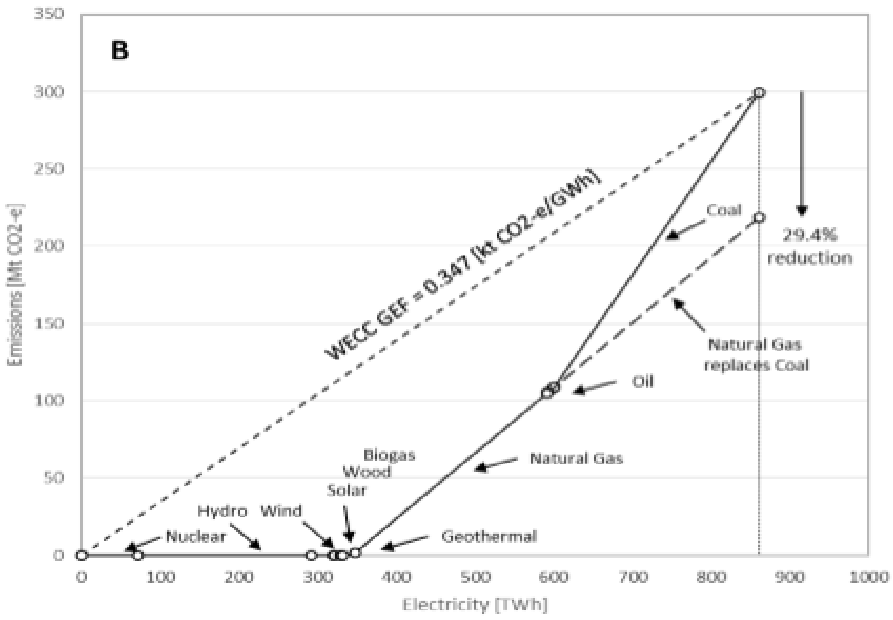


Figure 8:- WECC Emissions for Electricity Generation in 2010 and Reduced Carbon Emissions (M.R.W Walmsley et al., 2014)

Table 2 outlines the summary of the findings of the four scenarios of California regarding the Projected expended energy for new generation to meet low and high electricity demand growth in 2020 and 2020 low growth with natural gas (NG) in place of new solar (M.R.W Walmsley et al., 2014) using CEPA and EROI methods.

Table 2:-Shows findings of CEPA and EROI analysis results of the four scenarios of California

Scenario	In-State [TWh]	Emissions [Mt CO_2-e]	%Δ Emiss.	GEF	RPS [%]	EROI	2018 Cost [$/MWh]	%Δ Cost
1990	173	39.7	0	0.230	-	-	-	-
2010 (base)	205.7	50.6	27	0.246	15.1	11.4	163	0
2020 Low (NG)	231.3	52.2	31	0.226	20.9	11.94	155	-4.9
2020 Low (Coal)	231.3	61.4	55	0.265	21.1	12.6	146	-10.4
2020 Low (Solar)	231.3	39.7	0	0.172	34.0	10.5	176	8
2020 High (Solar)	250.3	39.7	0	0.158	39.0	10.2	181	11

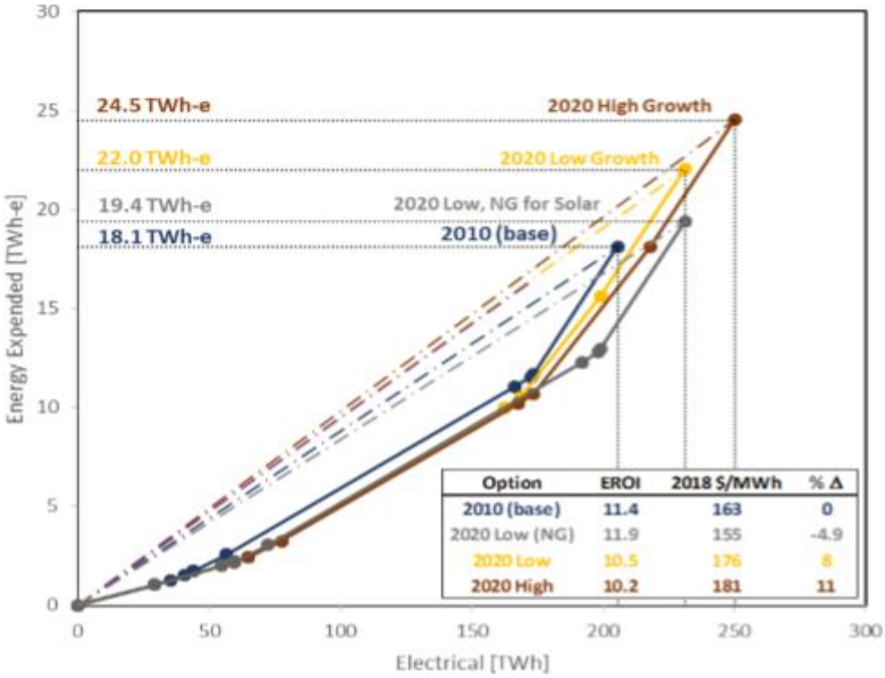


Figure 9:- Projected Expended Energy for new generation to meet low and high electricity demand growth in 2020 and low growth with natural gas (NG) in place for new solar (M.R.W Walmsley et al., 2014).

A feasibility study in New Zealand was also conducted using CEPA and EROI methods where by a target of 90% of renewable electricity generation by 2050 was achieved. At the same time allow for use on 50% of hybrid plug-in electric vehicles on light passenger in the transport sector. It also showed an annual rate of 1.5% increase in the production of electricity. In this regard, the composite curves of CEPA and EROI analysis indicated that the future targets of electricity generation and maintaining low emissions can be positively achieved with economical desirable levels of EROI. This is based on the facts of the results that the projection of New Zealand's electricity generation is between 70 and 75TWh by 2050. However, the capacities of 18TWh (wind), 13TWh (geothermal) and 5.6TWh (hydro) will outstrip the increase in electricity production. The energy expended will also minimized with respect to 1990 levels of carbon emissions constraints. The data results of the study are summarized in table 3 and their constructed composite curves are illustrated in Figures 10, 11, 12 and 13 (Michael R.W Walmsley et al., 2014)

Table 3: Summary of electricity capacity and generation in 2011 and new electricity capacity and generation needed to meet the demand for 2025 and 2050 in New Zealand (Michael R.W Walmsley et al., 2014)

	2011		2025 A		2025 B		2050 A, C		2050 B	
	Capacity MW	Gen. GWh	Capacity MW	Gen. GWh	Capacity MW	Gen. GWh	Capacity MW	Gen. GWh	Capacity MW	Gen. GWh
Wind	750	1931	800	2102	200	526	3000	7884	3000	7884
Hydro	5670	24831	300	1314	150	657	600	2628	600	2628
Geothermal	730	5770	600	4730	200	1577	600	4730	600	4730
Other renewables	300	627	130	654	60	319	750	2046	750	2046
Gas	1300	7955	-	-	-	-	1000	6132	100	613
Coal	350	2026	-	-	-	-	-	-	-	-
Total	9100	43138	1830	8801	610	3079	5950	23421	5050	17902

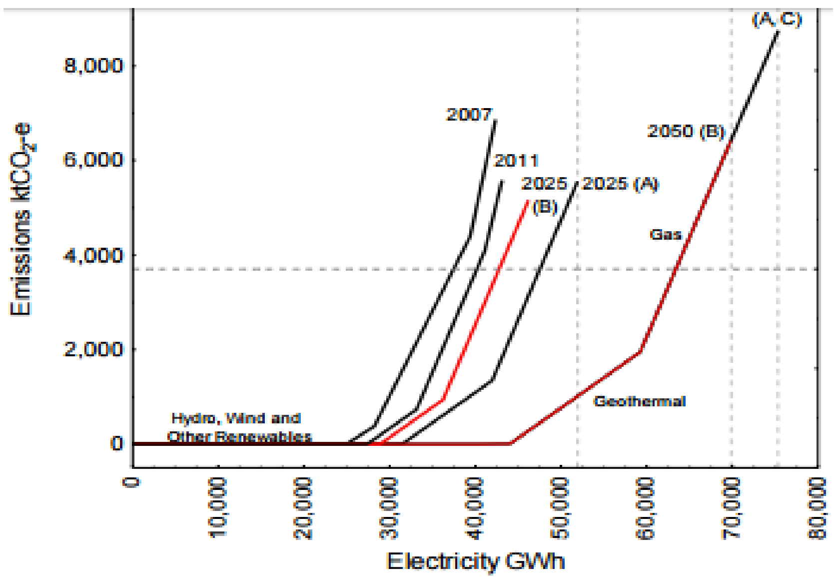


Figure 10:- Projected Composite Curves of electricity generation growth needed to meet the demand for 2025 and 2050 in New Zealand (Michael R.W Walmsley et al., 2014)

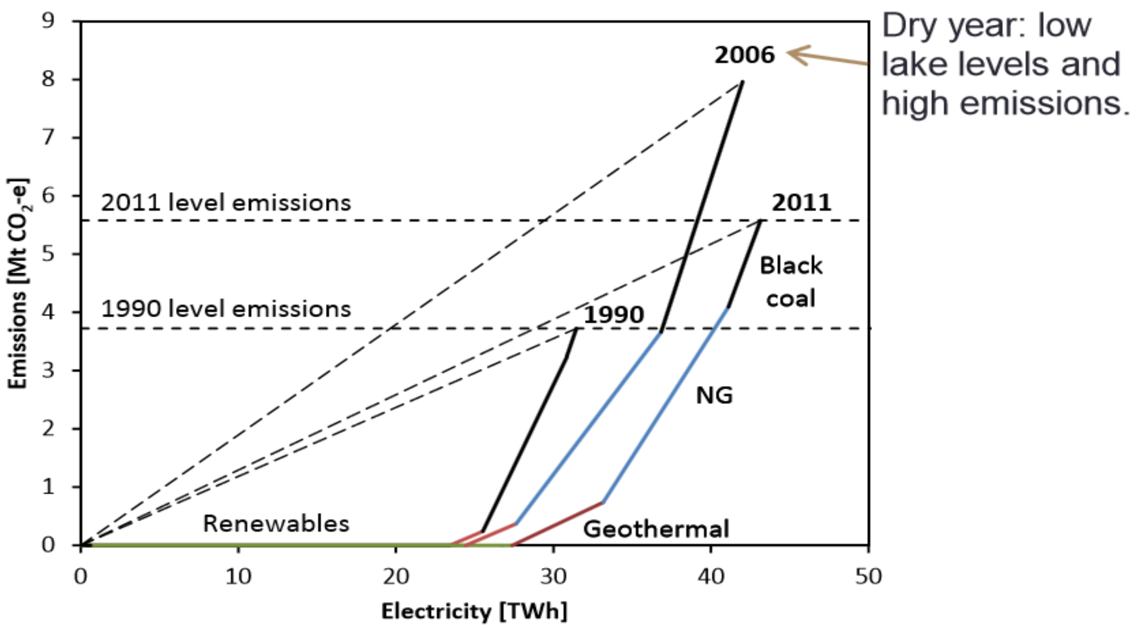


Figure 11:- CEPA showing New Zealand Electricity Supply and Carbon Emissions in 1990, 2006 and 2011 (Michael R.W Walmsley et al., 2014).

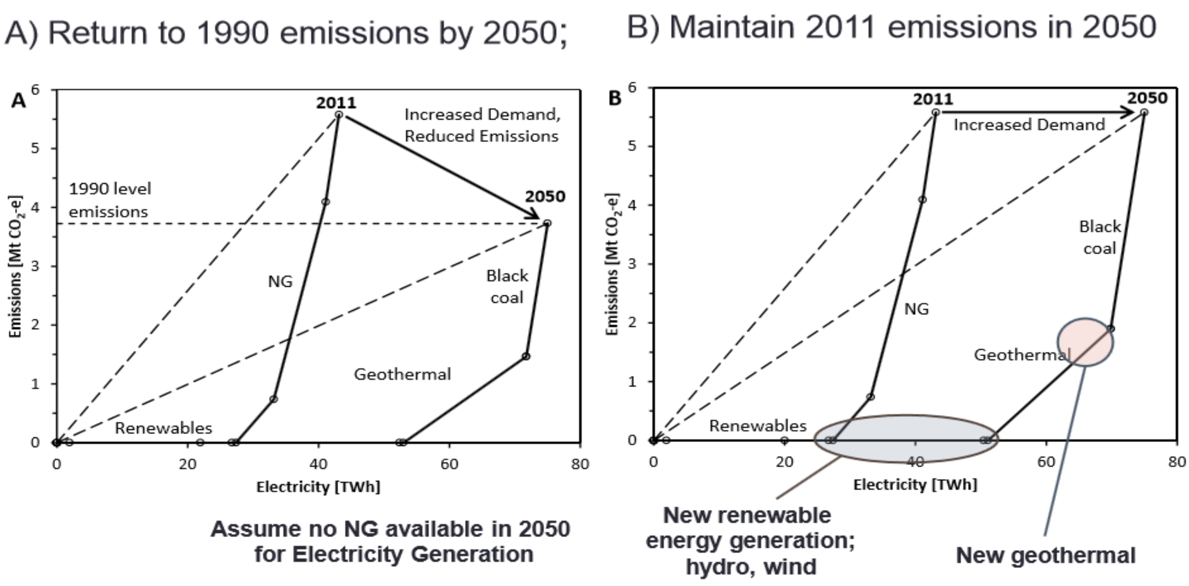


Figure 12:- CEPA showing the transitioning from 2011 to 2050 of different fuel resources and emission targets (Michael R.W Walmsley et al., 2014)

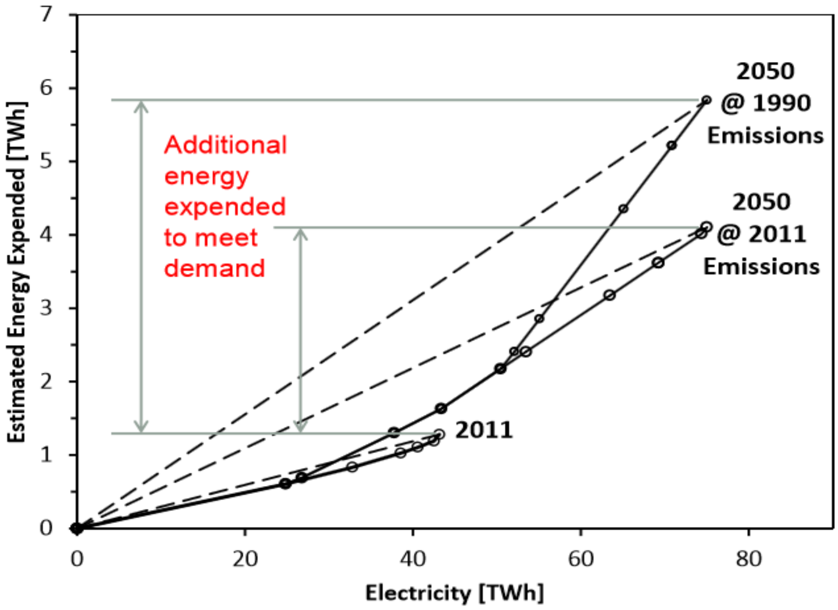


Figure 13:- EROI showing the energy expended for electricity generation in 2050 (Michael R.W Walmsley et al., 2014)

The CEPA method was also applied to the transport sector in Iskandar Malaysia. The study illustrated the reduction of energy demand from various modes of transportation in order to meet the emission reduction set target by the Malay government (Ramli, Muis, & Ho, 2017). They were to compare four different scenarios to demonstrate how transportation policy of Malaysia can affect the total fuel usage, total emissions and total cost of transportation. The government had set an emission target of 1100 kt CO_2. The first scenario was one where no policy was applied. The second was the current one which had been proposed by the government. The third one involves the use of electronic vehicles as part of the transportation mix. The fourth scenario is focused on the use of all options in to help in reduction of CO_2 emissions.

Table 4 below shows the projected population growth for the year 2025 as well as the expected energy demand. The modes of transport are divided into four categories and Table 5 shows their prospective policies in terms of fuel usage details for the year 2025. This is the data that was be used for the CEPA for Iskandar Malaysia for the year 2025. A target of 40% reduction by the year 2025 of the 2005 emission level was set (Ramli et al., 2017).

Table 4: Projected Data of Population Growth and expected demand for Iskandar Malaysia for 2025 (Ramli et al., 2017)

	2005	2025
Population	1353202	3,005,815
Passenger Transport demand (mil pass-km)	3816	8,677
Energy demand passenger (ktoe)	359	790
GHG emission passenger (kt CO_2)	1015	1,672

Table 5: Transportation data by mode and fuel type for Iskandar Malaysia in 2025 (Ramli et al., 2017)

Transportation Type	Fuel Type	Total Fuel Usage (TJ)	Transport Demand (Million passenger-km)	CO2 emission factor (t CO2/TJ)	Total emission factor (kt CO2)
Motorcar	Gasoline	1076.00	91015	68.60	73.82
	Diesel	661.51	559.80	73.33	48.51
	Natural Gas	12.56	10.63	55.82	0.70
Motorcar	Gasoline	13657.34	3342.63	68.60	937.03
	Diesel	8373.60	2051.48	73.33	614.65
	Natural Gas	150.72	36.89	55.82	8.41
Bus	Gasoline	452.17	609.12	68.60	31.02
	Diesel	276.33	372.24	73.33	20.26
	Natural Gas	419	5.64	55.82	0.23
Railway	Electricity	37.68	1222.00	0.00	0.00

The data from Table 4 and 5 was analyzed by constructing the graphical curves using the CEPA method as illustrated in Figures 14 and 15. The CEPA analysis showed the integration of all transportation prospective policies, including electricity for rail and motorcars plus natural gas buses gives a reduction in emissions. In this regard, the CEPA method was sufficient in illustrating the minimum amount of energy need to be reduced for each mode of transport to achieve the new transportation demand and new emission set target. (Ramli et al., 2017).

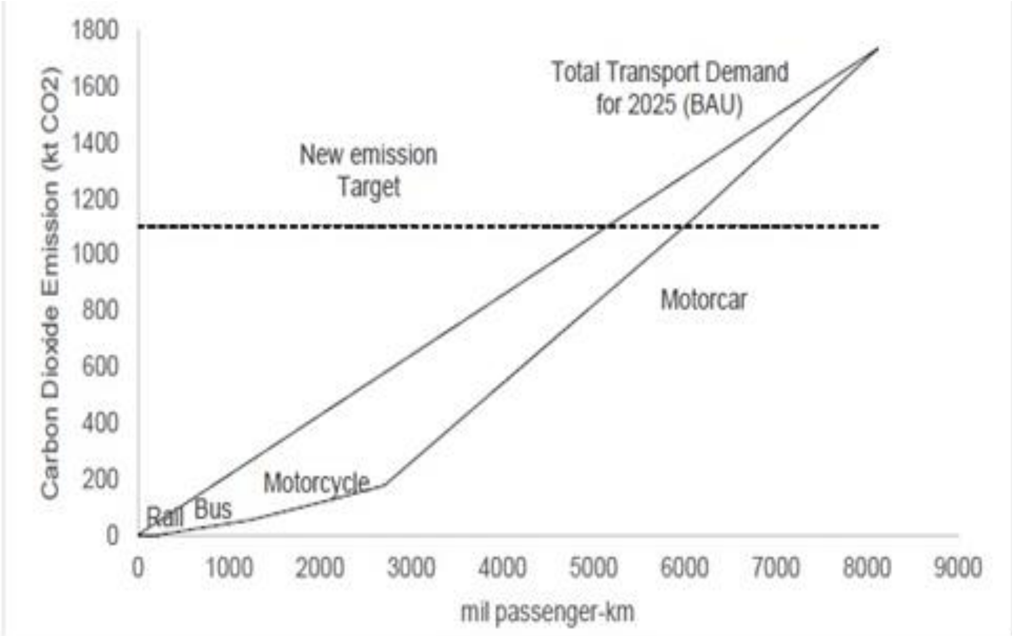


Figure 14:- Transportation demand in year 2025 for business as per usual scenario for Iskandar Malaysia in 2025 (Ramli et al., 2017)

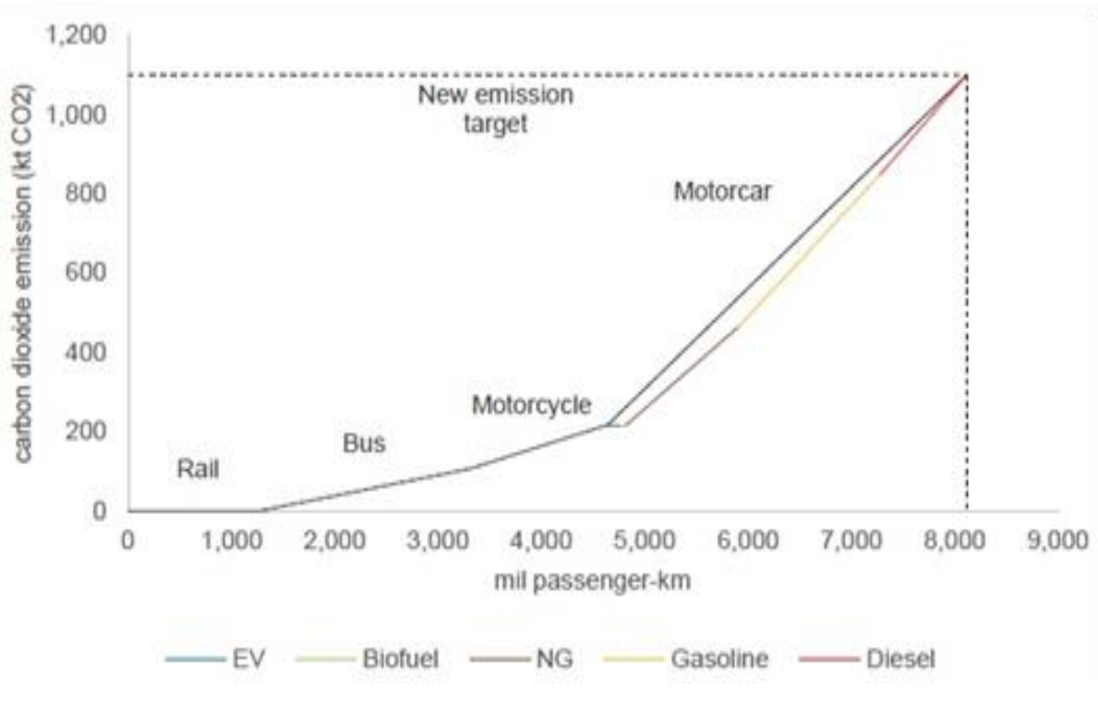


Figure 15:- Transportation demand for Iskandar Malaysia by integration of all carbon footprint reduction policies in 2025 (Ramli et al., 2017).

In a study conducted at State University of New York in USA, they defined the Energy Returned on Investment as a simple ratio between energy use and energy out of the system, in order to determine the economical viability of the desired system. Where the system boundry is drawn can have a significant effect on the ratios and this has made EROI studies have very varying results which in turn subjects the method of EROI to a lot of controversy. This problem tends to arise from the fact that there is some variations in the choices of the direct and indirect costs associated with the production of energy from its source. The choices in the costs considered affect the denominator in the EROI ratio formula. Since different studies consider different types of costs, the resulting EROI numbers vary (Hall, Lambert, & Balogh, 2013).

Researchers have tried to compensate for these potential differences by categorizing the EROI formulas according to the choice in costs;

i) Standard EROI: it divides the energy output by the sum of the direct and indirect cost
ii) Point of use EROI: it includes the cost of refining and transporting the fuel
iii) Extended EROI: it considers not only the energy required to extract the energy but also the use of a unit of energy
iv) Societal EROI: it is the overall EROI determined by getting the sum of all the gains and all of the costs of getting those energy gains

Furthermore, a case study was conducted that focused on the costs of energy for various developed countries in relation to their GDPs. The data collected for the study was from various sources. This created some difficulties in getting consistent results since not all countries collected the same kind of data for the EROI analysis. The findings showed varying EROI numbers for different countries and as well as the trends of the EROI numbers over time. The study found that the general global trend in EROI values for Oil and Gas is a decrease over the years. A similar trend has been found with the coal industry for the US and China. In the study the main conclusion was that the decline in EROI values of many non-renewable fossil fuels was due to the fact that the energy needed for extraction of the fossil fuel continues to increase over time (Hall et al., 2013).

CHAPTER 3: METHODOLOGY

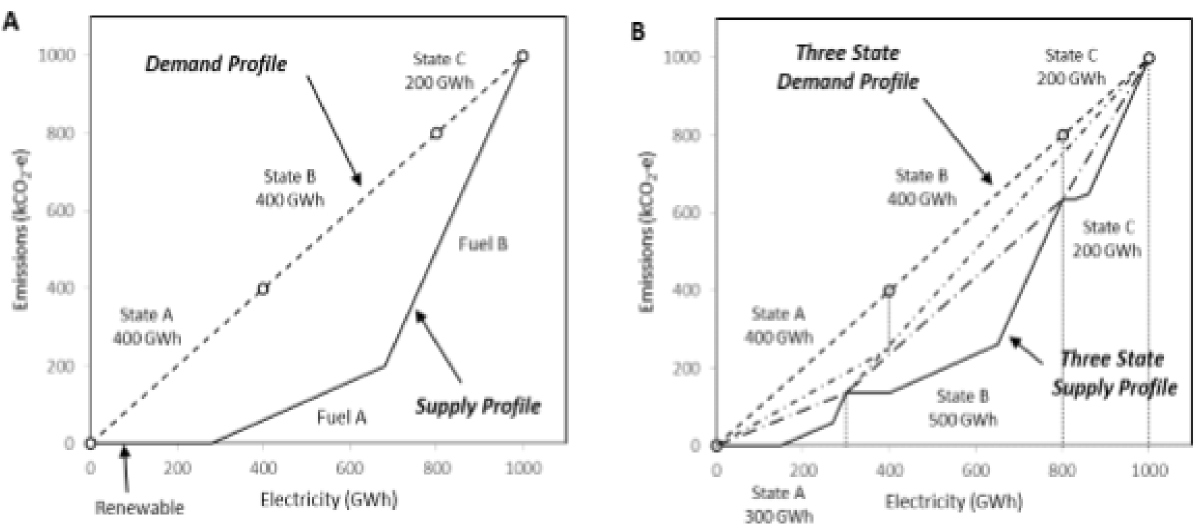
3.1 Carbon Emission Pinch Analysis (CEPA) Method

CEPA is a technique which was first developed by Tan, Foo, and co-workers (Tan & Foo, 2007). The method is used to analyze emissions constraints on various energy sectors and for clean energy planning. The method requires quantifying data on energy supply and demand by sector as well as imports and exports in order to plot simple composite curves. These composite curves define the total equivalent emissions of a particular operational system. For example, the data provided in Table 6 can compose curves illustrated in Figures 16a, 16b, 16c and 16d. Figure16a illustrate how the CEPA method is applied to electricity demand in three states and overall supply using renewables and two fuel types .For the three states A, B and C, there is an associated total emissions of 1000 kt CO_2 for a combined electricity production of 1000 GWh. Fuel B has the highest emission factor of 2.5 kt CO_2 /GWh followed by fuel A with 0.5 kt CO_2 /GWh and the renewable energy at 0 kt CO_2 /GWh. The breakdown of supply and demand profiles for each state is also presented in Figure 16b ,For in state generation the Gross Emission Factors (GEF) for state A,B and C are 0.3, 1.0 and 2.0 kt CO2-e/GWh respectively (Michael R.W Walmsley et al., 2014).

However the electricity supply for State A has a combined GEF of 0.55 kt CO2-e/GWh, total made up of the average GEF of the remaining States B and C network and the GEF of in-state generation in state A Similar emission analysis can be made for the other two states Band C and depending on the political nature of the union of the two state, GEF can be combined or treated separately. Emissions can be reduced through electricity generation from renewables to replace 160GWh electricity generation of fuel B the higher, if the new emissions target is 600 kt CO2-e/GWh. If a 40 emissions reduction is required by all three state how this can be achieved is graphically illustrated using the CEPA method in Figure 16c. This is also illustrated in figure 16d for the use in each state with renewable generation of 30GWh in State A, 80GWh in State B and 50GWh increase in State C (Michael R.W Walmsley et al., 2014).

Table 6:- Example of multi-state demand and supply composite curves (a) overall profiles, (b) individual state profiles (Michael R.W Walmsley et al., 2014).

	Quantity [GWh]	Inter-State [GWh]	Emissions [kt CO_2-e]	Emissions Factor [kt CO_2-e/GWh]
Demand				
State A	400		90	0.3
State B	400		510	1.0
State C	200		400	2.0
Total Demand	**1000**		**1000**	1.0
Supply to State A				
Renewable	150		0	0
Fuel A	120		60	0.5
Fuel B	30		75	2.5
Total Supply to A	**300**	**100 (imports)**	**135**	0.45
Supply to State B				
Renewable	100		0	0
Fuel A	250		125	0.5
Fuel B	150		375	2.5
Total Supply to B	**500**	**-100 (exports)**	**500**	1
Supply to C				
Renewable	30		0	0
Fuel A	30		15	0.5
Fuel B	140		350	2.5
Total Supply to C	**200**		**365**	1.825
Total Supply	**1000**		**1000**	1.0



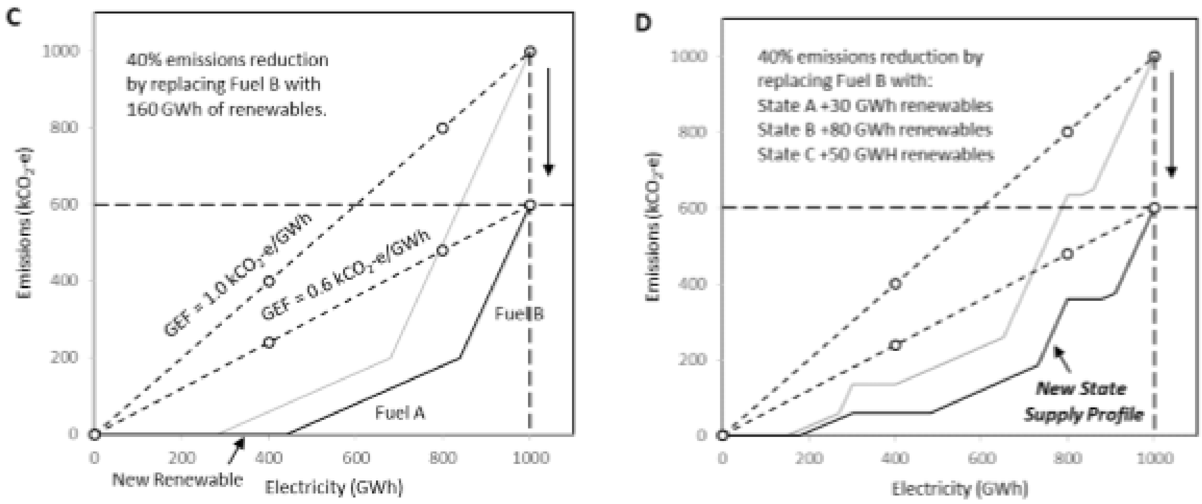


Figure 16:- Example of multi-state demand and supply composite curves (a) overall profiles (b) individual state profiles (c) 40% emissions reduction due to renewable and (d) state profiles for 40% emissions reductions (Michael R.W Walmsley et al., 2014)

While the CEPA method illustrate options for reducing carbon emission ,it does not reveal anything about the economic trade-off involved in switch fuels or energy resources .To better account for the economic trade-off to lower emissions, one method is to consider the energy foot print of the different electricity generation methods. This has been done in this thesis through using energy return on investment (EROI) approach.

3.2 Energy Return on Investment (EROI)

EROI is an energy ratio that provides a measure of the expected energy output for a given energy input to a system excluding the fuel. The ratio is different for different electricity generation technologies and can be used in a way to quantify the amount of energy a country must invest (the energy expended) to generate the energy they need to use (energy output). Therefore aim of using the EROI identify the most desirable technology for a country to invest in emission reduction in the future .The EROI for fossil fuel, electricity generation is generally considered to be geographical independence .The large plant required for typical Rankin cycle coal fired power generator or Bryton cycle gas turbine power generator, or the combination of the two, combined cycle gas turbine has expended energy values that don’t change with location. Electricity output is also independent of location and climate condition conditions .For similar technologies and fuel the EROI values are similar all around the world .For renewable electricity generation the EROI values are far more variable and depends on climate and hence geographic location. (Michael R.W Walmsley et al., 2014). Figure 17 shows the Sankey diagram which illustrates the energy process of a system whereby the EROI equation 1 is derived with and without carbon capture storage (CCS).

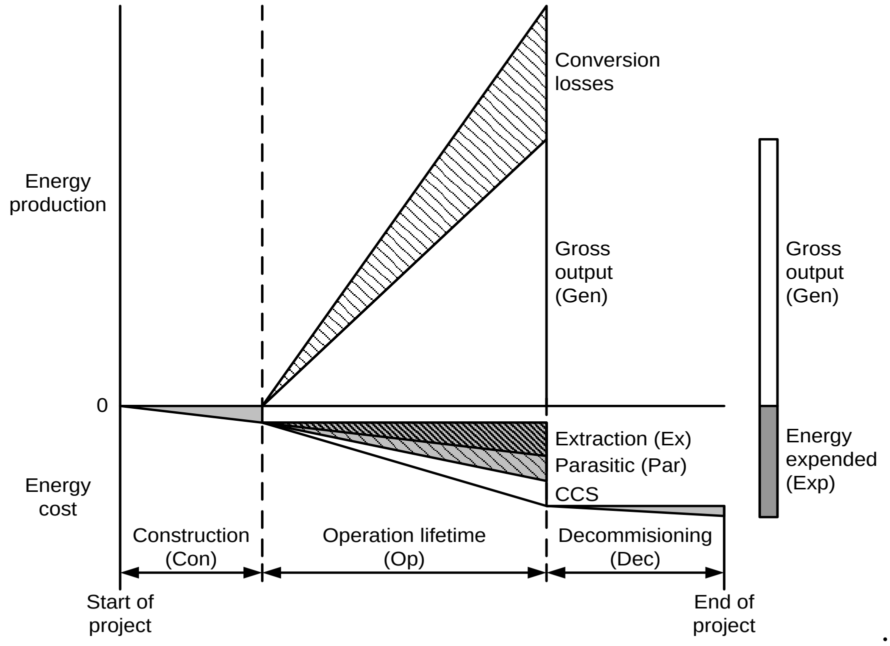


Figure 17:- Expression of the EROI equation 1 in terms of energy generation and expended across the lifetime of a typical energy generation project (Michael R.W Walmsley et al., 2014)

EROI equation 1 can be fully defined and expressed as;

$$EROI = \frac{\dot{E}_{use}}{\sum \dot{E}_{exp}} = \frac{\dot{E}_{use}}{\sum \left(E_{con} + E_{dec}\right)/t_{life} + \dot{E}_{ex} + \dot{E}_{pro}} \qquad (1)$$

Where E_{use} is the energy generated from the plant system but excluding the regenerated energy from waste heat of the plant. E_{exp} is the total energy expended, which is the sum of E_{con} and E_{dec} over t_{life} plus E_{ex} and E_{pro}. E_{con} is the energy used in construction of the pant embedded energy in the capital and work of the construction, E_{dec} is energy used in decommissioning, t_{life} is the plant life span, E_{ex} is the energy used for extraction and E_{pro} is the energy used for processing natural resources. EROI also relates to levelized costs on the assumption the expended energy will contribute significantly to the life cycle cost of the electricity generating technology Walmsley et al have proposed the relationship in equation 2 based on levelised cost data for California in 2014 using equation 2 ;(Walmsley 2014)

$$EROI = \frac{1850\left(\$/\text{MWh}_{exp}\right)}{C_{levelized}\left(\$/\text{MWh}_{gen}\right)} \qquad (2)$$

Therefore, with given energy use and expended energy data, Equation 1 can be applied or with given levelized cost value equation 2 can be used to determine the EROI value of an energy resource or technology. EROI value can be over a range. High EROI means that the analyzed energy resource has a lower levelized cost, which indicates that the energy resource is economically favorable. For example, energy resources which can present high EROI include; coal, natural gas and large-hydro energies. This is because the resources have a high EROI which enables conversion into work without the need for lots and lots infrastructure like with solar PV. Also their technologies are well established and have long been through significant improvements .(Michael R.W Walmsley et al., 2014).

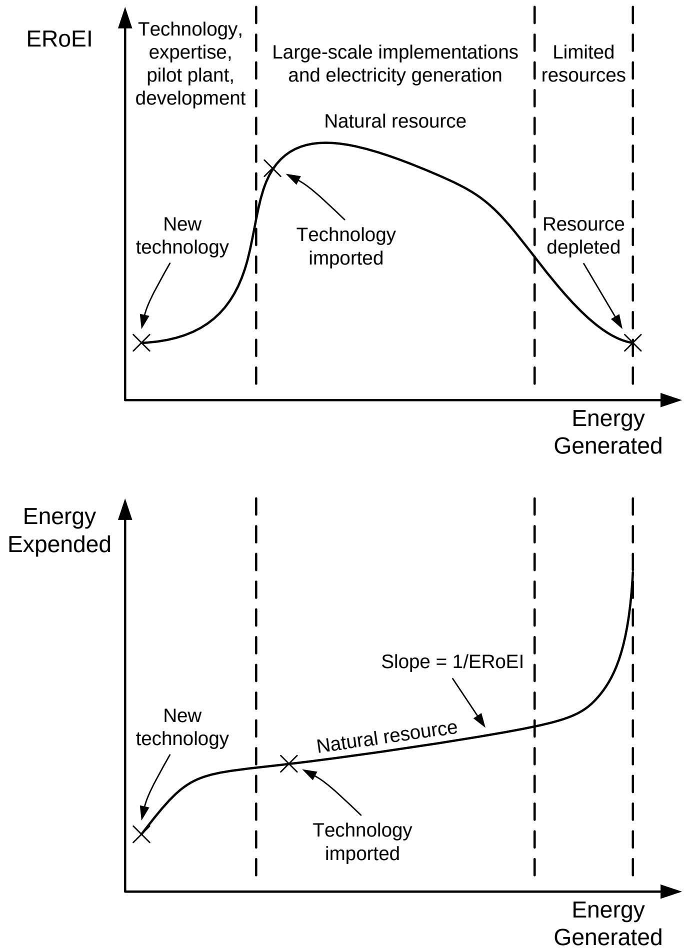


Figure 18:- Influence of technology development and availability of natural resource on EROI and the energy expended to utilise the resource respectively

Low EROI means that the analyzed energy resource has higher levelized cost and it's an indication of a less economically favorable energy resource. For example, resources which can present low EROI at this period of time include; solar, wind and small-hydro energies. This means that the resource or technology needs an attention in terms of its improvements in order to raise its EROI however there are natural limits as explained by the concept of energy quality or the second law of thermodynamics. (Michael R.W Walmsley et al., 2014). Table 7 shows the EROI values with the corresponding emissions factor and levelized costs of the generation types and energy resources respectively. These emissions factor are treated as standardized values with respect to the generation type. In this regard, with the given levelized costs of certain energy resources as highlighted in Table 7 the EROI values can be determined using Equation 2 Figure 19 (M.R.W Walmsley et al., 2014).

Table 7:-Emissions factor and EROI values (M.R.W Walmsley et al., 2014)

Generation Type	Emissions Factor [kt CO_2-e/GWh]	Levelized Cost (Ave) [2018$/MWh]	EROI [GWh/GWh-e] Low	Average	High
Large Hydro	0	66	3	28	77
On shore wind	0	69	7	28	41
Coal (*conventional)	0.733	74	20	25	30
Small Hydro	0	84	2	22	69
Geothermal	0.128	123	6	15	26
Natural Gas	0.422	142	7	13	25
Biomass	0	154	5	12	47
Off shore wind	0	206	4	9	19
Wave/Tidal	0	264	3	7	17
Nuclear	0	370	2	5	10
Solar PV	0	308	3	6	14
Solar PT	0	308	3	6	15

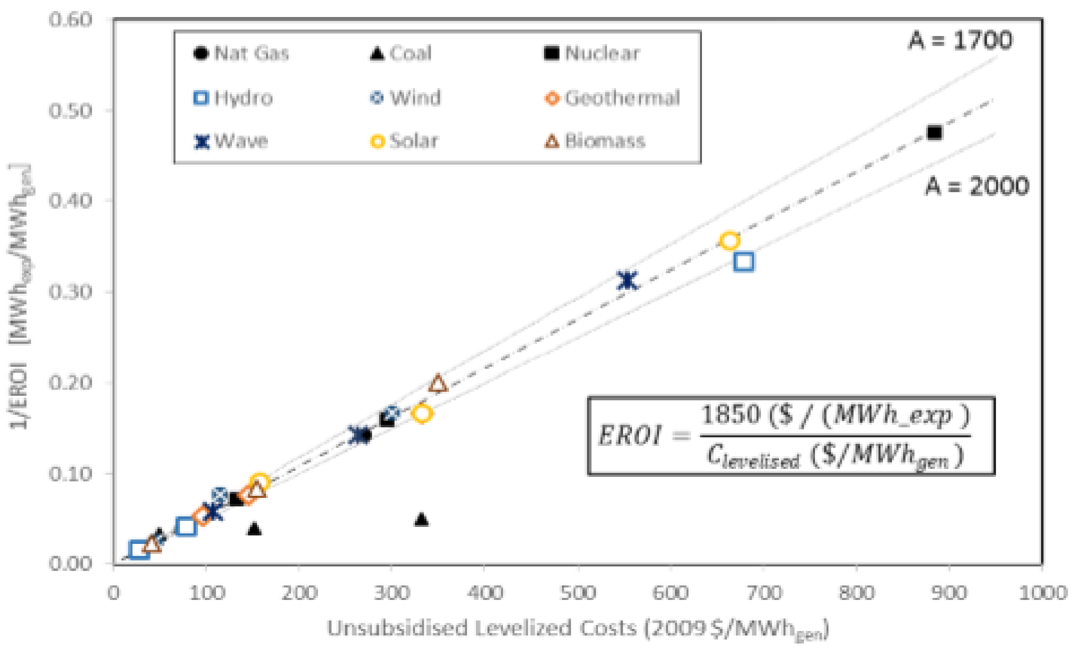


Figure 19:- Relationship between EROI values and levelized costs for different electricity generation options in California (M.R.W Walmsley et al., 2014)

3.3 Solar PV System Design Principles

The solar PV system design principles together with HOMER Pro software were found to be useful to this study in terms of estimation of the size of the system required to suit the parameters of a given building (Hussein, Khatiba, & Sopianb, 2013; Kaushika & Anil, 2006; Skunpong & Plangklang, 2010). The parameters required for pre-sizing the effective solar PV system started from establishing the geographical coordinates of the area where the building is located. Then collection of data of the annual global solar radiation (kWh/m2/day) of the same area. This will be followed by collection of all required information to determine energy demand energy used by equipment either in the building, power station, village or whatever is considered. Lastly the solar system components for energy supply is decided. The requirements can be outlined in details as follows;

3.3.1 The Site Solar Radiation Record

The actual sunshine can be recorded manually from the site but NASA satellite is the best tool used to download the solar radiation measurements of the site. Its advantage is that it can show the annual record of the solar radiation of a particular year needed for assessment (Hussein et al., 2013; Kaushika & Anil, 2006; Skunpong & Plangklang, 2010).

3.3.2 The Sizing Process

The sizing process is the setting up of the desired or an effective solar PV system. This involves the well sized parameters from the type of equipment used to the sizes of all components of the system needed (Skunpong & Plangklang, 2010). Therefore, the following process is considered;

i) the types of equipment that make up the system was selected.
ii) the average energy (kWh/day) required to operate the desired equipment or appliances
iii) the energy losses that occur in the solar PV system that can reduce the energy available for the appliances
iv) calculate the size of solar panels, inverter and other components that will be needed to meet the required load
v) calculate the size and type of the battery that will be needed to provide needed reliability of power

Therefore, the whole set up or designing process of the solar PV system involves the equations that are derived from the energy balance equation (Energy demand ≤ Energy Supply) (Skunpong & Plangklang, 2010) as follows;

3.3.3 The Energy Balance Derived Equations

Where;

Q is the Quality Factor of the Solar PV array

E_{load} is Real electricity output energy [Wh]

E_{th} is Theoretical output energy of the System[Wh]

E_{glob} is Global radiation of the site [Wh/m^2]

A_{array} is Area of PV array [m^2]

ή is Efficiency of the PV array [Decimal]

I_{STC} is Global radiation under Standard Test Condition-STC [1000W/m^2/day]

P_{peak} is Peak Power of PV array [W]

C_B is Battery capacity [Wh]

$E_{design\ load}$ is the Energy design load for the solar PV system which include 30% of all energy losses in the system.

$$E_{demand} \leq E_{supply} \quad \ldots\ldots (1)$$

$$Q = \frac{E_{load}}{E_{th}} \quad \ldots\ldots (2)$$

$$E_{design\ load} = 1.3\ x\ E_{load} \quad \ldots\ldots (3)$$

$$E_{th} = ή\ x\ E_{glob}\ x\ A_{array} \quad \ldots\ldots (4)$$

$$P_{peak} = ή\ x\ I_{STC}\ x\ A_{array} \quad \ldots\ldots (5)$$

Solving equation (4) and (5) we get (6);

$$E_{th} = P_{peak}\ x\ \frac{E_{glob}}{I_{STC}} \quad \ldots\ldots (6)$$

Solving equation (2) and (5) we get (7);

$$Q = \frac{E_{design\ load}}{E_{glob}\ x\ P_{peak}}\ x\ I_{STC} \quad \ldots\ldots (7)$$

Making P_{peak} subject of the formula from equation (7) we get (8);

$$P_{peak} = \frac{E_{design\ load}\ x\ I_{STC}}{E_{glob}\ x\ Q} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

$$Number\ of\ PV\ modules\ (N) = \frac{Peak\ power\ of\ PV\ array\ (W)}{Peak\ power\ of\ PV\ module\ (W)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

$$Inverter\ capacity\ (W) = 1.3\ x\ P_{peak}\ Power \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

NOTE: inverter is considered to be 20-30% bigger than the peak power of the system

$$Number\ of\ inverter\ (N) = \frac{Inveter\ capacity\ size\ (W)}{Rated\ power\ of\ each\ inveter\ (W)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

$$Battery\ capacity\ bank\ size\ (Ah) = Autonomy\ days\ x\ \frac{E_{design\ load}}{Battery\ voltage} \ldots\ldots\ldots\ldots\ldots(12)$$

Or

$$Battery\ capacity\ bank\ size\ (Wh) = Autonomy\ days\ x\ E_{design\ load} \ldots\ldots\ldots\ldots\ldots(13)$$

Or

$$C_B = 10\ x\ P_{peak} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

$$Number\ of\ batteries\ (N) = \frac{Battery\ bank\ size\ (Wh)}{Capacity\ of\ each\ Battery\ (Wh)}\ \textbf{Or}\ \frac{Battery\ bank\ size\ (Ah)}{Capacity\ of\ each\ Battery\ (Ah)} \ldots\ldots(15)$$

$$Charge\ controller\ capacity\ (A) = \frac{PV\ array\ size\ (W)}{Battery\ bank\ design\ voltage(V)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(16)$$

$$Number\ of\ Charge\ Controllers\ (N) = \frac{Charge\ controller\ size\ (A)}{Capacity\ of\ each\ charge\ controller\ (A)} \ldots\ldots\ldots\ldots(17)$$

3.3.4 The Solar PV System Costs Calculations

The designed solar PV system has to be reliable and economical sustainable. Therefore, the costs of all components of the desired solar PV system were estimated using the outlined costs equations (Arvind, Tiwari, & Chandra, 2009; Wilfried, Muizebelt, Jadranka, & Arthur, 2014). These equations worked together with the HOMER Pro software to make it easier for estimation of the Net Present Value of the preferred system.

Capital costs Equations:

$$Cost\ of\ PV\ array = No.of\ PV\ modules\ x\ PV\ module\ Peak\ Power\ x\ Cost\ per\ (W).(18)$$

$$Cost\ of\ Battery\ Bank\ size = No.of\ batteries\ x\ Battery\ capacity\ (Wh)\ x\ Cost\ per\ Wh \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(19)$$

$$Cost\ of\ Inveter\ size = No.of\ Inveter\ x\ Inverter\ capacity\ (W)\ x\ Cost\ per\ W \ldots (20)$$

$$Cost\ of\ Solar\ Charge\ Controller\ (SCC) = No.of\ SCC\ x\ SCC\ capacity\ (A)\ x\ Cost\ per\ (A) \ldots (21)$$

$$Capital\ Cost\ (Pcc) = Cost\ of\ PV\ array + Cost\ of\ Battery\ bank + Cost\ of\ Inverter\ size + Cost\ of\ SCC\ size \ldots (22)$$

Installation costs and Operation & Maintenance Equations:

$$Cost\ of\ System\ Installation = System\ design\ load\ x\ Cost\ per\ (W) \ldots (23)$$

$$Cost\ of\ System\ O\&M = 1\%\ of\ the\ capital\ cost \ldots (24)$$

Replacement cost Equations:

$$Replacement\ cost\ of\ Solar\ PV\ module\ (Rpv) = (100\%\ minus\ Rebate\ \%)\ x\ Cost\ of\ solar\ Pv\ module \ldots (25)$$

$$Replacement\ cost\ of\ Battery\ bank\ (Rbb) = (100\%\ minus\ Rebate\ \%)\ x\ Cost\ of\ battery\ bank \ldots (26)$$

$$Replacement\ cost\ of\ Inverter\ size\ (Ri) = (100\%\ minus\ Rebate\ \%)\ x\ Cost\ of\ Inveter\ size \ldots (27)$$

$$Replacement\ cost\ of\ SCC\ (Rscc) = (100\%\ minus\ Rebate\ \%)\ x\ Cost\ of\ SCC \ldots (28)$$

Present and Net Present costs Equations:

$$P_{resent\ Cost} = \frac{Replacement\ cost}{(1+i)^5} + \frac{Replacement\ cost}{(1+i)^{10}} + \frac{Replacement\ cost}{(1+i)^{15}} + \frac{Replacement\ cost}{(1+i)^{20}} \ldots (29)$$

$$P_{resent\ salvage\ value} = \frac{Salvage\ cost}{(1+i)^{25}} \ldots (30)$$

$$Net\ Present\ Costs = Capital\ cost\ (Pcc) + Present\ cost - Present\ salvage\ cost \ldots (31)$$

3.4 HOMER Pro Software Tool

Hybrid Optimization Model for Electric Renewable (HOMER Pro) was first developed in 1993 by the National Renewable Energy Laboratory (NREL) in the United States of America (NREL, 2016). Its application is used to simplify the task of assessing designs with different configurations of energy systems such as solar power, wind turbine, diesel generator and hydropower systems. The software performs a simulation and determines the cost effectiveness of the system as well as indicating whether the system is feasible. The system is defined to be feasible when it can able to sustain the load capacity with satisfaction of any constraints imposed. The constraints may or rise from the load details provided as inputs to the system. These inputs describe the load demand which must be served by the system. Therefore, the software analyzes the input load which includes capital, installation and operational & maintenance total costs by estimating system's life cycle cost over the system's life span. The system's life cycle cost is represented by the Net Present Cost (NPC) in the analysis. As a result the NPC compresses all the costs injected into the system's life time into a present cost as well as showing the cash flows. The software can also perform the sensitivity analyses if the sensitivity values are provided to the model analysis (Kassam, 2010; Kenneth, 2014; NREL, 2016)

HOMER Pro software contains a file which can provide all the information needed for the technology options, costs of components and required resources to assess the designs for the various power systems. The same file also contains the calculations required for optimizations and sensitivity analysis. Application of the software starts by defining and entering the hourly primary loads data of the system. This load data can be collected from the equipment vendors or by conducting specific audits at the site either by personal visit or by remotely collecting the data through an ammeter connected to the GPRS. ,The software will configure the load data into the daily power load profile as illustrated in an example shown in Figure 20 (Kenneth, 2014; NREL, 2016).

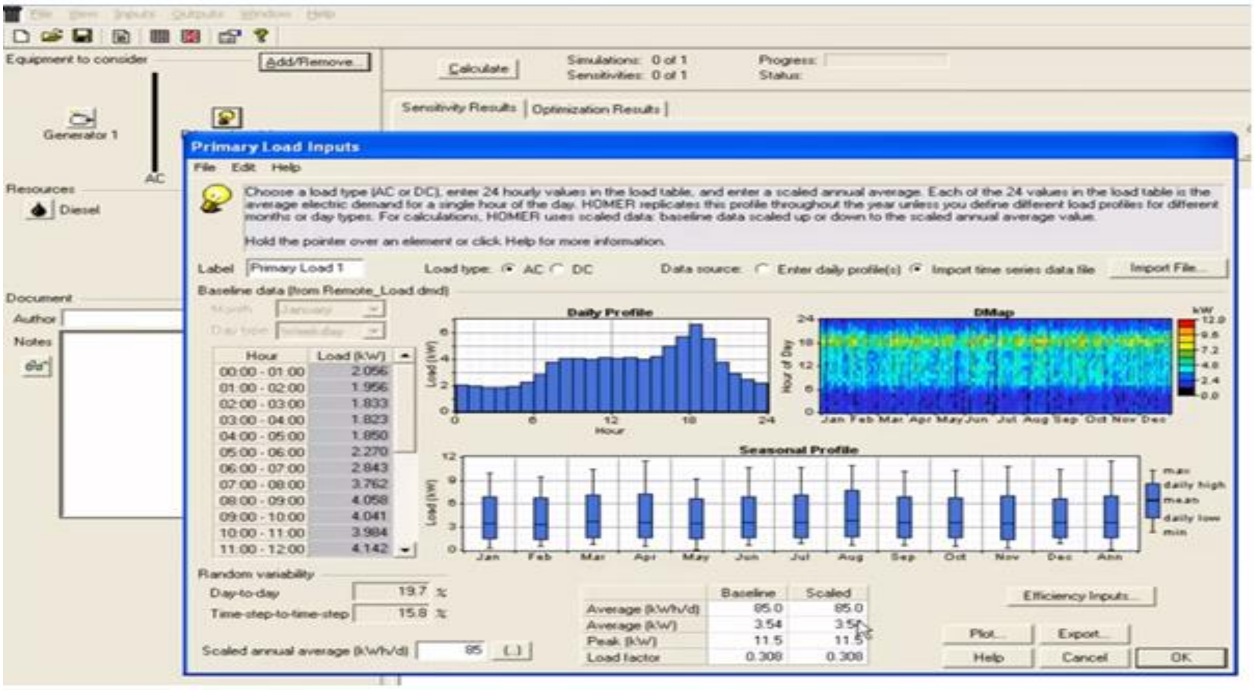


Figure 20:- Example of (HOMER software) the daily power profile from the configured load data provided by the system (Kenneth, 2014)

In the case of wind and solar resources, the software uses the GPS coordinates of the site to import data directly from NASA Surface meteorology and Solar Energy database. This data defines the daily solar radiation and the clearness index in for the solar resource. Figure 21 shows an example of the configured results of data from the NASA database with respect to the provided site location GPS coordinates (NREL, 2016) .

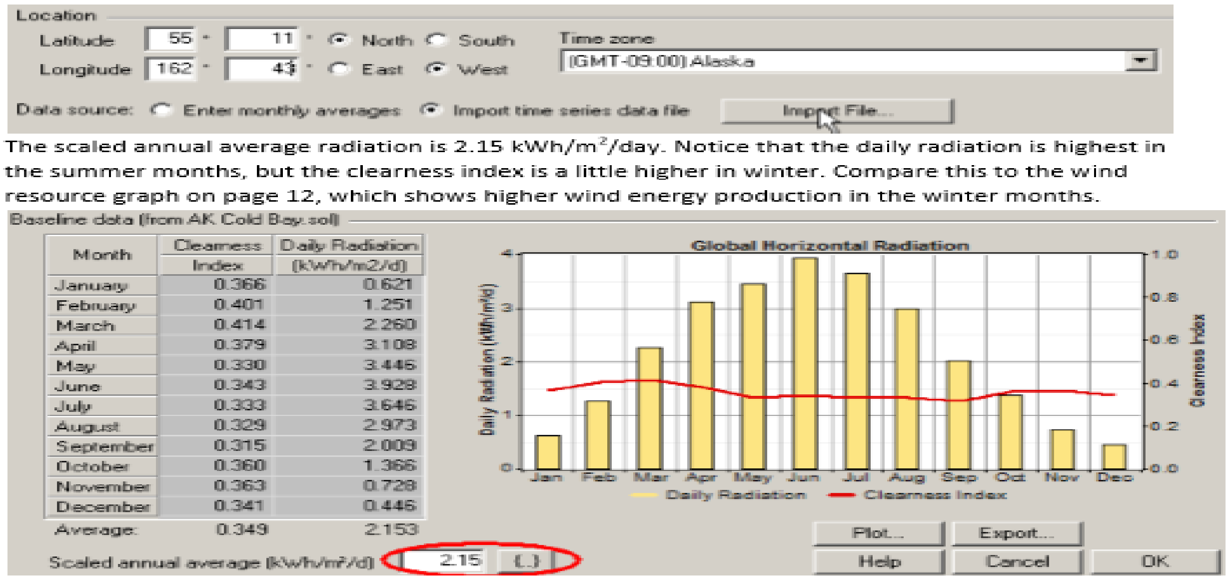


Figure 21:- Example HOMER software display results of the configured NASA data and site location GPS coordinates (NREL, 2016).

The software also requires information or data on the size and costs of the system components. These data will be used to run the optimum cost curve of the system with respect to the solar resources defined by the site location, the size and the life span of the components. The considered costs are capital, replacement, operational & maintenance costs. Figure 22 shows an example display of the system table for costs entered for the analysis (NREL, 2016) .

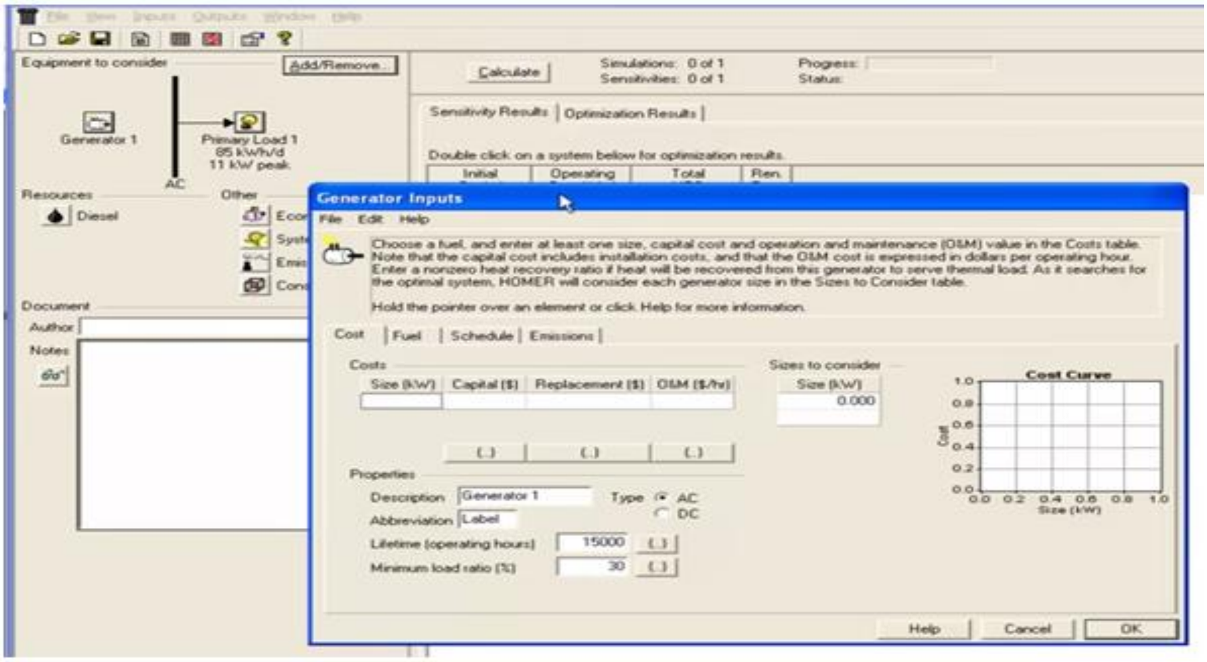
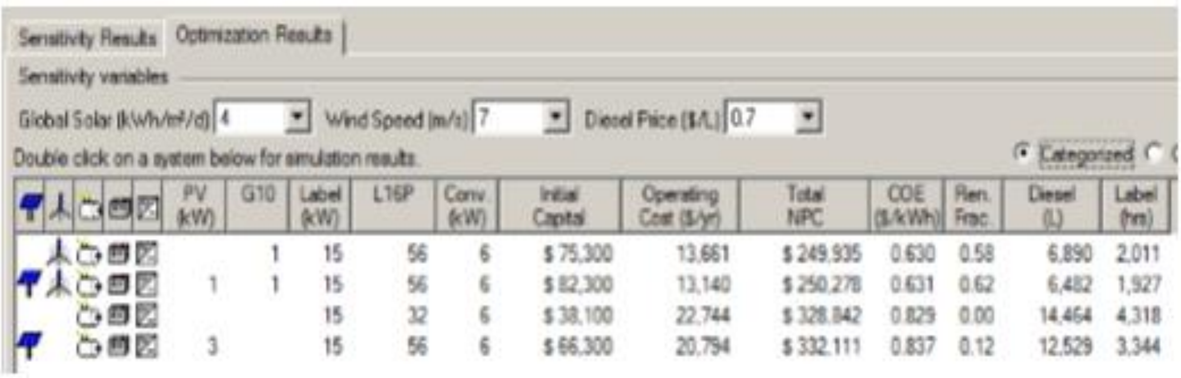


Figure 22:- Example of the display of the table for cost analysis (NREL, 2016)

Therefore, by clicking the calculate button the software will use the provided input data of the designs to simulate the optimum and feasible power system design with respect to the cost effectiveness indicated as Net Present Cost (NPC) as illustrated in Figures 23 (NREL, 2016) .



Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 4 | Wind Speed (m/s) 7 | Diesel Price ($/L) 0.7

Double click on a system below for simulation results.

PV (kW)	G10	Label (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)
	1	15	56	6	$ 75,300	13,661	$ 249,935	0.630	0.58	6,890	2,011
1	1	15	56	6	$ 82,300	13,140	$ 250,278	0.631	0.62	6,482	1,927
		15	32	6	$ 38,100	22,744	$ 328,842	0.829	0.00	14,464	4,318
3		15	56	6	$ 66,300	20,794	$ 332,111	0.837	0.12	12,529	3,344

Figure 23:- Example of the HOMER software display of the table for optimization results (NREL, 2016).

CHAPTER 4: OPTIONS FOR REDUCING CARBON EMISSIONS IN THE BOTSWANA ELECTRICITY SECTOR

4.1 Introduction

Botswana Government Ministry of Mineral Resources, Green Technology and Energy Resources (MMGE) conducted a coal road map study in 2012. The study outlines three major components to be carried out with coal: continue generation of electricity from coal, export more coal international and undertake research on coal to liquid as well as coal bed methane technologies (Paya, 2012). Currently the usage of coal for electricity production is very high, and in future high utilization of coal is still planned. Therefore, finding economic ways to reduce CO_2 emissions in Botswana are needed. Coal especially possesses negative impact to the environment long term. Unfortunately, the coal road map study of 2012 did not emphasize how coal and solar can be integrated to curb CO_2 emissions. Botswana has the potential to reduce CO_2 emissions by generating electricity from solar energy as another alternative to coal electricity generation.

An earlier study on solar versus radiation in Gaborone City was conducted in 1994. In 1997 the study was upgraded to analyze and discuss some anomalous phenomena of the different solar radiation components obtained in Botswana (P. V. Luhanga & Nijegorodov, 1997; P. V. C. Luhanga, 1994). It is highlighted that Botswana has a maximum daily direct normal solar radiation of $45MJ/m^2$ and concluded that the ozone layer was continuously depleting due to an increase of UV components in the atmosphere every year. The scope of this research was based on solar geographical analyses. The gap and link between the abundance of solar radiation, the cost effectiveness of solar systems, and the possible solar technologies that can be used was not analyzed.

In this chapter options for reducing carbon emissions in the Botswana electricity section are investigated. The current generation mix in Botswana and surrounding countries of SADC are analyzed using the CEPA method. This is followed by the development of these emission reduction options to identify the level of solar renewables, coal bed methane on CCS required to reach given targets in Botswana by 2020 and 2030.

4.2 Primary Energy Resources in Botswana

The primary energy resources of Botswana are composed of; coal, biomass, biofuel, solar and wind. To date renewable energy activities of biodiesel, solar and wind are limited to small projects scale. Figure 24 illustrates the 2012 percentage energy supply data for coal, oil, biofuel and electricity imports of the total supply of about 109 165TJ (EIA, 2011).

4.2.1 Coal

The primary energy resources in Botswana are composed of; coal, biomass, biofuel, solar and wind which is only limited to small projects scale. There is about 212 billion tonnes of abundant of coal in Botswana, but only about 3.4 million tonnes is mined per year. Mined coal is mainly used for electricity generation and process steam generation for heating in commercial buildings such as Hospitals, industries such as Breweries and in mining industries such as Copper & Soda Ash Mines. Another portion of coal is exported to other countries like Zimbabwe, Zambia & DRC. Coal makes up about 15% of the total primary energy supply of Botswana as shown in Figure 24 (Grynberg, 2012; UNDP, 2012).

4.2.2 Biomass and Biofuel

Biofuel especial fire wood is mostly used in rural communities, mainly for space heating and cooking. Its percentage energy supply is about 24% as shown in Figure 24. However, the main challenge is the sustainable ways of using fuel wood. In addition, there are some small scale bio-diesel production from used cooking oil. The local production of biodiesel however, is faced by the challenge of using acceptable blending ratios with imported petroleum based fuels. Currently, there is a pilot project study in progress on the jatropha plant to identify the best species for Botswana Climate conditions. The study is to produce biodiesel from jatropha seeds in future prior to the successful of the study (UNDP, 2012).

4.2.3 Petroleum

Oil makes up to 48% of Botswana’s energy supply (Figure 24) and 100% of the liquid fuels are imported from South Africa. Petroleum products include; gasoline, diesel, paraffin, LPG and Jet fuel. These products are used mostly in the transport sector and in large industries, like the mines, for transportation and diesel power generation (UNDP, 2012).

Botswana receives over 3200hrs of sunshine a year at an average daily radiation of 21MJ per m^2 on a horizontal surface. A renewable energy strategy was drafted and set some targets of 15% and 25% of renewable contribution for electricity supply by 2020 and 2030 respectively. Government is hoping that the high level of solar will drive solar implementation in the country, but in general of solar radiation still remains underutilized as electricity source. The current status of solar is that it contributes less than 1% of solar electricity supply, out of the set targets. N.P, Botswana commissioned the first Solar PV Plant with a capacity of 1.3 MW at Phakalane in 2012. The plant is used as a pilot project such that similar solar PV plants can be developed and rolled out to the entire country of Botswana. There is also a plan to installing a 100MW concentrated solar thermal plant (CSP) by 2018 and an investible feasibility study was completed in 2013. Another renewable energy initiative was the 485 Solar Home Systems project in rural community areas that have been fitted with small stand-alone solar PV systems, whereby the total capacity was about 100kW. In terms of wind energy, the potential is very low with an average of 3 m/s, and it is only used in windmills for water pumping systems in rural communities (UNDP, 2012).

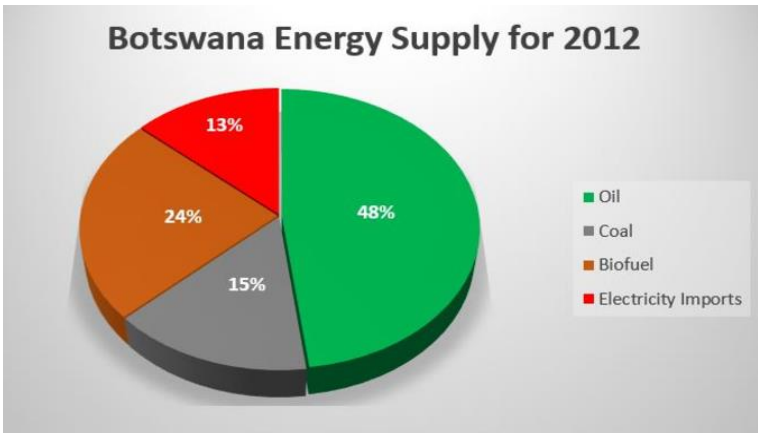


Figure 24:- Botswana 2012 energy supply for total supply (EIA, 2011).

4.3 Electricity Situations in Botswana

The electricity business in Botswana is a single buyer model, which is owned by government through Botswana Power Corporation (BPC). BPC is an established company that manages the electricity from generation to distribution as well as a service provider to the whole nation's consumers. Access to electricity across the whole country is limited to about 70%. With the BPC business model, all electricity imports or exports and in country generation from Independent Power Producers (IPP) is channeled through BPC. At the moment there is no electricity generated in Botswana from the IPP and there is no electricity exported (Mothebe, 2013). Currently, the electricity sector is undergoing reforms regarding the amendment of the electricity supply Act of 2007. The reformation is a way of supporting and introducing electricity generation from IPPs as well as setting up an Energy and Water Regulator (BEWRA) to regulate all national utilities tariffs. The reformation structure is presented in Figure 25 (Mothebe, 2013).

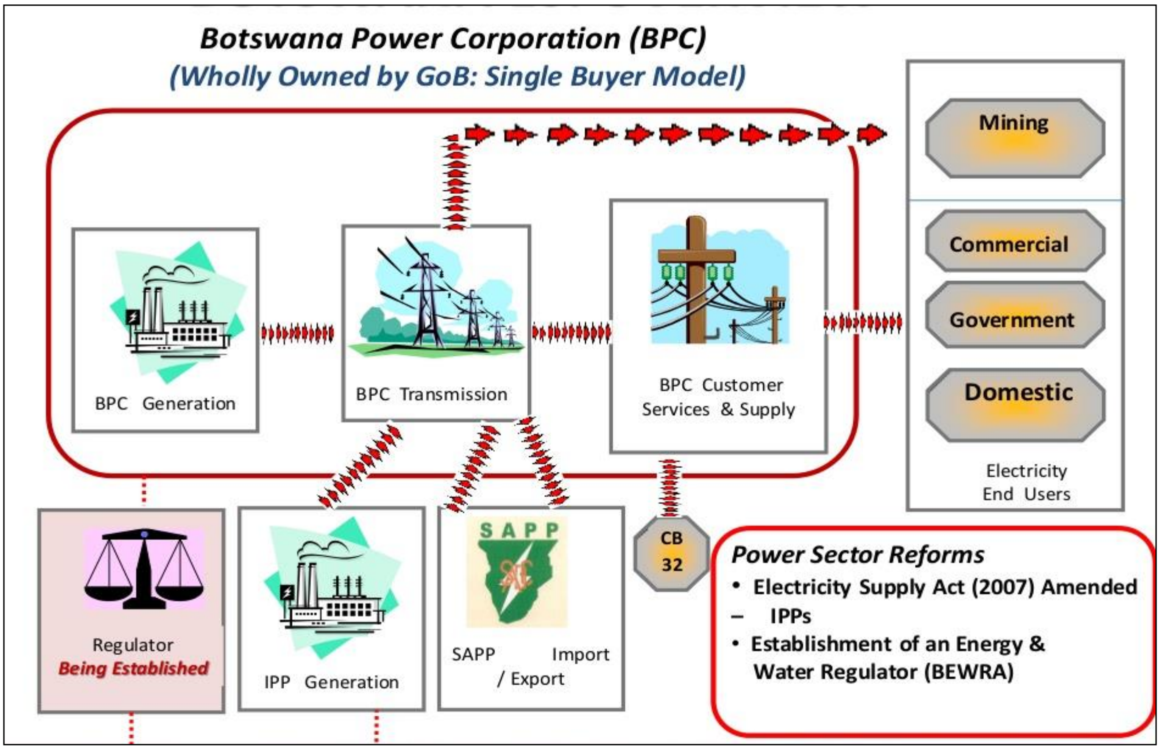


Figure 25: - Utility management system processes by BPC (Mothebe, 2013)

Currently, the electricity tariff rates are regulated by the ministry MMGE. The electricity tariff rates in Botswana are all charged in BWP/kWh as outlined in Table 8. There is a maximum demand charge which is charged to large business category like mining industry because of their maximum peak demand. The maximum demand charge is the extra kWh the large business strikes at its peak in a month. Then the business will face a penalty charge of maximum demand of that peak consumption value for a 12 months period. After 12 months period then the charges goes back to normal cycle until the next peak strike.

Table 8:- 2017 revised electricity tariffs rates in Botswana (BPC, 2017)

Currency	Categories	Energy Charge		Max. Demand Charge
		0-200kWh	More than 200kWh	
Pula/kWh	Domestic	0.6993	0.9711	
NZ$/kWh		0.09	0.13	
		0-500kWh	More than 500kWh	
Pula/kWh	Small Business	0.8462	1.2547	
NZ$/kWh		0.11	0.17	
Pula/kWh	Medium Business	0.639		
NZ$/kWh		0.09		
Pula/kWh	Large Business	0.5762		168.7716
NZ$/kWh		0.08		23.32
Pula/kWh	Government	1.790		
NZ$/kWh		0.24		
Pula/kWh	Water Pumping	1.291		
NZ$/kWh		0.17		

Botswana has expanded its generation capacity in 2015 by constructing 600MW coal fired station. The plant meets the national demand which was about 600MW in 2015. Domestic electricity production has enabled Botswana to reduce electricity imports from SADC countries. Botswana has also made a plan to increase electricity generation from coal by engaging on several projects as illustrated in Table 9 (Mothebe, 2013).

Addition electricity generation is planned using coal, 2 x 300MW size plant in 2016/2017, two oil supplied plants of 90MW and 70MW, with the latter being for emergency back-up. Coal bed methane CCGT plant of 90MW also planned, but the date of construction is yet to be determined. Combined the 7 projects represent a capacity increase of 1582MW for Botswana as outlined in Table 9. Note that no large scale renewable electricity projects are planned and emission reduction will only come from fuel switching to less carbon emitting fuels like methane and oil as compared to coal.

Table 9: - Electricity installed and planned from coal & oil generation capacities in MW (Mothebe, 2013)

POWER PLANTS	CAPACITY [MW]	TIMING	STATUS
COAL FIRED			
Morupule A	132	-	Planned (Refurbishment)
Morupule B	600	2015	Installed (commissioning ongoing)
IPP Brown Field	300	2016/17	Planned (Morupule B phase 2 Unit 5&6)
IPP Green Field	300	2016/17	Planned
OIL			
CCGT	90	-	Installed combined gas and diesel generator (Currently operated on diesel of about 32000L/hr)
Emergency Diesel Generator	70		Installed (currently in operation)
METHANE			
CCGT	90		Planned (Feasibility conducted shows the potential of Coal Bed Methane (CBM) of about 5.6 trillion m^3. Plan is to run the CCGT on CBM)
TOTAL	**1582**		

4.4 Electricity and CO_2 Emissions Situations in SADC Countries

Botswana is one of the SADC countries which is experiencing electricity shortage due to not using a self-sufficient electricity sector. Figure 26 and 27 illustrate the status of each of the SAPP (Southern African Power Pool) countries in terms of electricity consumption per capita (Miketa & Merven, 2013). South Africa has the highest per capital electricity consumption of 4500 kwh/person, followed by Namibia and Botswana with little over 1500kwh/person. Next is Zimbabwe at around 750kwh/person, followed by Zambia and Mozambique near 500kwh/person and the next below 250kwh/person. All 9 countries from part of the Southern Africa Power Pool and therefore carbon emissions for all these countries have been included in the situation analysis part of the study.

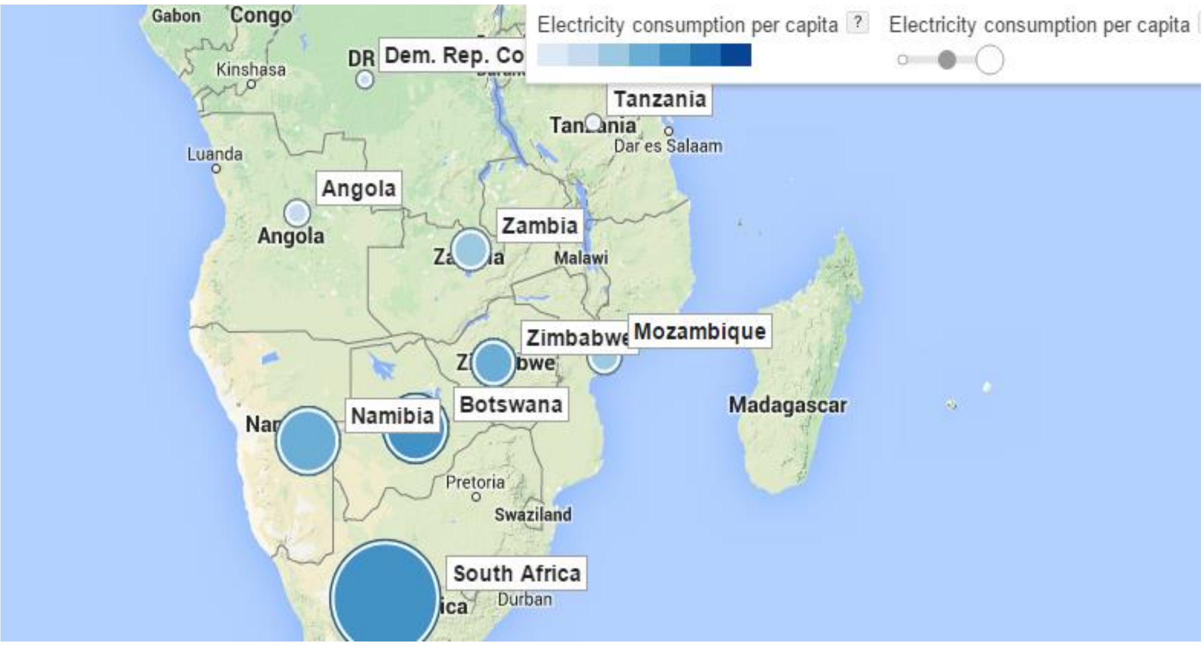


Figure 26:- Comparison of the electricity consumption in kWh per capita of the members of SADC region, (The World Bank Group, 2015)

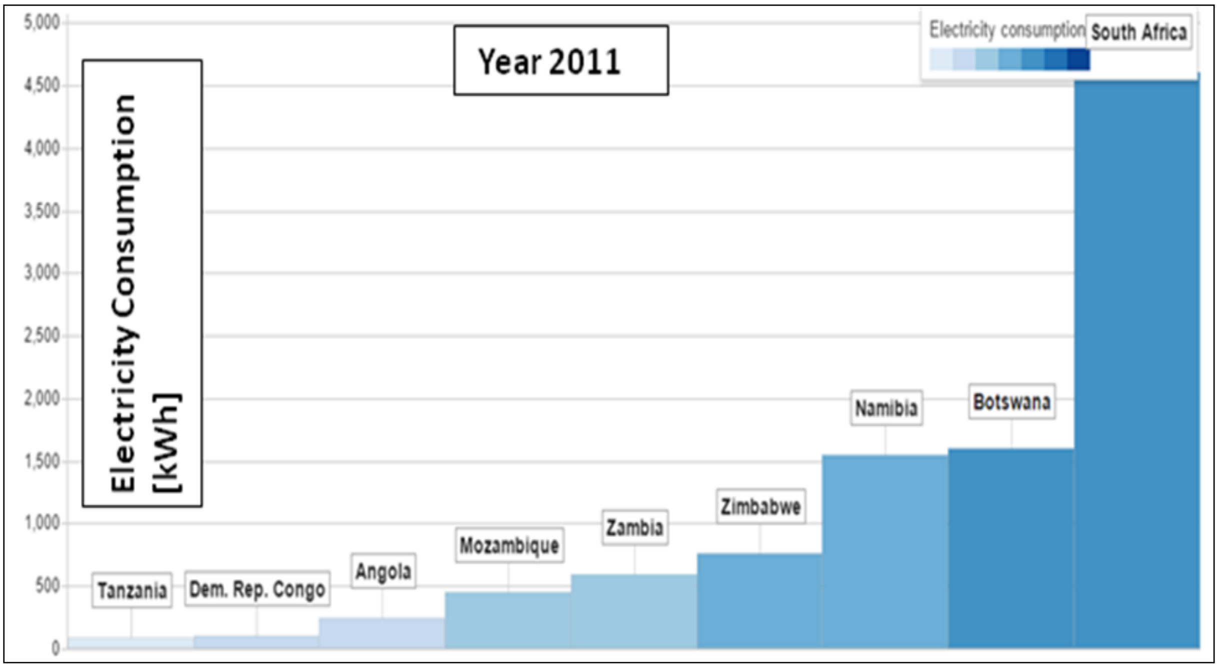


Figure 27:- Comparison of the electricity consumption in kWh per capita of the members of SADC region, (The World Bank Group, 2015)

Botswana relies mostly on coal for electricity generation but apart from electricity generation, coal is also used for process steam generation as discussed in section 4.2.1.Coal is also mined and exported to neighboring countries like Zimbabwe, Zambia & DRC where it again is used for electricity production (Grynberg, 2012; UNDP, 2012). With the current plan is to maximize coal to power generation (Table 9) and at lowest evaluated cost possible (Paya, 2012). As this focus will lead to a significant CO_2 emission challenge for Botswana and most of the SAPP countries. According to the 2010 World Bank statistical data analysis in terms of CO_2 emissions per capita in the Southern African Development Community (SADC), Botswana was second highest to South Africa and Lesotho was the least with 2.66, 9.04 and 0.01t CO_2/capita respectively (The World Bank Group, 2015). This is illustrated in Figure 28 for all SADC member of states.

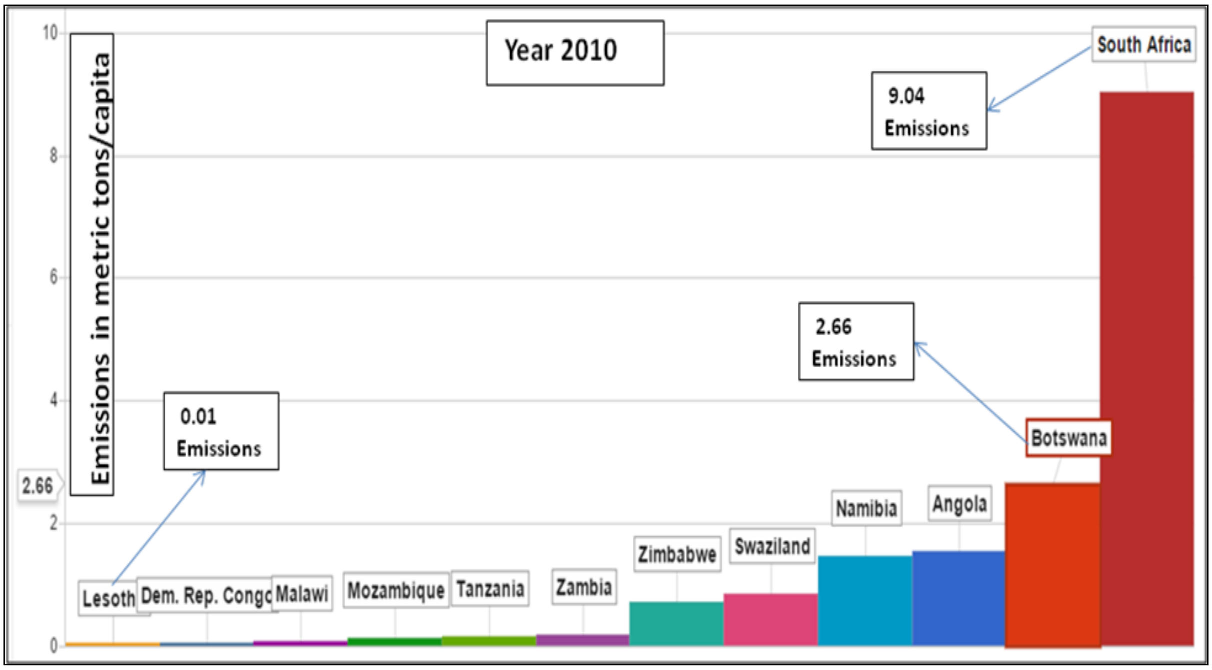


Figure 28:- CO_2 emissions amongst SADC members of states in metric tons per capita (The World Bank Group, 2015).

The CO_2 emission analysis on the electricity sector in Botswana, highlights that high level of CO_2 emissions is the result of power generation from coal, oil resources and minimum renewables. The CEPA method has used to evaluate options to reduce CO_2 emissions in the Botswana electricity sector by different technologies; (1) Solar PV on building, (2) CCS on coal fired power stations and (3) Using coal bed methane for electricity generation has a carbon emission factor of 0.599 Kt CO_2/ GWh methane electricity production compared to 0.955 Kt CO_2/ GWh of coal. Four different options made up of a mix of emission reduction technologies have been studied being: (1) 15% renewable for solar, (2) 25% renewable for solar, plus diesel replaced by CCGT, (3) 25% renewables, plus coal bed methane as CCGT, (4) 25% renewable solar, plus CCS from coal. Results of this analysis are presented in the next section.

4.5 Results of CO_2 Emission Reduction on Electricity Sector in Botswana

4.5.1 Carbon emissions analysis of the SAPP Members of States

Data of electricity generation mix [GWh] for the 12 member of states of SADC/SAPP in 2012 was collected and is available combined in Appendix A1 to A14. This data was used to construct carbon emissions composite curves in terms of the five energy resources and for each country (Figure 29).

The CO_2 emissions produced per fuel or technology type (Figure 29) indicates that coal is the fuel most that contributes to the emissions at 93.1%, followed by diesel 5.93% and then CCGT 0.99%. In terms of electricity generation coal produces 72.9%, followed by hydro at 17.4 %, the diesel 4.97%, nuclear 3.51% and CCGT 1.23%. Analyzing the same data per country as shown in Figure 30, South Africa stands out and as the dominant electricity produces with high per capita emissions driven by coal generation with some CCGT, nuclear and hydro.

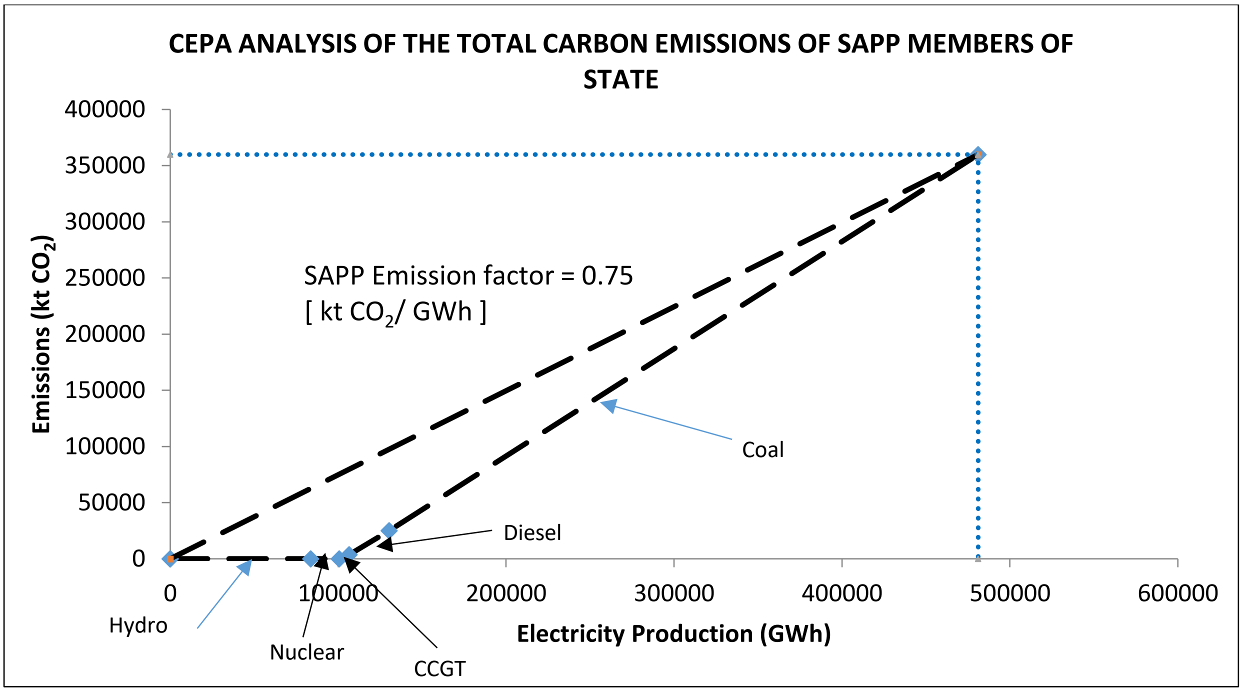


Figure 29:- CO_2 emissions produced per fuel type by SAPP members in 2012

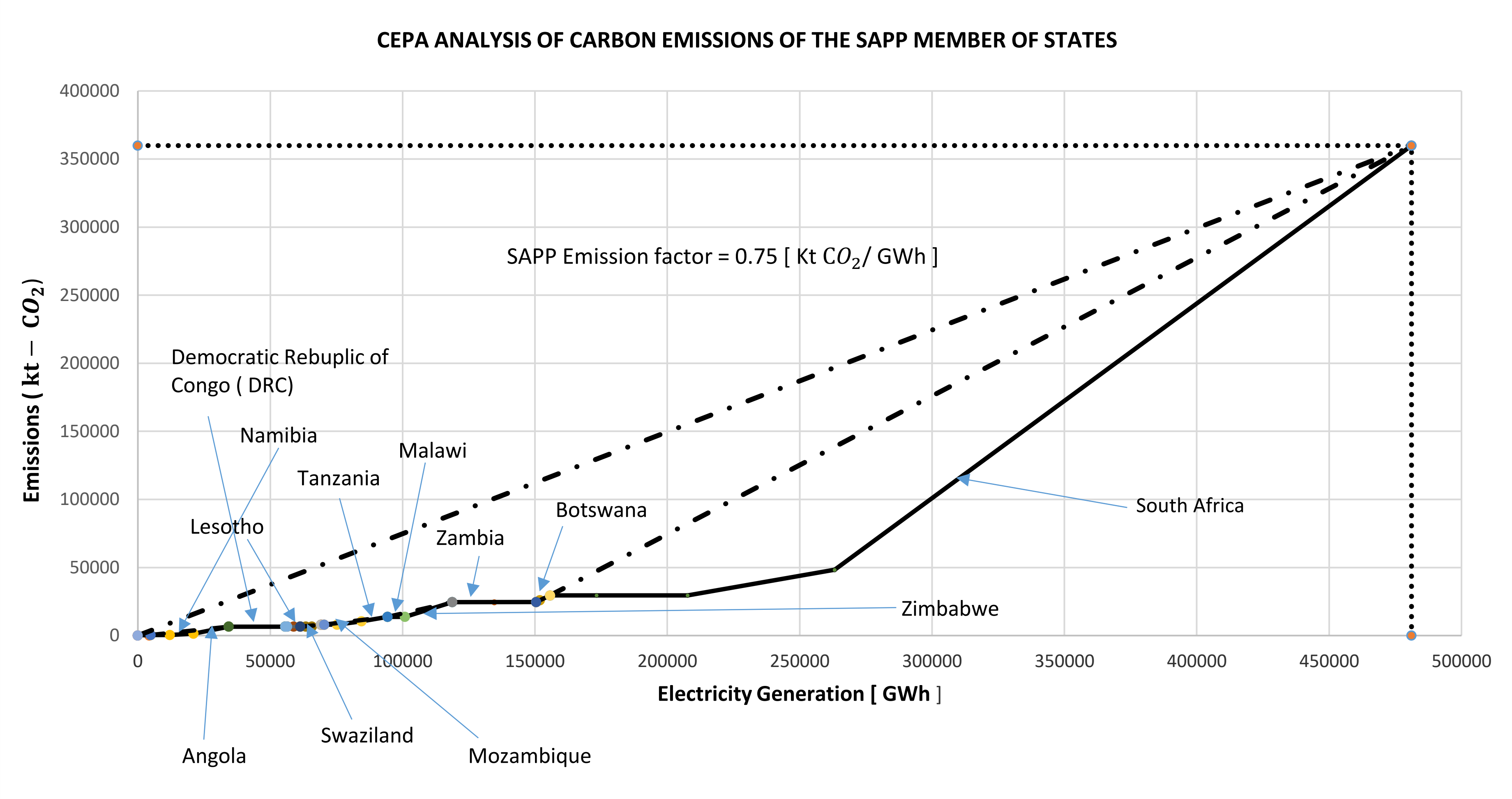


Figure 30: - CO_2 emissions produced per member of states of SAPP in 2012

4.5.2 CEPA of Botswana's CO2 Emissions for the Years 2000 and 2012

The 2000 and 2012 data available from the electricity generation mix [GWh] of the installed capacity in Botswana were used to construct the composite curves as shown in Figure 31, which indicate the CO_2 emissions and electricity generation produced from the electricity sector. As a result, it shows that Botswana was polluting because of its energy resources such as coal and diesel for electricity generation. These energy resources have high carbon emission factors. Figure 32 indicates the percentage increase of carbon emissions under the same electricity generation from 2000 to 2012. The data used for plotting the composite curves is highlighted on appendix A14 and appendix B1 to B2.

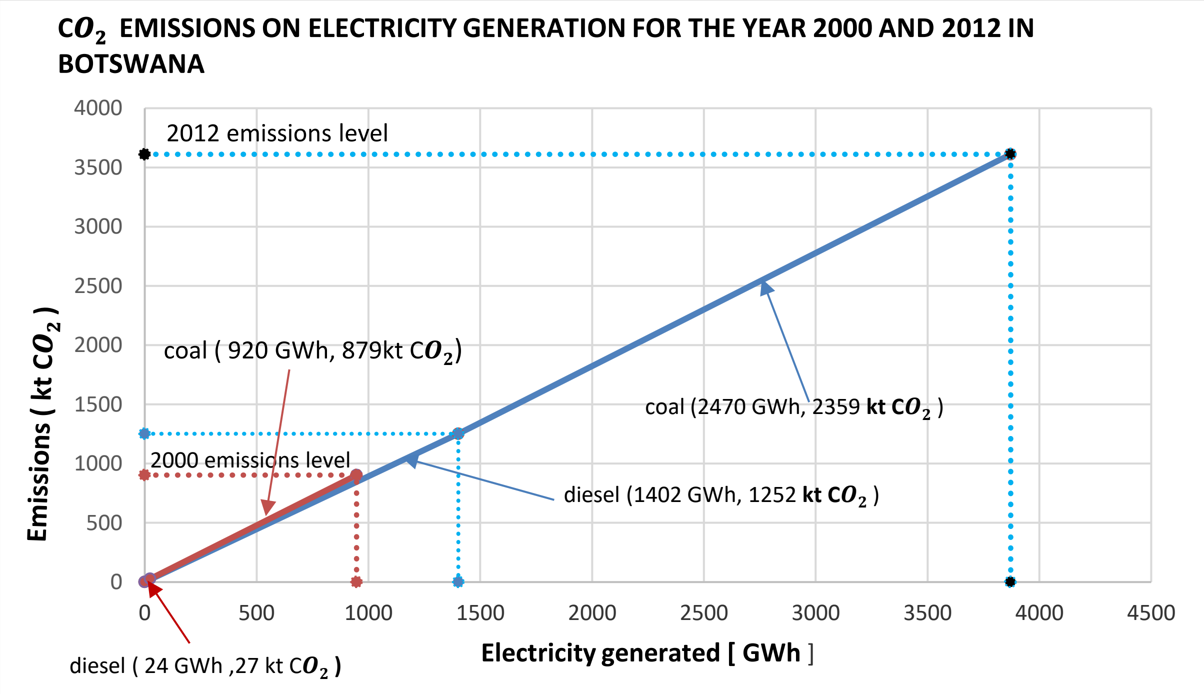


Figure 31: - CO_2 emissions and electricity generation produced from year 2000 to 2012

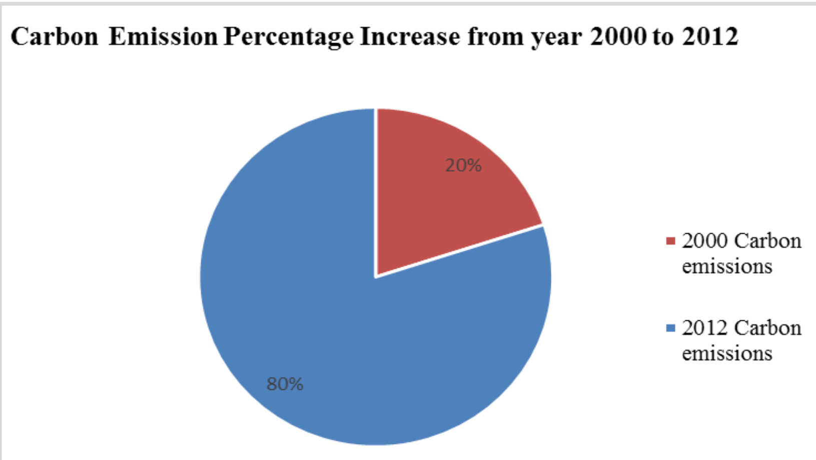


Figure 32:- CO_2 emissions percentage increase from 2000 to 2012 in Botswana

4.5.3 Renewable energy options for reducing CO_2 Emission in Botswana in 2020 and 2030

Planned electricity generation data for 2020 and 2030 were used to estimate the CO_2 emissions for the Botswana electricity sector compared to business as usual. The prediction included the increase of coal generation as well as the contributions of 15% (option 1) and 25% (option 2) renewable resources on the electricity energy mix [GWh] by 2030. Predictions indicate that the emissions remain high for both 15% and 25% increase of the renewable by 2020 and 2030 respectively. This is because of large quantity of coal increase in the electricity generation plan by 2030. Nevertheless, the analysis indicate the emission reduction of 14.82% and 26.3% for both option 1 and 2 from their business cases scenarios of 2020 and 2030 respectively. This is outlined in Figure 33 and 34. A further detailed comparison of the same two options is made in Figure 35. The data used for plotting the graphs is highlighted in appendix B3 and B4.

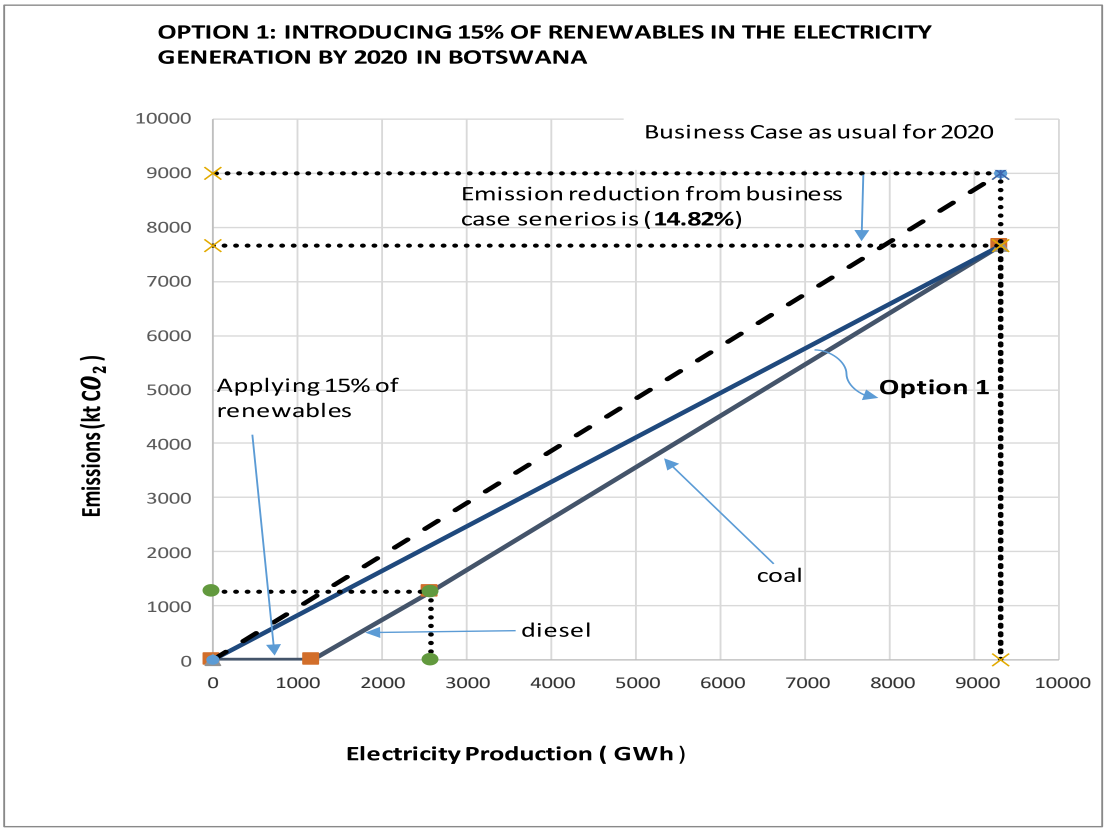


Figure 33: - CO_2 emissions for Botswana electricity sector for business as usual to 2020 versus 15% of renewable energy to the electricity generation mix

The diesel generation in option 1 was replaced by coal bed methane (CBM) generation as indicated in option 2 in Figure 34, and gave a subsequent more in emission reduction of 26.3% by 2030 as compared to 14.82% in option 1 of 2020 targets.

4.5.4 Renewable energy plus large scale Coal to CBM for emission reduction in Botswana by 2030

Renewable energy generation from solar PV combined with substitution of coal for Coal Bed Methane (CBM) as option 3, has the potential to lower CO2 emissions by 44.6 % compared to business case as usual in 2030. CEPA graph plots presented in Figure 36 have been composed using data in appendix C1.

The economic feasibility of using CBM and renewable solar PV to reduce future emissions in Botswana is an important consideration. EROI analysis has been used to evaluate the energy expended or footprint trade-off involved and this analysis is presented in section 4.5.6.

4.5.5 Renewable Energy plus CCS for Coal Electricity Generation for Emission Reduction in Botswana by 2030

Further reduction in carbon emissions is possible through CCS applied to Coal electricity generation using modern heat integrated strategies. The benefits of option 4 for using CCS are shown in Figure 37 compared to business as usual in 2030 it shows that 82.1 % emission reduction is possible with 10,731 GWh of clean CCS Coal generation. The data used for plotting option 4 graph is available in Appendix C2.

Again the economic feasibility of using CCS on coal fired power stations is highly dependable even after considerable heat integration developments. Section 4.5.6 attempts to quantify the economic feasibility through EROI analysis as shown in Tables 10 to 13.

4.5.6 EROI analysis of Botswana's Electricity sector for 2010, 2020 and 2030

Table 10 presents the predicted levelised costs of common energy resources, that also include the electricity generation resources used by the SAPP member states (Seebregts & Tosato, 2010). Using Equation 2 (section 3.2) electricity generation levelised costs were used to estimate the EROI values for each of the generation methods applicable to the SAPP member states. These are shown in Tables 11, 12 and 13.

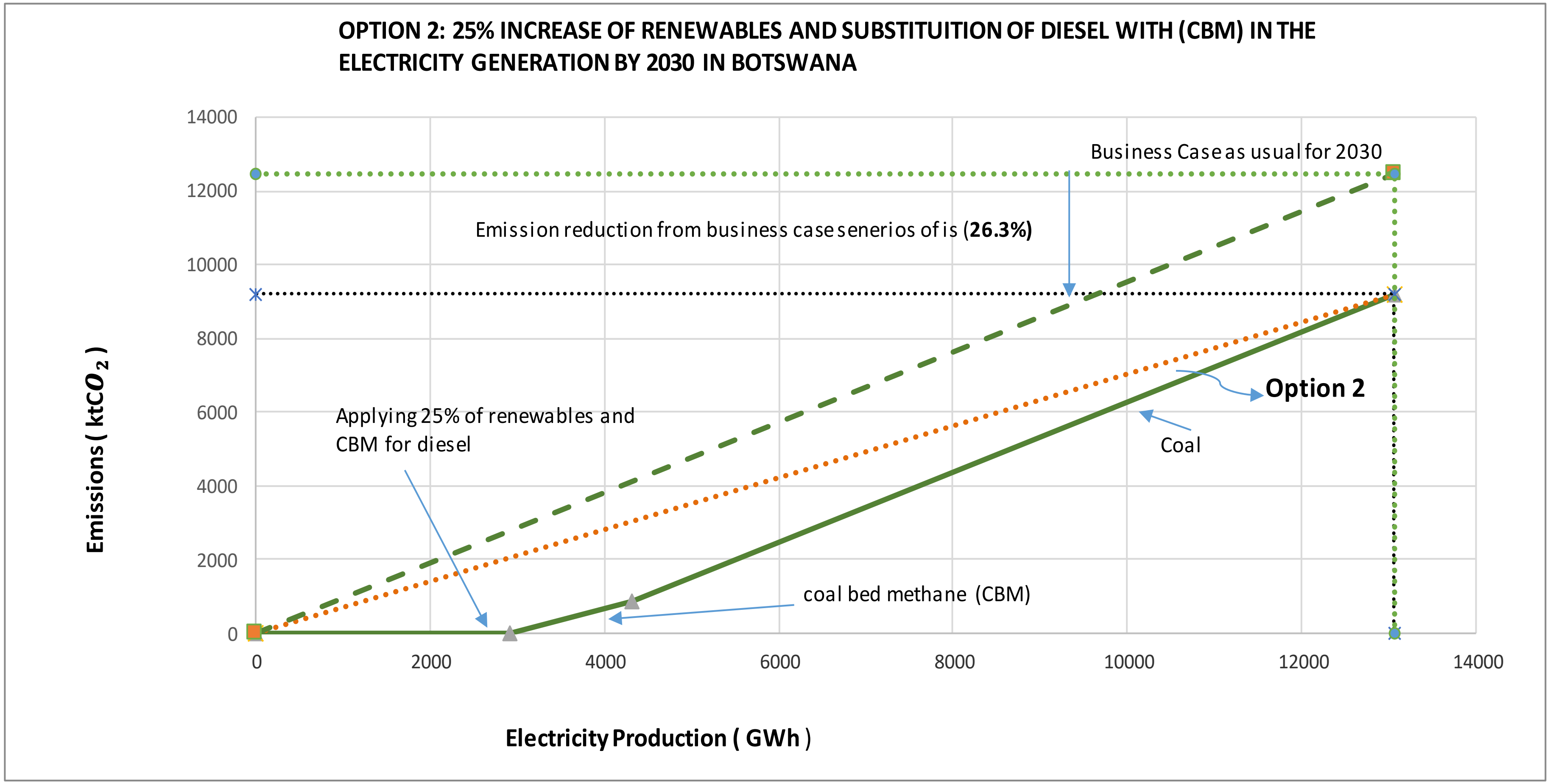


Figure 34: - CO_2 emissions for Botswana electricity sector in 2030 for business as usual versus 25% of renewable energy and switching from diesel to CBM

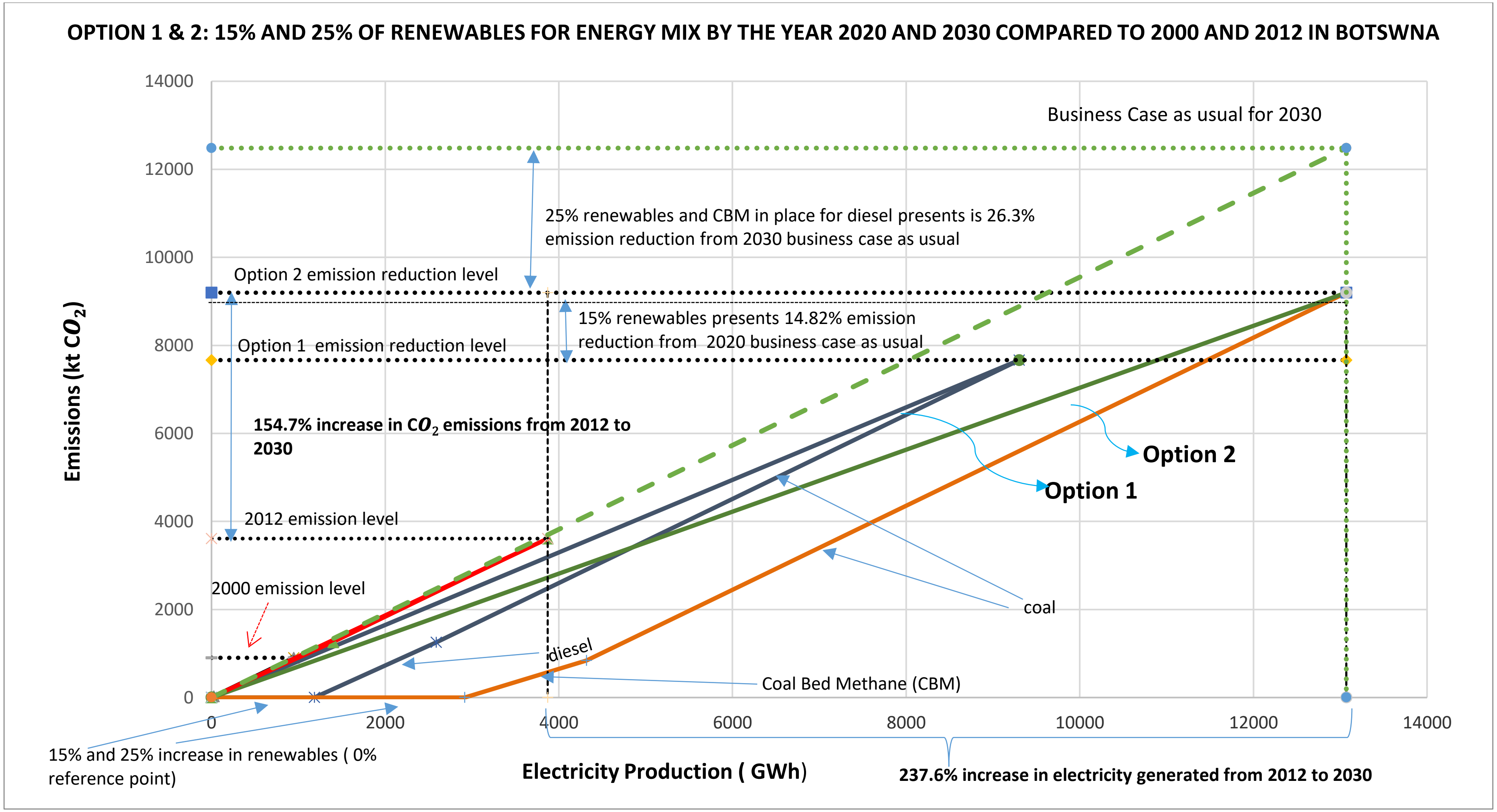


Figure 35:- Comparison between 2020 and 2030 CO_2 emissions reduction levels in Botswana

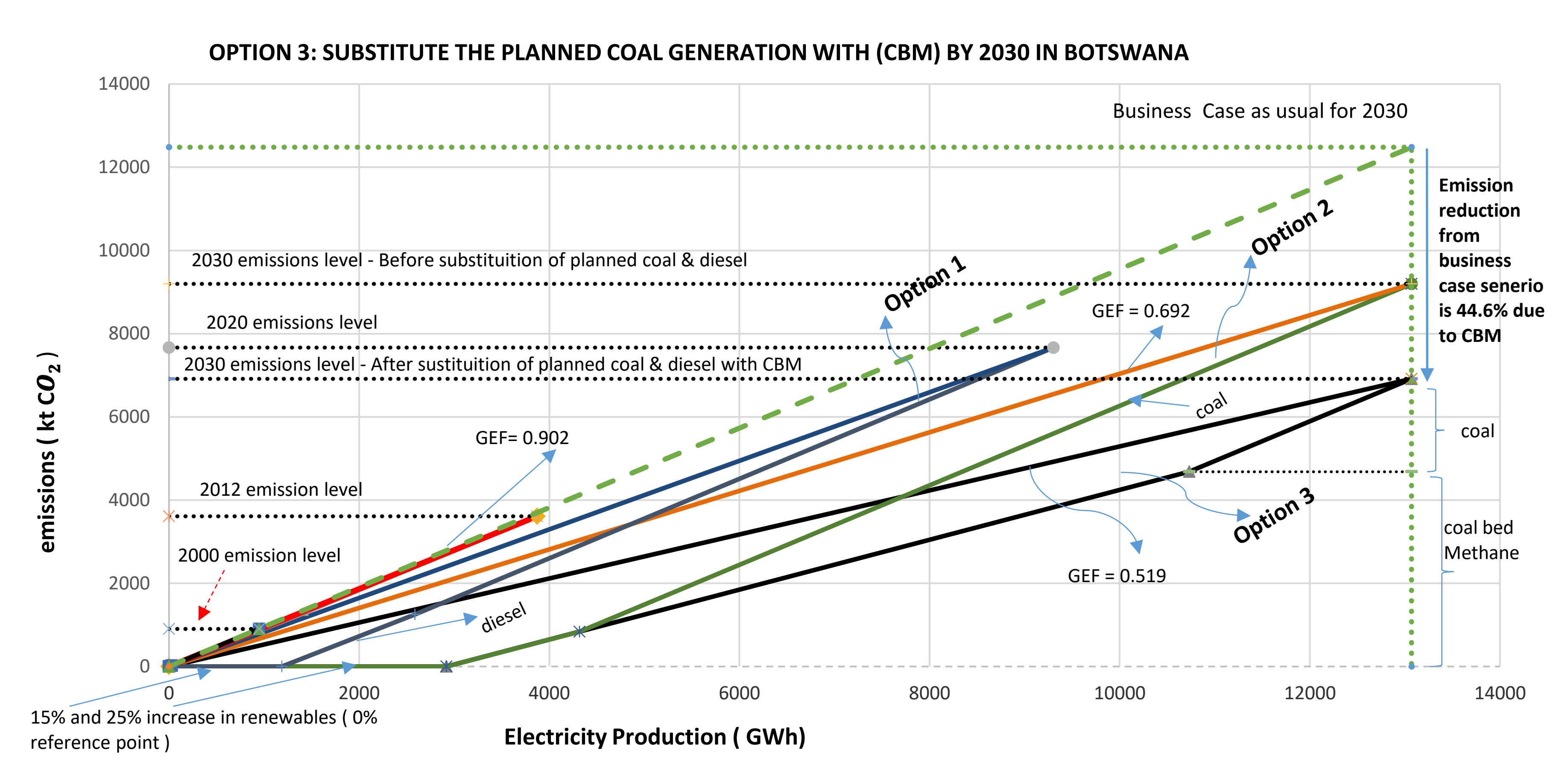


Figure 36:- CEPA analysis predictions of CO_2 emissions to be produced when switching the planned electricity generation from coal with CBM by 2030.

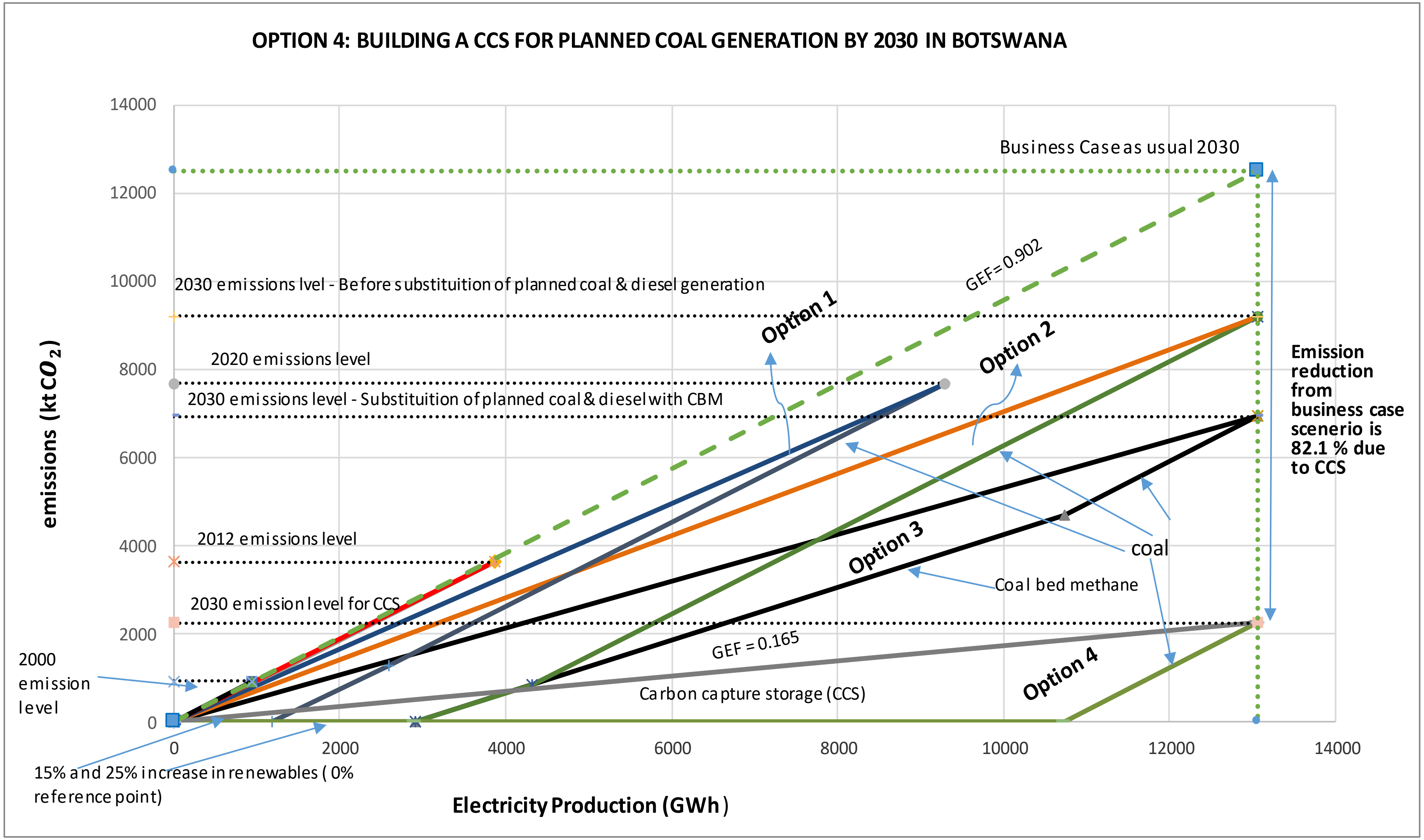


Figure 37: - CEPA analysis predictions of CO_2 emissions to be produced when building carbon capture storage for the planned electricity generation from coal by 2030.

Table 10:- Levelised costs of electricity generation technologies and energy resources from 2010 to 2030 (Miketa & Merven, 2013)

Generation method	2010	2020	2030
Diesel Centralized	291	325	339
Dist. Diesel 100kW	320	355	371
Dist. Diesel/Gasoline 1Kw	604	208	216
HFO	188	154	216
OCGT (Imported Gas/ LNG)	141	98	161
OCGT (Imported Gas/ LNG)	90	143	102
Supercritical coal with CCS	133	88	149
Supercritical coal	80	111	92
Nuclear	111	62	111
Hydro	62	97	62
Small Hydro	107	92	89
Biomass	104	101	86
Bulk Wind (30%CF–w.trans. costs)	118	88	92
Bulk Wind (30%CF-no.trans.costs)	102	101	81
Solar PV (utility)	121	94	84
Solar PV (roof top)	143	109	96

Table 11:- EROI values for energy resources used for electricity generation in 2010

Generation type	Emission Factor [kt CO2-e/GWh]	Levelized Cost [2010$/MWh]	EROI [GWh/GWh-e]
Diesel centralized	0.893	291	6
Supercritical coal	0.955	80	23

Table 12:- EROI values for energy resources estimated for electricity generation in 2020, options 1, 2 and 3.

Generation type	**Emission Factor [kt CO2-e/GWh]**	**Levelised Cost [2020$/MWh]**	**EROI [GWh/GWh-e]**
Diesel centralised	0.893	325	6
Supercritical Coal	0.955	88	21
Solar PV (roof top)	0	94	19
Solar CSTP	0	139	20
Biomass	0	92	13

Table 13:- EROI values for energy resources estimated for electricity generation in 2030 options 1, 2, 3 and 4.

Generation type	**Emission Factor [kt CO2-e/GWh]**	**Levelised Cost [2030$/MWh]**	**EROI [GWh/GWh-e]**
Diesel	0.893	339	5
Supercritical Coal	0.955	92	20
Solar PV (roof top)	0	84	22
Solar CSTP	0	117	16
Biomass	0	86	22
Methane - CCGT	0.599	102	18

EROI = Electricity generation / energy expended

4.6 Summary

Option 1 and 2 of introducing 15% and 25% of renewables as well as shifting the diesel powered generation to CBM fired generation by 2020 and 2030 provides significant CO_2 emissions reduction compared to business as usual case. However, the large increase in electricity generation from 2012 to 2030, still results in the CO_2 emission increasing by about 154.7% compared to 2012 levels, for 237.6% increase in generation.

Option 3 looks favorable with 44.6% reduction in emissions since 2012 with 91.5% increase in generation for overall Grid Emission Factor (GEF) reduction of (0.902 – 0.519) / 0.902 =

42.5%. The corresponding expended energy increase for large scale adoption of Solar PV on commercial building and CBM substitution in place of diesel is 26.3% as option 2.

Option 4 gives the largest emissions reduction with 82.1% = (0.902 – 0.165) / 0.902) decrease in the GEF. Option 3 is revealed as the best, however CCS is still not a proven technology and the costs are still very preliminary with a high degree of uncertainty. Wide use of Solar PV may also require significant electrical storage to cover the night time electrical area. The out of battery storage is very high. Botswana has a number of options for reducing CO_2 emissions but in all cases coal remains an important primary energy source along with large scale solar PV and some biomass. Botswana energy policies: i) Clean technologies should be supportive for converting coal to liquid, ii) large scale implementation of solar PV and some biomass in the energy mix, iii) further consideration of chapter 5 which deals with the usability of solar PV system implemented in office buildings in Botswana are investigated, to see if this is an economic option for wide scale solar PV uptake for minimum electricity storage across the country.

CHAPTER 5 : RENEWABLES SITUATIONAL ANALYSIS AND RESULTS OF A SOLAR PV CASE STUDY IN OFFICE BUILDING IN BOTSWANA

5.1 Introduction

Since Botswana generates electricity mainly from coal. The country is facing a challenge to economically adopt clean coal electricity generation technologies in order to minimize carbon emissions. An alternative to this challenge is to maximize on the utilization of renewable energy resources, especially solar. Botswana is extremely sunny with solar radiation of about 3200hrs of sunshine a year, at an average daily radiation between 21- 28MJ per meter square on a horizontal surface (UNDP, 2012). Table 14 illustrates an example of the monthly temperature differences for summer and winter seasons of Gaborone City, Botswana. It is indicated that the highest temperature of 40^{o}C were recorded in November and February in summer and the lowest temperature of -2^{o}C was recorded in July in winter (AfricanRegionalCentre, 2016; Weatherbase, 2012). Currently the electricity generation from solar is very inadequate more likely to be invisible as highlighted in chapter 4, section 4.2. 4. However, there is need to research more about solar in order to identify economical solar technology applications with the various electricity demand sectors.

Table 14: – Monthly temperature differences for summer and winter of Gaborone City, Botswana recorded in 2010 (AfricanRegionalCentre, 2016; Weatherbase, 2012).

Climate data for Gaborone (Sir Seretse Khama Airport, 1981–2010) [hide]													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	39 (103)	40 (104)	39 (102)	37 (98)	33 (91)	29 (84)	28 (83)	33 (91)	39 (103)	38 (100)	40 (104)	39 (103)	40 (104)
Average high °C (°F)	32.7 (90.9)	32.1 (89.8)	30.8 (87.4)	28.4 (83.1)	25.6 (78.1)	23.1 (73.6)	22.9 (73.2)	26.2 (79.2)	30.0 (86)	32.0 (89.6)	32.3 (90.1)	32.5 (90.5)	29.1 (84.4)
Daily mean °C (°F)	25.7 (78.3)	25.2 (77.4)	23.7 (74.7)	20.6 (69.1)	16.8 (62.2)	13.7 (56.7)	13.5 (56.3)	16.9 (62.4)	21.2 (70.2)	24.0 (75.2)	24.7 (76.5)	25.3 (77.5)	20.9 (69.6)
Average low °C (°F)	19.7 (67.5)	19.3 (66.7)	17.4 (63.3)	13.5 (56.3)	8.3 (46.9)	5.0 (41)	4.4 (39.9)	7.5 (45.5)	12.3 (54.1)	16.3 (61.3)	17.7 (63.9)	18.8 (65.8)	13.4 (56.1)
Record low °C (°F)	14 (57)	13 (55)	11 (52)	0 (32)	−1 (30)	−1 (30)	−2 (28)	0 (32)	5 (41)	7 (45)	8 (46)	11 (52)	−2 (28)

5.1.1 Renewable Situation Analysis for Botswana

A feasibility study on solar energy in Botswana was conducted by the Department of Energy with assistance from the United Nation Development Planning (UNDP) body in 2009/10. In addition to the previous studies, the high costs of solar technology, installation and maintenance as well as inadequate expertise in solar technology applications were revealed as the main barrier that are leading to the slow uptake of solar in Botswana. Nevertheless, the study did emphasize that with possible improvement in the cost effectiveness of solar technologies, solar uptake will rise. In this regard, Botswana have planned for implementation of some high capacity renewable projects. The purpose of the plan is to meet the set targets of 15% and 25% electricity generated from renewable by 2020 and 2030 respectively (UNDP, 2012). The Table 15 illustrates three renewable planned renewable electricity projects.

Table 15: - Electricity installed and planned from renewable generation capacities in MW (Mothebe, 2013)

RENEWABLE POWER PLANTS	CAPACITY (MW)	TIMING	STATUS
Solar PV mini grid plant	1.3	Completed (2012)	Installed and connected to the national grid (currently in operation)
IPP mini plants from Biogas & Solar	75	TBA	Planned (REFIT Tariff study completed in 2011)
Concentrated Solar Thermal Plant	100	2017/18	Planned (Feasibility study completed in 2013)
TOTAL	**176.3**		

The electricity generation mix for all SADC/SAPP member of states is forecast to increase from 53 GW in 2010 to 156 GW in 2030 as shown in Figure 38. Fossil fuels of coal, oil and gas makeup approximately 80% of the electricity generation mix in 2016. By 2030 it is predicted that more than half of all electricity generation will be from renewables source of hydro, biomass, solar and wind with solar PV predicted to be about 75% of the total at approximately 40 GW of solar PV generation is installed. Note it is not clear whether the solar PV installation is based on the peak or average generation. If solar PV generation in this data applies to peak production, then 40 GW of solar PV peak is equivalent to only 10 GW of average generation,. Because of this large difference there is value in matching supply and demand to minimise energy storage, and to reduce system costs as much as possible.

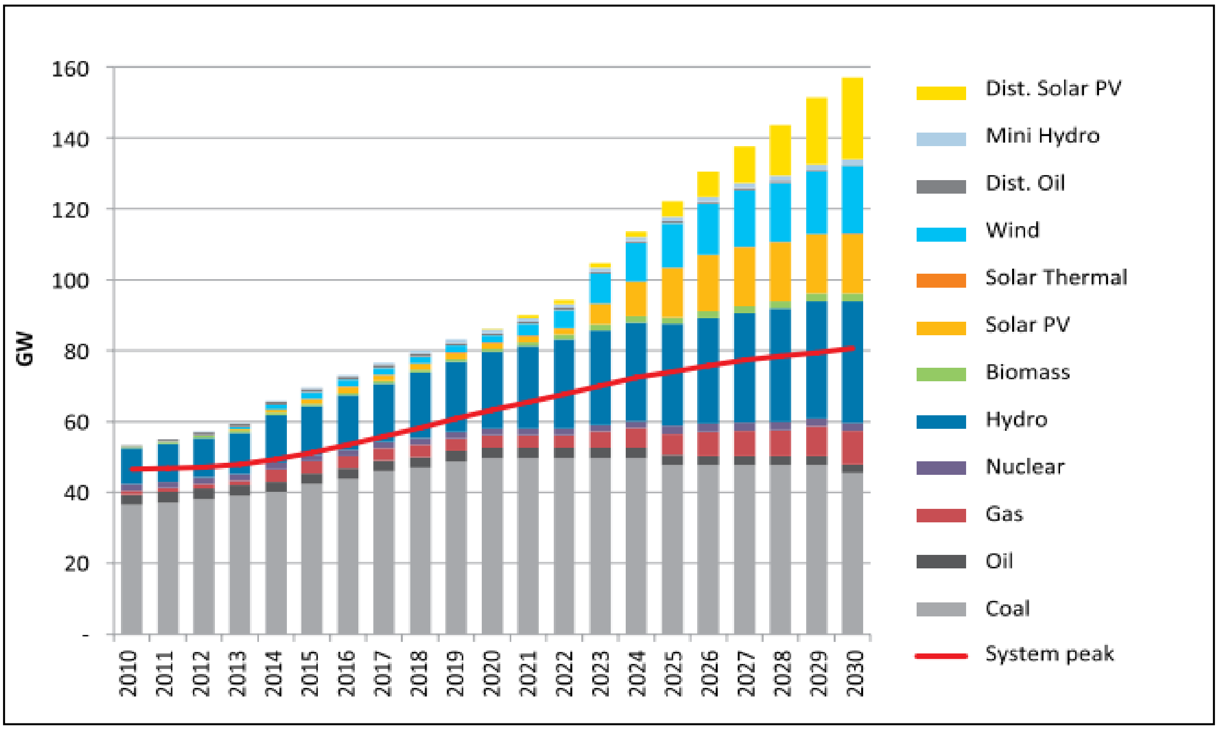


Figure 38:- 2010 to 2030 shares (GW) of electricity generation and forecasts of the renewable promotion scenario for SAPP (Miketa & Merven, 2013)

Figure 39 compares the percentage shares of electricity generation mix and forecasts under the renewable promotion scenario between SAPP members of states for the years 2010 and 2030 (Miketa & Merven, 2013). In this regard, it is highlighted that Botswana is not doing well in terms of utilization of renewable energy, provided there is high opportunity in solar energy in the country. The negative percentages are net imports being the electricity generation surplus to give away to other countries in need. In 2010, it indicates that Mozambique and South Africa were having extra from their electricity generations. Therefore, the predictions of 2030 it shows that Botswana, DRC, Malawi and Mozambique will have extra electricity generation to give away to other countries (Miketa & Merven, 2013).

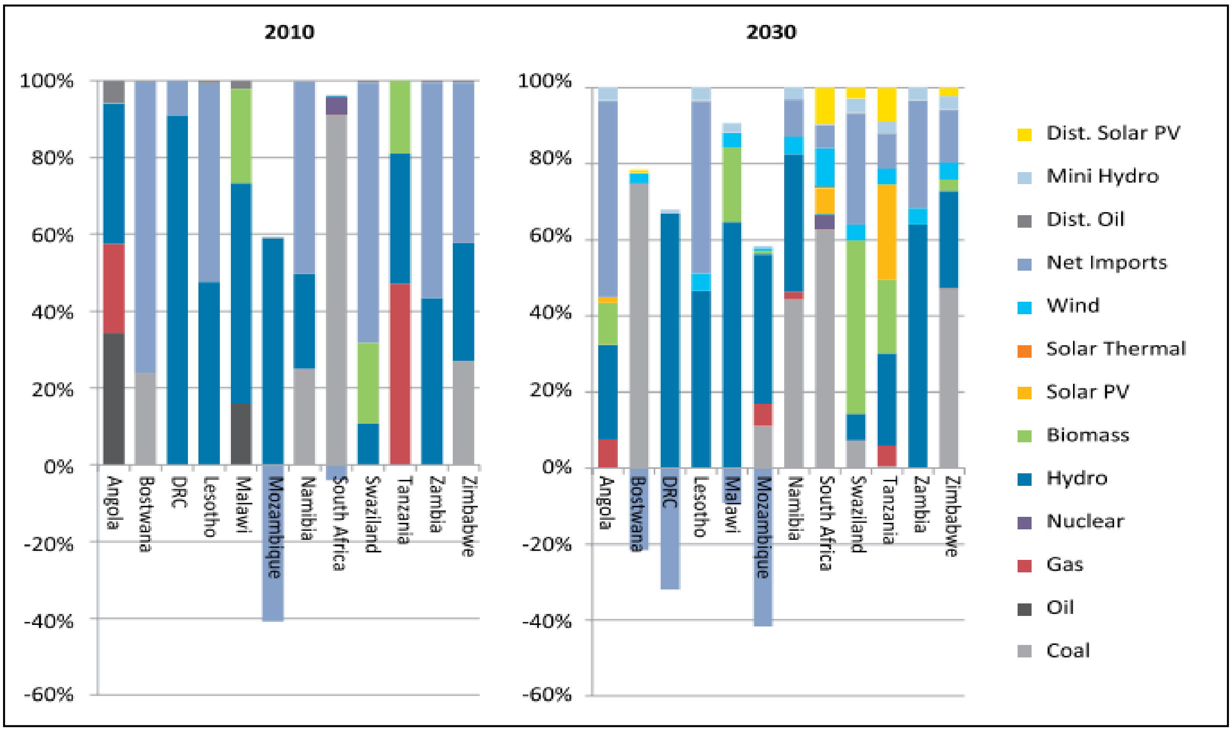


Figure 39:- Percentage shares of electricity generation mix and forecasts of the renewable promotion between SAPP members from 2010 and 2030 (Miketa & Merven, 2013)

5.2 General Information on Solar PV System

Solar PV systems generally consist of three main components solar panels, inverter and batteries for storage (Dolphin, 2012). The process of solar PV generation is to absorb sun light and convert it into DC electricity initially and then into into AC electricity for generally distribution. Most solar system technologies installed in buildings involve DC to AC conversion and converted to DC again. One of the factors to these conventions is that most electricity distribution network are AC and and many electronic office equipment are DC powered. It makes sense that there may be some economic advantage to use solar PV directly as DC electricity rather than to go through two conversion steps of DC-AC and then AC-DC.

It is well known the solar electricity generation undergoes energy losses with every conversion processes electricity generation processes. These losses all contribute to reducing the overall energy efficiency solar electricity generation systems plus each additionally contribute to the costs at design stage solar PV system (Fregosi et al., 2015).

It is with this perspective that the research in this thesis has been undertaken into an economic and efficient solar PV system for office buildings in Botswana and preferably for commercial and government office. The solar PV system has been designed and evaluated with the help of HOMER Pro software methods/tools as explained in section 3.3. Three options have been considered in the Botswana case study. The aim has been to find the lowest cost solar PV system through curbing costs on energy conversion and storage processes that maximizes the reduction in CO_2 emission in office buildings.

The case study was conducted at Botswana Oil Limited building which is located in Gaborone city in Botswana. The building foot print is 21.782m by 10.620m. Figures 40 and 41 show the picture/image of the building. The building is composite of two floors plus ground floor and the total of about 28 employees. The appliances used in the building and their energy consumptions are outlined in Tables 16, 17 and18 and Figures 42, 43, 44 and 45.

Figure 40:- Front view of Botswana Oil Limited Pty Ltd taken in 2017

Figure 41:- Side view of Botswana Oil Limited Pty Ltd taken in 2017

5.3 Results of Botswana Oil Limited Office Building Survey

5.3.1 Survey of electrical appliances

The Table 16 presents the results of the number of electrically run appliances that are in the Botswana oil limited (BOL) office. The appliances are grouped into AC and DC devices type, therefore, a graph was plotted showing numbers of AC appliances against DC appliances as outlined in Figure 42. The same data was plotted in a pie chart to show the percentage numbers of appliances occupancy in terms of AC and DC types. This is indicated in a pie chart on Figure 43, and it shows that 92% of the appliances in the building are DC type which is dominated by lights while 8% are AC type. Figure 44 outlines the percentage of appliances in the building, whereby the lighting system is the highest by 75.04% and the printers/fax being the lowest at 0.67%.

Table 16:- Number, percentages and total power rates of AC and DC appliances in a building

Names of Major Appliances	**Totals of Appliances**	**Appliances by AC vs DC type**					
		Number of AC Appliances	Number of DC Appliances	%age numbers of Appliances	Max. Total Rated Power of AC Appliances **(kW)**	Max. Total Rated Power of DC Appliances **(kW)**	%age Total Power Ratings of Appliances
Computer monitors screen only	33	-	33	5.53%	-	0.64	0.50%
Computer CPUs only	38	-	38	6.37%	-	4.86	3.83%
Printers/Fax machines	4	-	4	0.67%	-	5.8	4.57%
Server Room appliances	17	-	17	2.85%	-	3.37	2.66%
Air Conditioning	23	23	-	3.85%	78.2	-	61.65%
Other office electric appliances	11	7	4	1.84%	2.69	1.53	3.33%
Board room appliances	8	-	8	1.34%	-	0.56	0.44%
Light systems	448	-	448	75.04%	-	9.40	7.41%
Kitchen appliances	15	15	-	2.51%	19.8	-	15.61%
TOTAL	**597**	**45**	**552**		**100.69**	**26.17**	
					126.86		

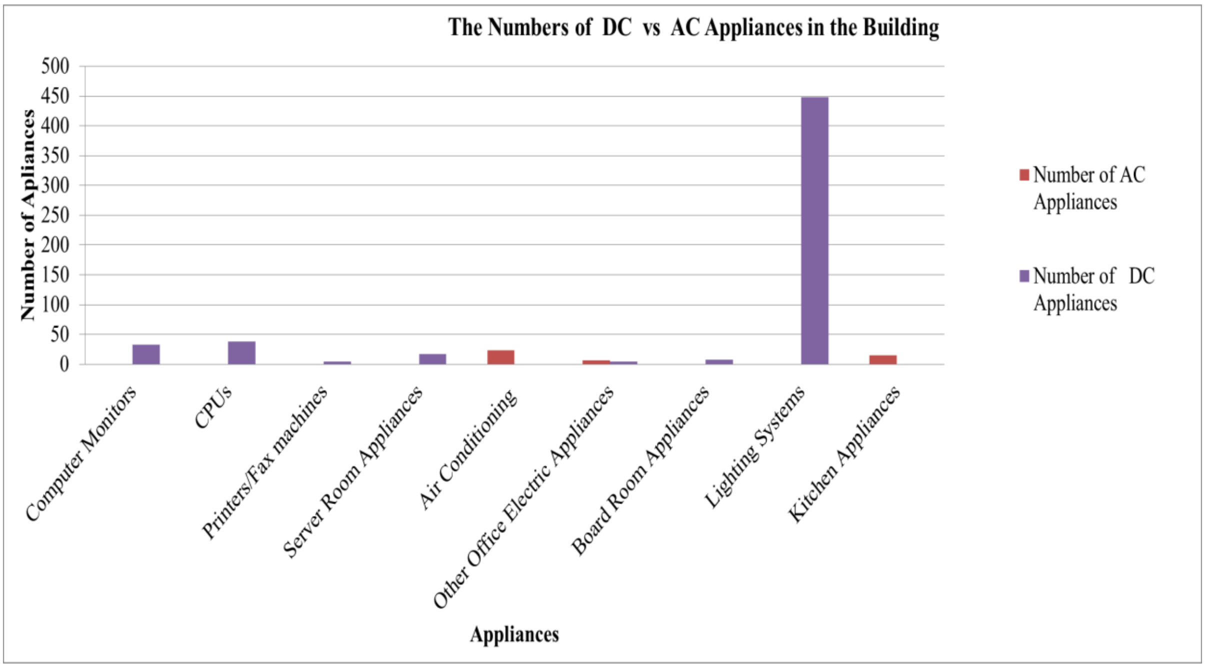


Figure 42:- Numbers of AC vs DC appliances in the building

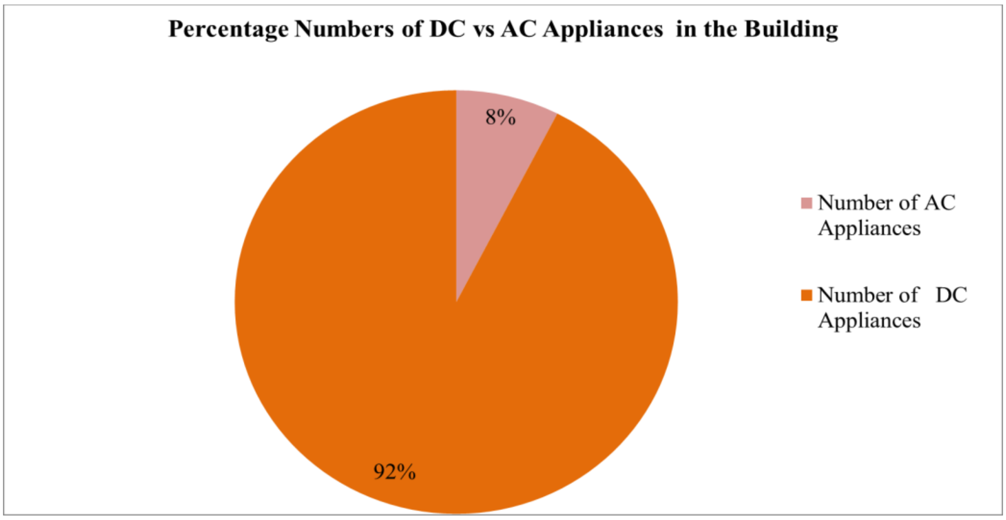


Figure 43:- Percentage numbers of AC vs DC appliances in the building

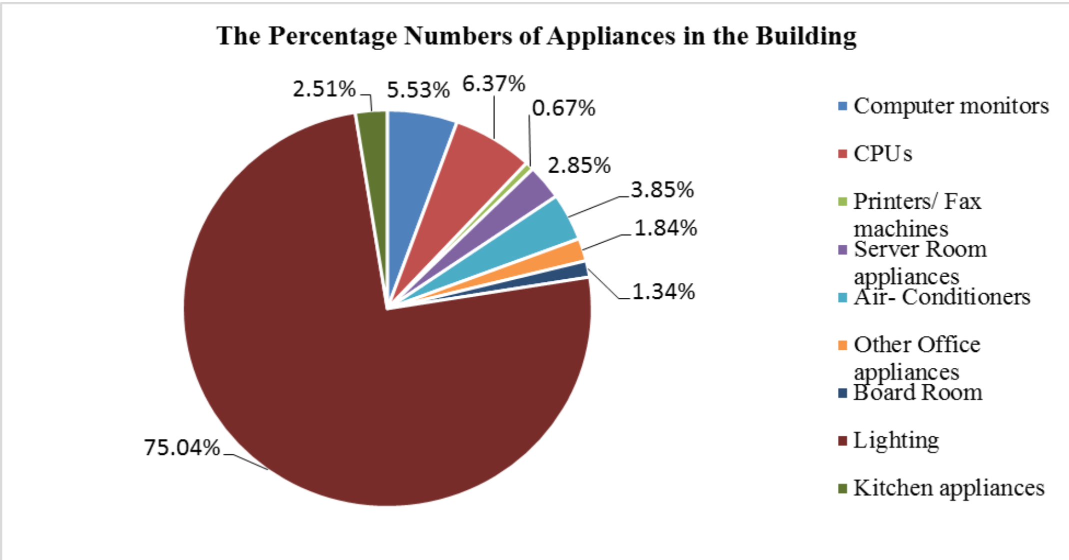


Figure 44:- Percentage number of appliances in the building

Another graph was plotted showing power ratings totals of AC appliances against DC appliances as indicated in Figure 45. The same data was plotted in a pie chart to show the percentage power ratings totals of appliances in terms of AC and DC types. This is indicated in a pie chart on Figure 46, and it shows that the highest 79% power ratings totals of the appliances in the building are AC type which is dominated by air conditioning, while 21% are power ratings totals of the DC type. Figure 47 outlines the percentage power ratings totals of appliances in the building, whereby the air conditioning is the highest by 61.65% and the board room appliances being the lowest at 0.44%.

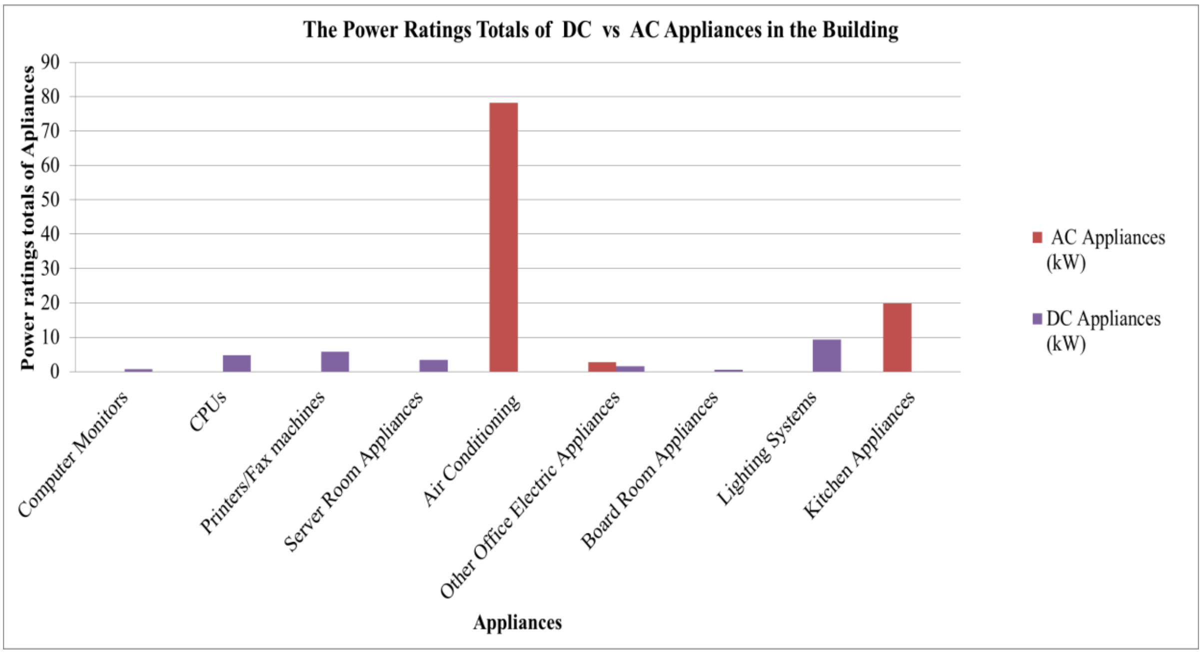


Figure 45:- Power ratings totals of AC vs DC appliances in the building

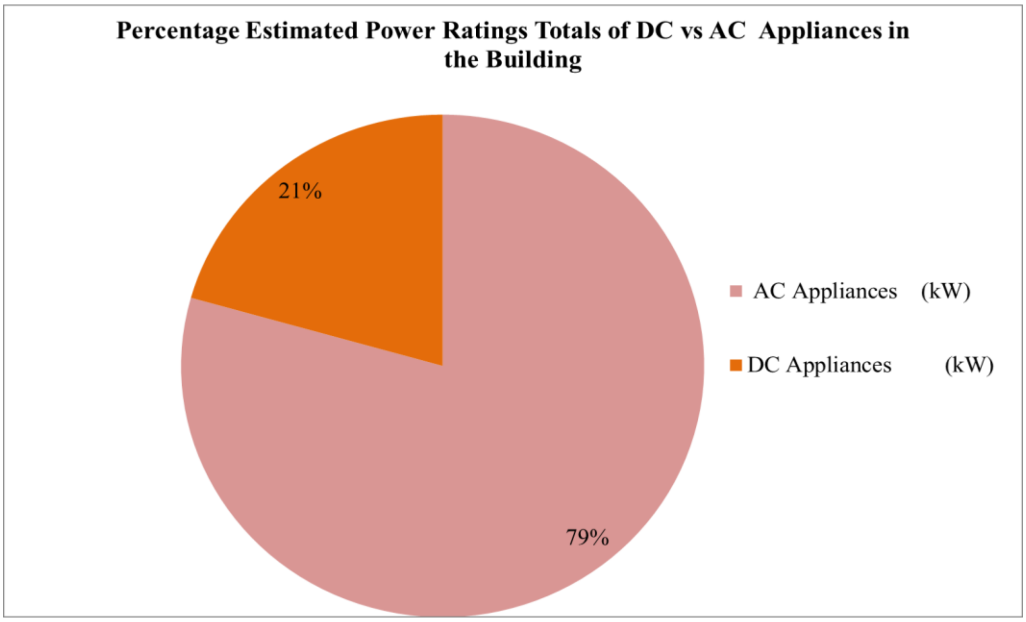


Figure 46:- Estimated percentage power ratings totals of AC vs DC appliances in the building

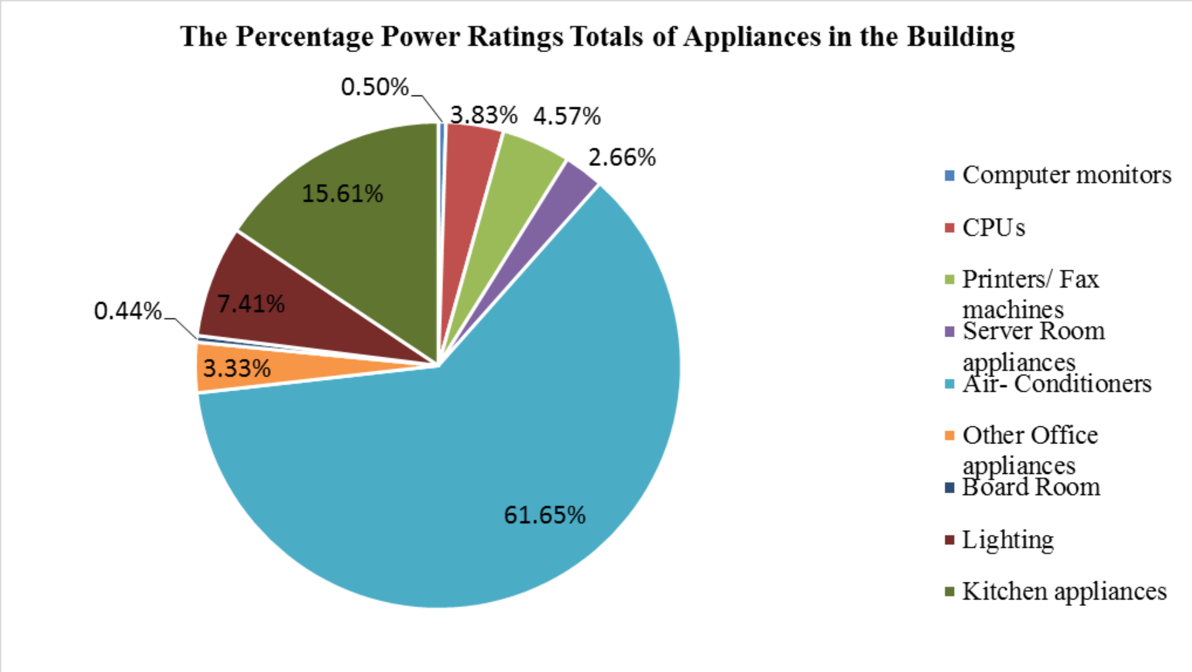


Figure 47:- Estimated percentage power ratings totals of appliances in the building

5.3.2 The Electricity Consumption Data of the Same Building Collected from Botswana Power Corporation (BPC)

Table 17 present the average power for various groups of appliances in the BOL building consumption for the January 2015 on Thursday 15 (summer season). The data was collected with the help of the Botswana Power Corporation (BPC).The electricity consumption was recorded per appliance type with the use of data logger equipment. The same data was plotted against time (hour) on Figure 48 to show the daily electricity consumption of the appliances in the building. The data indicated that high consumption takes place between 1500hrs and 1600hrs and the air conditioning is the highest consuming appliance.

The calculations were performed using the data from Table 17, in order to conform to the electricity bill of the building for the month of July 2017. The electricity charge rate is $0.08/kWh in Botswana. In this regard assumptions were made that the measured power used for one day weekend is 288kWh ($23/weekend day). Over 2 days weekend the electricity use is 576kWh ($46/weekend day). Similarly, for a work day use data from Table 17 is 841.44kWh/day ($67.32/working day). Over 5 working days the electricity use is 4207.2kWh ($336.58/ working days). Hence a week is 4207.2kWh/ 5days + 576kWh/ 2weekend days = 4783.2 kWh/week which gives an electricity bill of $382.66/week.

For full month of 30days, assume 4 weekends (8days) and 22 days of work days electricity use = (8 weekend days X 288 kWh/day) = (22 work days X 841.44 kWh/day =20815.68kWh/month. At $0.08/kWh this gives electricity bill of $1665.25 which is close to the July electricity bill as indicated in appendix D2: thus BWP12, 169.56 which is equivalent to NZ$1,640.30.

Table 17:- A summer day, 24 hrs recorded electricity consumption (in **Watts**) of the building per appliance type

End of Period	Computer Monitors Screen Only	Computer CPUs Only	Printers/Fax machines	Server Room Equipment	Air Conditioning (Cooling)	Other Office Electric Devices	Board Room Devices	Lighting Systems	Kitchen Appliances	Hourly TOTALS [Watts]
00:00:00	88,8	674,0	804,4	467,4	10844,9	585,2	77,7	1303,8	2745,9	**17592**
01:00:00	60,5	459,7	548,7	318,8	7397,6	399,2	53,0	889,4	1873,1	**12000**
02:00:00	58,7	446,0	532,2	309,2	7175,7	387,2	51,4	862,7	1816,9	**11640**
03:00:00	56,4	428,5	511,4	297,1	6894,6	372,1	49,4	828,9	1745,7	**11184**
04:00:00	57,4	435,8	520,1	302,2	7012,9	378,4	50,2	843,1	1775,7	**11376**
05:00:00	58,0	440,4	525,6	305,4	7086,9	382,4	50,8	852,0	1794,4	**11496**
06:00:00	55,1	418,4	499,3	290,1	6731,8	363,3	48,2	809,3	1704,5	**10920**
07:00:00	75,3	571,9	682,5	396,6	9202,6	496,6	65,9	1106,4	2330,1	**14928**
08:00:00	170,4	1293,7	1544,0	897,1	20816,9	1123,4	149,1	2502,7	5270,8	**33768**
09:00:00	258,3	1961,3	2340,6	1360,0	31558,2	1703,0	226,0	3794,1	7990,5	**51192**
10:00:00	283,0	2148,9	2564,5	1490,1	34576,5	1865,9	247,6	4157,0	8754,7	**56088**
11:00:00	313,7	2382,4	2843,2	1652,0	38334,5	2068,7	274,5	4608,8	9706,2	**62184**
12:00:00	326,4	2479,0	2958,4	1719,0	39888,0	2152,5	285,6	4795,5	10099,5	**64704**
13:00:00	328,3	2492,8	2974,9	1728,5	40109,9	2164,5	287,2	4822,2	10155,7	**65064**
14:00:00	281,0	2134,2	2546,9	1479,9	34339,8	1853,1	245,9	4128,5	8694,7	**55704**
15:00:00	369,1	2802,6	3344,7	1943,4	45095,9	2433,6	322,9	5421,7	11418,1	**73152**
16:00:00	399,5	3033,4	3620,1	2103,4	48809,5	2634,0	349,5	5868,1	12358,4	**79176**
17:00:00	288,1	2187,5	2610,6	1516,8	35197,9	1899,4	252,1	4231,7	8912,0	**57096**
18:00:00	207,5	1576,0	1880,8	1092,8	25359,0	1368,5	181,6	3048,8	6420,8	**41136**
19:00:00	178,7	1357,2	1619,7	941,1	21837,8	1178,5	156,4	2625,4	5529,3	**35424**
20:00:00	114,2	867,1	1034,8	601,3	13951,9	752,9	99,9	1677,4	3532,6	**22632**
21:00:00	72,2	548,0	654,0	380,0	8818,0	475,9	63,1	1060,1	2232,7	**14304**
22:00:00	74,1	562,7	671,6	390,2	9054,7	488,6	64,8	1088,6	2292,6	**14688**
23:00:00	70,8	537,9	641,9	373,0	8655,2	467,1	62,0	1040,6	2191,5	**14040**
Day TOTALS	**4156,8**	**31565,5**	**37670,8**	**21888,0**	**507905,8**	**27408,7**	**3637,2**	**61063,0**	**128600,2**	**841488**

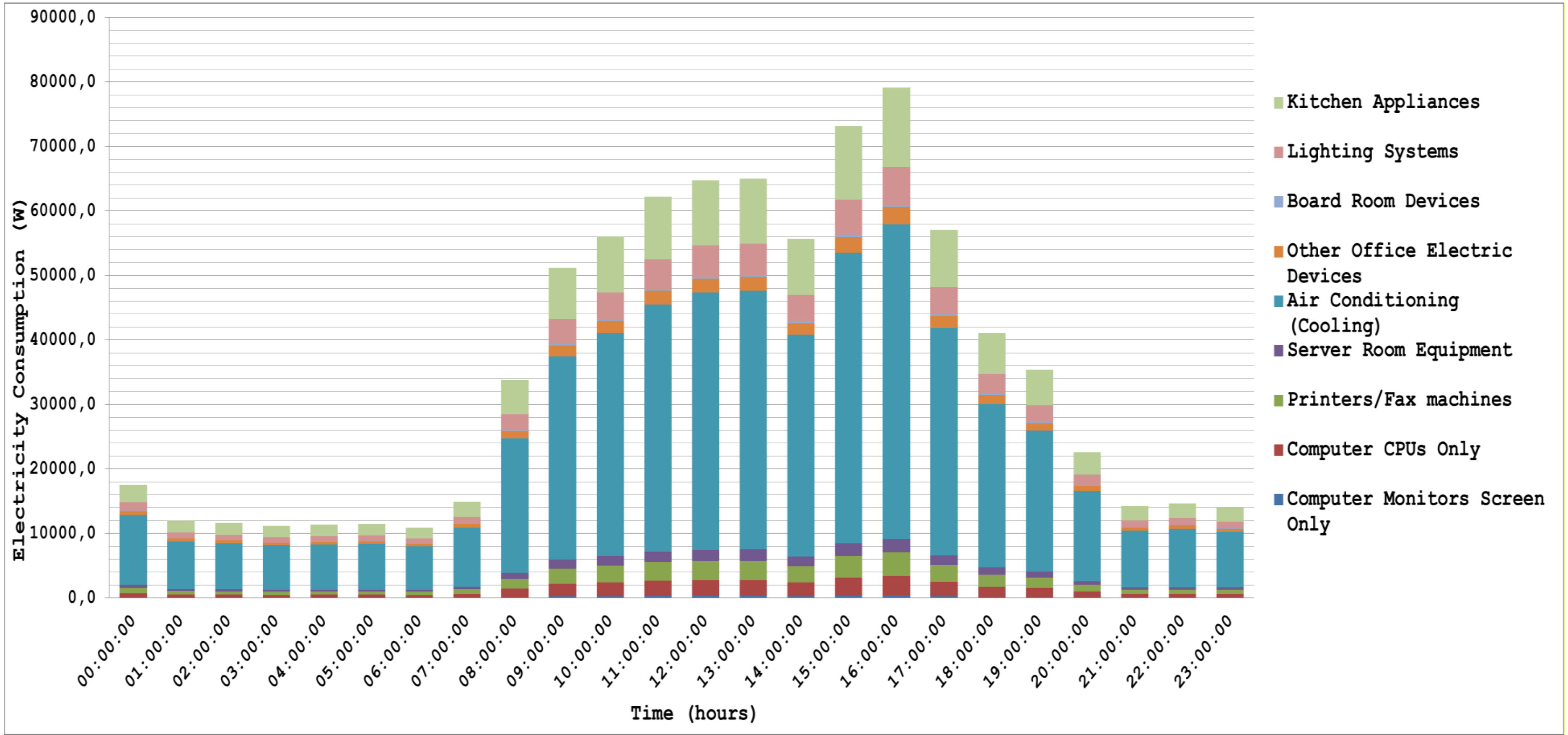


Figure 48:- Appliances electricity consumption data from the commercial office building in Botswana (summer season)

Table 18 outlines the electricity consumption data for the month of June 2015 on Wednesday 18 (winter season). The data was collected by the help of Botswana Power Corporation (BPC). Then with the use of data logger equipment the electricity consumption was recorded per appliance type. The same data was plotted against time (hour) in Figure 49 to show the daily electricity consumption of the appliances in the building. In the graph it is indicated that high consumption takes place between 0900hrs and 1000hrs the air conditioning as the most consuming appliance.

The calculations were performed using the data from Table 18, in order to conform to the electricity bill of the building for the month of July 2017. The electricity charge rate is $0.08/kWh in Botswana. The same assumptions were made that the measured electricity use for one day weekend is 288kWh ($23/weekend day). Over 2 days weekend the electricity use is 576kWh/ weekend days ($46/weekend days). Similarly, for a work day use data from Table 18 is 588.3kWh/day ($47.06/working day). Over 5 working days the electricity use is 2941.5kWh ($235.32/working days). Hence a week is 2941.5kWh/ 5days + 576kWh/ 2weekend days = 3517.5 kWh/week which gives an electricity bill of $281.4/week.

For full month of 30days, assume 4 weekends (8days) and 22 days of work days electricity use = (8 weekend days X 288 kWh/day) + (22 work days X 588.3 kWh/day =15246.6kWh/month. At $0.08/kWh this gives the power bill of $1219.73/month.

Table 18:- A winter day, 24hrs recorded electricity consumption (in Watts) of the building per appliance type

End of Period	**Computer Monitors Screen only**	**Computer CPUs only**	**Printers/Fax machines**	**Server Room Equipment**	**Air Conditioning (Heating)**	**Other Office Electric Devices**	**Board Room Devices**	**Lighting Systems**	**Kitchen Appliances**	**Hourly TOTALS [Watts]**
00:00:00	46,0	349,4	417,0	242,3	5622,2	303,4	40,3	675,9	1423,5	**9120**
01:00:00	74,2	563,7	672,7	390,8	9069,5	489,4	64,9	1090,4	2296,4	**14712**
02:00:00	75,2	571,0	681,5	395,9	9187,8	495,8	65,8	1104,6	2326,3	**14904**
03:00:00	75,0	569,2	679,3	394,7	9158,3	494,2	65,6	1101,1	2318,8	**14856**
04:00:00	72,8	552,6	659,5	383,2	8891,9	479,8	63,7	1069,0	2251,4	**14424**
05:00:00	74,1	562,7	671,6	390,2	9054,7	488,6	64,8	1088,6	2292,6	**14688**
06:00:00	72,9	553,5	660,6	383,8	8906,7	480,6	63,8	1070,8	2255,2	**14448**
07:00:00	129,2	981,1	1170,9	680,3	15786,5	851,9	113,0	1897,9	3997,1	**25608**
08:00:00	211,1	1602,7	1912,7	1111,3	25788,1	1391,6	184,7	3100,4	6529,5	**41832**
09:00:00	250,0	1898,8	2266,0	1316,6	30552,2	1648,7	218,8	3673,1	7735,7	**49560**
10:00:00	222,3	1688,2	2014,7	1170,6	27164,1	1465,9	194,5	3265,8	6877,9	**44064**
11:00:00	224,7	1706,6	2036,7	1183,4	27460,0	1481,9	196,6	3301,4	6952,8	**44544**
12:00:00	226,1	1716,7	2048,7	1190,4	27622,7	1490,6	197,8	3320,9	6994,0	**44808**
13:00:00	195,8	1486,8	1774,4	1031,0	23923,9	1291,0	171,3	2876,3	6057,5	**38808**
14:00:00	208,0	1579,7	1885,2	1095,4	25418,2	1371,7	182,0	3055,9	6435,8	**41232**
15:00:00	196,4	1491,4	1779,9	1034,2	23997,9	1295,0	171,9	2885,1	6076,2	**38928**
16:00:00	158,9	1206,4	1439,7	836,5	19411,4	1047,5	139,0	2333,7	4914,9	**31488**
17:00:00	149,4	1134,7	1354,1	786,8	18257,3	985,2	130,7	2195,0	4622,7	**29616**
18:00:00	76,0	577,4	689,1	400,4	9291,4	501,4	66,5	1117,1	2352,6	**15072**
19:00:00	46,5	353,1	421,4	244,8	5681,4	306,6	40,7	683,0	1438,5	**9216**
20:00:00	45,4	344,8	411,5	239,1	5548,2	299,4	39,7	667,0	1404,8	**9000**
21:00:00	46,6	354,0	422,5	245,5	5696,2	307,4	40,8	684,8	1442,3	**9240**
22:00:00	45,3	343,9	410,4	238,5	5533,4	298,6	39,6	665,3	1401,0	**8976**
23:00:00	46,1	350,3	418,1	242,9	5637,0	304,2	40,4	677,7	1427,3	**9144**
Day TOTALS	**2968,1**	**22538,8**	**26898,1**	**15628,7**	**362660,9**	**19570,7**	**2597,1**	**43600,9**	**91824,6**	**588288**

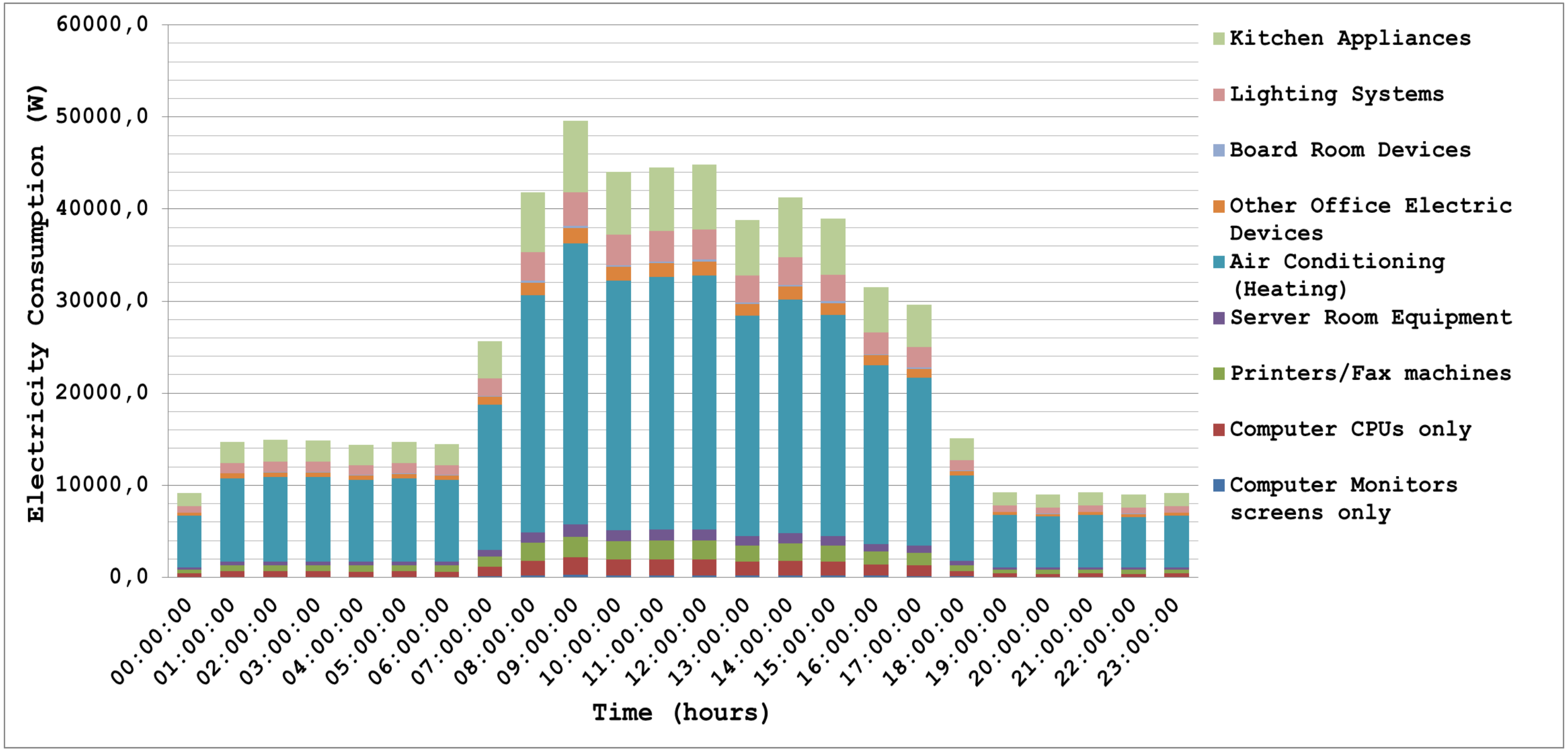


Figure 49:- Appliances electricity consumption data from the commercial office building in Botswana (winter season)

5.3.3 HOMER Pro Software Modelling of Solar PV - Office Building Case Study

HOMER Pro software was used to obtain the meteorological solar data of the Gaborone city in Botswana which the building for the case study is situated. The software is configured to NASA surface meteorology and solar energy database as well as GPS coordination for site location. In this case, the coordinates of Latitude (24°5'S) and Longitude (25°5'E) written in degrees or Latitude (-24.5) and Longitude (25.5) written in decimal minutes were used. The average solar radiation and clearness data within Latitude (-24.5) and Longitude (25.5) location is illustrated in Figure 50. This compares with annual average solar radiation for Botswana (5.72 kWh/m2/day) which is also outlined.

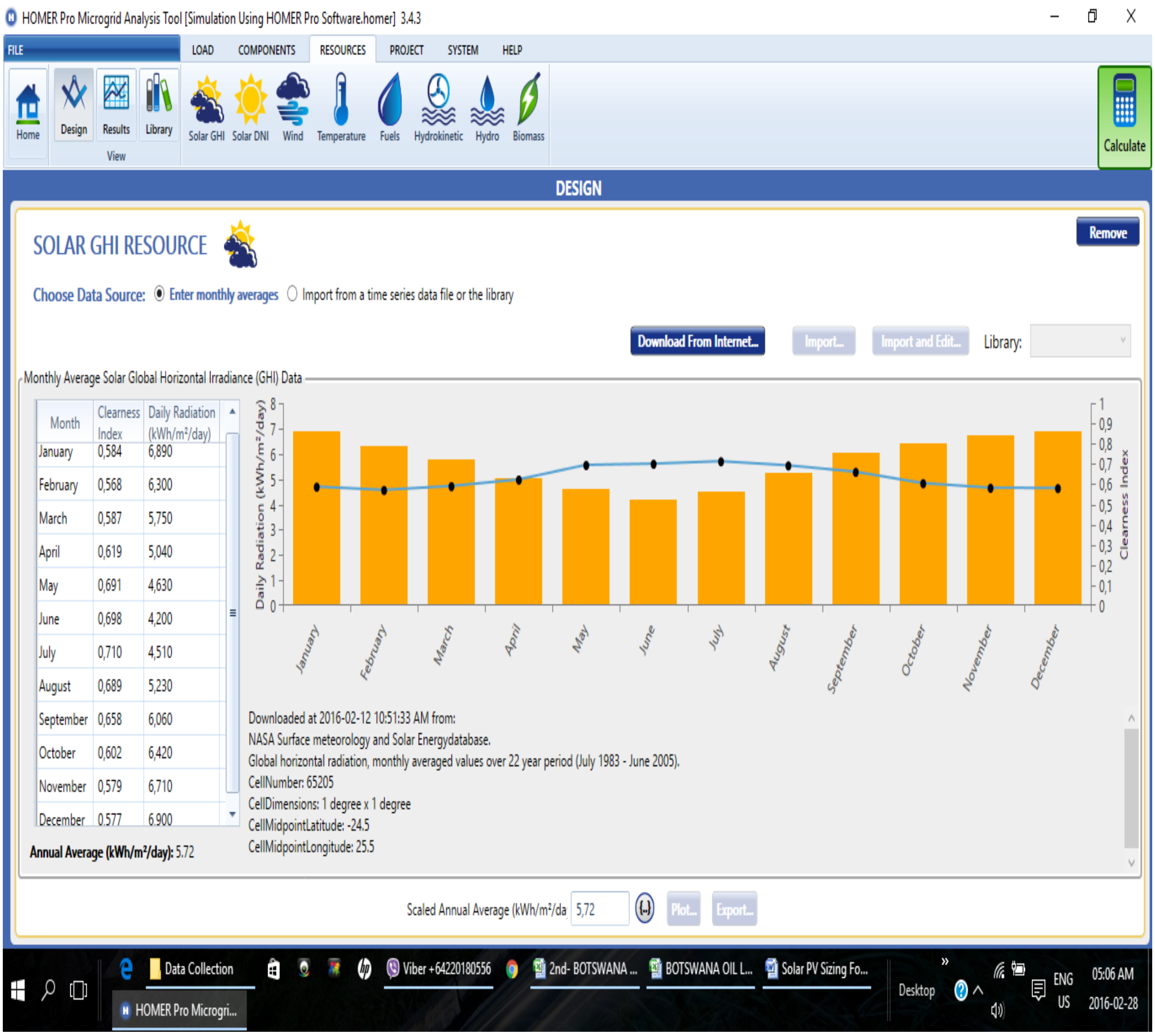


Figure 50:- Simulated daily solar radiation and clearness index at the location of the office building

The hourly electricity consumption data (appliances load totals) of the building recorded in January (summer season) by BPC as indicated in Table 17 was used in HOMER Pro to simulate the daily, seasonal and yearly load (kW) profiles of the building as illustrated in Figure 51. The baselines of energy average load (841.48 kWh/day) and peak power (132.79 kW) for the system designs were also outlined.

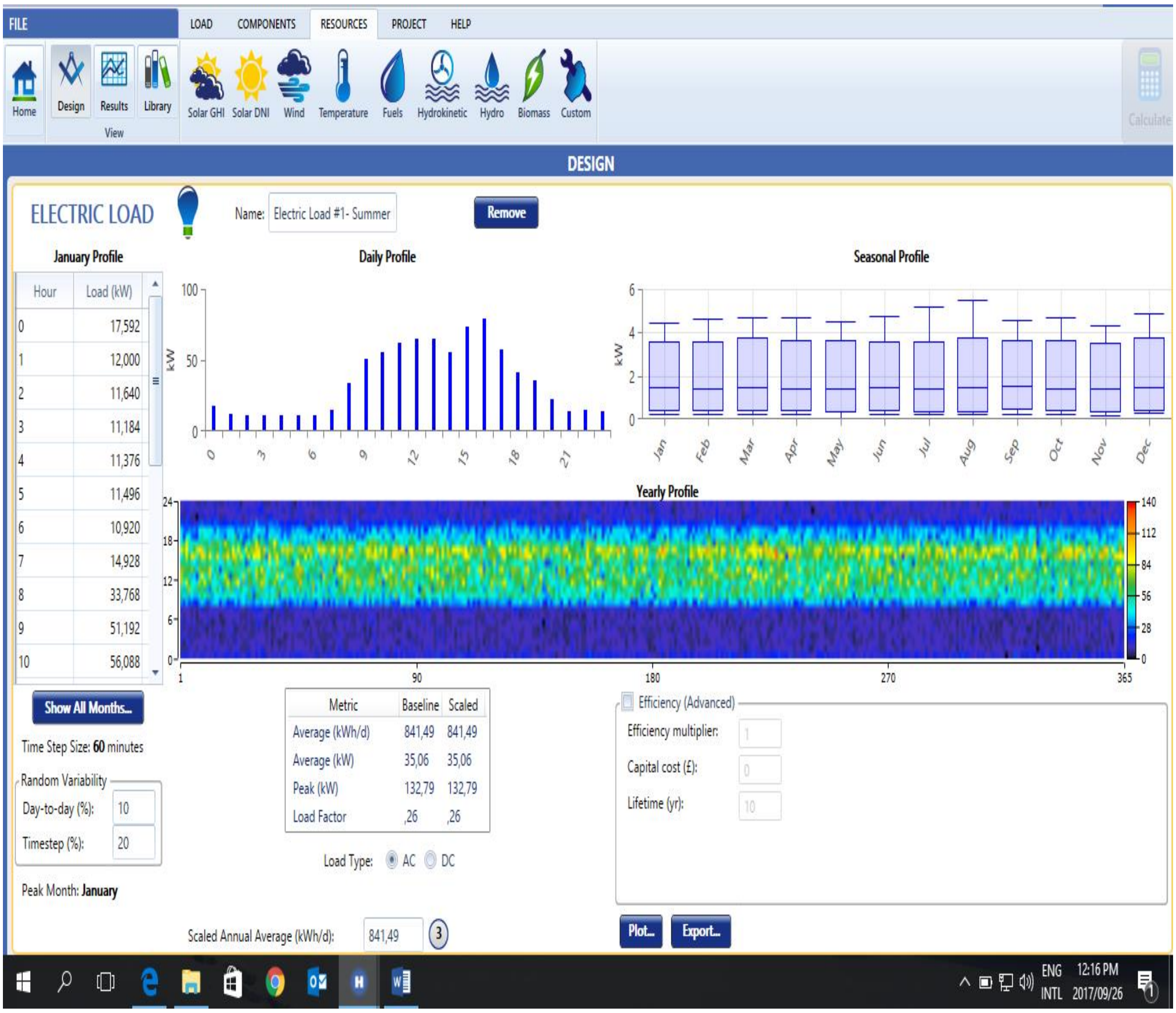


Figure 51:- Simulated daily, seasonal and yearly electricity load profiles of the office building

5.3.4 Solar Design and Cost Estimates for the Solar PV – Commercial Office Building Case Study

5.3.4.1 Modelling Calculations

In addition to the HOMER Pro software simulation, the solar design equations were used to calculate the solar PV system for each AC and DC systems. The procedure is outlined in step 1 to step 8. An Excel sheet was developed for doing the calculations and the spreadsheet accounted for Time of consumed energy (hours), Monthly average solar radiation levels, System peak power load, Number of components, Replacement, Capital, Present, NPC, and Levelized costs of the systems. As a result, the data is summarized in Tables 19 to 26 by using the equations 3 to 32. The specifications and cost estimates of the chosen components and system installation are outlined in appendixes E1 to E3. The abbreviations of the equations are outlined in details in Chapter 3-Methodology-section 3.3.3 (Arvind et al., 2009; Skunpong & Plangklang, 2010).

Step 1 - Sizing the Solar PV Modules

Using the data of the daily energy use profile from Table 17 and Figures 50 and 51:

The Design Energy Load

$$E_{design\ load} = 1.3\ x\ E_{load} \quad \ldots\ldots(3)$$

NOTE: 30% of energy catered for all energy losses in the system.

a) AC type

$$E_{design\ load} = 1.3\ x\ 841.488 \frac{kWh}{day} = \frac{1093.93kWh}{day}$$

b) DC type

$$E_{design\ load} = (1.3 - 0.1) x\ 841.488 \frac{kWh}{day} = \frac{1009.78kWh}{day}$$

NOTE: Minus 10% of energy loss to inverter

The Peak Power Needed for the Solar PV Array [after catering for the quality of PV arrays (Q) and design load] is:

$$P_{peak\ power} = \frac{E_{design\ load}\ x\ I_{STC}}{E_{glob}\ x\ Q} \quad \ldots\ldots(8)$$

NOTE:

Q is choosen from appendix D1, thus the average quality factor of the solar PV array system.

$\mathbf{I_{stc}}$ is global radiation under Standard Test Condition (1kW/m²/day).

$\mathbf{E_{glob}}$ is taken from Figure 50 as 5.72kWh/m²/day. This is the global radiation of the site location of the building.

a) AC type

$$P_{peak\ power} = \frac{1093.93kWh\ x\ 1kW\ x\ day\ x\ m^2}{5.72kWh\ x\ 0.85\ x\ day\ x\ m^2} = 225kW$$

b) DC type

$$P_{peak\ power} = \frac{1009.78\ kWh\ x\ 1kW\ x\ day\ x\ m^2}{5.72\ x\ 0.85\ kWh\ x\ day\ x\ m^2} = 207.69kW$$

The peak power was converted to peak energy load (kWh) by multiplying its designed peak power data (kW) by the 7 hours average/day of higher sunlight in Botswana. Thus:

a) AC type

$$P_{peak\ Energy\ Load} = 225kW\ x\ 7days = 1575kWh$$

b) DC type

$$P_{peak\ Energy\ Load} = 207.69kW\ x\ 7days = 1453.83kWh$$

$$Number\ of\ PV\ modules\ (N) = \frac{Peak\ power\ of\ PV\ array\ (W)}{Peak\ power\ of\ PV\ module\ (W)} \quad \text{………………………….……..….(9)}$$

a) AC type

$$Number\ of\ Solar\ PV\ modules = \frac{225kW}{0.34\ kW} = 662$$

b) DC type

$$Number\ of\ Solar\ PV\ modules = \frac{207.69kW}{0.34\ kW} = 611$$

Step 2 - Sizing the Inverter

$$Inverter\ capacity\ (W) = 1.3\ x\ P_{peak}\ Power \quad \text{……………………………………….……(10)}$$

NOTE: inverter is considered to be 20-30% bigger than the peak power of the system

AC type

$$Inverter\ capacity = 1.3\ x\ 225kW = 292.5kW$$

$$Number\ of\ inverter\ (N) = \frac{Inveter\ capacity\ size\ (W)}{Rated\ power\ of\ each\ inveter\ (W)} \quad \text{…………………….………...…..(11)}$$

$$Number\ of\ inverters = \frac{292.5kW}{9\ kW} = 33$$

Step 3 - Sizing the Battery

$$Battery\ capacity\ bank\ size\ (Wh) = \ Autonomy\ days\ x\ \ E_{design\ load}$$ ……………....(13)

a) AC type

$$Battery\ capacity = 2\ days\ x\ 1093.93\frac{kWh}{day} = 2187.86kWh$$

b) DC type

$$Battery\ capacity = 2\ days\ x\ 1009.78\frac{kWh}{day} = 2019.56kWh$$

NOTE: Days of autonomy (the number of days to operate the system when there is no power produced from the PV modules) = 2 days

$$Number\ of\ batteries\ (N) = \ \frac{Battery\ bank\ size\ (Wh)}{Capacity\ of\ each\ Battery\ (Wh)}$$ ……………………………..(15)

a) AC type

$$Number\ of\ batteries = \frac{2187.86kWh}{9\ kWh} = 243$$

b) DC type

$$Number\ of\ batteries = \frac{2019.56kWh}{9\ kWh} = 225$$

Step 4 - Sizing the Solar Charge Controller Rating

$$Charge\ controller\ capacity\ (A) = \ \frac{PV\ array\ \ Peak\ power\ (W)}{Battery\ bank\ design\ voltage(V)}$$ ……………….……….(16)

a) AC type

$$Charge\ controller\ capacity = \frac{225kW}{1152V} = 195.31A$$

b) DC type

$$Charge\ controller\ capacity = \frac{207.69kW}{1152V} = 180.3A$$

Table 19 summaries the calculations of number of solar PV panels, inverters and batteries achieved through excel using equations 9, 11 and 15. It shows that the AC solar PV system types requires more panels and batteries compared to DC solar PV system types. Thus DC solar PV system types is 7.8% of solar panels and 7.4% of batteries less than AC solar PV system types.

Table 19:- Numbers of each component required per system

	Number of Solar PV Panels	**Number of Inverters**	**Number of Batteries**
Solar PV AC+Inverter+Batteries	681	33	243
Solar PV AC+Inverter	681	33	0.00
Solar PV DC+ Batteries	628	0.00	225
Solar PV DC Only	628	0.00	0.00

Table 20 summaries the data calculations of the building electricity demand load, solar energy system design load, peak energy load and energy surplus. The calculations are achieved through excel sheet manipulated using equations 3 and 8.

Table 20:- Energy load parameters of the four different solar PV system models with the demands and peak loads

Renewable energy Systems	**Building Electricity Demand Load [kWh]/day**	**Solar Energy System Design Load [kWh]/day**	**Peak Energy Load [kWh]/day**	**Energy Suplus [kWh]/day**	
Solar PV AC+Inverter+Batteries	841.44	1093.94	1575.00	481.06	Stored in Batteries
Solar PV AC+Inverter	841.44	1093.94	1575.00	481.06	Feed to the Grid
Solar PV DC+Batteries	841.44	1009.78	1453.83	444.05	Stored in Batteries
Solar PV DC only	841.44	1009.78	1453.83	444.05	For load shift storage

The data information on building average peak power load, AC & DC solar PV systems peak power loads and their numbers of solar modules (solar PV panels) is summarized in Table 21 and the same data is plotted in Figure 52. The graph trends show that when increasing the renewables electricity supply, the higher the peak power loads for the building, increases the peak power loads of solar PV systems and the more the number of solar modules (solar PV panels) is required. The calculations are achieved through excel sheet by using equations 8 and 9.

Table 21:- Summarised data of the building peak power, AC Vs DC peak power of solar PV systems and number of solar PV panels agaisnt percentage increase in renewables.

		Solar PV AC-System		**Solar PV DC-System**	
Renewable Percentage (%)	**Building Aveg. Peak Power Load [kW]/day**	**Solar PV AC Peak Power [kW]/day**	**Solar PV AC - No. Of Panels [N]**	**Solar PV DC Peak Power [kW]/day**	**Solar PV DC - No. Of Panels [N]**
		Equation (8)	Equation (9)	Equation (8)	Equation (9)
0	0.00	0.00	0	0.00	0
10	8.64	23.14	68	21.36	63
20	17.28	46.28	136	42.72	126
30	25.92	69.43	204	64.09	188
40	34.56	92.57	272	85.45	251
50	43.26	115.71	340	106.81	314
60	51.84	138.85	408	128.17	377
70	60.48	162.00	476	149.54	440
80	69.12	185.14	545	170.90	503
90	77.76	208.28	613	192.26	565
100	86.64	231.42	681	213.62	628

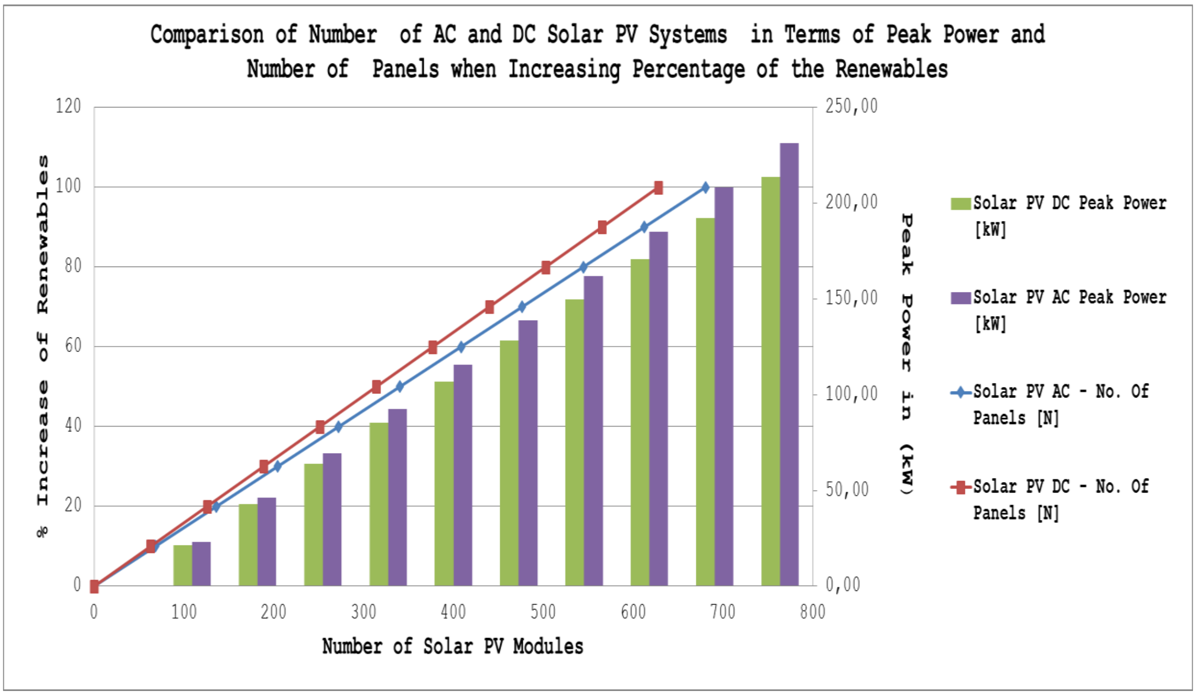


Figure 52:- AC Vs DC peak power of solar PV systems and solar PV panels against percentage increase in renewables.

5.3.4.2 Costs Estimates Calculations

Table 22 indicates variable factors; cost per unit component capacity, percentage rebate rate for replacement and the percentage interest rate. These factors were used in the calculation of the cost estimates of the AC and DC solar PV system models. It also summaries the chain calculations of capital, Installation and O&M costs, Replacement, Present, NPC and Levelized costs which contribute the net preset costs the system. This is outlined from step 5 to step 8.

Table 22:- Variable factors and costs calculated using equations 22 to 32 (Arvind et al., 2009)

	AC Solar PV+Inverter+Batteries	**AC Solar PV+Inverter**	**DC Solar PV+Batteries**	**DC Solar PV only**
Step 5 :- Capital Cost				
Cost of PV array per (kW)	$500.00	$500.00	$500.00	$500.00
Cost of Battery per (kWh)	$200.00	$200.00	$200.00	$200.00
Cost of Inverter per (kW)	$200.00	$200.00	$200.00	$200.00
Cost of Solar Charge Controller (SCC) per (A)	$200.00	$200.00	$200.00	$200.00
Capital Cost	US$648234	US$210662	US$543817	US$139905
Step 6 :- Installation and O&M Cost				
Cost of Installation per (kWh)	$450.00		$450.00	
Cost of Installation	US$492268.5.	US$492268.5	US$454401	US$454401
Step 7 :- Replacement Cost				
Rebate (%)	95%			95%
Total Replacement Cost	US$565948.4	US$150255	US$516626.15	US$132909.75
Step 8 :- Present and NPC Cost	US$ 2068279.31	US$587673.24	US$1840105.75	US$473394.53
Interest rate (*i*)	4%			4%
Present Cost	$50396.54			$43959.16
Number of Years of Replacement	20			20
Number of Years of Salvage	25			25
Net Present Costs (at 100% renewable)	US$ 2068279.31	US$587673.24	US$1840105.75	US$473394.53
Levelized Costs per kWh (at 100% renewable)	US$1.89/kWh	US$0.54/kWh	US$1.82/kWh	US$0.47/kWh

Step 5 - Capital costs:

Using costs per unit component from Table 22, the capital costs of the components are calculated as:

Table 23:- Total capital cost calculation for each componets system using eqautions 18 to 21 from chapter 3, section 3.3.4

AC type

Components Capacity		**Components Capacity Cost**
Cost of PV array (225kW)	US$500.00 *225kW	US$112500
Cost of Battery (2187.86kWh)	US$200.00*2187.86kWh	US$437572
Cost of Inverter (292.5kW)	US$200.00*292.5kW	US$59100
Cost of Solar Charge Controller (SCC) (195.3A)	US$200.00*195.31A	US$39062
DC type		
Cost of PV array (207.69kW)	US$500.00 *207.69kW	US$103845
Cost of Battery (2019.56kWh)	US$200.00*2019.56kWh	US$403912
Cost of Inverter	0	0
Cost of Solar Charge Controller (SCC) (180.3A)	US$200.00*180.3A	US$36060

Therefore, using the component costs from Table 23- the total capital costs of the systems are;

$$Capital\ Cost\ (Pcc) = \ Cost\ of\ PV\ array + Cost\ of\ Battery\ bank + Cost\ of\ Inverter\ size + Cost\ of\ SCC\ size \quad (22)$$

a) **AC Solar PV +Batteries+Inverter**

$$Capital\ cost = US\$112500 + US\$437572 + US\$59100 + US\$39062 = \boldsymbol{US\$648234}$$

b) AC Solar PV+Inverter

$$Capital\ cost = US\$112500 + US\$59100 + US\$39062 = \boldsymbol{US\$210662}$$

c) DC Solar PV+Batteries

$$Capital\ cost = US\$103845 + US\$403912 + US\$36060 = \boldsymbol{US\$543817}$$

d) DC Solar PV only

$$Capital\ cost = US\$103845 + US\$36060 = \boldsymbol{US\$139905}$$

Step 6 - Installation costs and Operation & Maintenance:

$Cost\ of\ System\ Installation = \ System\ design\ load\ x\ \ Cost\ per\ (kWh)$…..…………….....(23)

Using costs per unit component and variable factors from Table 22, the Installation, and O&M of the systems are calculated as:

a) AC type

$Installation\ cost = 1093.93kWh\ x\ US\$450/kWh = \boldsymbol{US\$492268.5}$

b) DC type

$Installation\ cost = 1009.78kWh\ x\ US\$450/kWh = \boldsymbol{US\$454401}$

$Cost\ of\ System\ O\&M = \ 1\%\ \ of\ the\ \ capital\ cost$……………………...………………….(24)

The O&M costs of the systems are:

a) **AC Solar PV+Inverter+Batteries**

$Cost\ of\ System\ O\&M = 0.01\ x\ US\$648234 = \boldsymbol{US\$6482.34}$

b) AC Solar PV+Inverter

$Cost\ of\ System\ O\&M = 0.01\ x\ US\$210662 = \boldsymbol{US\$2106.62}$

c) DC Solar PV+Batteries

$Cost\ of\ System\ O\&M$ = 0.01 x US$543817 = **US$5438.17**

d) DC Solar PV only

$Cost\ of\ System\ O\&M = 0.01\ x\ US\$139905 = \boldsymbol{US\$1399.05}$

Step 7 - Replacement cost of the System:

Using costs per unit component and variable factors from Table 22, the replacement costs of the components are calculated as:

Table 24:- Summarised data of replacement cost calculation for each componets by using equations 25 to 28 from chapter 3, section 3.3.4

AC type

Components Capacity	Rebate%	Components capacity Cost	Components Replacement Costs
Cost of PV array (225kW)	0.95	US$112500	US$106875
Cost of Battery (2187.86kWh)	0.95	$437572	US$415693.4
Cost of Inverter (292.5kW)	0.95	$6600	US$6270
Cost of Solar Charge Controller (SCC) (195.3A)	0.95	$39062	US$37108.9
DC type			
Cost of PV array (207.69kW)	0.95	$103845	US$98652.75
Cost of Battery (2019.56kWh)	0.95	$403912	US$383716.40
Cost of Inverter	0	0	
Cost of Solar Charge Controller (SCC) (180.3A)	0.95	$36060	US$34257

Using the components costs from Table 24 - The total replacement costs of the systems are:

Replacement Costs of Systems = PV array replacement cost + Battery replacement cost + Inverter replacement cost + SCC replacement cost;

a) AC Solar PV +Batteries+Inverter

$$Replacement\ cost = US\$106875 + US\$415693.4 + US\$6270 + US\$37108.9 = \boldsymbol{US\$565948.4}$$

b) AC Solar PV+Inverter

$$Replacement\ cost = US\$106875 + US\$6270 + US\$37108.9 = \boldsymbol{US\$150255}$$

c) DC Solar PV+Batteries

$$Replacement\ cost = US\$98652.75 + US\$383716.40 + US\$34257 = \boldsymbol{US\$516626.15}$$

d) DC Solar PV only

$$Replacement\ cost = US\$98652.75 + US\$34257 = \boldsymbol{US\$132909.75}$$

Step 8 - Present and Net Present costs of the Solar PV Systems:

Using costs per unit component and variable factors from Table 22, the Present, NPC and Levelized costs of the systems are calculated as:

$$P_{resent\ Cost} = \frac{Replacement\ cost}{(1+i)^5} + \frac{Replacement\ cost}{(1+i)^{10}} + \frac{Replacement\ cost}{(1+i)^{15}} + \frac{Replacement\ cost}{(1+i)^{20}} \quad .(29)$$

From Table 22 the total present costs of the systems are:

a) AC Solar PV+Inverter+Batteries

$$P_{resent\ Cost} = \frac{\boldsymbol{US\$565948.4}}{(1+0.04)^5} + \frac{\boldsymbol{US\$565948.4}}{(1+0.04)^{10}} + \frac{\boldsymbol{US\$565948.4}}{(1+0.04)^{15}} + \frac{\boldsymbol{US\$565948.4}}{(1+0.04)^{20}} = \boldsymbol{US\$1420045.31}$$

b) AC Solar PV+Inverter

$$P_{resent\ Cost} = \frac{\boldsymbol{US\$150255}}{(1+0.04)^5} + \frac{\boldsymbol{US\$150255}}{(1+0.04)^{10}} + \frac{\boldsymbol{US\$150255}}{(1+0.04)^{15}} + \frac{\boldsymbol{US\$150255}}{(1+0.04)^{20}} = \boldsymbol{US\$377011.24}$$

c) DC Solar PV+Batteries

$$P_{resent\ Cost} = \frac{\boldsymbol{US\$516626.15}}{(1+0.04)^5} + \frac{\boldsymbol{US\$516626.15}}{(1+0.04)^{10}} + \frac{\boldsymbol{US\$516626.15}}{(1+0.04)^{15}} + \frac{\boldsymbol{US\$516626.15}}{(1+0.04)^{20}} = \boldsymbol{US\$1296288.75}$$

d) DC Solar PV only

$$P_{resent\ Cost} = \frac{\boldsymbol{US\$132909.75}}{(1+0.04)^5} + \frac{\boldsymbol{US\$132909.75}}{(1+0.04)^{10}} + \frac{\boldsymbol{US\$132909.75}}{(1+0.04)^{15}} + \frac{\boldsymbol{US\$132909.75}}{(1+0.04)^{20}} = \boldsymbol{US\$333489.53}$$

$$P_{resent\ salvage\ value} = \frac{Salvage\ cost}{(1+i)^{25}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (30)$$

$$P_{resent\ salvage\ value} = \frac{0.00\ US\$}{(1+0.04)^{25}} = US\$0.00 \quad \text{(For all systems)}$$

$$Net\ Present\ Costs = \ Capital\ cost\ (Pcc) + \ Present\ cost - Present\ salvage\ cost\ \ldots\ldots. \quad (31)$$

a) AC Solar PV+Inverter+Batteries

$$Net\ Present\ Cost = US\$648234 + \ US\$1420045.31 - \ US\$0\ .00\ = \boldsymbol{US\$\ 2068279.31}$$

b) AC Solar PV+Inverter

$$Net\ Present\ Cost = US\$210662\ + \ US\$377011.24 - \ US\$0\ .00\ = \boldsymbol{US\$587673.24}$$

c) DC Solar PV+Batteries

$$Net\ Present\ Cost = US\$543817\ + \ US\$1296288.75 - \ US\$0\ .00\ = \boldsymbol{US\$1840105.75}$$

d) DC Solar PV only

$$Net\ Present\ Cost = \ US\$139905 + US\$333489.53 - \ US\$0\ .00\ = \boldsymbol{US\$473394.53}$$

$$Levelized\ Costs = \frac{Net\ Present\ Cost}{System\ Capacity} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(32)$$

a) AC Solar PV+Inverter+Batteries

$$Levelized\ Costs = \frac{\boldsymbol{US\$\ 2068279.31}}{1093.94kMWh} = \boldsymbol{1.89}\ \frac{\boldsymbol{US\$}}{\boldsymbol{kWh}}$$

b) AC Solar PV+Inverter

$$Levelized\ Costs = \frac{\boldsymbol{US\$587673.24}}{1093.94MWh} = \ 0.\boldsymbol{54}\ \frac{\boldsymbol{US\$}}{\boldsymbol{kWh}}$$

c) DC Solar PV+Batteries

$$Levelized\ Costs = \frac{\mathbf{US\$1840105.75}}{1009.78\mathrm{MWh}} = \mathbf{1.82}\ \frac{\boldsymbol{US\$}}{\boldsymbol{kWh}}$$

d) DC Solar PV only

$$Levelized\ Costs = \frac{\mathbf{US\$473394.53}}{1009.78MWh} = \ 0.\boldsymbol{47}\ \frac{\boldsymbol{US\$}}{\boldsymbol{kWh}}$$

Table 25 indicate the data of different Net Present Cost (NPC) for the AC solar PV system modeled with inverter + batteries, AC solar PV system with inverter only, DC solar PV system with batteries only and DC solar PV only at 100% renewable. The data is summarized by using equation 31 and it was used to plot the graph (Figure 53) which indicates low NPC for the DC solar PV system only (US$473394.53) when compared to AC solar PV with inverter system (US$587673.24). Similarly, the NPC for the DC solar PV system + batteries (US$1840105.75) is low as compared to the AC solar PV system with inverter + batteries (US$ 2068279.31).

Table 25:- Summarised net present costs of the four solar PV system models at 100% renewable

	Net Present Cost [US$]
Solar PV AC+Inverter+Batteries	2068279.31
Solar PV AC+Inverter	587673.24
Solar PV DC+ Batteries	1840105.75
Solar PV DC only	473394.53

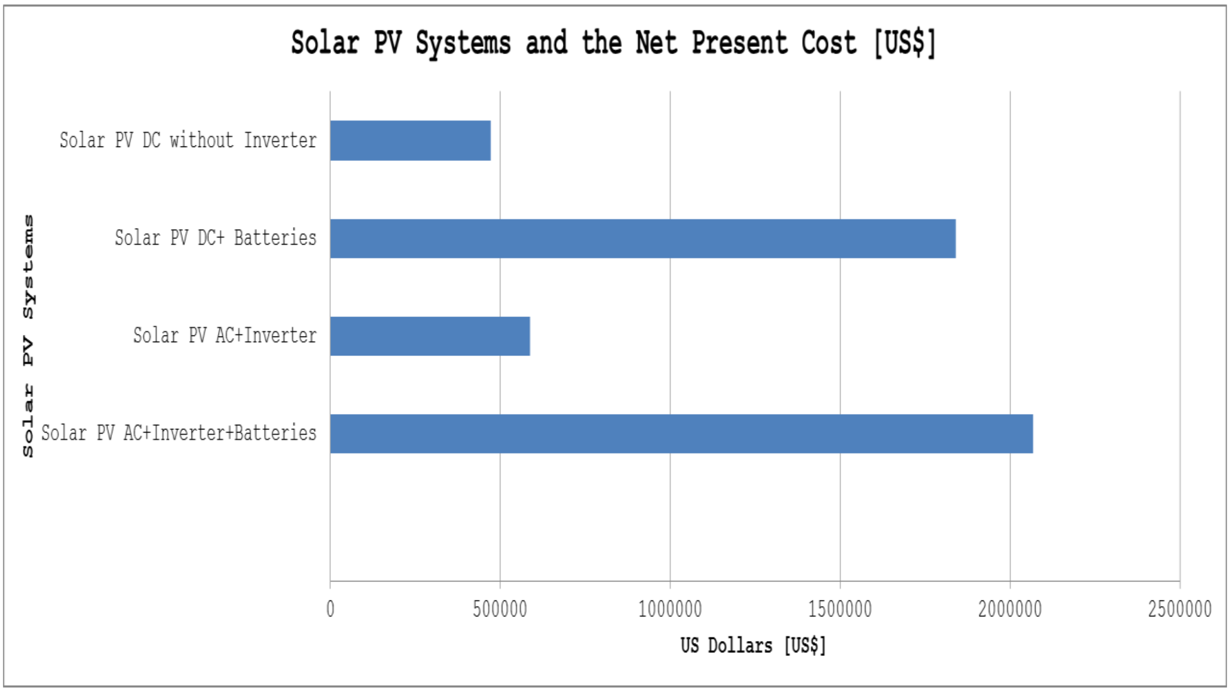


Figure 53:- Net NPC costs of the four different solar PV system models at 100% renewable

Table 26 indicates the calculated data using the equations 31 to 32 and it indicates the change of the NPC and levelized costs of the four different solar PV systems with regard to the increase in renewable electricity supply. The same data is emphasized more on the plotted graph on Figure 54 which indicates that when increasing the renewable also increases the levelized cost of the solar PV systems. In ellaboration, the levelized cost for the DC solar PV system only is less by 14.9% when compared to AC solar PV system with inverter. Consequently, the levelized cost for the DC solar PV system with batteries is less by 3.8% when compared to AC solar PV system with inverter + batteries.

Table 26:- Summarised data of the NPC of four different solar PV systems agaisnt percentage increase in renewable.

Renewable (%)	Solar PV AC+Inverter+Batteries		Solar PV AC+Inverter		Solar PV DC+ Batteries		Solar PV DC Only	
	Net Present Costs (US$)	**Levelized Costs (US$/kWh)**	**Net Present Costs (US$)**	**Levelized Costs (US$/kWh)**	**Net Present Costs (US$)**	**Levelized Costs (US$/kWh)**	**Net Present Costs (US$)**	**Levelized Costs (US$/kWh)**
0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
10	206827,93	0,19	58767,32	0,05	184010,58	0,18	47339,45	0,05
20	413655,86	0,38	117534,65	0,11	368021,15	0,36	94678,91	0,09
30	620483,79	0,57	176301,97	0,16	552031,73	0,55	142018,36	0,14
40	827311,72	0,76	235069,30	0,21	736042,30	0,73	189357,81	0,19
50	1034139,66	0,95	293836,62	0,27	920052,88	0,91	236697,27	0,23
60	1240967,59	1,13	352603,94	0,32	1104063,45	1,09	284036,72	0,28
70	1447795,52	1,32	411371,27	0,38	1288074,03	1,28	331376,17	0,33
80	1654623,45	1,51	470138,59	0,43	1472084,60	1,46	378715,62	0,38
90	1861451,38	1,70	528905,92	0,48	1656095,18	1,64	426055,08	0,42
100	2068279,31	1,89	587673,24	0,54	1840105,75	1,82	473394,53	0,47

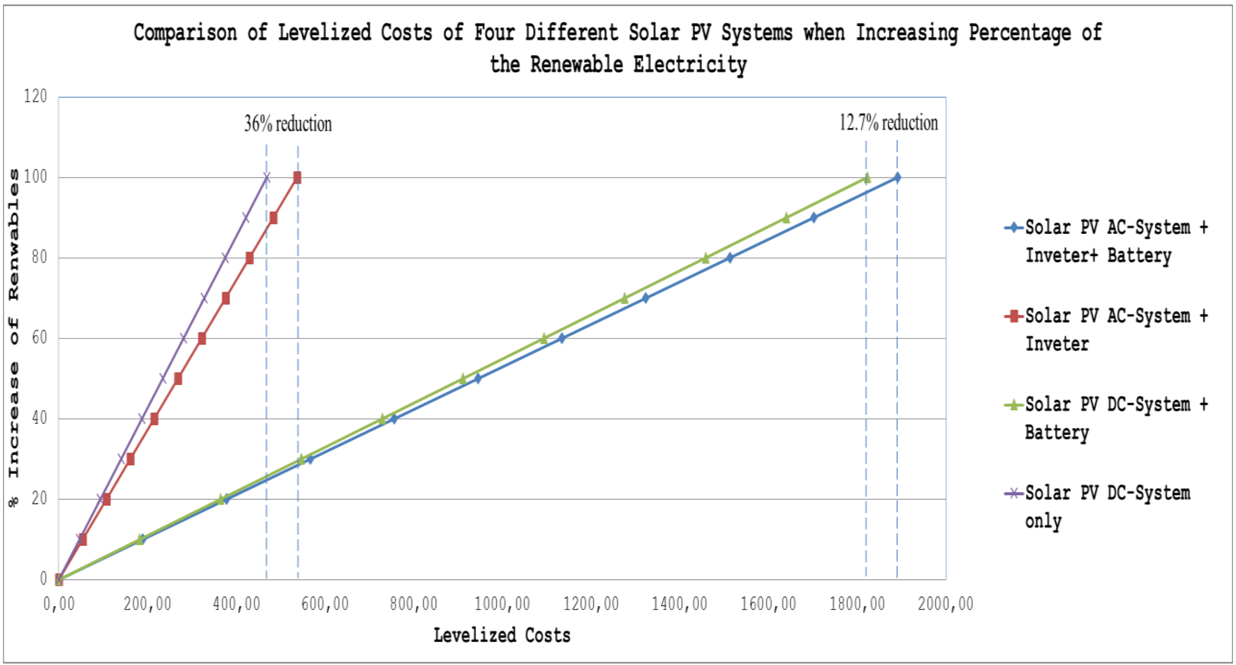


Figure 54:- NPC of four different solar PV systems against increasing percentage of the renewables.

5.4 Summary

The four solar PV system; AC solar PV system with inverter only, AC solar PV system with inverter + batteries, DC solar PV system without inverter and DC solar PV system with batteries were investigated to find the most economic solar PV model. It can be concluded that the solar PV system without the battery are more economical compared to the solar PV system with batteries, however the new battery options requires grid connection to cover power deficit and surplus and different times of the day for these two options. As the results, it shows that the levelized costs at 100% renewable for DC solar PV system only (US$ 0.47) is 14.9% less than the AC solar PV system without batteries with inverter (US$ 0.54). Similarly DC solar PV solar PV system with batteries (US$ 1.82) is 3.8% lower as compared to levelized costs for AC solar PV system with batteries and with inverter (US$ 1.89).

CHAPTER 6: POTENTIALS FOR SCALING UP THE SOLAR PV RESULTS TO ALL OFFICE BUILDINGS IN BOTSWANA

6.1 Introduction

The government and commercial sector, which comprises of 6063 and 5501 buildings respectively, of which both the sectors (11564 buildings) rely solely on the national grid for their supply of energy. They building of both sectors do not have standalone solar power generation units to supplement their power supply. A large part of the country, mostly rural, also depends on fuel wood meet their energy needs in terms of cooking, lighting, and heating.

The country does not have solid infrastructure for solar power generation on a national scale. All projects that involve power generation via solar power are still at pilot project scale, despite the fact that Botswana is said to have a direct normal radiation of 21 MJ/m^2/day, which considered to be one of the highest in the world (Sampa, 2011).

The energy use of the Botswana has always been on the rise in energy use, which means a rise in energy demand. This is in turn overwhelms the current energy supply. Therefore the steps need to be taken to accommodate the rise in the energy demand. These changes are not straightforward, as they have to conform to the modern day standards of power generation. Consequently environmental impacts have to be minimized, which results in reduction in greenhouse emissions, and looking into renewable energy sources. Botswana had to deal with a rise in the energy use over the years. It has been noted to be on a steady increase of about 11% per annum between the years of 1988 to 1999. The commissioning of the Morupule B power plant was done to help with this problem (Bakaya-Kyahurwa, 2004). The increases in the population and development of the country have also contributed to the increase in demand.

Botswana's economy in terms of source of income is highly dependent on the mining sector, which also takes the highest portion of energy consumption. It is seen in Table 25 that the mining sector is the highest energy consumer for over thirteen year period, consuming about a 34% share of electricity in 2012 as compared to the 28.5% for commercial, 27.5% for government and 10% for domestic sectors (Essah & Ofetotse, 2014).

Table 27 shows the electricity consumption and percentage shares of the commercial and the government sectors for the years 2000 to 2012. In both years it is shows that the mining sector consumes more than the other sector. When combining the commercial and government electricity consumptions they become more than the other sectors.

Table 27:- Energy consumption and percentage shares of electricity for each sector from 2000 – 2012 (Essah & Ofetotse, 2014)

Year	Electricity consumption by sector (GWh)					Shares of electricity consumption by sector (%)			
	Mining	Commercial	Domestic	Government	Total	Mining	Commercial	Domestic	Government
2000	760	492	280	139	1671	45.5	29.4	16.8	8.3
2001	899	462	334	147	1843	48.8	25.1	18.1	8.0
2002	920	478	371	187	1955	47.0	24.5	19.0	9.5
2003	1001	533	420	196	2150	46.6	24.8	19.5	9.1
2004	1077	573	489	227	2366	45.5	24.2	20.7	9.6
2005	1047	613	539	217	2416	43.3	25.4	22.3	9.0
2006	1184	631	584	227	2626	45.1	24.0	22.3	8.6
2007	1199	634	682	262	2777	43.2	22.8	24.6	9.4
2008	1186	684	745	274	2889	41.0	23.7	25.8	9.5
2009	1123	735	769	290	2917	38.5	25.2	26.4	10.0
2010	1141	831	829	308	3109	36.7	26.7	26.7	9.9
2011	1117	820	873	308	3118	35.8	26.3	28.0	9.9
2012	1086	910	879	323	3198	34.0	28.5	27.5	10.0

As previously stated that the solar power generation in Botswana is still in its infancy. The country currently has a solar PV pilot project which has the capacity of 1.3MW (Africa, 2010). The state-owned Botswana Power Corporation and Electricite de France, with support of the UNDP and the Global Environmental Facility formed the BPC Lesedi which was to utilise solar energy in order to supply electricity to the rural areas (Nachmany et al., 2015).

Energy efficiency has no standard national measure, so in some cases, energy intensity is often used as a proxy indicator by measuring the amount of energy required to produce one USD of GDP (REN21, 2015). Compared to other SADC countries, Botswana is seen as having the lowest energy intensity as compared to other African nations as seen in the graph below.

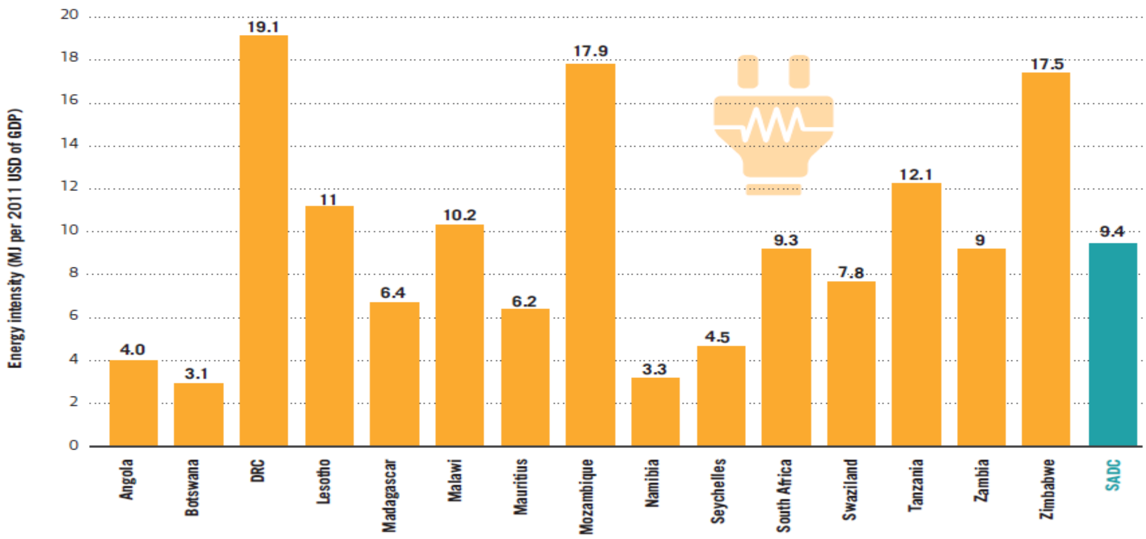


Figure 55:- Energy intensities of the SADC countries (REN21, 2015).

Apart from solar implementation, the government of Botswana has come up with some initiatives to help improve in the energy efficiency sector. Some of these initiatives have failed while others have yielded some positive results. This may also attributed to the fact that the government still lacks a solid energy efficiency plan (REN21, 2015).

The most effective of these initiatives that has been rolled out by the government, include the Compact fluorescent light rollout programme, which resulted in more than 1 million CFL bulbs being installed. Automated load monitoring and curtailment is also one of the initiatives, which means that electricity supply to a residence is cut for 60 minutes if the consumption exceed 2.3 kW during high demand hours. Perhaps one of the more known initiative is the use of solar water heaters, which has been pushed by the government since the 1970s. These were predominantly found in government buildings, including schools and clinics, however a lack of maintenance of the heaters has been a major hindrance to their usage (REN21, 2015).

6.1.1 Carbon Emissions

The emissions in Botswana come mainly from energy-coal, agriculture, waste land-use change and forestry sectors (DMS, 2012). Greenhouse gases are mostly carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4) and nitrous oxide (N_2O). Botswana is however considered to be a major carbon dioxide sink because of the large uptake of carbon dioxide by trees (Gwebu, 2002). In 2000, Botswana's greenhouse gas emissions were at 7.362Gg CO_2 eq whilst the removal of greenhouse gases was at 42,941 Gg CO2eq. The difference between these two values gives a value of 35,779 Gg CO2eq, meaning that the country is actually a greenhouse gas sink. In the same year, it was seen that carbon dioxide is the biggest contributor to the greenhouse gases emitted which accounts for 98.3% and methane only contributing 1.7% (DMS, 2012). The burning of fossil fuels, more specifically contribute the most to the emission of CO_2 gas because it is the most abundant fossil fuel in the country. The coal is used in the combustion chambers of the power stations. Oil fuel also contributes a great deal to the emission of CO_2. In 1990, oil fuel contributed about 5.9 Gg of CO_2 (DMS, 2012).

Methane gas emissions are usually occur during the mining of fossil fuels like coal and drilling of oil. In Botswana, it is a by-product of the mining of coal and in 1990 was seen t contribute to 18.8 Gg from biomass combustion and 10.6 Gg from coal mining respectively. Nitrous oxide emissions are also from coal mining industries and even forest fires. The figures of this gas in the year 1990 were at 0.015Gg for biomass and 1.6 Gg for coal. Vehicles also contribute to the emission of greenhouse gases, since they are consumers of petrol and diesel. The table below shows emissions estimates by vehicles in 1990 (DMS, 2012).

Botswana's GHG emissions are predicted to be on the rise in the future. The commissioning of the new power plants, Morupule C and D, will mean an increase in the mining of coal to fuel the power plants. For the year 2015/2016, GHG emissions were predicted to increase 15 compared to the 1750Gg estimated for 1994 (Africa, 2010). In terms of carbon capture, Botswana is still at its infancy. So far, the idea is still in its testing phase in order for the government to determine the feasibility of the project. A company by the name of CIC energy which is has plans of building a coal mine in Mmamabula is has already considered building a capture ready power station to help with the reduction of carbon emissions in the country (Africa, 2010).

6.2 Results

It is in this regard, that the same electricity demand data from Botswana Oil Limited as one of the commercial office building in Botswana was used to estimate the reduction of CO2emssions when the DC solar PV system is rolled out to other office buildings, which is extended to both government and commercial office buildings. Therefore, two analysis calculations were performed 1) using the electricity demand of the case study for the minimum sized building to estimate the CO_2 emissions reduction for the other buildings putting in a state that all buildings are equal in size. 2) Using the exact electricity demand data for all buildings with their different sizes to estimate their CO_2 emission reduction.

6.2.1 Using Estimated Electricity Demand Data

Table 28 Indicates the summarized electricity demand data from the BOL building as commercial building to estimate its CO_2 emission reduction and the same data was used to estimate CO_2 emission reduction for 11564 office buildings in Botswana. The total floor area of all the buildings is unknown but as an estimate the average floor area has been assumed to be equal to the BOL building. The graphs on Figure 56 and 57 show the plotted data which indicate that; Figure 56 presents CO_2 emission reduction for one building as 0.00865% and Figure 57 indicates that using the same data of one building to estimate for other buildings, assuming they are of the same sizes (minimum) it resulted in a percentage of 11.45% CO_2 emission reduction as per calculations.

Table 28:- Electricity demand and CO_2 emission reduction for single BOL building and 11564 commercial buildings in Botswana (assuming similar size).

Year 2012	**BOL-HQ Building Electricity Demand [GWh]**	**BOL-HQ Building Reduced Carbon Emissions (ktoe CO_2)**	**Estimated number of Government and Commercial Office Buildings in Botswana**	**Using Estimated value of Electricity Demand from One Building to Government and Commercial Office Buildings in Botswana[GWh]**	**Estimated Reduced CO_2 Emissions of Government and Commercial from one building's electricity demand (ktoe CO_2)**
January	0.002647	0.002528	11564	30.61	29.23
February	0.002465	0.002354	11564	28.50	27.22
March	0.002753	0.002629	11564	31.84	30.40
April	0.002611	0.002494	11564	30.20	28.84
May	0.002659	0.002540	11564	30.75	29.37
June	0.002581	0.002465	11564	29.84	28.50
July	0.002692	0.002571	11564	31.13	29.73
August	0.002754	0.002631	11564	31.85	30.42
September	0.002560	0.002444	11564	29.60	28.27
October	0.002653	0.002534	11564	30.68	29.30
November	0.002558	0.002443	11564	29.58	28.25
December	0.002741	0.002618	11564	31.70	30.27
TOTAL	**0.031674**	**0.030249**		**366.28**	**349.80**

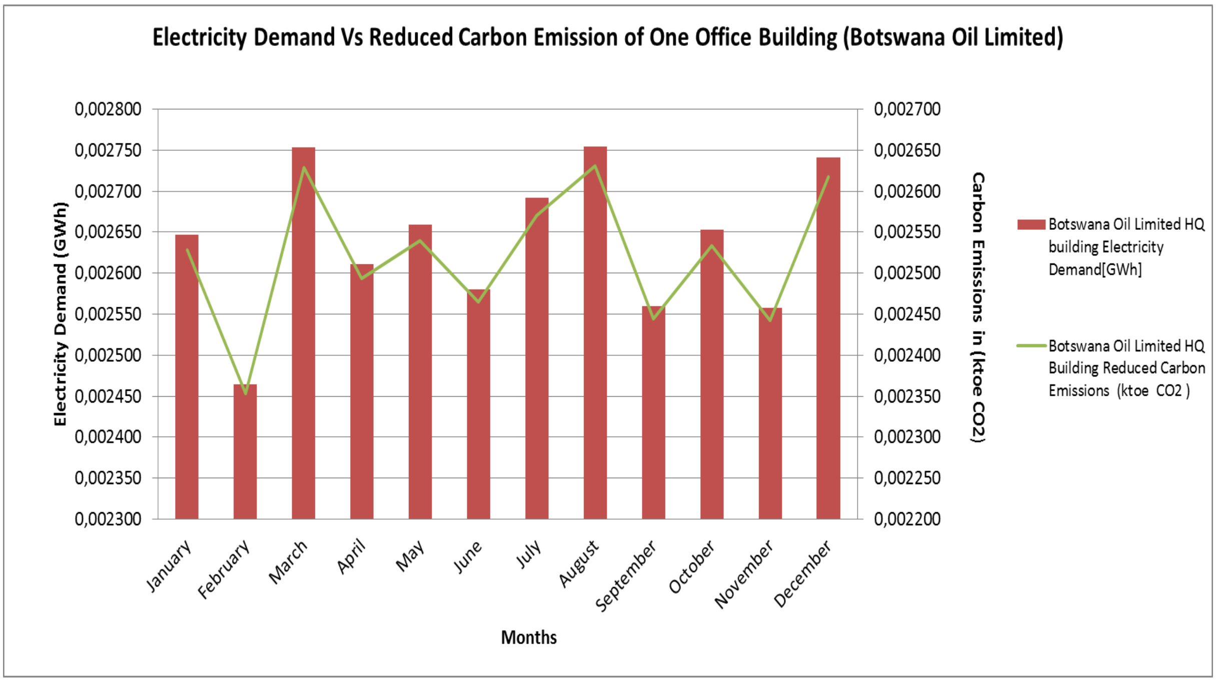


Figure 56:- Electricity demand and CO_2 emissions reduction for one building (BOL) with Solar PV installed.

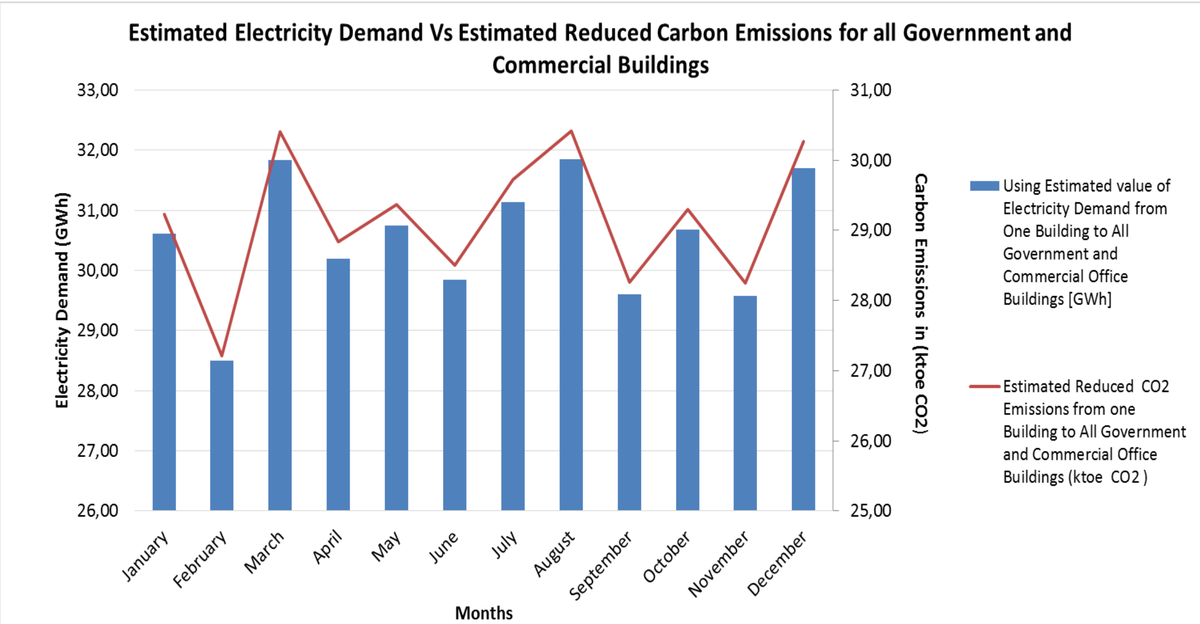


Figure 57:- Estimated electricity demand and CO_2 emissions reduction potential for 11564 office buildings with solar PV system installed.

6.2.1.1 Calculations CO_2 Emissions Estimates for Botswana Oil Limited (One) Office Building

Using the total data from Table 28

$$CO_2\ Emission\ Percentage\ Reduction = \frac{CO_2\ of\ one\ office\ building}{CO_2\ of\ all\ office\ buildings}\ x\ 100\%$$

$$CO_2\ Emission\ (\%)tage\ Reduction = \frac{0.030249\ ktoe\ CO_2}{349.80\ ktoe\ CO_2} = 0.0000865\ x\ 100\% = \mathbf{0.00865}\%$$

6.2.1.2 Calculations of CO_2 Emissions Estimates to All Office Buildings

Using 2012 total data from Table 27

$$CO_2\ Emission\ for\ all\ Sectors = 3198\ GWh\ x\ 0.955\frac{GWh}{ktoe\ CO_2} = \mathbf{3054.09\ ktoe\ CO_2}$$

Using the total data from Table 28

$$CO_2\ Emission\ Percentage\ Reduction = \frac{CO_2\ of\ all\ office\ buildings}{CO_2\ of\ all\ sectors}\ x\ 100\%$$

$$CO_2\ Emission\ Percentage\ Reduction = \frac{349.80\ ktoe\ CO_2}{3054.09\ ktoe\ CO_2} = 0.1145\ x\ 100\% = \mathbf{11.45}\%$$

6.2.2 Using Exact Electricity Demand Data

Table 29 indicates the summarized exact electricity demand data from government and commercial office buildings. The data was used to estimate the exact CO_2 emissions which can be reduced in 11564 (government and commercial) office buildings regarding their different sizes and electricity consumptions. The Figure 58 illustrates the fluctuation curve of CO_2 emission reduction plotted against electricity demand of all buildings. The Figure 59 shows the differences of CO_2 emission reduction comparisons starting from one building value, estimated of 11564 buildings assuming of same size to the exact value of 11564 buildings considering their different sizes. As per calculations it is highlighted than an increase of 38.6% CO_2 emission reduction is realized when using the exact electricity demand data.

Table 29:- Actual electricity demand and CO2 emission reduction potential for all office buildings in Botswana.

Year 2012	Electricity Demand of Government and Commercial Office Buildings in Botswana[GWh]	Estimated number of Government and Commercial Office Buildings in Botswana	Estimated Reduced CO_2 Emissions of Government and Commercial from their exact electricity demand (ktoe CO_2)
January	102.63	11564	98.01
February	101.54	11564	96.97
March	102.61	11564	97.99
April	100.60	11564	96.07
May	101.83	11564	97.25
June	103.76	11564	99.09
July	104.85	11564	100.13
August	104.70	11564	99.99
September	102.70	11564	98.08
October	102.65	11564	98.03
November	102.50	11564	97.89
December	102.63	11564	98.01
TOTAL	**1233.00**		**1177.52**

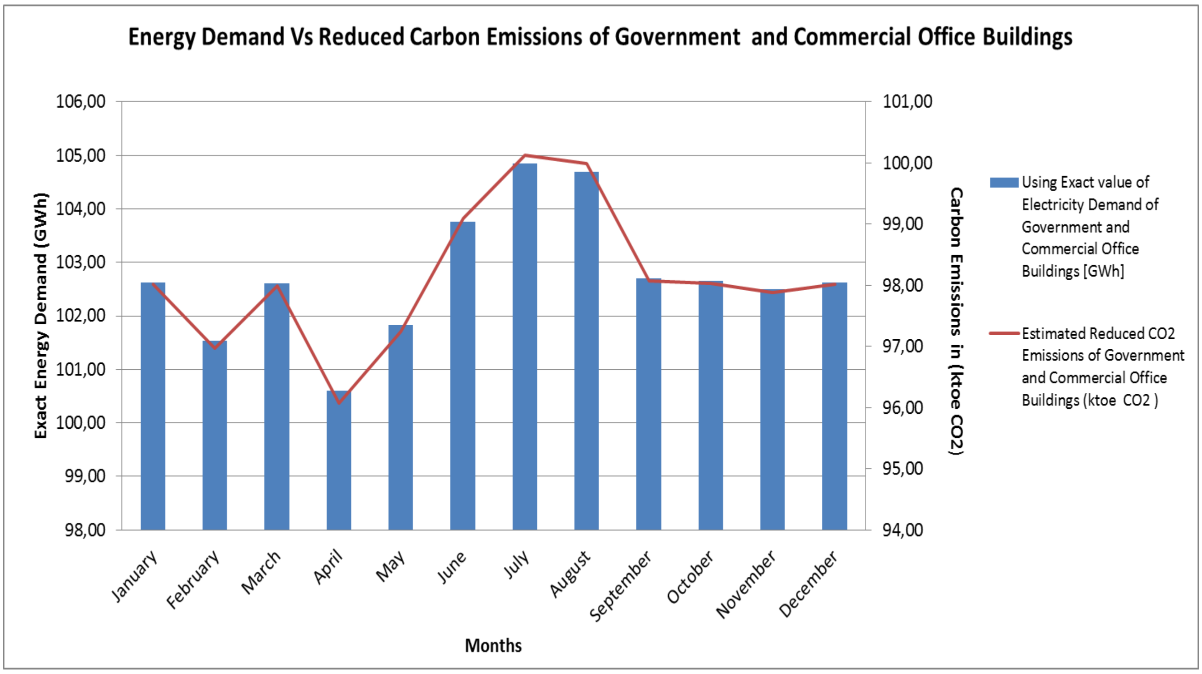


Figure 58: - Electricity demand versus reduced emissions of all office buildings

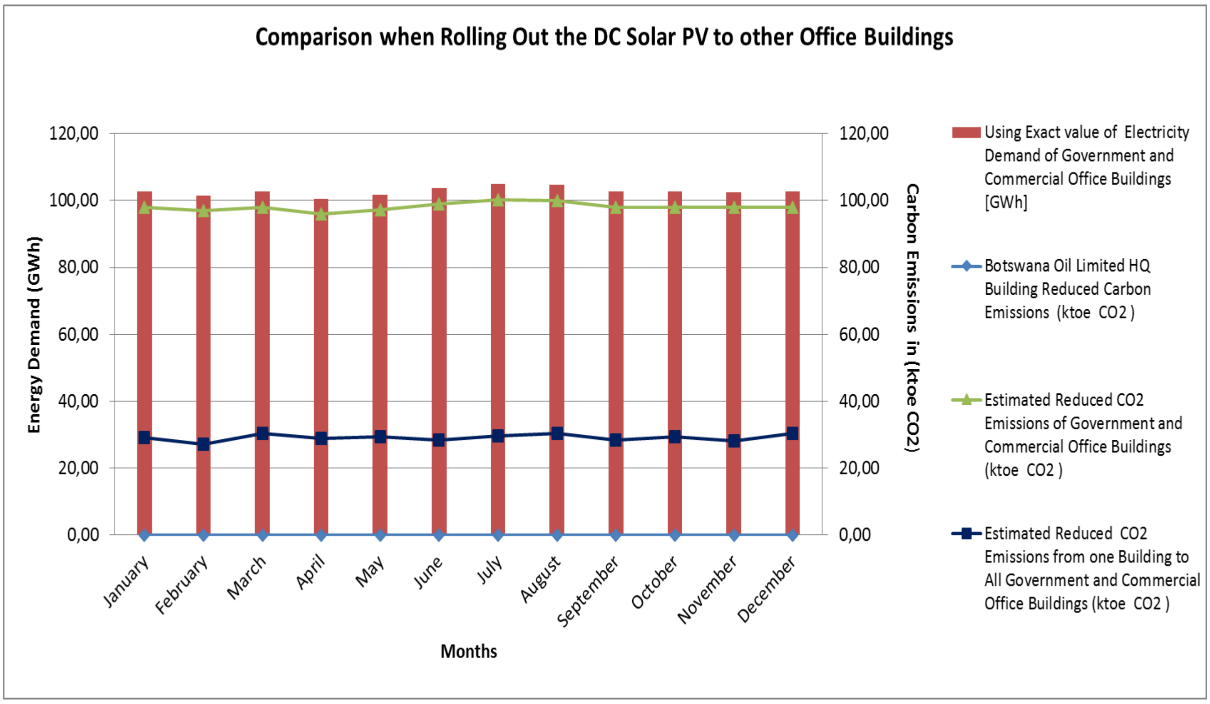


Figure 59:- Comparison when rolling out DC Solar PV to other Office Buildings in Botswana

6.2.2.1 Calculations Using the Exact Values to Estimate CO_2 Emissions for All Office Buildings

Using the total data from Table 29

$$CO_2\ Emission\ for\ all\ Office\ Buildings = 1233\ GWh\ x\ 0.955 \frac{GWh}{ktoe\ CO_2} = \mathbf{1177.52\ ktoe\ CO_2}$$

$$CO_2\ Emission\ Percentage\ Reduction = \frac{CO_2\ of\ all\ office\ buildings}{CO_2\ of\ all\ sectors}\ x\ 100\%$$

$$CO_2\ Emission\ Percentage\ Reduction = \frac{1177.52\ ktoe\ CO_2}{3054.09\ ktoe\ CO_2} = 0.386 = \mathbf{38.6}\%$$

6.3 Summary

Chapter 6 concludes that the CO_2 emission reduction for one building (minimum size) is 0.00865%. Therefore, estimating the same results to other 11564 office buildings assuming there are of the same electricity consumption and building size (minimum), the CO_2 emission reduction is 11.45%. Therefore, more CO_2 emission reduction (38.6%) is realized when considering using the exact electricity demand value, from all 11564 of different electricity consumption and sizes of the buildings. Thus means that the rolling out of DC solar PV system to all office buildings can reduce CO_2 emissions from 11.45% to 38.6% depending on the electricity consumption and size of the buildings.

CHAPTER 7: OVERALL CONCLUSION AND RECOMMENDATIONS

7.1 Overall Conclusion

Firstly, the CEPA and EROI study identified that for option 1 and 2 introducing 15% renewables in 2020 and 25% of renewables plus CBM in place of diesel by 2030 while also expanding coal generation reduced CO_2 emissions 15% (option 1) and 25% (option 2) below business as usual. Option 3 presents the most favorable results of 44.6% CO_2 emission reduction from business as usual by replacing planned coal generation with CBM. Option 4 indicates the largest change of 82.1% emission reduction by building the Carbon Capture Storage (CCS) alongside the system to capture CO_2 emissions. Option 3 is considered as the best for application because option 4 presents uncertainty around possible high CCS technology costs and its unproven technology. In addition, the EROI results from Table 13 predict that in 2030, the level of EROI for solar PV is high when compared to coal but is expected to increase with further developments. As EROI improves for solar technology in the future then it will become more economical viable compared to traditional generation methods.

Secondly, the study also investigated solar PV system installed in office buildings especially commercial and government offices. The analysis was done using HOMER Pro software and solar PV system modeling equations as methods. A case study was conducted by analyzing data in one of the commercial building (Botswana Oil Limited) in Botswana. The analyzed data was used to model a solar PV system suitable for application in office buildings. Four solar PV system models were investigated; AC solar PV with inverter + batteries, AC solar PV with Inverter, DC solar PV system without Inverter and DC solar PV with Batteries only. In terms of economic benefits the DC solar PV system without inverter and batteries is cheaper than AC solar PV system with inverter (NPC of US$ 473,394.53 and US$ 587,673.24) respectively. Similarly, the DC solar PV with batteries only is cheaper than AC system with inverter + batteries (NPC of US$ 1,840,105.75 and US$ 2,068,279.31) respectively. It can be concluded that US$ 114,278.71 and US$ 228,173.56 respectively can be saved when considering DC solar PV system only and the DC solar PV system with batteries as compared to AC solar PV system with inverter only and AC solar PV system with inverter + batteries. The levelized costs for DC solar PV system without inverter and batteries is 0.47 US$/kWh which is 14.9% less than the AC solar PV system with inverter without batteries at 0.54 US$/kWh. Similarly, the DC solar PV system with batteries is 1.82 US$/kWh, 3.8% lower as compared to levelized costs for AC solar PV system with batteries and inverter at 1.89 US$/kWh.

Thirdly, the investigation was also extended to find how much CO_2 emissions can be reduced in commercial and government office buildings. As a result, it was estimated that if the same DC solar PV model was to be rolled out for installation in all 11564 commercial and government office buildings with conditions; 1) all office buildings have equal minimum sizes and electricity consumptions then about 11.45% of CO_2 emission was going to be reduced from all electricity consuming sectors. 2) all office buildings are of different sizes and load capacities then about 38.6% of CO_2 emissions was going to be reduced as the exact electricity demand data was used for estimations. This means the rolling out of DC solar PV system to all commercial and government buildings has a potential to reduce of CO_2 emissions from 11.45% to 38.6% in all electricity consuming sectors in Botswana.

7.2 Recommendations

In regard to the conclusion drawn from this study, the following areas can be recommended for further researches;

i) In terms of EROI analysis of the systems, this study did not cover the detailed EROI calculations for both price-based and exergy-based. In the case of considering option 4 which presented the largest 82.1% carbon emission reduction than option 3. Therefore, further analysis of detailed calculations on the EROI value of the CCS system as well as its complexity technology is recommended, in order to determine the economical viability of the system.

ii) It is recommended for further research on the storage system of solar PV system. Other economic and efficient energy storage system instead of batteries can be used in order to make the DC solar PV system even more efficient than it is in this study. Therefore, a detailed research on supercapacitors on energy storage can be considered for the system efficiency especially in reducing the storage size. The exergy-based EROI analysis of the DC solar PV system can also be considered for further research to close the gap of economic viability of the system.

iii) The highest percentage result of reduced CO_2 emissions of 38.6% in commercial and government office buildings in this study is still have an opportunity to further increase the percentage. In this regard, further research on applying the DC solar PV system in small scale industrial business in Botswana can be considered in order to reduce even more CO_2 emissions. This is because the electricity billing system in industrial business in Botswana shows that small scale business is more than the medium and large scale business. Currently, all of them are supplied from the electricity grid.

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APPENDICES

APPENDICES-A

Appendix A1:- 2012 data for electricity generation mix [GWh] obtained from SAPP members

SAPP Utility Generation Mix in [GWh]													
Utility	**Botswana**	**Mozambique**	**Angola**	**Malawi**	**South Africa**	**Lesotho**	**Namibia**	**Swaziland**	**DRC**	**Tanzania**	**Zimbabwe**	**Zambia**	**TOTAL**
Based load Hydro		4362	7297	2505	17520	631	2102	552	21392	4914	6570	15786	83632
Coal	2470	-	4310	-	331400	-	1156	79	-	-	11344	-	350759
Nuclear	-	-	-	-	16907	-	-	-	-	-	-	-	16907
CCGT	-	-	1664	9	-	-	-	-	-	4249	-	-	5922
Distillate (oil)	1402	447	-	-	21103	-	184	-	-	683	-	88	23906
TOATL	**3872**	**4809**	**13271**	**2514**	**386929**	**631**	**3443**	**631**	**21392**	**9846**	**17914**	**15873**	

Appendix A2:- 2012 data for electricity generation mix [GWh] from SAPP Utility Stations

SAPP Utility Stations	**2012**					
Electricity Generation Fuel Type	**Total Production (GWh)**	**Total Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Total Production (GWh)**	**Total Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	83631,72	0	0		0	0
Nuclear	16906,8	0	0		83631,72	0
CCGT	5921,76	0,599	3547		100538,52	0
Distillate (oil)	23906,04	0,893	21348		106460,28	3547
Coal	350759,16	0,955	334975		130366,32	24895
					481125,48	359870
Total	**481125,48**	**2,447**	**359870**			
Demand	**0**	**0**	**0**			
	481125,48	**2,447**	**359870**			

Appendix A3:- 2012 data for electricity generation mix [GWh] for Mozambique

Mozambique (EDM)	**2012**					
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	4362,48	0	0		0	0
Oil	446,76	0,893	399		4362,48	0
					4809,24	399
Total	**4809,24**	**0,893**	**399**			
Demand	**0**	**0**	**0**			
	4809,24	**0,893**	**399**			

Appendix A4:- 2012 data for electricity generation mix [GWh] for Angola

Angola (ENE)	**2012**					
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	7297,08	0	0		0	0
CCGT	1664,4	0,599	997		7297,08	0
Coal	4309,92	0,955	4116		8961,48	997
					13271,4	5113
Total	**13271,4**	**1,554**	**5113**			
Demand	**0**	**0**	**0**			
	13271,4	**1,554**	**5113**			

Appendix A5:- 2012 data for electricity generation mix [GWh] for Democratic Republic of Congo (DRC)

DRC (SNEL)	**2012**					
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	21391,92	0	0		0	0
					21391,92	0
Total	**21391,92**	**0**	**0**			
Demand	**0**	**0**	**0**			
	21391,92	**0**	**0**			

Appendix A6:- 2012 data for electricity generation mix [GWh] for Lesotho

Lesotho (LEC)	**2012**					
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	630,72	0	0		0	0
					630,72	0
Total	**630,72**	**0**	**0**			
Demand	**0**	**0**	**0**			
	630,72	**0**	**0**			

Appendix A7:- 2012 data for electricity generation mix [GWh] for Malawi

Malawi (ESCOM)	**2012**					
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	2505,36	0	0		0	0
CCGT	8,76	0,599	5		2505,36	0
					2514,12	5
Total	**2514,12**	**0,599**	**5**			
Demand	**0**	**0**	**0**			
	2514,12	**0,599**	**5**			

Appendix A8:- 2012 data for electricity generation mix [GWh] for Namibia

Namibia (Nam Power)	**2012**					
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	2102,4	0	0		0	0
Oil	183,96	0,893	164		2102,4	0
Coal	1156,32	0,955	1104		2286,36	164
					3442,68	1269
Total	**3442,68**	**1,848**	**1269**			
Demand	**0**	**0**	**0**			
	3442,68	**1,848**	**1269**			

Appendix A9:- 2012 data for electricity generation mix [GWh] for South Africa

South Africa (Eskom)		**2012**				
Electricity Generation Fuel Type	Production (GWh)	Emissions factor (kt CO2/GWh)	Emissions (kt CO2)		Production (GWh)	Emissions (kt CO2)
	0	0	0		0	0
Based load Hydro	17520	0	0		0	0
Nuclear	16906,8	0	0		17520	0
Oil	21102,84	0,893	18845		34426,8	0
Coal	331399,56	0,955	316487		55529,64	18845
					386929,2	335331
Total	**386929,2**	**1,848**	**335331**			
Demand	**0**	**0**	**0**			
	386929,2	**1,848**	**335331**			

Appendix A10:- 2012 data for electricity generation mix [GWh] for Swaziland

Swaziland (SEC)		**2012**				
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	551,88	0	0		0	0
Coal	78,84	0,955	75		551,88	0
					630,72	75
Total	**630,72**	**0,955**	**75**			
Demand	**0**	**0**	**0**			
	630,72	**0,955**	**75**			

Appendix A11:- 2012 data for electricity generation mix [GWh] for Tanzania

Tanzania (TANESCO) **2012**						
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	4914,36	0	0		0	0
CCGT	4248,6	0,599	2545		4914,36	0
Oil	683,28	0,893	610		9162,96	2545
					9846,24	3155
Total	**9846,24**	**1,492**	**3155**			
Demand	**0**	**0**	**0**			
	9846,24	**1,492**	**3155**			

Appendix A12:- 2012 data for electricity generation mix [GWh] for Zimbabwe

Zimbabwe (ZESA) **2012**						
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	6570	0	0		0	0
Coal	11344,2	0,955	10834		6570	0
					17914,2	10834
Total	**17914,2**	**0,955**	**10834**			
Demand	**0**	**0**	**0**			
	17914,2	**0,955**	**10834**			

Appendix A13:- 2012 data for electricity generation mix [GWh] for Zambia

Zambia (ZESCO)	**2012**					
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Based load Hydro	15785,52	0	0		0	0
Oil	87,6	0,893	78		15785,52	0
					15873,12	78
Total	**15873,12**	**0,893**	**78**			
Demand	**0**	**0**	**0**			
	15873,12	**0,893**	**78**			

Appendix A14:- 2012 data for electricity generation mix [GWh] for Botswana

Botswana (BPC)	**2012**					
Electricity Generation Fuel Type	**Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Oil	1401,6	0,893	1252		0	0
Coal	2470,32	0,955	2359		1401,6	1252
					3871,92	3611
Total	**3871,92**	**1,848**	**3611**			
Demand	0	0	0			
	3871,92	**1,848**	**3611**			

APPENDICES-B

Appendix B1:- 2020 and 2030 data of planned electricity generation [GWh] for Botswana

Reduction of Emissions from Electricity Energy Production for 2020 and 2030							
YEAR	**ELECTRICITY SOURCE**	**PLANNED TOTAL CAPACITY [MW]**	**PLANNED TOTAL CAPACITY [GW]**	**TOTAL PRODUCTION TARGETS OF REDUCING FOSSIL FUELS [GWh]**	**Emissions factor [kt CO2/GWh]**	**Emissions [kt CO2]**	**Total Production for Planned Capacity [GWh]**
2020	Renewable (Solar & Biogas)	176	0,1763	1185	0	0	
	Oil	160	0,16	1402	0,893	1252	778
	Coal	902	0,902	6716	0,955	6414	11508
TOTAL				**9303**			**12286**
2030	Renewable (Solar & Biogas)	176	0,1763	2917	0	0	
	Methane	160	0,16	1402	0,599	840	778
	Coal	1332	1,332	8751	0,955	8357	11508
TOTAL				**10153**			**12286**

Appendix B2:- 2000 data for electricity generated [GWh] for Botswana

Botswana		**BPC** **2000**				
Electricity Generation Fuel Type	**2000 Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
	0	**0**	**0**		**0**	**0**
Oil	27	0,893	24		0	0
Coal	920	0,955	879		27	24
					947	903
Total	**947**	**1,848**	**903**			
Demand	**0**	**0**	**0**			
	947	**1,848**	**903**			

Appendix B3:- 2020 data by introducing 15% of renewable in the electricity generation mix [GWh]

OPTION 1 - Introducing 15% of Renewables						
Botswana (BPC)		**2020**				
Electricity Generation Fuel Type	**2020 Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
Renewables (Solar PV, CSTP & Biomass))	**1185**	**0**	**0**		**0**	**0**
Oil	1402	0,893	1252		1185	0
Coal	6716	0,955	6414		2587	1252
					9303	7666
TOTAL	**9303**	**1,848**	**7666**			
	0	**0**	**0**			
DEMAND	**9303**	**1,848**	**7666**			

Appendix B4:- 2030 data by increasing 25% of renewable and switch diesel with CBM in the electricity generation mix [GWh]

OPTION 1 - Increasing 25% of Renewable and Switch Diesel to CBM						
Botswana (BPC)		**2030**				
Electricity Generation Fuel Type	**2030 Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
Renewables (Solar PV, CSTP & Biomass)	**2917**	**0**	**0**		**0**	**0**
Methane	1402	0,599	**840**		2917	0
Coal	8751	0,955	**8357**		4319	840
					13070	9197
TOTAL	**13070**	**1,554**	**9197**			
	0	**0**	**0**			
DEMAND	**13070**	**1,554**	**9197**			

APPENDICES-C

Appendix C1:- 2030 data for substituting the planned coal generation with CBM in electricity generation mix [GWh]

OPTION 2: All the Planned Coal Electricity Generation to be CBM Generated by 2030						
Botswana (BPC)		**2030**				
Electricity Generation Fuel Type	**2030 Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
		0	**0**		**0**	**0**
Renewables (Solar PV, CSTP & Biomass)	**2917**	**0**	**0**		**0**	**0**
Methane (CBM)	7814	0,599	**4681**		2917	0
Coal	2339	0,955	**2234**		10731	4681
					13070	6914
TOTAL	**13070**	**1,554**	**6914**			
	0	**0**	**0**			
DEMAND	**13070**	**1,554**	**6914**			

Appendix C2:- 2030 data for substituting the planned coal generation with building CCS for the electricity generation mix [GWh]

OPTION 3: Building CCS for all Planned Coal Electricity Generation by 2030						
Botswana (BPC)		**2030**				
Electricity Generation Fuel Type	**2030 Production (GWh)**	**Emissions factor (kt CO2/GWh)**	**Emissions (kt CO2)**		**Production (GWh)**	**Emissions (kt CO2)**
			0		**0**	**0**
Renewables (Solar PV, CSTP & Biomass)	**2917**	**0**	**0**		**0**	**0**
Carbon Capture Storage (CCS)	7814	0	**0**		2917	0
Coal	2339	0,955	**2234**		10731	0
					13070	2234
TOTAL	**13070**	**0,955**	**2234**			
	0	**0**	**0**			
DEMAND	**13070**	**0,955**	**2234**			

APPENDICES D

Appendix D1:- shows the quality factors of components and different solar PV systems (Skunpong & Plangklang, 2010)

Component/System	*Q*
Solar PV module (crystalline)	0.85 – 0.95
Solar PV array	0.80 – 0.90
Solar PV system (Grid-connected)	0.60 – 0.75
Hybrid system (PV/Diesel)	0.40 – 0.60

Appendix D2:- the electricity bill of Botswana Oil Limited for month of July 2017

BOTSWANA POWER CORPORATION
CUSTOMER SERVICE CENTER: PLOT 186, QUEENS ROAD, MAIN MALL
P.O.BOX 48 GABORONE, TEL: 360 7000 FAX: 3607074
VAT Number: C03642301112

Plot No: 54373/DB4 - 1

BOTSWANA OIL LIMITED
P/BAG BO173 BONTLENG
GABORONE, Botswana

Tax Invoice
Invoice No: 500003494397
Invoice Date: 19/07/2017

July 2017

BUSINESS PARTNER	CONTRACT NUMBER	READING	TARIFF CATEGORY	DEPOSIT/GUARANTEE HELD	
40414297	002000626349	REGUL	B2	P23,888.76	
METER NUMBER	**READING DATE**	**MULTIPLIER FACTOR**	**DAYS BETWEEN READINGS**	**AVERAGE DAILY CONSUMPTION**	**AVERAGE MONTHLY CONSUMPTION/KWH**
55089705	18/07/2017	20.0	30	201.33	6,593.70

DESCRIPTION	TOTAL
ELECTRICITY CONSUMPTION	
METER# OPENING CLOSING MULT KWH	
55089705 13,923.00 14,225.00 20.0 6,040.00	
55089705 DEMAND READ:28.200 BILLED:44.240	
MAXIMUM DEMAND CHARGES	P7,082.27
ELECTRICITY CHARGE	P3,446.65
STANDING CHARGE	P67.12
SUBTOTAL OF CURRENT CHARGES	P10,596.04
VAT @ 12%	P1,271.52
NATIONAL STANDARD COST LEVY	P302.00

REMITTANCE ADVICE

BOTSWANA OIL LIMITED

P/BAG BO173 BONTLENG
GABORONE, Botswana

BUSINESS PARTNER: 40414297

CONTRACT NUMBER: 002000626349

AMOUNT DUE: P24,380.47

PAYMENT METHODS

AMOUNT PAID

BANK STAMP

REMITTANCE ADVICE

BOTSWANA OIL LIMITED

P/BAG BO173 BONTLENG
GABORONE, Botswana

APPENDICES E

Appendix E1:- shows the specifications and cost estimates of the chosen components - solar panels and inverter

Specifications for Choosen System's Components and Installation Cost Estimates

a)	Solar PV module specifications				
	Solar PV module Type:	Suniva OPT340-72-4-100 Silver Mono Solar Panel			
	Manufactured from:	United States of America and Canada			
	Manufacturer:	Suniva			
	Life time (years):	25			
	PV panel area (m2):	1,9503			
	PV module cost per Watt:	0,5	US$ / W	500	US$ / kW
	Cost per PV module:	170	US$ each		
	Pmax	340	W	0,34	kW
	Vmpp	37,8	VDC		
	Impp	8,99	A	**Pmax** is maximum power of the PV module	
	Voc	46	VDC	**Vmpp** is maximum power point voltage of the PV module	
	Isc	9,78	A	**Impp** is maximum power point current of the PV module	
	ήm	0,1743	17,43%	**Voc** is open circuit voltage of the PV module	
				Isc is short circuit current of the PV module	
				ήm is the solar PV module efficiency	
b)	**Inverter specifications**				
	Inverter model:	SMA Sunny Boy 9000TL-US-12 Inverter			
	Manufactured from:	United States of America and Germany			
	Manufactured by:	SMA Inverters			
	Inverter cost per Watt:	0,2	US$ / W	200	US$ / kW
	Input battery voltage	600	VDC		
	Norminal AC output voltag	208 / 240	VAC		
	Maximum input current	27,1	A		
	Output frequency &accurac	60	Hz		
	Inverter efficiency	0,987	98,7%		
	AC output power capacity	9000	W	9	kW
	Strings per MPP input	6			

Appendix E2:- shows the the specifications and cost estimates of the chosen components - batteries and solar charger controller

c) **Battery specifications**					
Battery Type:	Solar-One HUP SO-6-85-25-12V Flooded Battery				
Manufactured from:	Mexico				
Manufactured by:	SolarOne Batteries				
Life time:	10	years			
Battery cost per (Wh):	0,2	US$ / Wh	200	US$ / kWh	
Norminal Voltage	1152	VDC			
Rated Watt / hrs (20hrs)	9000	Wh	9	kWh	
d) **Solar Charge Controller / Maximum Power Point Tracking (MPPT) specifications**					
Solar Charge Controller Type: Magnum PT-100 charge controller					
Manufactured from:	America				
Manufactured by:	Magnum Energy				
Charger regula. method:	Automatic three-stage				
MPPT cost per Watt:		0,2	US$ / Amp	200	US$ / Amp
Max.PV input voltage	=	200/240	VDC		
Max.PV operating voltage	=	187	VDC		
Max.PV short circuit current =		100	ADC		
Conti. Charger output current =		100	ADC		
Norminal battery voltage	=	12 / 24 / 48	VDC		
Battery charger outputvoltage=		10 to 66	VDC		
Night time power consump. =		<2	W		
Peak efficiency	=	0,99	99%		
Number of strings	=	6			

Appendix E3:- the cost estimates of the system installation and other plant balance of the system

				Plant Balance of system		
e)	**System Installation Cost**			items includes;	i)	**Wiring Cables**
	System installation cost per kWh of system design load:		0,45	US$ / kWh		
	Plant System Power Capacity:		841488,00	W		
					ii)	**Battery Racks/ Boxes**
					iii)	**Others**