Institute of Water and Energy Sciences (including Climate Change)

A COMPARATIVE ASSESSMENT OF HYBRID RENEWABLE ENERGY SYSTEMS FOR SUSTAINABLE RURAL ELECTRIFICATION IN CAMEROON

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DECLARATION

I, **Erasmus MUH** hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other work presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

ABSTRACT

Cameroon is blessed with a vast potential of renewable energy resources: solar, biomass, hydropower, wind and geothermal energies. These resources are currently poorly developed and valorised. The country depends mainly on hydropower (73.2% in 2014) for her electricity supply and traditional biomass (64.1% in 2015) for energy consumption. This dependence on a single energy source causes acute power shortage nationwide especially in remote communities where grid access is limited. Rural electrification is mainly conducted through costly grid extensions, small hydro systems and isolated diesel plants with enormous health and environmental effects. This study assesses the feasibilities of hybrid renewable power systems for remote applications in Cameroon using satellite derived datasets of meteorological parameters. Due to the diverse climatic variations in the country, three case studies from the three major climate zones of Cameroon are used and nine different hybrid system systems compared in each of the sites. HOMER is used to perform the comparative analysis. The overall result was classified using two major parameters: economics and sustainability; considering ten design parameters. Based on economics, PV/diesel/small hydro/battery, PV/diesel/small hydro/battery and PV/wind/diesel/small hydro/battery systems showed optimum performances in the West, Center-South, and Northern part of the country with respective cost of energy of 0.443 $/kWh, 0.526 $/kWh, 0.656 $/kWh. With regards to externalities and sustainability, PV/wind/small hydro/battery was the most feasible system all over the country with a cost of energy of $0.674/kWh, $0.677/kWh, $0.583/kW for West, Center-South, and Northern parts of Cameroon respectively. These systems are proven through sensitivity analysis to show very little changes in performances (resilient) to variations in stream flow, interest rate, fuel price and PV cost multiplier. Despite the relatively high cost of energy from these systems compared to grid power in Cameroon, the hybrid systems have proven to be suitable for remote and isolated applications for environmental, accessibility, vast omnipresent resource availability, ease of implementation, limited operation and maintenance reasons. Thus, these systems are highly valuable for Cameroon to improve her low rural energy access.

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

UNDESA	United Nations Department of Economic and Social Affairs
IEA	International Energy Agency
REN21	Renewable Energy Policy Network for the 21st Century
UNDP	United Nations Development Programme
IRENA	International Renewable Energy Agency
USAID	The United States Agency for International Development
CIA	Central Intelligence Agency
HOMER	Hybrid Optimization of Multiple Energy Resources
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organisation
LED	Light Emitting Diode
GIS	Geographical Information System
PV	Photovoltaic
kWh/KW	Kilowatt hour/Kilowatt
TWh	Terawatt hour
GWh	Gigawatt hour
MW	Megawatt
TJ	Terajoule
bbl	barrels
W/m^2	Watts per square metres
TPES	Total Primary Energy Supply
LPG	Liquified Petroleum Gas

DNI	Direct Normal Irradiation
GHI	Ground Horizontal Irradiation
GDP	Growth Domestic Product
PPP	Purchasing Power Parity
CO_2	Carbon dioxide
KV/KVA	Kilovolts/Kilovolts Amperes
DC/AC	Direct Current/Alternating Current
DOD	Depth of Discharge
LCOE	Levelized Cost of Energy
MPPT	Maximum Power Point Tracker
LPSP	Loss of Power Supply Probability
NPV	Net Present Value
$\beta/\alpha/\lambda$	beta/alpha/lambda
km/mm	Kilometre/Millimetre
m/s	meters per second
l/s	litres per second
$/USD	United States dollars
€	Euros
FCFA	Franc de Colonais Française d’Afrique

LIST OF TABLES

LIST OF FIGURES

1 CHAPTER ONE: INTRODUCTION

1.1 Background of study

Energy is inherently linked to socio-economic development and the provisions of affordable and reliable modern energy services is a key driver for economic growth in both emerging and industrialised countries. Access to adequate energy services can contribute immensely to poverty eradication, improved public health, food security, enhance education and income generation (UNDESA, 2014). Electricity is a basis for development irrespective of the source and is one of the cleanest energy transfer option (Sahu et al., 2014). Access to electricity and increasing availability of electricity contributes to improve health, social development and fosters economic growth. The prosperity and wealth of developed countries arise from their unrestricted access to energy whereas the developing nations are still struggling to meet up with their energy demand. (Sanchez and Tozicka, 2013). IEA, 2010 estimated that about 22% of the world's population lived without electricity and this represents 1.5 billion people as of 2008. Most of these people lived in remote and isolated areas with difficult access to the regional or national grid. Also, 85% of these people without electricity access lived in peri-urban or rural areas in developing countries, most of whom are found in South Asia and sub-Saharan Africa. The IEA further predicts that if nothing is done to alleviate energy poverty (new policy introduction) by 2030, 1.6 billion people (16% of world population) mostly in South Asia and Africa will still be refused energy access (IEA, 2010). Nearly 3 billion people worldwide rely on traditional biomass for cooking heating and lighting and this has resulted in about 3.1 million premature death annually especially in developing countries as a result of indoor air pollution of incomplete biomass combustion (UNDESA, 2014). In sub-Saharan Africa and Asia-Pacific, 2.7 billion people (38% of global population) lack clean cooking facilities (REN21, 2016). In Africa, about 60% of the population (majority in sub-Saharan Africa, electrification rate 32%) has no access to electricity. The energy access in rural areas can be increased in three ways: using isolated devices and systems for power generation as well as for heating, cooking and productive uses, through community level mini or micro-grid systems and through grid based electrification (REN21, 2016). In sub-Saharan Africa as of 2008, 70% of the population (587 million people) lacked access to electricity and by 2030, it is estimated that 698 million people will still lack electricity access in sub-Saharan Africa (UNDP, 2013). These countries (except South Africa) have low public and households grid or off-grid energy access rates, unreliable power supply, high energy cost and inadequate production capacities to meet the rapidly growing energy demand. Two-third of the sub-Saharan population live in remote, isolated and sparsely populated areas without access to the national grid. Grid connections is often highly expensive in most cases and off-grid (decentralised) generations is certainly the most viable option to ensure a reliable and affordable energy access to these localities (UNDP, 2013). REN21, 2016 Renewable Energy Global Status Report show that about 17% of the world population (1.2 billion people) mostly in Asia-Pacific and sub-Saharan Africa still have no access to electricity (REN21, 2016). This number has reduced from the 1.5 billion estimated by IEA in 2010 mainly due to the used of distributed renewable power generations to provide energy to these populations. In order to address the rapid growth in global energy demand and electricity access deficits especially in the rural communities of developing countries, it is imperative that energy is produced and used in a sustainable way as to achieve sustainable energy for all (UNDESA, 2014). Therefore, there is a high need for alternative and clean energy resource development to meet these needs. This will improve energy security, increase energy access particularly to remote communities, reduce dependence on grid electricity, increase productivity and contribute to energy diversification and security (UNDESA, 2014).

1.2 Problem Statement

1.2.1 State of the art

Research in renewables and hybrid energy systems are limited in Cameroon. However, a number of quality research papers has been documented in literature cutting across resource potential assessments, policies and regulations, technologies, socio-economics and power generation and transmissions. Abanda (2012), carried out a study on the renewable energy resources of Cameroon with more emphasis on the potentials, benefits and enabling environment. He noticed that there is limited and scattered research work on the potentials of renewable in Cameroon, with their exact sizes, benefits and market potentials still not properly known. He also found out that wind energy is feasible in some regions despite the fact that solar and biomass exists in vast quantities almost everywhere in the country. In addition, he realised that literature about geothermal that exists are either contradictory or provide no clear conclusion about their exact potential. Tidal energy is still to be notice in the country. Also, Abanda et al., 2016 investigated the feasibilities of residential standalone PV systems in Cameroon for the electrification of three residential buildings: T4, T5 and T6 in the capital, Yaoundé. They sized the systems taking into consideration the energy from the sun and the load from the building and noticed that the average unit cost of electricity for T4, T5 and T6 respectively were higher than the average unit cost of grid residential electricity in Cameroon. Mas'ud et al., 2015 assesses the renewable energy readiness for Cameroon and Nigeria and concluded that although both countries are developing renewable to power their local economies, but they are still to incorporate renewable into the national grid in larger scale. In another study, Ayompe and Duffy, 2014 evaluated the energy generation potentials of PV systems in Cameroon using satellite derived solar datasets. They evaluated the energy output, capacity factor and performance ratio of PV systems at 33 sites in the country using average monthly daily global horizontal solar radiation from satellite datasets available in SolarGIS software. They made an economic evaluation and realised a payback period of 5.6 years and LCOE of 6.79 €c/kWh in sites with annual power output of 1764 kWh/kWp, and with a capital cost and discount rate of 1500 €/kWp and 5% respectively. Nfah and Ngundam, 2008 modelled Wind/diesel/battery systems for electrification of typical rural households and schools in remote areas of the Far North region of Cameroon using the wind resource data of Maroua Salack from 1991-1995. The overall result obtained in their study pointed out that there is a high possibility of increasing electricity access rate in the Far North region of Cameroon using only Wind/diesel/battery systems without considering grid extensions, thermal power plants or independent diesel plants to supply power to the remote communities of this region. In another similar modelling, Nfah et al., 2007 investigated the performance of hybrid Solar/diesel/battery system for the same locality of Cameroon. In this Particular study, they use the Hay's anisotropic model to calculate the hourly solar radiation received on a south-facing tilt module from the hourly global horizontal radiation of Garoua. Furthermore, Nfah and Ngundam (2009) studied the feasibilities of pico-hydro and PV hybrid systems with the incorporation of biogas generator for remote villages in Cameroon using 73 kWh/day and 8.3 kWp load. HOMER was used in these simulations, using the load of a hostel, the solar radiation of Garoua and the flow rate of the Mungo river. Both pico-hydro and PV hybrid systems required the parallel operation of a 3.3 kW battery inverter and a 10 kW biogas generator. Here, it was observed that the pico-hydro/biogas/battery systems simulated for isolated communities in South Cameroon with a minimum flow rate of 92 l/s was more economical than a PV/biogas/battery systems simulated for isolated areas in North Cameroon with a minimum insolation level of 5.55 kWh/m^2/day. Nfah et al., 2008 in another piece of work uses HOMER to simulate off-grid generation options for remote villages in Cameroon using 110 kWh/day and 12 kWp load. Again, they make use of typical village load, flow rate of Mungo river and the solar resource of Garoua to analyse their systems. They simulated three different hybrid systems: micro-hydro, PV and LPG hybrid systems. In this study, they found out that the micro-hydro hybrid was the cheapest for remote areas in southern Cameroon with a minimal flow rate of 200 l/s; PV hybrid the cheapest for villages in Northern Cameroon with an insolation level of 5.55 kWh/m^2/day. From all these literature, it is evidently true that there is little and where available scattered scientific work on renewable energy potentials, technology and applications especially hybrid systems in Cameroon. There is no sufficient effort made so far by the government of Cameroon to ensure adequate uptake of these technology. It is for these reasons that this study is being carried out to boast the level of research work in this area and to facilitate and encourage the applications of these technologies to improve energy access in the country. In most of the above literature consulted, studies are only conducted in the northern and southern part of the country. Very limited studies so far are identified from West Cameroon. Most of the systems consulted in this study combine renewables with either diesel or LPG. This present study intends to expand on the present studies especially that of Nfah et al., 2008 and considers a broad range of hybrid systems and considering the use of pure renewable energy hybrid systems. The scope of the work is also broadened to include almost all regions of the country.

1.2.2 Knowledge gap

Electrical energy powers almost all services in Cameroon especially in urban and industrial centres. The lack or limited supply of this energy will serve as a major hindrance to these economic activities and hence growth and development of the country. Limited supply of electrical energy will lead to the non-optimal or malfunctions of industries, institutions, schools and hence the national economy (Abanda, 2012). The use of off-grid renewable energy systems and off-grid hybrid renewable energy systems is not well known, appreciated and encouraged in Cameroon where about 70% of the population live in rural areas without access to the grid or an independent power generating system such as diesel system, mini or micro hydro (Nfah and Ngundam, 2008). This is mainly due to the country dependence of large and centralised hydropower systems with restricted grid transmission networks to supply the country urban and some rural areas. For the past decades, power cuts in the country has been very frequent. Reports in 2002 pointed out that out of the 30 000 villages in Cameroon, just 2 000 has access to electricity and only 40% of city dwellers had access to electricity, giving a total of 11% rural access (Nfah and Ngundam, 2008). In Peri-urban and remote rural communities, thousands of people lack access to the grid and rely on Lead-acid batteries (those who can afford) for lighting and to run their appliances. A majority rely on traditional biomass for cooking, heating and lighting and this has adverse effects on their health especially children and women (World Bank, 2005). This dependence on fuel wood causes air and environmental pollutions, forest degradations and consequently climate change and health related effects (respiratory diseases) (Abanda et al., 2016). Despite all these challenges in generation, transmission, power shortages, off-grid renewables and hybrid off-grid energy systems are still to be considered as a viable option for improving energy access in Cameroon especially in the rural communities given the naturally abundant renewable energy resources in various parts of the country (Nfah and Ngundam, 2008). Currently, it is still not clear as to what extent renewables (except large hydro) can contribute to the energy need of Cameroon, partly due to limited institutional and regulatory framework, limited research to stimulate their deployment as well as elaborate research and documentation on the actual potentials of these renewables present (Abanda, 2012). Scholarly work in this area in the country is also limited. Although there exist a number of research work on this area, there is a high need for more research and development in renewables and hybrid renewable energy generation systems in order to improve energy access to rural Cameroonians and boast the production capacity of the country as a whole. It is for these reasons that this study is being carried out to assess the feasibilities and reliabilities of renewable energy based hybrid systems as off-grid solutions to increase energy access to isolated communities in Cameroon where the traditional grid access method is impossible as well as in maintaining the national energy security through resource diversification.

1.3 Research question

- What are the feasibilities (technical, economic and environmental) of renewable energy based hybrid systems for rural electrification in Cameroon?

1.4 Research Hypothesis

- Renewable energy based hybrid systems (PV, wind, mini hydro) can improve energy access in remote and isolated areas of Cameroon.

1.5 Research objectives

1.5.1 Main objective

- To comparatively asses the feasibilities of hybrid renewable energy systems (PV/wind/mini hydro) for reliable energy supply to remote and isolated communities in Cameroon.

1.5.2 Specific objectives

The specific objectives are:

- To assess, evaluate and review the renewable energy potential of Cameroon.
- To review the current rural electrification systems, policies and strategies.
- To make a review of hybrid energy systems for off-grid electrification.

- To study and model solar PV, wind, small hydro and diesel energy systems and compare the feasibilities of their hybrid for rural electrification in Cameroon.
- Analyse the trends in meteorological parameters (wind speed, rainfall, temperature etc.) of study sites over time.

1.6 Significance of the study

This study will:

- Provide alternative and sustainable solution to rural electrification in Cameroon.
- Improve energy access to remote and isolated communities in Cameroon and also serve as a policy tool for making useful energy policy and planning for the country.
- Contribute to socio-economic development of Cameroon by ensuring a secure and reliable power supply especially in the rural communities.
- Contribute to sensitization on renewable energy awareness campaigns in Cameroon and in the role of renewable in ensuring the country energy security.
- Contribute to the improvement of the share of renewable energy in power generation in Cameroon as well as serve as a tool to investors and attracts government attention for significant investment in the renewable energy sector.
- It will also add on the current knowledge on renewables and climate change mitigation in the country and the world at large.

1.7 Delimitation and limitation of research

This study will mainly focus on off-grid renewable energy alternative solutions with the exception of large hydropower as it is the primary technology of electrification in Cameroon. Also, hybrid renewable energy technologies with storage will be chosen for system design in order to avoid the problem of intermittencies in renewable power generation and ensure reliable and affordable power supply. The system design will be based on the resource potentials of the chosen sites. As a result of the great climatic and vegetational variations across the country with unequal resource distributions, it will be difficult to select a particular technology or design a system that can be implemented in all remote locations in Cameroon. Therefore, in areas with no sufficient renewable energy potential, a system comprising of a renewable energy component and a fossil based component (diesel gensets, LPGs) will be recommended.

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Brief description of Cameroon

Cameroon (fig. 2.1) is located between latitudes 2º and 13º N and longitude 8º and 16º E (Kendjio et al., 2000). Cameroon, located at the Gulf of Guinea with it larger and smaller land mass in Central and West African regions (Abanda, 2012; Ayompe and Duffy, 2014) actually belongs to the Central African region. Cameroon is Africa in miniature with great diversity (race, ethnic, culture, religion, natural vegetation, climate etc.). It is bordered by Nigeria in the West, Chad in the North, Central African Republic in the East and Gabon, Equatorial Guinea and Congo in the South (Mas'ud et al., 2015, Wirba et al., 2015). Cameroon is considered as the economic power house of the central African region with three of its regions: Littoral, South West and South bordering the Atlantic Ocean and having major rapidly growing and industrialising cities like Douala, Limbe and Kribi respectively. The population and industrialisation of these cities have tremendously advance during the past decades (Nkongho et al., 2016). The population of Cameroon as of July 2016 was estimated at 24 360 830 inhabitants with a growth rate of 2.58% and a total surface area of 475,440 km^2 (472,710 km^2 land and 2,730 km^2 water). Estimates in 2015 revealed that 54.4% of the population lives in urban areas with a 3.6% urbanisation rate between 2010-2015 and the majority of the peoples live in the two major cities of Yaoundé, the capital with a population of 3.066 million and Douala, the economic capital with a population of 2.943 million (2015) (CIA, 2015). Also, about 48% of Cameroon's population live below poverty line in 2000. Rural poverty in Cameroon results from inadequate access to modern energy services, high illiteracy rates, poor telecommunication infrastructures, low employment rate and poor access to information (Ackom et al., 2013). Agriculture covers 20.6% of the total land mass with 13.1% of the landmass used as arable land, 3.3% permanent crops, 4.2% permanent pastures. Forest covers 41.7% of the land mass, 37.7% others (2011) and irrigated land occupies 290 km^2 (2012) of the surface area. The major agricultural products are: cotton, coffee, bananas, cocoa, rubber, cassava, timber, grains, oilseeds and livestocks. The country has a coastline of 402 km with a climate that varies within the terrain from semi-arid and hot in the north to tropical in the coast. The terrain however diverse varies from plains in the north, to mountains in the west, coastal plains in the southwest and to dissected plateau in the Center (CIA, 2017). Cameroon has a GDP (PPP) of $77.24 billion (2016, 2016 dollars); GDP (official exchange rate of $30.87 billion (2015) with a GDP growth rate of 4.8% (2016). In 2016, the GDP (PPP) per capita was $3 300. Services contributes 47.9% of the country GDP, industry 30.8% and agriculture 21.3% (CIA, 2017).

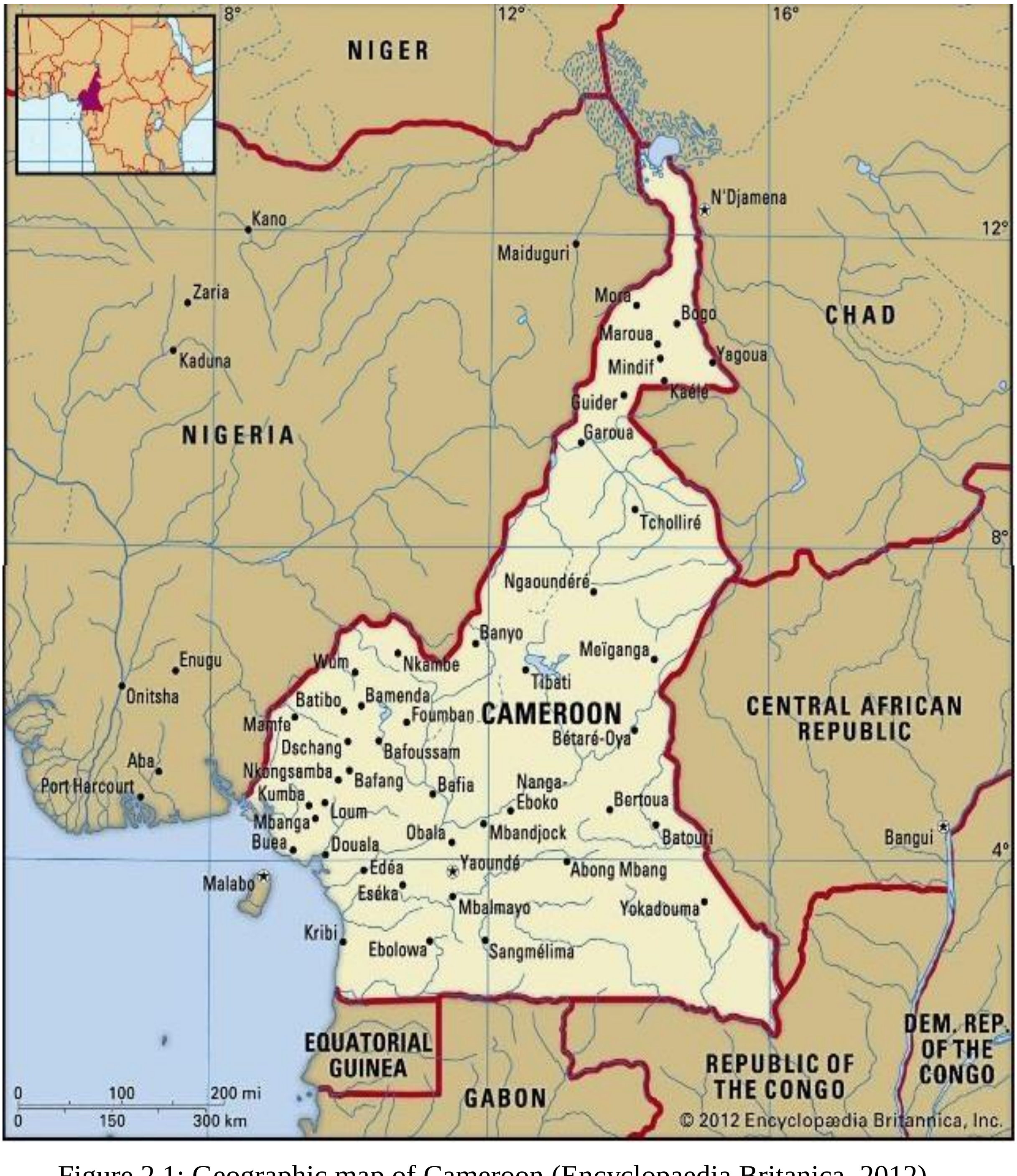


Figure 2.1: Geographic map of Cameroon (Encyclopaedia Britanica, 2012)

2.2 The energy situation of Cameroon

2.2.1 Energy demand and supply

The major energy sources in Cameroon are oil, coal, biofuel and waste and hydropower. Biofuels and waste contribute 64.1% of the country's primary energy consumption, oil (27.2%), hydro (5%) and natural gas (3.7%) (Mas'ud et al., 2015). This distribution of total primary energy consumption is as shown in figure 2.2.

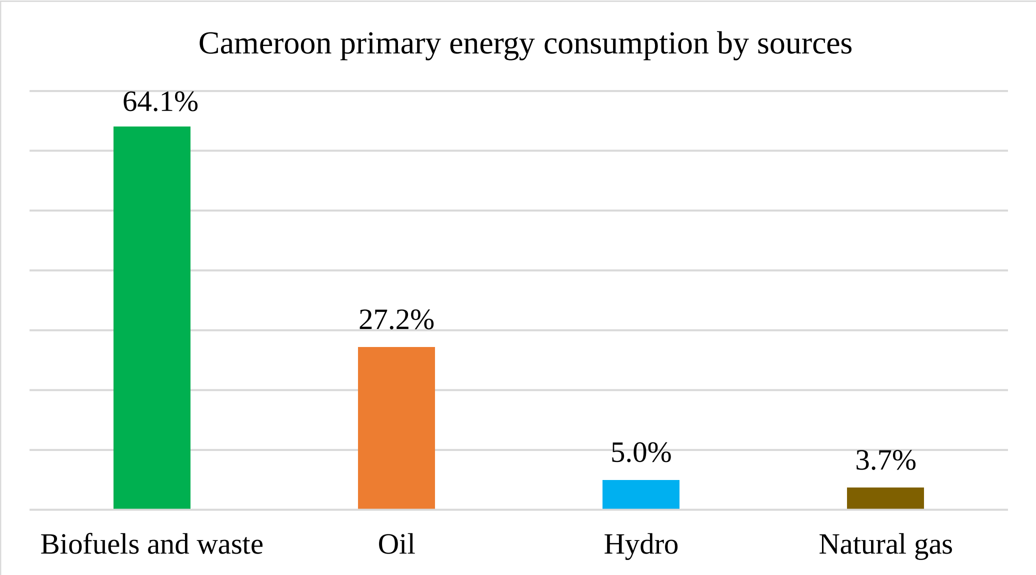


Figure 2.2: Distribution of Cameroon energy consumption by sources (Mas'ud et al., 2015)

Despite of the oil rich nature of the country, the exportation of crude oil is done only to import refined petroleum products in return (Ackom et al., 2013). In 2015, the country produces 95,960 bbl/day of crude oil, exports 50,830bbl/day and imports 37,600 bbl/day in 2013 (CIA, 2017). In 2014, Cameroon's total primary energy supply (TPES) was estimated at 7,603 ktoe. Biofuels and waste (mainly traditional biomass), the country's principal source of energy accounted for 64.5% of the TPES followed by oil, the second largest with 22.5% (fig. 2.3a). Among the solid traditional biomass, firewood is the dominant source of energy for cooking, heating and lighting especially in rural areas and also in most urban settings. Hydropower accounts for 5.7% of the energy supply and natural gas 7.3% (IEA, 2014a). Cameroons energy production in 2010 was estimated at 8,521 ktoe (a little higher than 7,603 ktoe in 2014) with 53%, 42.7% and 4.3% from biomass, oil and electricity respectively;

Giving a final consumption per capita of 0.12 toe (2010) (Abanda et al., 2016).

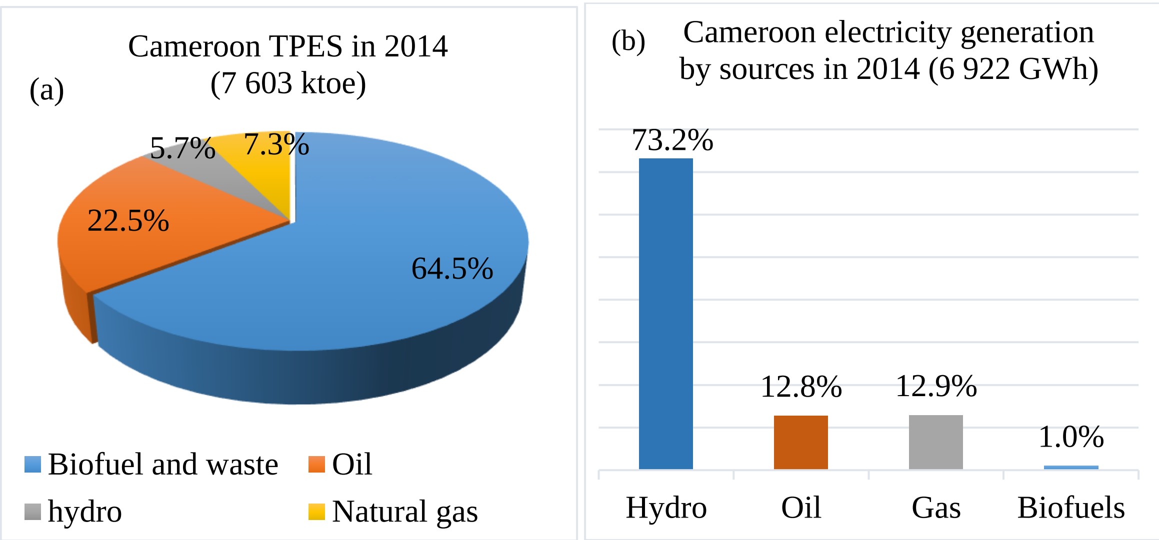


Figure 2.3: 2014 Cameroon energy and electricity production (IEA, 2014a)

In 2014, the electricity generation in the country by sources was 6,922 GWh with a percentage distribution of 73.2%, 12.8%, 12.9% and 1.0% for hydro, Oil, Natural gas and Biofuels respectively (fig. 2.3b). By sector, the consumption patterns were according to the proportions 54.9 : 23.0 : 20.9 : 1.4 respectively for the industrial, commercial, residential and agricultural sectors (fig. 2.4a) and this totals to 5,485 GWh out of 6,922 GWh supply. Self-consumption by the generation plants add up to 757 GWh. This indicates a net loss of 680 GWh, mainly transmission losses (IEA, 2014b). In terms of the general usages of the 6,922 GWh electricity supply in 2014, the industry was the major consumer with 43.5%, followed by commercial and services with 18.2%, the residential with 16.4%, agriculture 1.1%, generation plants self-consumption of 10.9% and 9.8% (680 GWh) losses (IEA, 2014b), as shown in fig. 2.4b.

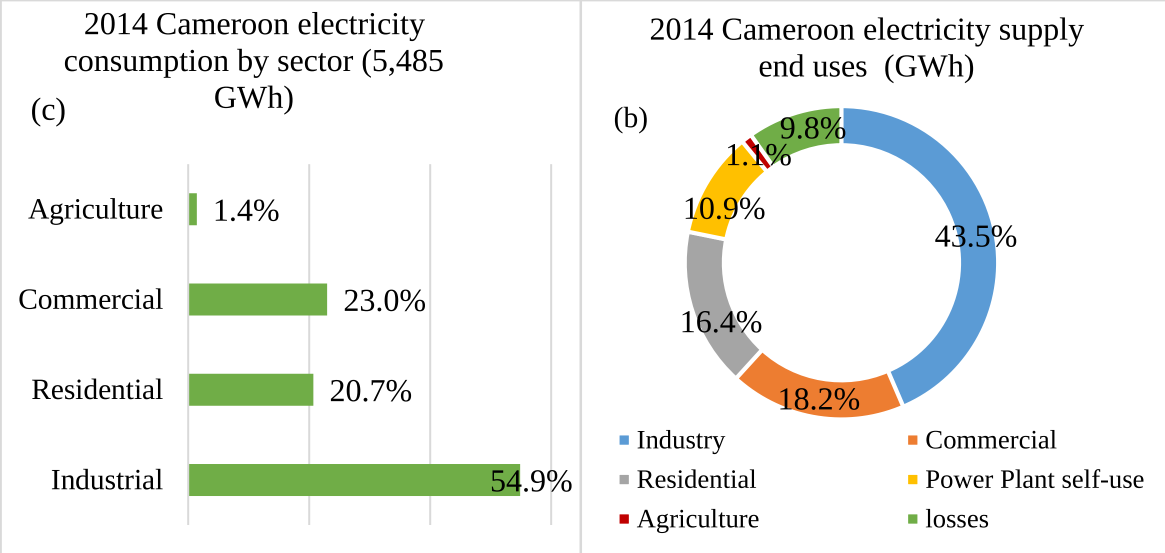


Figure 2.4: 2014 Cameroon electricity consumption and end uses (IEA, 2014b)

The losses are mainly attributed to inefficient generation equipments and poor or old infrastructures especially at the level of transmission. With regards to natural gas, production stood at 25,862 TJ, supply 25,862 TJ and the end usage showed that 37.0% were used for power generation, 43.0% in the industries and 20.0% were lost (IEA, 2014b). Hydropower is the dominant electricity source in the country with only very little efforts made to harnessed wind, solar, and biomass energies (Mas'ud et al., 2015). Cameroon electricity generation capacity in 2015 was 817 MW, 88% from hydropower and the rest from thermal generations (oil and gas). The major hydropower plant in the country are located along the Sanaga river and the rest in other parts of the country. Electricity demand in Cameroon is estimated to reach 5,000 MW by 2020. The government however, planned to boast electricity production by installing additional 25,00 MW capacity between 2012-2020 and had planned for a 298 MW thermal Installations before 2013. However, these plans have not been fully implemented (Mas'ud et al., 2015). Electricity production in 2014 was estimated at 6.8 billion kWh and consumption 6.1 billion kWh. As of 2012, 71.5% of electricity production came from hydropower plants and the remaining 28.5% of the installed capacity from fossils (thermal sources). The contribution of renewables (wind, solar, biomass and geothermal) to electricity generation was negligible (zero percent) in 2012. Cameroon has a proven crude oil reserves of 200 million barrels (bbl) (January 2016) with a production of 95,960 bbl/day (2015). Natural gas proven reserves are estimated at 135.1 billion m^3 (January 2016) with a production of 469 million m^3 (2014). All the country energy production and consumption results in a cumulative CO_2 emissions of 6.5 million metric tonnes in 2013 (CIA, 2017). Energy consumption by households in Cameroon is used mostly for heating, warming water and cooking; in the transport sector for powering and fuelling vehicles; in the public and commercial services for education, healthcare, business and administrative services; in the industry for heating, cooling and equipment powering and in the agricultural sector for fuelling tractors, powering or heating processing crops and for producing fertilizers (Wirba et al., 2015). The currently high societal and socio-economic demand for fossil energies in Cameroon could be reduce with the use of modern biofuels. The drive or recent interest into bioenergy in Cameroon is attributed to energy security issues, the need for more revenues from the forestry and agricultural sectors, cost savings from imported refined oil reduction as well as socio-economic benefits especially for rural areas (Ackom et al., 2013).

2.2.2 Electricity transmission and distribution

Electricity supply in Cameroon is operated by three discontinuous transmission lines or grid which inhibits the transfer of electricity between the grids. These grids are: the southern interconnected grid (SIG), the northern interconnected grid (NIG) and the eastern isolated grid (Nfah and Ngundam, 2009; Thomas et al., 2010). Each grid is solely responsible for generating power to meet the needs of its customers. The country's sub-divisional and district capitals are usually supplied by 24 kW, 6.4 MW independent mini-grids and the divisional and regional capitals in the north, east and south powered by three separate or discontinuous transmission grids (Nfah and Ngundam, 2009). The Northern Interconnected Grid (NIG) with power source from Lagdo and 14 MW thermal plant supply the northern regions of the country; the Eastern Isolated Grid (EIG) powered by 86 small thermal units supply the eastern region of the country and Southern Interconnected Grid (SIG) powered the southern regions (Ackom et al., 2013). Electricity transport in the country is done through three distinct transmission lines: 225 kV, 90 kV and 15 kV as well as medium and low voltage lines. There is considerable tension drops and energy losses arising from very long distances between energy production and distribution centers (Thomas et al., 2010). Cameroon is blessed with a great potential of renewable energy resources (solar, wind, biomass, hydropower, geothermal) but the currently level of exploitation of these resources is very low, leaving the majority of Cameroonian to rely solely on solid biomass fuels (firewood, charcoal) for their basic energy needs especially for cooking and lighting (Wirba et al., 2015). The main sources of energy are hydropower, petroleum, coal, biofuels and waste (Wirba et al., 2015) and the major natural resources are petroleum, Iron ore, timber, hydropower and bauxite (CIA, 2017). In spite of all these resources, very little resources have been allocated for their developments and in most cases all resources are channelled to hydropower resource development, the main power source of the country. This however leaves the country at a very high state of energy insecurity and a faulty or poor production in the hydropower systems can results in acute energy shortage in the country or energy dilemma which will hinder almost all activities in the country. The rural communities will be the most affected. Except for a few rural healthcare facilities (clinics, hospitals) with standalone PV and pico-hydro systems, most rural areas in Cameroon rely only on candles and kerosene lamps even for emergency situations such as childbirth and so on (Ackom et al., 2013).

2.2.3 Trends in energy supply and consumption

The trends in the country’s total primary energy supply from 1972-2014 (fig. 2.5) also confirmed the reliance of the Cameroon on biofuels and waste as main energy source followed by petroleum products (oil and natural gas) and then hydropower. The contribution of natural gas into the country energy mix took effect as from 2006 and grows in magnitude with others till date with a fluctuating productions patterns as do other sources.

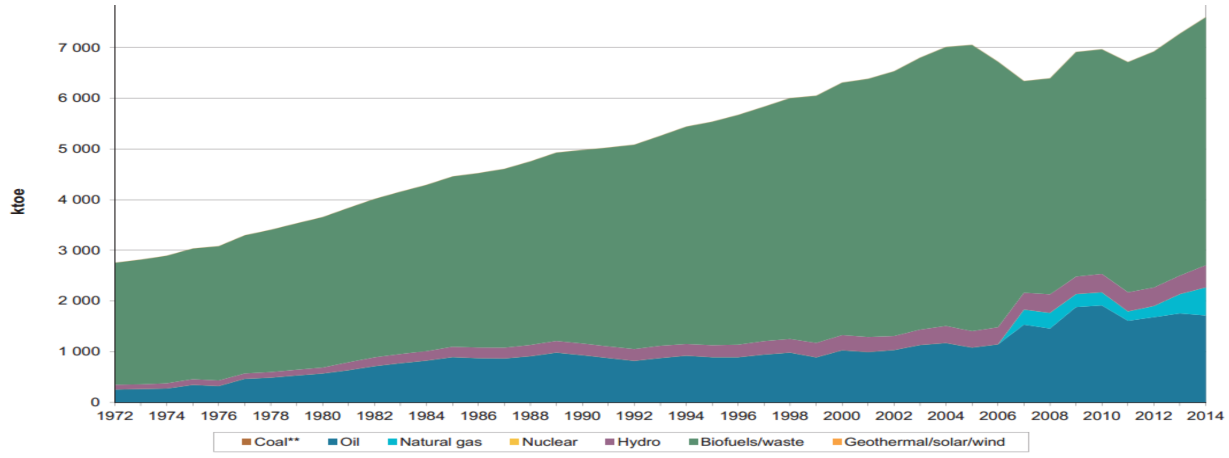


Figure 2.5: Trends in total primary energy supply of Cameroon from 1972-2014 (IEA, 2014a).

A similar trend (fig.2.6) is observed with the electricity production by fuels patterns for the country. There is the total dependence on hydro within this period especially from 1972-2000. As from 2000 upwards, there is the significant contribution of oil in power generation through thermal plants, then followed by natural gas and biofuels between 2005-2006. Natural gas contributions in power generation increases from then till today. However, with biofuels, there is no much advances made by the country to produce power from this sector, evidence from the diminishing trends of biofuels in fig. 2.6.

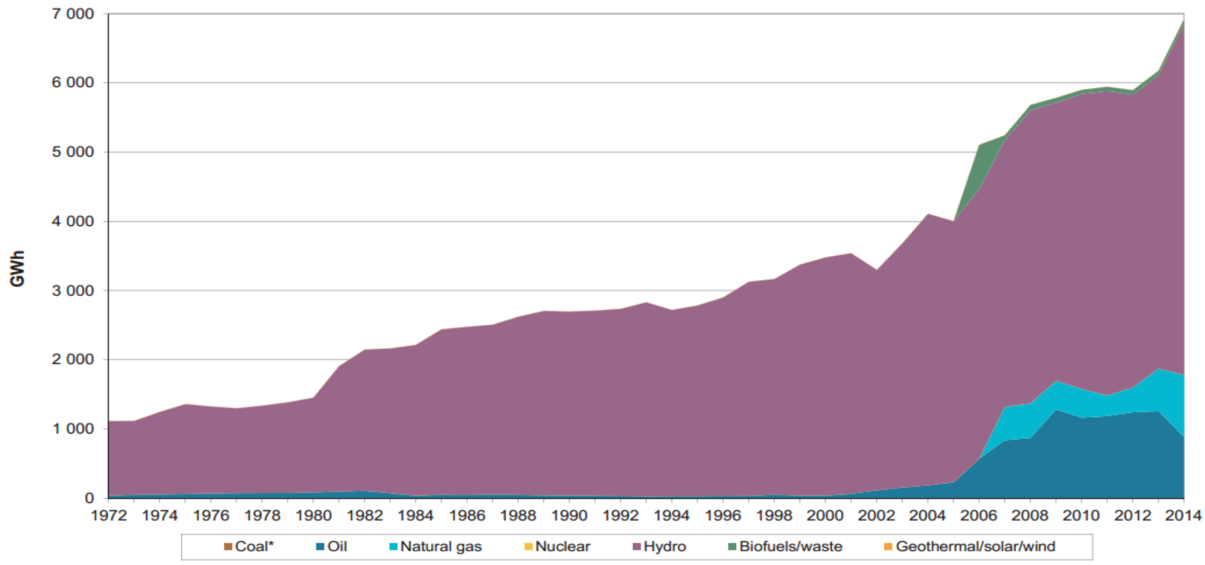


Figure 2.6: Electricity generation by fuels of Cameroon from 1972-2014 (IEA, 2014a)

The trends in petroleum products consumption in Cameroon are illustrated in figure 2.7. Regarding oil products, fuel oil (kerosene), gasoline and liquified petroleum gas (LPG) are mostly consumed. This points to the fact that modern bioenergy (biofuels) such as biodiesel, bio-gasoline, bio-alcohols for transportation and biomethane for cooking will be highly valuable for the country especially in cutting down dependence on oil products as well as ensuring the country's energy security. However, the country is currently not investing or encouraging the exploitations of this rich bioenergy potentials due to lack of policies, incentives and regulation regarding modern biofuels. From this, it is evident that there is a high prospects and market for biofuels in Cameroon.

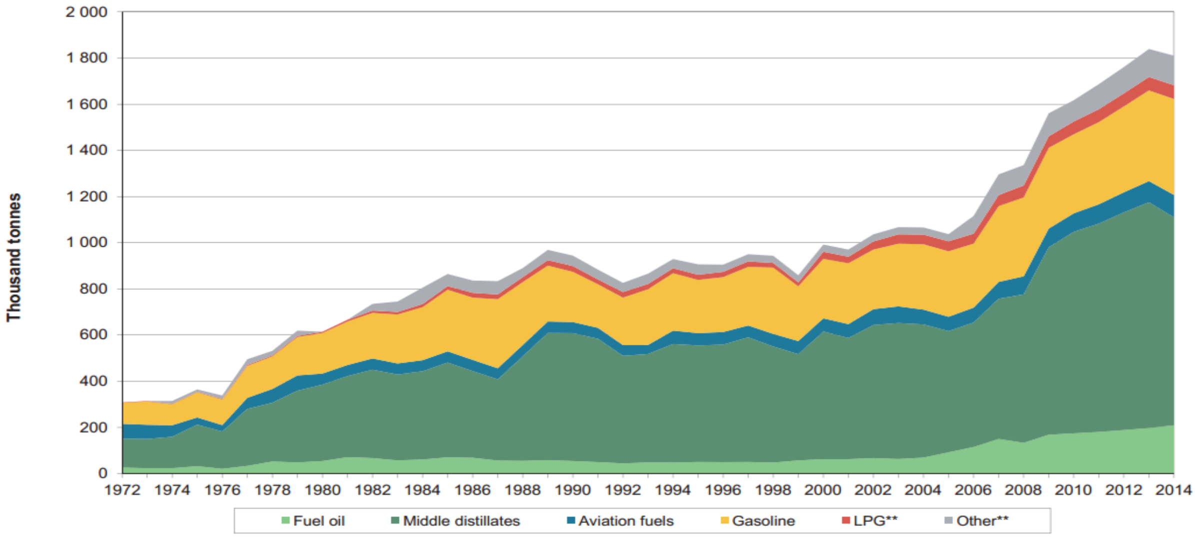


Figure 2.7: Trends in oil products consumption in Cameroon from 1972-2016 (IEA, 2014a)

2.2.4 Energy access

Cameroon has a moderate national and urban energy access. However, access to electricity in many communities is still limited and unaffordable, with very little or minimal power availability in rural areas (Abanda, 2012). Other studies estimate that access to electricity and domestic gas in the urban population of Cameroon is only 15% and 18% respectively with a more critical condition in rural areas with a 5% access (Abanda, 2012). Very few rural facilities (schools, clinics, businesses etc.) are electrified. Electrification is mainly through grid extensions and this requires very high investments for grid extensions to rural communities, less cost effective due to their distances from the grid and available funding and funding mechanisms. In Peri-urban and remote rural communities, thousands of people lack access to the grid and rely on Lead-acid batteries (those who can afford) for lighting and to run their appliances. A majority rely on traditional biomass for cooking, heating and lighting and this has adverse effects on their health especially children and women (World Bank, 2005). In order to tackle these energy issues, the government of Cameroon through the Growth and Development Strategy Paper hopes to boast domestic power supply and to become an electricity exporter by tripling electricity generation capacity between 2020-2025. As a result of decentralized electrification programs, new energy laws, policies, energy targets and rural electrification programs and master plan in the last decade that saw significant investment into energy development in Cameroon, there have been a lot of improvements in the energy access of Cameroon. Presently, the country has an electrification rate 55% with 10 million people without access to electricity in 2013 (REN21, 2016). An urban electrification rate of 88% and 17% rural as of 2016 (USAID, 2016). The country now has an installed capacity of 1,475 MW, mainly from hydro (around 90%) and the rest from thermal plants. There is still the reliance on grid extensions with the inclusion of diesel generation and mini-hydro plants to improve energy access and rural electrification in the country (USAID, 2016). The government however plan to introduce energy efficiency measures and off-grid renewable energy investments for rural electrifications through the rural electrification master plan but cost related issues is the major hindrance to this initiative despite the vast alternative energy resources (except hydro). According to CIA 2017, 46.6% of Cameroon population live in rural areas whereas 54.4% live in urban centres. Rural access to energy is relatively low with an electrification rate of 17% (USAID, 2016) despite the high rural populations. The reasons for this limited energy access in rural communities are due to the fact that electrification in Cameroon is mainly through grid extensions which practically is difficult in rural settings due to the sparse rural population settlement and distributions, poor accessibility in terms of road and infrastructure, rough terrains etc. In cases where grid extensions are possible, its often very expensive especially the transmission lines and this makes the grid connect power to be expensive and unaffordable to the rural dwellers as their living standards are relatively very low (Abanda, 2012). Also, isolated diesel systems are commonly used to improve energy access in rural communities in Cameroon. This method, although cheap has great environmental and health consequences due to it polluting nature and thus not a good option. Estimates in Cameroon shows that a 100m distance cost of a grid electricity line of two 8 or 9m poles will cumulate to electricity bills of roughly 7 years and 14 years for a high and low energy household (Abanda, 2012). These challenges with grid rural electrification in Cameroon paved the way for the need of off-grid standalone systems to fill this gap or highlight the importance of off-grid renewables energy systems for rural electrification. These systems also serve as a means of reducing the CO_2 emission level of Cameroon and thus serving as an adaptive measure for climate change in the country).

2.3 Renewable energy resource potentials of Cameroon

Energy plays a vital and central role in socio-economic growth and in the proper functioning of both modern and developing economies. Energy is key to development and there can be no meaningful development in whatever form it might be without energy. The energy sector in all economies remains the backbone and the best attracting sector for growth strengthening and foreign investments. In Cameroon, lack of access to reliable power or electricity is one of the main drawbacks for investor to do business in Cameroon and the cost the country a close to 2% loss in GDP according to the World Bank Investment Climate (Wirba et al., 2015). One of the major diversification strategies in Cameroon put in place to reduce greenhouse gas emissions from energy consumption while meeting the full country energy demand is the adoption of hydropower as the main energy source. Despite this, the potential extent to which renewables such as solar, wind and biomass could contribute in meeting fully the energy needs of Cameroon are still not clearly stated or well-known. This is partly due to limited policies in place, research and development to facilitate the uptake of renewables (Abanda, 2012). Cameroon is endowed with a huge potential of renewable energy resources which have not yet been fully developed mainly due to poor government actions and policies in encouraging and fostering the development of these resources. These resources are:

2.3.1 Solar energy

The solar resource potential of Cameroon is huge but exploitation level is very low. This low state of development is mainly due to very poor government interest in boasting the sector (Wirba et al., 2015). Although some actions are currently ongoing to stimulate this sector, these actions are quite insufficient and more actions or steps are needed to better improve the performance of this sector especially with regards to rural electrification where it will be highly applicable and needed to enhance energy access to remote communities. The solar intensity of Cameroon can be divided into two categories; the Northern and Southern regions intensities. In the North, the solar intensity is estimated to average 5.8 kWh/m^2/day and 4 kWh/m^2/day in the South, with recent studies indicating a value of 4.9 kWh/m^2/day in the South (Abanda, 2012). Solar energy reaching the surface of the earth in Cameroon slightly varies from one region to another with an estimated 900 trillion kWh of solar energy reaching the earth surface in Cameroon yearly (Abanda et al., 2016). Solar energy is mainly used in Cameroon to power cellular telecommunications, street lightings, standalone power generations in the form of solar homes systems and as few mini-grid systems (Wirba et al., 2015). The recent applications of solar energy in Cameroon is in street lightings in Douala and Yaoundé as literature reports. However, the applications are growing to include standalone solar home systems in homes, hotels, schools, hospitals, telecom systems etc. but the level of deployment is very low. The poor deployment of solar energy in Cameroon is attributed to the poor commitment of the government to boast the sector, poor maintenance of the existing facilities and the absence of a clear government policy to encourage investors (local and international) into the sector. Another application is the installation of the energy-keep it simple and safe (e-kiss) mobile off-grid solar PV system, a product of Antaris solar ESI-Africa; that generate electricity on a standalone basis. This technology is capable of supplying power of up to 2 kW to remote and isolated communities (Mas'ud et al., 2015). The direct normal irradiation and global horizontal irradiation maps of Cameroon are as show in figure 2.8.

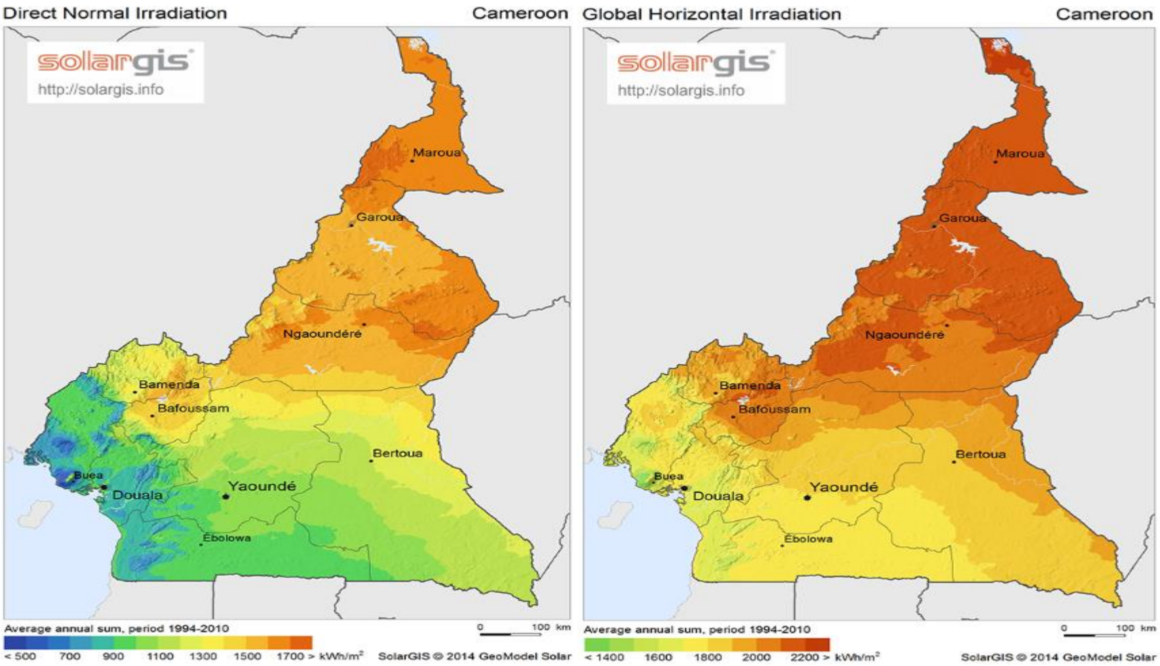


Figure 2.8: DNI and GHI maps of Cameroon (SolarGIS, 2014)

2.3.2 Wind energy

The Wind potential of Cameroon is not as huge as the solar energy resource potential. The northern and coastal areas of the country are highly favourable for wind power generation with a current two wind turbines installed at a hotel in Douala. The average wind speed at 100 m high in the country is between 2-4 m/s (Wirba et al., 2015). This is quite moderate. The wind potential of Cameroon as of now have not yet received any meaningful considerations although there are several efforts made to evaluate this potential in terms of research publications and power generation evaluations. Most of these studies are concentrated in the Northern part of the country where wind potentials are very much significant and most of these studies made use of meteorological data. These studies also shows that the wind potential of Cameroon decreases down to the South from the North, with wind speeds between 2.8 and 4.1 m/s in towns in the North and speeds of about 1.2 – 1.8 m/s in some towns in the South such as Ebolowa (Abanda, 2012). Wind energy evaluation for the establishment of wind turbines in the North West region regions of Cameroon for a 20 years power supply to the region has been conducted by a Spanish firm, Ecovalen in collaboration with the government of Cameroon (Wirba et al., 2015). Practically, the use of wind energy in Cameroon is non-existent or very limited with a few applications of recent. This is mainly due to the fact that fossils and firewood are readily available in the country, the majority of electrical energy requirement of the country comes from hydropower and the lack of proven technology and government measures to stimulate the sector (Kendjio et al., 2000). One major application of wind energy in Cameroon now is a wind electric pumping system installed at Ndoh Djutissa. According to the Cameroon Meteorological service report, wind energy are inadequate for wind turbines developments in some areas of the country but there are no studies made so far to approve this (Mas'ud et al., 2015). Nkongho et al., 2016 made a feasibility study using 31 years NASA monthly average wind data of Cameroon's coastal towns of Douala, Limbe and Kribi to assess the potential for the installation of an offshore or onshore wind farm in these towns. They concluded that in terms of power density and the most probable wind speed for power generation, Kribi was the most probable site for wind farm installation although the average wind speeds in all these towns falls below the normal cut-in speed. Kaoga et al., 2014 in a study aimed at assessing the potential of wind energy for small scale applications such as water pumping systems for rural households in the far north region of Cameroon affirmed the suitability of wind energy for such end use and in other minor applications such as water farms for livestocks and in small scale irrigation schemes.

2.3.3 Hydropower

Cameroon has the second largest hydropower potential in Africa immediately after the Democratic Republic of Congo with a gross theoretical production potential of 294 TWh/year, a technically feasible production potential of 115 TWh/year and an economic feasible generation potential of 103 TWh/year. Only 5.5% of the technically feasible potential have been developed (Abanda, 2012). Hydropower remains the main power source in Cameroon with an overall potential of about 23 GW and a production potential of 103 TWh/year (Mas'ud et al., 2015). Mini and micro hydro potentials up to 1 MW approximate 1.115 TWh but these potential have not been in full use (Wirba et al., 2015). Many hydropower plants are currently under development in Cameroon but the major ones are: Edéa (263 MW), Song Loulou (378 MW) and Lagdo (72 MW). In a drive to improve energy access in the country, the state plans to extend the national grid to many localities, rehabilitate existing power plants, diesel plants and small hydro stations and finally to construct new ones. Despite of the country vast hydropower potentials, the country electricity supply is unevenly distributed providing grid access only to 20% of the population (Wirba et al., 2015). Studies, based on field survey and studies by the Ministry of Mines, Water and Energy resources of Cameroon indicates that the regional site distribution of hydropower potential are as shown in table 2.1 (Abanda, 2012).

Table 2.1: Regional distribution of hydropower potentials of Cameroon (Abanda, 2012)

Regional distribution of Hydropower resource potentials of Cameroon			
Region	Micro hydro	Major hydro	Total
Adamawa	13	14	27
Centre	8	24	32
East	6	6	12
Littoral	3	11	14
North	0	4	4
North West	8	8	16
West	7	6	13
South	14	8	22
South West	15	8	23
Total	74	89	163

There are currently a number of ongoing projects in the country, some already at the verge of completion (Wirba et al., 2015).

Table 2.2: Future hydropower investment in Cameroon (Wirba et al., 2015)

Future Hydropower investment in Cameroon		
Name/location	Capacity (MW)	Investment (€m)
Edéa/Song Loulou	30	76.22
Lom Pangar	170	76.22
Nachtigal	280	228.67
Warak	57	114.33
Song Dong	280	266.78
Menve'ele	200	304.9

2.3.4 Geothermal energy

Potentials for geothermal energy exist in Cameroon. There are areas or regions with hot springs (water) but no studies have so far been carried out to determined their exact potentials. These areas with hot springs are: the Ngounderé area, Mount Cameroon and the Manengoumba areas with Lake Moundou (Wirba et al., 2015). Others studies according to Abanda, 2012 gives contradictory views as to whether geothermal potential exist in Cameroon or not. While some shows positive views, others completely deny the fact that there is geothermal potential in the country. With all these arguments, no real numerical figures have so far been presented to show the real value of the disputed geothermal potential of Cameroon and literature on this as well is very scarce.

2.3.5 Biomass energy

Cameroon has the third largest biomass resource potential in Africa with over 25 million hectares of forest covering almost two third of its territory (Mas'ud et al., 2015) and over 66.7% of the national energy consumption from biomass. These biomass resource of Cameroon come from wood, agriculture, animals and forest resources and the residues of these resources exist in vast quantities throughout the country in the different regions (Abanda, 2012; Mas'ud et al., 2015). In the Adamaoua plateau, there is a significant forest resources which constitute a huge potential source of dendro-energy. The country‘s lignocellulose biomass resource which is estimated and evaluated at 21 million hectares covers over 45% of the country's surface area (Fondja, 2013). The biomass resource potential of Cameroon is very large and unutilized, mainly from agricultural and forest residues. Biomass is used in virtually all sectors in the country (mainly residential and industrial) and it provides up to 75% of residential energy consumption and 90% of industrial energy demand. The use of palm oil for biodiesel production is also growing and this is mainly used for agricultural purposes. In 2006, 66 site for biomass transformation of up to 2.7 million m^3 were identified (Wirba et al., 2015). The extremely high reliance of the country on biomass as the major source of energy for heating, lighting and cooking especially in remote communities has resulted in a massive deforestation as well as the use of palm oil for energy purposes and this has great environmental and health related effects (Mas'ud et al., 2015).

2.4 Cameroon energy policy

Cameroon as of now has no well-defined energy policy available for public usage. Cameroon 1990 and 1998 energy policy focuses only on hydropower resources but has not been implemented. The 2035 emergence vision of the country envisage a significant investment into the country energy sector with the inclusion of renewables. This will increase electricity production and delivery as well as oil and gas products and services to promote economic development. There is the rural electrification master plan that focuses on the electrification of remote areas of the country. There is no clear policy regarding renewables alone. There are still plans to develop such policy (Mas'ud et al., 2015; Wirba et al., 2015).

2.5 Renewable energy systems and applications

2.5.1 Solar energy and generators

The energy from the sun (solar energy) is an infinite energy source which can be used directly or indirectly. Solar energy plays a leading role in the global response to reduce greenhouse gas emissions from electricity production as it is the cleanest energy source of all the renewable energy sources. It has little or no effects on cultivated land, reduces the cost of grid extensions and improves access to electricity and quality of life in remote communities that uses this technology, although the initial capital cost is apparently very high (Akikur et al., 2013). Solar energy systems are highly applicable globally in electrifying isolated areas mainly as standalone or hybrid systems due to the proven and well-known ability of solar energy systems to produce power, it successful global implementations and high technology maturity. It has the potential of meeting global energy demand. However, despite the huge research and development in solar energy technologies in the past decades, the contributions of this energy source in global energy demand is still limited. Much efforts in terms of policies and regulation strategies are still required to boast the sector, although most governments are currently implementing such polices.

2.5.1.1 Solar energy technology and systems

There is currently a vast number of technologies and devices available in the market globally meant for the exploitation of solar energy. These technologies are either active or passive depending on the nature of solar energy it uses or exploit. Passive technologies are those that uses the heat or radiations from the sun directly into other energy forms without the use of special conversion devices such as solar dryers and solar cookers. The various solar energy technologies currently available in the market are shown in figure 2.9 (Akikur et al., 2013). Among these technologies, the PV technology is the most advance and widely used technology.

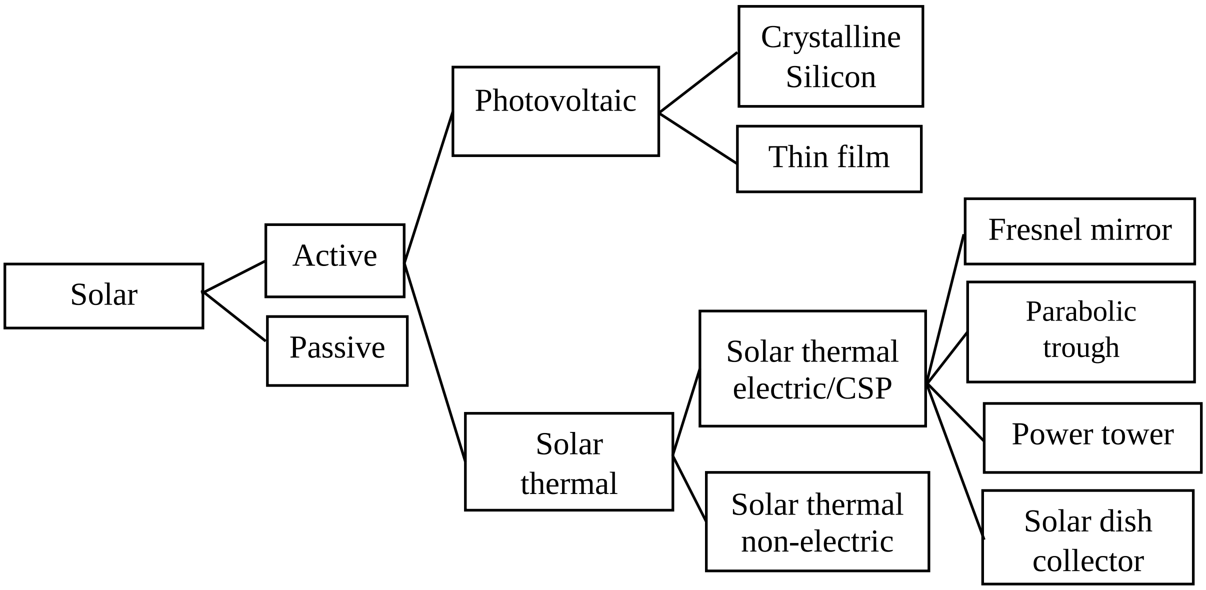


Figure 2.9: Solar technology available in the market (Akikur et al., 2013)

2.5.1.1.1 Solar Photovoltaic technology

The PV technology is an active solar energy technology as it converts solar energy into electricity with the use of solar cells whereas solar dryers are passive technologies as they use the heat from the sun directly to dry crops (Akikur et al., 2013). Solar PV cells convert solar radiation directly into direct current electricity through photon electricity or photovoltaic effect (Oğuz and Ozsoy, 2015). The PV array is an interconnection of PV modules (series or parallels) that produces direct current from solar radiations falling on it (Ghasemi et al., 2013). There are currently three forms of solar cells: monocrystalline with 12-16% efficiency range, polycrystalline with 11-14% efficiency range and amorphous solar cells with 6-8% average efficiency range. Among these cells, amorphous is the least expensive followed by the polycrystalline cells (Oğuz and Ozsoy, 2015). The PV cells are very reliable at the generation site with very low operation and maintenance cost. However, the initial capital cost of solar cells is very high but with increasing research and development, the cost is expected to fall in the nearest future. Today, solar cells are very economical for small scale applications (Oğuz and Ozsoy, 2015). The power generated from a PV system depends on the module or cell temperature and sunlight intensity falling on the module. This solar electricity can either be feed directly into the grid, electrical load or stored in batteries for use when there is no enough sunlight or for night use (Abanda et al., 2016). Solar PV modules are usually tilted at an angle equivalent to the latitude of the site of installation to increase the amount of radiation capture and reduces reflection losses. The output power (P_{output}) of a PV module is calculated as shown in equation 1 (Adaramola et al., 2014).

$$P_{output} = Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{G_{T,STC}} \right) \left[1 + \alpha_p (T_c - T_{c,STC}) \right] \qquad \text{Equation 1}$$

Where:

Y_{pv} = is the rate capacity of the PV module or output power (kW) under standard test conditions, f_{pv} = PV derating factor (%), $\overline{G_T}$ = solar radiation incident on the module surface (kW/m^2), $G_{T,\ STC}$ = incident solar radiation at standard test conditions (1000 W/m^2), α_p = temperature coefficient of power (%/^{o}C), T_c = PV cell temperature in ^{o}C and $T_{c,\ STC}$ = PV cell temperature under standard test conditions (25 ^{o}C).

In situations where the temperature effect on the PV module is neglected, α_p is assumed zero and equation 1 reduces to equation 2 as shown.

$$P_{output} = Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{G_{T,STC}} \right) \qquad \text{Equation 2}$$

2.5.1.1.2 Solar PV systems

There are three basic types of PV systems: grid connected, standalone and hybrid PV systems. Standalone systems are mostly applicable in small scale applications such as solar home systems, used for provision of energy to small and large businesses, schools, hotels, hospitals etc. especially in isolated places. The grid connected systems mainly used for large scale solar power generation, mini grid systems and in some solar home systems where excess energy are sent to the grid and vice versa. The hybrid PV systems involve the use of a PV generation in combination with any other power generator (wind, biomass, gas, diesel, hydropower etc.). Among all these three PV systems, the standalone system is the most commonly used. In Cameroon, PV systems are used mainly in residential areas , street lightings (Abanda et al., 2016) and for small mini-grids.

2.5.1.1.3 Standalone solar PV system

A standalone Solar PV system consist of a PV module, a storage device (battery or fuel cell), a charge controller, a central control unit and an Inverter (DC/AC) to convert the DC solar current into the AC that is required by the load system. A general representation of these components is as shown in figure 2.10.

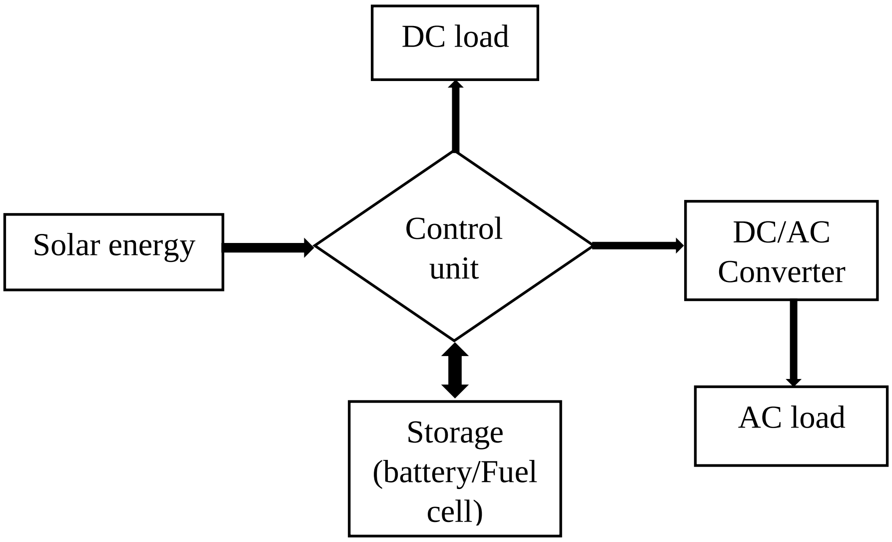


Figure 2.10: General representation of a standalone PV system (Akikur et al., 2013).

The storage system of standalone PV systems (battery), is recommended to be less expensive, have long lifetime, highly energy efficient, have low maintenance and self-discharge and most importantly easy to operate. In most cases Lead acid batteries are used due to their cost and longer lifetimes. The exact size of the battery is usually dependent on the load and the exact backup period (days of autonomy) (Akikur et al., 2013). Other storage systems such as the fuel cell systems are becoming more applicable and thus serve as the best alternative substitute of battery storage systems although this technology is still new and not much in applications. Research and development in this storage system is still limited but the prospects for the future are high.

2.5.1.1.4 Hybrid Solar PV system

Hybrid energy systems are electrical power systems consisting of two or more energy sources, either all renewable energy sources or a combination of both renewable and conventional energy sources. They also contain storage systems such as batteries or fuel cells and are mostly used to electrify remote areas as well as can be grid connected. Examples are either wind or solar combined with other sources such as hydro, geothermal, biomass or diesel, gas generators (Akikur et al., 2013). Figure 2.11 shows an overview of a PV hybrid energy system and components.

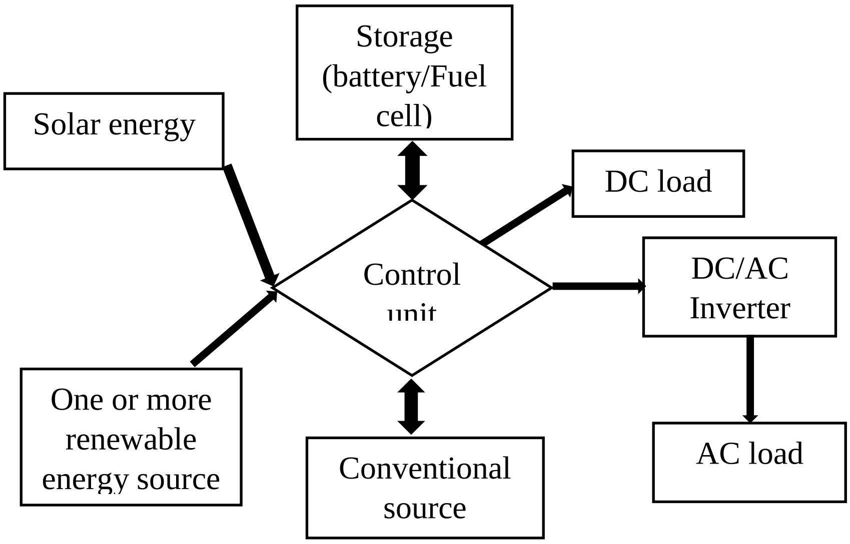


Figure 2.11: Schematic overview of a hybrid PV system (Akikur et al., 2013).

2.5.1.1.5 Components of a PV system

A PV system consist of four main components: the PV generator or module, charge controllers, battery and inverters (fig. 2.12), together with balance of system components (wires, installation stands, circuit breakers etc.). The charge controller regulates the output DC power/current to the load, battery or AC load to the grid. It does this by turning off the PV generator from charging the battery during full battery charge. In order to convert the PV direct current to an alternating current, DC/AC inverters are used (Abanda et al., 2016).

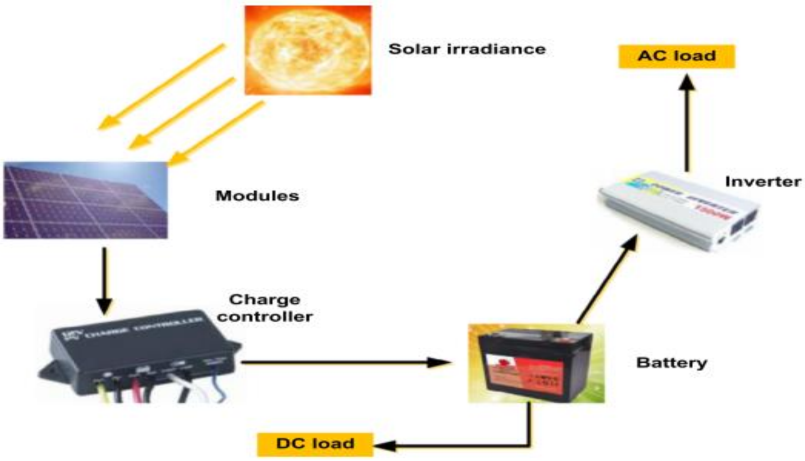


Figure 2.12: Components of solar PV system (Abanda et al., 2016).

2.5.2 Wind energy and generators

The energy (kinetic energy) in moving wind is converted into electrical energy through the use of wind turbine in which is incorporated a generator to convert the mechanical energy of the rotating turbine shaft into electrical energy. Wind turbine are grouped based on their power capacity, blade number, area of use and axis structure (horizontal or vertical axis). The electrical power output of a wind turbine depends on: the number of turbine's blade, the blade angle and diameter, the wind speed (depends on surface roughness and height), output power constant and air density (varies with seasonal pressure and temperature) (Oğuz and Ozsoy, 2015). Generally, the mechanical power (P_w) generated from a wind turbine according to Oğuz and Ozsoy, (2015) is given as in equation 3:

$$P_W = \frac{1}{2}\rho\pi R^2 V^3 C_p(\lambda, \beta) \qquad \text{Equation 3}$$

Where:

ρ = density of air, V = wind speed, R = radius of rotor blade, C_p = turbine power constant (C_p = Betz law or Limit = 0.593 maximum for high speed turbines and ranges 0.2 - 0.45 for low speed turbines), λ = blade speed ratio and β = blade incline angle.

2.5.3 Hydropower energy and generators

Micro-hydro power systems are usually installed in areas with ample and constant yearly river run-off or stream flow (Bhandari et al., 2014). They are mostly applicable in run-off rivers and the construction of large dams and reservoirs are not needed.

The amount of energy generated depends on the available amount of water and yearly flow availability (Kenfack et al., 2009).

2.6 Mathematical modelling of renewable energy systems and components

Researchers over the past decades have developed several models to evaluate the performances of hybrid energy systems. Individual system component performance modelling is done through either a deterministic or probabilistic approach (Deshmukh and Deshmukh, 2008). Some of these models are as:

2.6.1 Wind energy system modelling

Wind velocity usually varies with time of the day, season of the year, location of measurement, weather and height above ground level. In order to better forecast wind energy production, there is need for proper modelling of wind speed variability. This modelling can be achieved through the use of the Weibull wind speed probability density function. The Weibull distribution function together with wind turbine output power and the power law according to Chauhan and Saini, (2014) is given by:

$$f(V, k, c) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \qquad \text{Equation 4}$$

Where:

$f(V, k, c)$ = Weibull wind speed (V) probability, c = scale parameter, k = shape parameter and $V \geq 0$, $k>1$ and $c>0$.

Generally, the energy output from a wind turbine (P_{WT}) of swept area A (m^2), hub height velocity V (m/s), air density ρ (kg/m^3) and the power coefficient (C_P) is given as (Hosseinalizadeh et al., 2016):

$$P_{WT} = \frac{1}{2} \text{ x } C_P \text{ x } \rho \text{ x } A \text{ x } V^3 \qquad \text{Equation 5}$$

Wind energy output power is dependent on the wind turbine rated power (P_r), the cut-in (ci), cut-out (co) and rated speed (V_r) of turbine. The power output of wind turbine P_{WT} (kW/m^2) is given mathematically as follows (Deshmukh and Deshmukh, 2008):

$$P_{WT} = \begin{cases} 0 & V < V_{ci} \\ (aV^3 - b)P_r & V_{ci} \leq V < V_r \\ P_r & V_r \leq V \leq V_{co} \\ 0 & V > V_{co} \end{cases} \qquad \text{Equation 6}$$

Where

$$a = \frac{P_r}{(V_r^3 - V_{ci}^3)} \ , \qquad b = \frac{V_{ci}^3}{(V_r^3 - V_{ci}^3)}$$

The wind turbine power characteristic of equation 6 is illustrated graphically as shown in figure 2.13.

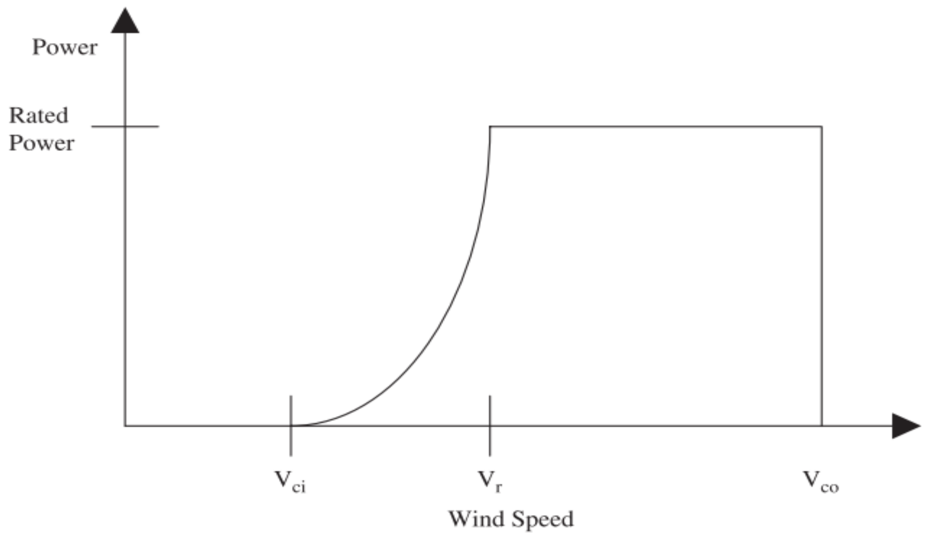


Figure 2.13: Wind turbine power characteristic curve (Deshmukh and Deshmukh, 2008)

The actual available power from a wind turbine is given by:

$$P = P_{WT} A_W \eta \qquad \text{Equation 7}$$

Where

A_w = total turbine blade swept area, η = system efficiency (wind turbine efficiency and corresponding converters)

The annual wind energy production (E_{WES}) at a specific location can be estimated as follows (Chauhan and Saini, 2014):

$$E_{WES} = 365 \text{ x } 24 \left(\sum_{V=0}^{V_{co}} P_{WT} \text{ x } f(V, k, c) \right) \qquad \text{Equation 8}$$

Since wind speed are usually measured at particular heights, usually different from that of the turbine hub height, the measured wind speed needs to be adjusted to the speed at the turbine hub height for wind power evaluation and computations. The turbine hub height wind speed is usually estimated according to the power law expression shown in equation 8 (Deshmukh and Deshmukh, 2008; Chauhan and Saini, 2014; Adaramola et al., 2014a).

$$\left(\frac{V}{V_r}\right) = \left(\frac{h}{h_r}\right)^{\alpha} \qquad \text{Equation 9}$$

Where:

V = wind speed at hub height h, V_r = wind speed at reference height h_r and α = power law exponent or surface roughness given by (1/7 or 0.14) and varies from less than 0.10 in very flat or plain areas, water or ice to more than 0.25 in very forested areas (Kaabeche and Ibtiouen, 2014). Other versions of equation 8 are reported in (Bekele and Tadesse, 2012; Bekelea and Boneya, 2012; Kaabeche and Ibtiouen, 2014). HOMER calculates the Wind turbine output power as follows:

- Determine the average wind speed of a given hour at the anemometer height from the monthly wind speed,
- Compute the corresponding wind speed at the wind turbine's hub height using the power law,
- Use the power curve to calculate the power output at the calculated wind speed assuming standard air density and
- Multiply the calculated output power by the air density ratio.

The air density ratio is given by:

$$\frac{\rho}{\rho_0} = \left(1 - \frac{BZ}{T_0}\right)^{\frac{g}{RB}} \left(\frac{T_0}{T_0 - BZ}\right) \qquad \text{Equation 10}$$

Where:

ρ_o = air density at standard temperature and pressure (1.225kg/m^3), T_o = standard temperature (288.16 K), B = lapse rate (0.00650 K/m), R = molar gas constant (287 J/kg/K), Z = elevation (m), g = acceleration due to gravity (9.81m/s^2) and ρ = air density at the wind turbine hub height.

2.6.2 Mathematical models for micro hydropower (MHP)

In hydropower production, the kinetic energy moving water is used to rotates hydro turbines. Hydro power turbines are using connected to the shaft and generation and the rotation of the turbines automatically causes the rotation of the shaft and generator to produce electricity. The power output of micro and large hydro schemes depends on the flow rate of river (water discharge) and the height at which the water falls to turn the turbine (H). Theoretically, power and annual power generation of micro hydro system is given as (Chauhan and Saini, 2014).

$$P_{MHP} = 9.81\eta_0\rho_W Q H_{net} \qquad \text{Equation 11}$$

Where:

Q = discharge/flow rate (m^3/s), H_{net} = net head (m), ρ_W = density of water (kg/m^3)

η_o = overall system efficiency (given by the product of the efficiencies of the turbine, generator and brush gear).

The annual power production of micro hydro schemes is estimated according to the equation 12.

$$E_{MHP} = (365 \text{ x } 24 \text{ x capacity factor})P_{MHP} \qquad \text{Equation 12}$$

2.6.3 Mathematical modelling of PV system

The total solar radiation at a point on the surface depends on the sun's position in the sky and vary from one month to another. The power output of PV systems is depended upon the amount of diffuse and bean radiations falling on the PV modules. The total radiation (I_T) on an inclined PV surface and total output power are estimated as shown (Deshmukh and Deshmukh, 2008; Chauhan and Saini, 2014; Hosseinalizadeh et al., 2016):

$$I_T = I_b R_b + I_d R_d + (I_b + I_d)R_r \qquad \text{Equation 13}$$

Where:

I_b and I_d = direct normal and diffuse radiations, R_d and R_r = tilt factors for diffuse and reflected solar radiations on the surface.

The total hourly output power from a PV system when a total solar radiation of I_T (kWh/m^2) incident on the PV surface of area A_{pv} (m^2) and on an average day of j^{th} month of the year is estimated according to equation 13.

$$P_{PV,j} = \eta I_{Tj} A_{PV} \qquad \text{Equation 14}$$

where $P_{PV,j}$ = PV total output power on the j^{th} month of the year, η = system efficiency given by:

$$\eta = \eta_m \eta_{pc} P_f \qquad \text{Equation 15}$$

η_m is the PV module efficiency given by:

$$\eta_m = \eta_r[1 - \beta(T_c - T_r)] \qquad \text{Equation 16}$$

Where:

η_r = module reference efficiency, η_{pc} = power conditioning efficiency (efficiency of auxiliary components), P_f = packing factor,

β = array efficiency temperature coefficient, T_r = cell efficiency reference temperature and T_c = mean monthly cell temperature, given by:

$$T_c = T_a + \frac{\alpha\tau}{U_L} I_T \qquad \text{Equation 17}$$

T_a = instantaneous ambient temperature,

$$\frac{U_L}{\alpha\tau} = \frac{I_{T,NOCT}}{(NOCT - T_{a,NOCT})} \qquad \text{Equation 18}$$

NOCT = nominal operating cell temperature, $T_{a,\,NOCT}$ = 20ºC, $I_{T,\,NOCT}$ = 800W/m^2, for a wind speed of 1m/s.

The annual power production from a PV system (P_{PV})is given by:

$$P_{PV} = \sum_{j=1}^{n} P_{PV,j} \qquad \text{Equation 19}$$

2.6.4 Modelling of diesel generator

Diesel systems are often integrated into hybrid energy systems to meet load demands in periods where battery and the renewable systems are incapable of meeting the load demand and this depends on the nature of load to be meet. The following two case scenarios according to Deshmukh and Deshmukh, (2008) are most oftenly used to determine the rated capacity of the generator.

- The diesel generator rated capacity must be at least equal to the optimum load if the diesel generator is directly connected to the load and
- The current produced by the generator should not be higher than $\frac{C_{Ah}}{5}$ A (C_{Ah} = battery capacity in Ah), if the diesel generator is used to charge the battery.

The overall generator efficiency is given by:

$$\eta_{overall} = \eta_{brake\ thermal} \times \eta_{generator} \qquad \text{Equation 20}$$

Where:

$\eta_{\text{brake thermal}}$ = brake thermal efficiency of diesel engine, η = generator efficiency

2.6.4.1 Fuel curve

The fuel consumption of diesel systems are estimated according to equation 21 (Adaramola et al., 2014a). This shows the amount of fuel a generator consumes in units per hour to produce electricity.

$$F_c = aP_{rated} + bP_{gen} \qquad \text{Equation 21}$$

Where:

F_c = generator fuel consumption (L), a = generator fuel curve intercept (L/h/kW), b = generator fuel curve slope (L/h/kW), P_{rated} = generator rated capacity (kW) and P_{gen} = generator output power (kW).

2.6.4.2 Efficiency curve

The diesel generator efficiency, η_{gen} in (kWh/l) according to Kaabeche and Ibtiouen, (2014) is defined as:

$$\eta_{gen} = \left[\frac{P_{gen}(t)}{F_c(t)}\right] = \left[\frac{1}{(a+b)x\ \frac{P_{gen.\ rated}}{P_{gen}(t)}}\right] \qquad \text{Equation 22}$$

2.6.5 Battery system modelling

Battery are size normally to meet load during days of autonomy (when there is no available power from renewable sources), usually taken as 2 or 3 days. The sizing of battery system is dependent on the battery maximum depth of discharge, battery rated capacity, battery life and the temperature correction factor. Battery capacity and the amount of charge in a battery at any given time t, according to Deshmukh and Deshmukh, (2008) are computed as follows:

$$B_{rc} = \frac{E_{c(Ah)}D_s}{(DOD)_{max}\eta_t} \qquad \text{Equation 23}$$

Where:

B_{rc} = battery required capacity, $E_{c(Ah)}$ = load in Ah, D_s = number of days of autonomy, DOD_{max} = maximum depth of discharge and η_t = temperature correction factor.

The charging and discharging state of the battery are usually determined by the difference in power between the power generation and the load. Positive difference implies charging and negative difference, implies discharging. At any given time (t), the amount of charge in the battery bank (battery state of charge), subjected to $E_{Bmin} \leq E_B(t) \leq E_{Bmax}$ constraint where E_{Bmin} and E_{Bmax} are the minimum and maximum battery bank charging quantity is given by:

$$E_B(t) = E_B(t-1)(1-\sigma) + \left(\frac{E_{GA}(t) - E_L(t)}{\eta_{Inv}}\right)\eta_{battery} \qquad \text{Equation 24}$$

Where

$E_B(t)$ and $E_B(t-1)$ = battery bank charge quantities (energy) at time t and t-1, σ = hourly rate of self-discharge, $E_{GA}(t)$ = total energy generation by renewable source after losses from converters, $E_L(t)$ = load demand at time t and η_{inv} and $\eta_{battery}$ = inverter and battery efficiency.

The charging and discharging state of the battery are represented mathematically as follows (Kaabeche and Ibtiouen, 2014):

Charging process

$$E_B(t) = E_B(t-1)(1-\sigma) + \left(\frac{E_{GA}(t) - E_L(t)}{\eta_{Inv}}\right)\eta_{battery} \qquad \text{Equation 25}$$

Discharging process

$$E_B(t) = E_B(t-1)(1-\sigma) + \left[\frac{E_L(t)}{\eta_{Inv} - E_{GA}(t)}\right] \qquad \text{Equation 26}$$

The battery bank nominal capacity B_{rc} is considered as the battery maximum stored energy E_{Bmax} and E_{Bmin} is determined by the minimum DOD, given as E_{Bmin} = (1-DOD). In this study, the minimum DOD is taken as 40% and maximum 60%.

2.6.5.1 The Battery

Batteries are of two forms: primary and secondary. Primary batteries are unrechargeable and with the exhaustion of the initial reactants, they cannot be restored by any electrical means. Secondary batteries are rechargeable as they can have their chemical reactions reversed through the supply of electrical energy to the cell. Renewable energy systems use mainly deep cycle Lead acid battery which are designed to be more tolerant with respect to charging and discharging with variable energy sources (Al-Badi, 2011). Determination of the correct configuration of the battery bank needs a detailed analysis of the state of charge and discharge requirements of the battery with the inclusion of load, output and the pattern of alternative energy sources (Agarwal et al., 2013).

2.6.5.2 Battery dispatch strategies

HOMER model battery system in two dispatch strategies: load-following and cycle-charging. With load following, the renewable energy sources charge the battery while the generators produce enough energy to meet the load demand but do not charge the battery. In cycle-charging, the generators whenever in operation usually produce more energy than the load requirement and the excess is stored in the battery. Cycle-charging is always recommended as it can preserve both the battery and diesel generator lifetime, thus reducing battery over-discharging and associated risks (Dalton et al., 2008; Adaramola et al., 2014a; Adaramola et al., 2014b).

2.7 Hybrid energy systems

The IEA and World Bank estimate that in order to meet the energy demand of developing countries in the next 40 years, it will requires doubling of the installed global energy capacity (Akikur et al., 2013). Lack of adequate energy in an economy is a viable source of economic and social poverty as the access to modern energy services plays a fundamental role in poverty reduction and socio-economic growth (Adaramola et al., 2014b). This indicates that improving energy access to remote communities is a viable and effective tool for sustainable development. Conventional and exhaustible energy sources such as coal, oil, natural gas is currently the major source of global energy use. However, with increasing population growth and energy demand, there is need to exploit alternative infinite, natural abundant, free and non-polluting energy sources, renewable sources (Akikur et al., 2013). Even though grid electrification are first choice measures of electricity supply in most developing countries, it is often uneconomical and expensive especially in low demand and isolated areas. This is evidence that there is need for alternative energy sources to enhance global energy access especially in developing countries. The use of renewable energy resources (solar and wind in particular) started being very attractive and cost effective in the early 1970s due to the oil crisis in the 70s (Deshmukh and Deshmukh, 2008). Renewable energies have received a lot of attention in the past decades as supplements to fossil energies most especially in power generation mainly due to the fluctuating generation and supply of fossil energies, the fear of fossil energy depletion, price variations, growing demand of power due to its rapidly expanding end use and most importantly, the fast growing awareness on the associated dangers of climate change mainly resulting from carbon dioxide emissions from fossil energy use (Akikur et al., 2013). Single technology based renewable energy system is a viable option to improve energy access of remote and isolated areas and their applications vary with topology, resource availability and weather conditions. Solar Photovoltaic (PV) is suitable in plain areas, roof-top PV in buildings of urban areas, biomass gasifier/biogas system in forest remote areas and micro-hydro system in remote hilly areas. However, due to site specificity and the intermittent nature of some of these renewables (solar and wind) that gives rise to variations in their natural abundances and geographical distributions, standalone systems are often not reliable in power supply and are often costly due to the integration of storage systems to manage supply variations (Chauhan and Saini, 2014). In addition, the independent use of standalone systems requires considerable over-sizing of components to ensure system reliability and this often makes the systems very costly (Deshmukh and Deshmukh, 2008). A viable solution to this is to combine different renewable energy sources to form a hybrid system where a deficiency in the output of one system will be complemented by the other. In hybrid energy systems, energy sources balance and stabilizes one another's weakness with the goal of supplying a 24-hour grid quality power to remote areas. These systems cost less, can provide cheap power to remote villages, have less gestation periods, are almost pollution free, are user and socially friendly and are important sources of energy for school, hospitals and clinics, shops and public places in remote areas (Ashok, 2007). Also, they enhance energy efficiency, energy conservation, reduce and/or avoid storage, improve power quality and supply reliability. A schematic representation of a typical hybrid/integrated energy system (solar/wind/micro hydro) is as shown in figure 2.14 (Chauhan and Saini, 2014).

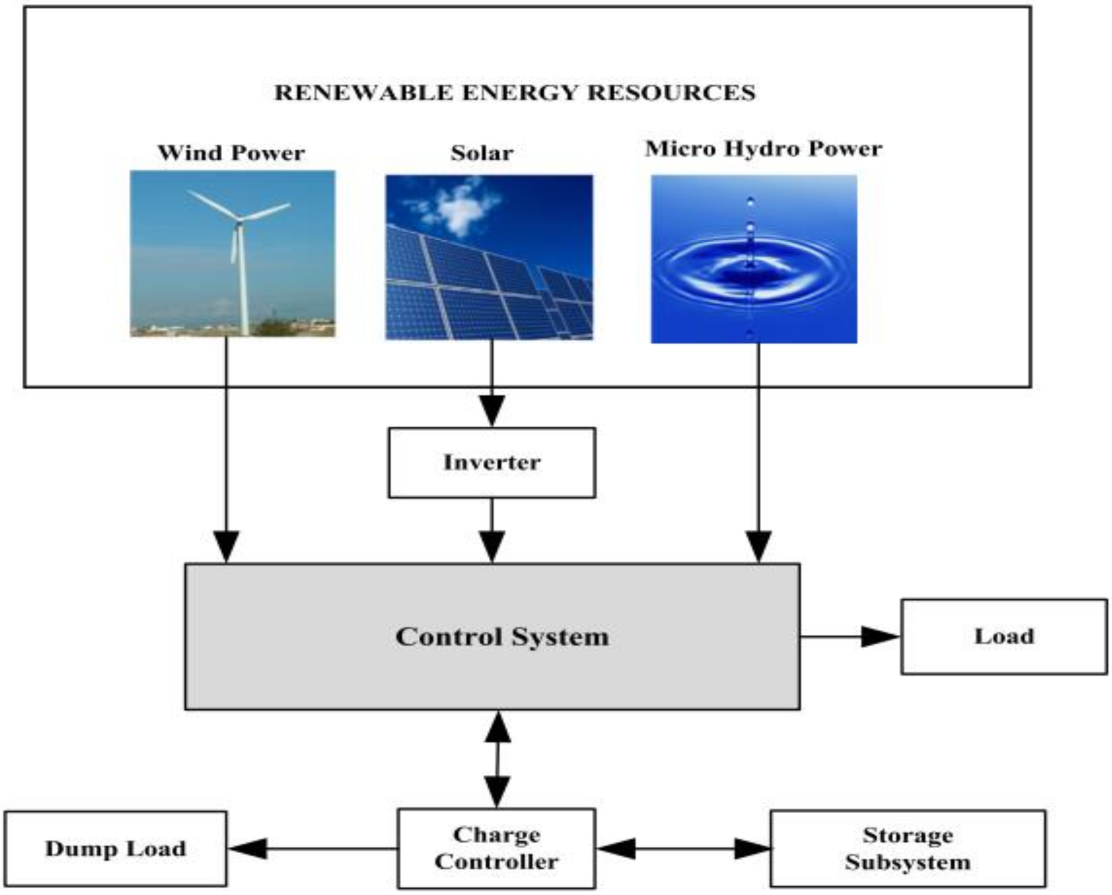


Figure 2.14:A schematic representation of a hybrid energy system (Chauhan and Saini, 2014)

Hybrid energy systems consist of at least two energy generators, usually a renewable energy source (wind, solar etc.) and a fossil generator (diesel) or a combination of pure renewable energy sources (Deshmukh and Deshmukh, 2008; Asrari et al., 2012). With regards to hybrid system operations, the energy resources complement each other's effects. The renewable energy resources (wind, solar, hydro etc.) during normal operations produce enough energy to feed the load and excess is stored in the battery bank. In situations where the battery is fully charge and there is still excess energy from the renewable energy generators, the excess energy is dissipated as dump load. The stored energy is then used in period of sudden load increase or decrease in production from the renewable sources with weather and climatic variations (Al-Badi, 2011). To improve reliability and power supply in renewable energy systems, backup systems consisting of energy storing devices and conventional generators are usually used (Bhandari et al., 2014). The provision of information and communication among the various system components are achieved through the use of a central control system. The control system performs the following functions:

- Regulates energy sources output power and generate signals for storage and dump load scheduling.
- Protects storage system overcharging thereby helping them operate within the required level or limit.
- Sends excess power to the storage system for storage and when storage is fully charged, it sends power excess to dump load which is wasted and can be used for baking, cooking, water heating and so on. With power deficiency, the stored power is retrieved and used.

2.7.1 Some research studies on hybrid energy systems

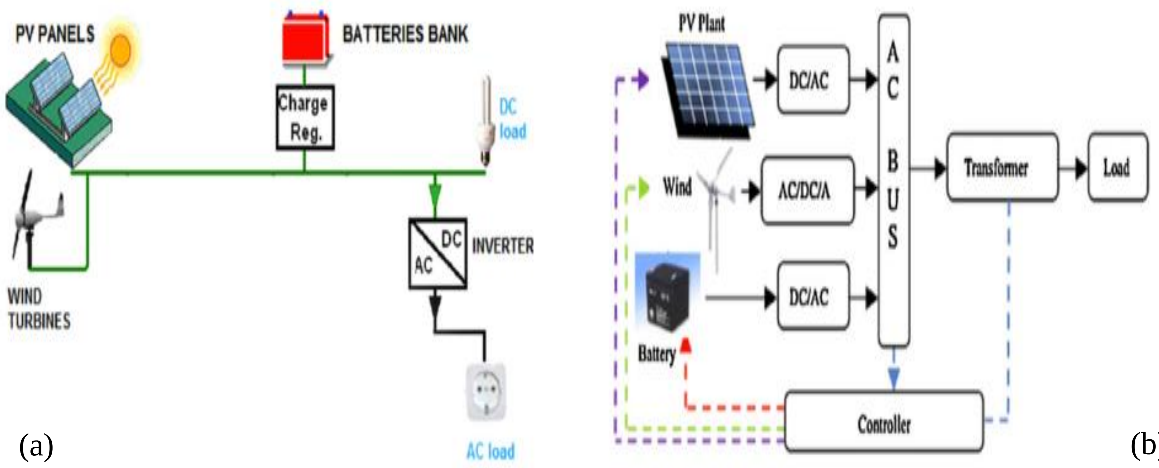
Over the past decades, a vast number of research has been conducted on hybrid power systems particularly for off-grid applications. These studies mainly focused on assessing the feasibilities, performance, technical and economic viabilities as well as the optimization and reliabilities of hybrid energy systems. These studies have revealed that hybrid power systems are more reliable and have lower energy generation cost than standalone systems (Adaramola et al., 2014b). Bekele and Palm, (2010) evaluated the feasibilities and economic viability of standalone hybrid solar/wind system for power supply in a remote community in Ethiopia using HOMER software. Agarwal et al., (2013) optimized an autonomous PV/diesel/battery system for use in the Indian remote villages of Uttar Pradesh using decision variables such as the total PV array area, the number of PV modules, number of battery, diesel generator and yearly fuel consumption. Their objective was on cost and CO_2 minimization for the system. Al-Badi, (2011) assesses the techno-economic feasibility of hybrid Wind/PV/diesel systems for the electrification of the AL Hallaniyat Island of Oman using HOMER and found out that PV/wind hybrids were techno-economically viable options for electrification of AL Hallaniyat Island. Asrari et al., (2012) studied the economic feasibilities of diesel based renewable energy system and grid connected renewable energy system for rural electrification in India. Bernal-Agustín and Dufo-López, (2009) reviewed various models and tool that has been developed and are currently used for the design, simulation and optimization of hybrid systems. Deshmukh and Deshmukh, (2008) reviewed and present various methodologies for modelling, design and evaluation of hybrid systems and components. In a study by Adaramola et al., (2014a) investigating the possibility of electricity generation with hybrid solar/diesel system for rural and semi-urban areas in Northern Nigeria using HOMER, they found out that PV/generator/Battery system was a more economical and suitable option compared to standalone systems for decentralised power generation in Northern Nigeria. Al-Karaghouli and Kazmerski, (2010) uses HOMER to analysed PV systems for a rural health clinic in Southern Iraq with the aim of estimating systems size and life cycle cost necessary to supply power to the clinic. They compared PV system (PV/diesel) with a standalone diesel generator system and concluded that in terms of economic, technical and social perspectives, the PV system was preferable. An economic analysis for the feasibility of solar/wind/diesel hybrid for applications in rural communities in southern Ghana using the LCOE and NPC constraints was done by Adaramola et al., (2014a) and found that this system was capable of meeting the area load demand with an LCOE of $0.281/kWh. Abdullah et al., (2010**)** investigated the performances solar/diesel/hydro/fuel cell hybrid energy for rural electrification of a Telecenter in the Kelabit highland of Sarawak, Malaysia taking into account sustainability factors such as weather, fuel cost, system efficiency, maintenance cost. They found the hybrid system to be more reliable and sustainable in electricity supply to the Telecenter than a standalone PV system.

2.8 Types of hybrid energy systems

There exist a variety of hybrid energy systems currently in existence globally but the solar hybrids are the most successful and prominent. Pure renewable energy hybrids (especially solar hybrids) are widely used and are observed to reduce fossil dependency. Conventional energy sources on the other hand (especially diesel systems) are found to be more reliable and cheaper in some settings and are often used in combination with solar in most cases (Akikur et al., 2013). Advances in technology over the past few decades have given high viability to renewable energy resources based hybrid systems in replacing diesel systems for energy provision in remote and isolated areas. However, more research and developments are still needed in order to boast this area.

2.8.1 Pure renewable based hybrid energy systems

Hybrid renewable energy systems consist mainly of a combination of two or more renewable energy resources with or without storage system depending on the application. These systems have found great applications in off-grid electrifications especially solar hybrids due to the great naturally abundant solar resource. Some of these systems are: solar/wind, solar/biogas, Solar/small hydro, Solar/wind/fuel cell, Solar/wind/small hydro etc. These systems functions with or without storage systems depending on the nature of application and load requirements. Figure 2.15a and 2.15b shows a schematic representation of a PV/wind/battery system.



(a) (b)

Figure 2.15: (a) Block diagram of PV/wind/battery system (Fadaeenejad et al., 2014), (b) with feedback control signals (Fadaee and Radzi, 2012)

The enhance the performance of PV-Wind-Battery system under various weather conditions, the wind turbine blade angle pitch control and MPPT of the Photovoltaic system need to be incorporated into the system (Fadaee and Radzi, 2012).

2.8.2 Fossil based hybrid renewable energy system

Diesel power systems are most commonly used for power generation in remote areas of developing countries as it is proven to be cost effective and reliable. However, the long-term effects (environmental and health) are numerous making it uneconomical for use. As a result, diesel systems are often used in combination with renewable energy system (solar, wind, biomass or hydro) to counteract it adverse effects especially emissions reductions. Despite the fact that the diesel system is matured and when properly operated are usually very reliable and robust, it noisyness, polluting effects and high maintenance cost are enormous. Thus, diesel systems in combination with renewables sources will counteract these challenges (Al-Badi, 2011). Some of these combinations are: PV/diesel, wind/diesel, PV/wind/diesel etc. with or without battery bank. A schematic overview of a hybrid PV/wind/diesel/battery systems is illustrated in figure 2.16.

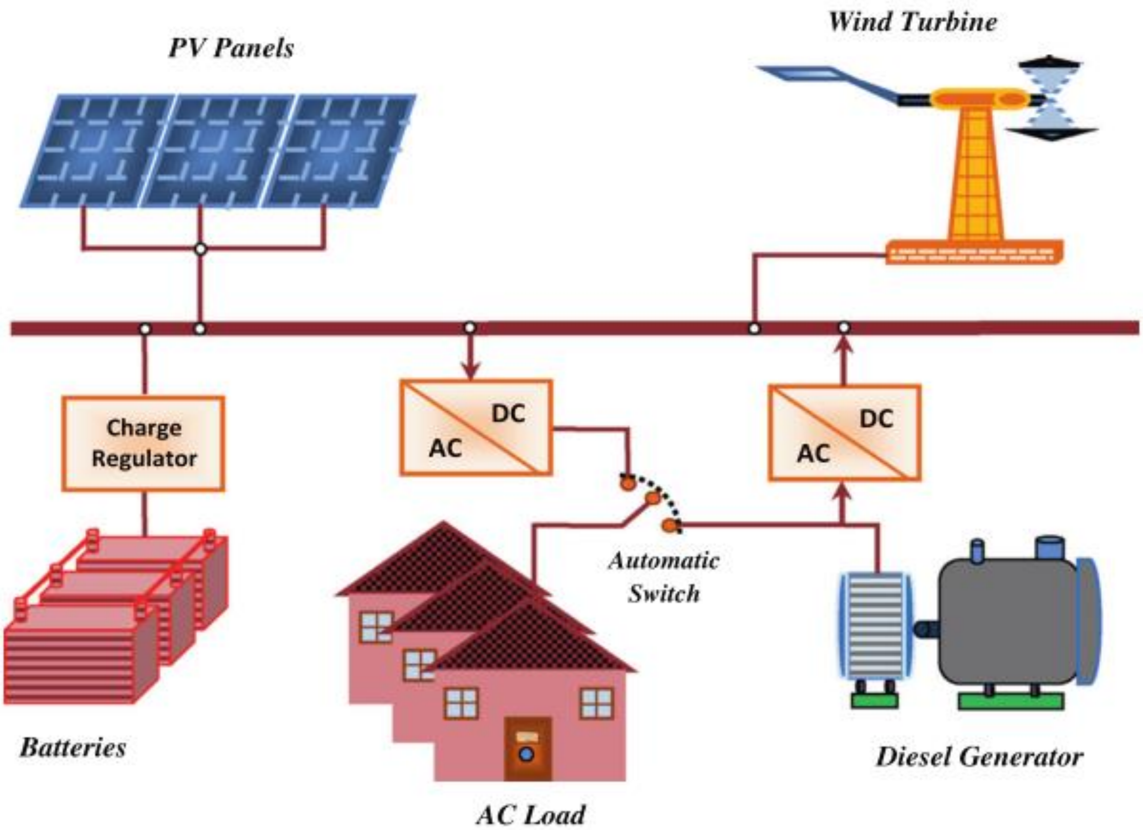


Figure 2.16: Block diagram of PV/wind/diesel with battery (Kaabeche and Ibtiouen, 2014)

2.9 Sizing methodologies for hybrid energy systems

Various sizing techniques are reported in literature and used by various researchers for the evaluation of hybrid energy systems. These techniques include: artificial intelligence (AI), genetic algorithms (GA), artificial neural networks (ANN), particle swarm optimization (PSO), biogeography based optimization (BBO), harmony search (HS), ant colony optimization (ACO), simulated annealing (SA), fuzzy logic (FL)), multi-objective design, Analytical approach (considers LPSP, NPV and LCOE for system reliability and cost modelling), iterative technique, probabilistic approach, graphical construction methods and computer tools (HOMER, HYBRID2, HOGA, TRNSYS etc.) (Chauhan and Saini, 2014). The merit and demerits of these methodologies are indicated in table 2.3.

Table 2.3: Merits and demerits of hybrid systems sizing methods (Chauhan and Saini, 2014)

Sizing methods	Merits	Demerits
Artificial Intelligence	Find the global optimum system configuration with relatively computational simplicity.	-
Multi objective design	Can optimize simultaneously at least two conflict objectives.	-
Iterative technique	Easy code	Increased computational efforts and sub optional solutions.
Probabilistic approach	Eliminate the need of time series data.	Cannot represent the dynamic changing performance of the system.
Graphic construction method	-	Only two parameters can be included in the optimization process.
HOMER	User friendly and suitable for prefeasibility, optimization and sensitivity analysis.	Cannot enable the user to intuitively select appropriate system components.
HOGA	Optimize single or multiple objective problem genetic algorithms, option for sensitivity analysis, require less time.	Sensitivity and probability analysis are not included. It can simulate within the daily load 10 of kWh.
HYBRIDS	Comprehensive in terms of optimization variables, and requires higher level knowledge of system configurations.	Only simulate one configuration at a time.
HYBRID2	User friendly, available of dispatch option, much electrical load option.	Require long term data for better performance and economic analysis of hybrid system. This tool has limited access to parameters and lack of flexibility.
TRNSYS	Flexible computer tool for simulating transient be behaviour of integrated system.	Cannot simulate nuclear, wave, tidal and hydropower.
RETscreen	Excel based tool, strong meteorological database.	No data input options, limited options for retrieval, search and visualization features.

2.9.1 Hybrid systems simulation and optimization tools/softwares

Over the past decades, a wide varieties of computer tools have been developed and used by research scientists to design, model, simulate and optimise hybrid systems (table 2.4). Among these tools, HOMER (Hybrid Optimization Model for Electrical Renewables) has been widely used in simulation and optimization (Bernal-Agustín and Dufo-López, 2009; Adaramola et al., 2014a). The United States National Renewable Energy Laboratory (HOMER developer) recommend HYBRID2 to be used in enhancing hybrid systems design and optimization after HOMER has been used to acquire the best optimum design (Bernal-Agustín and Dufo-López, 2009).

Table 2.4: Hybrid system simulation and optimization tools (Bernal-Agustín and Dufo-López, 2009)

	HOMER	HYBRID2	HOGA	HYDROGENS + TRNSYS	HYBRIDS	INSEL	ARES	RAPSIM	SOMES	SOLSIM
Free download and use	x	x	x							
PV, Diesel, Battery	x	x	x	x	x	x	x	x	x	x
Wind	x	x	x	x	x	x		x	x	x
Mini-Hydro	x	x	x	x						
Fuel cell, electrolyzer, hydrogen tank	x	x	x	x						
Hydrogen load	x	x	x	x						
Thermal load	x	x		x						
Control strategies	x	x	x							
Simulation	x	x	x	x	x	x	x	x	x	x
Economic optimization	x		x	x						
Multi-objective optimization, GA			x							

HYBRID2 was developed by Massachusetts University Renewable Energy Research Laboratory (RERL). With this tool, the hybrid system may consist of three loads, multiple and different wind turbines, PV generators, multiple diesel generators, battery and four different power conversion devices as well as fuel cells and electrolyzer. HYBRID2 defines time interval from 10 minutes to 1 hour, giving very precised simulation and very high control strategies (Bernal-Agustín and Dufo-López, 2009).

2.9.2 Hybrid system design

The design of hybrid energy systems is dependent on individual system component performances and the proper modelling of these components enables the better prediction and control of the hybrid system performance and supply reliability (Deshmukh and Deshmukh, 2008). Cost and reliability are two important factors that are usually strictly considered when designing hybrid energy systems for power production (Bernal-Agustín and Dufo-López, 2009). The cost of such energy systems often depends on the available resource's quality, quantity and the cost of components. The design and optimization of hybrid energy systems depends on resource availability, weather conditions and the energy demand to be met. This is often complex with a very high risk of failure (Akikur et al., 2013). Mathematical models are frequently used to describe, design or model the performance of the various hybrid system components.

2.9.3 HOMER software

HOMER is a powerful computer software modelling tool for simulating, designing and analysing standalone and grid-connected power systems containing many combinations of conventional generators, wind turbines, PV arrays, run-off river hydropower, biomass power plant, micro-turbines, hydrogen storage, batteries, combined heat and power, fuel cells, boilers, electrolysers, AC/DC bi-directional converters and others, to serve both thermal and electric loads (Asrari et al., 2012; Bekele and Tadesse, 2012). This tool simplifies and facilitates design options for grid connected and off-grid hybrid power systems for distributed generation applications. The optimization and sensitivity analysis of this model permit for the evaluation of the economic and technical feasibilities of large technological options as well as give account for the variations in energy resource availability and technology cost thereby allowing comparison of different hybrid options (Al-Karaghouli and Kazmerski, 2010). HOMER carry out three basic calculations in systems design and optimizations: simulation, optimization and sensitivity analysis. In simulation analysis, HOMER model hybrid system performances hourly to provide their technical feasibility and life cycle cost. This also gives a feasible system which satisfies the load requirement and other constraints applied to it. HOMER optimization searches for a system that satisfies the technical and economic constraints at the lowest life cycle cost, through the simulation of several different system configurations and displays the system configurations (Ghasemi et al., 2013).

After simulation and optimization, HOMER displays the possible output combinations of the hybrid system components in ascending order of the net present value, putting the most feasible system first. It also displays each system component performance, energy cost, energy surplus or shortage and sensitivities of input parameters (Bekele and Tadesse, 2012). With sensitivity analysis, HOMER performs several optimizations using a range on input data in order to investigate the effects of input changes or uncertainty on the system performances (Al-Badi, 2011; Adaramola et al., 2014a, Adaramola et al., 2014b). It should be noted that HOMER uses Graham algorithm to synthesise solar radiation values (monthly or yearly average) to yearly hourly values. This hourly data obtained here is realistic and easily used as only latitudes and monthly average radiation values required (Dursun, 2012).

2.9.3.1 HOMER input data

HOMER analysis requires input data such as energy resource data, load data, component types and specifications (size, cost, lifetime, maintenance and replacement cost, operation cost etc.), costs of installation, design flow rate, head of hydropower and economic constraints (interest and inflation rate), expected lifetime, efficiency levels and so on (Asrari et al., 2012; Bekele and Tadesse, 2012). A summary of the major inputs and output characteristic of HOMER are shown in figure 2.17.

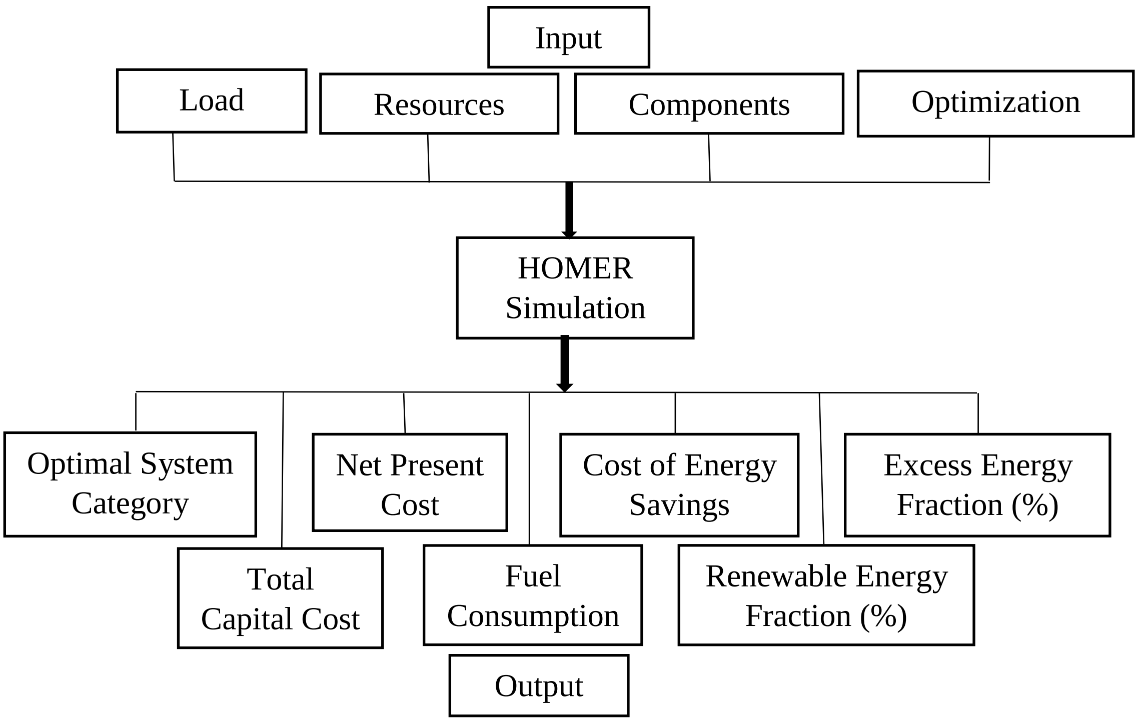


Figure 2.17: HOMER input and output characteristics (Erdinc and Uzunoglu, 2012)

2.10 Hybrid system coupled configurations

The integration of renewable energy sources is often done in according to specific standards as these energy sources vary in operational and energy output characteristics. Three coupling configurations are often used when integrating renewable energy sources. These include: AC coupled, DC coupled and hybrid coupled configurations (Chauhan and Saini, 2014).

2.10.1 DC coupled configuration

In this coupling configuration, all the renewable energy sources are connected to only one DC bus by means of a proper and highly efficient power electronic interfacing circuits (Chauhan and Saini, 2014). This is illustrated in figure 2.18.

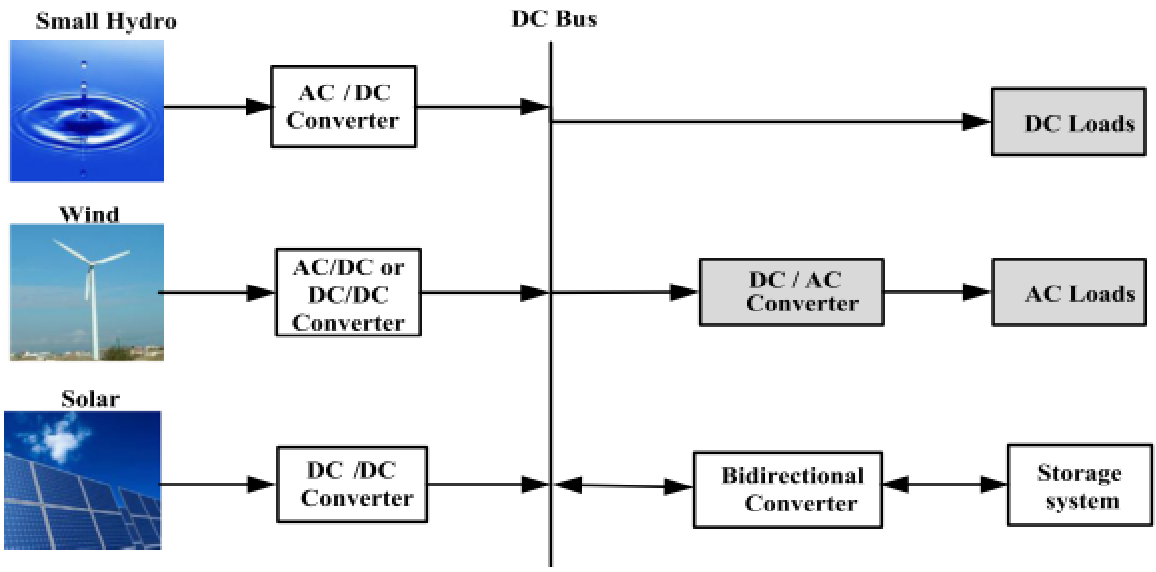


Figure 2.18: Schematic presentation of a DC coupled configuration (Chauhan and Saini, 2014)

The DC power sources are connected directly to the DC bus and the DC load served from the bus with the help of DC/DC inverters in order to keep the consumer (end user) DC voltage constant. In case of AC loads, DC/AC inverters are used to convert DC power from the DC bus to AC power for usage but in case of inverters failures, no AC power will be delivered. This configuration is simple as no synchronisation is required.

2.10.2 AC coupled configuration

This configuration is categorised into power frequency AC coupled (PFAC) and high frequency AC (HFAC) integration. Here, the renewable energy sources are connected to power frequency AC bus by means of a proper power electronic circuit. A schematic representation of PFAC coupled system is shown in figure 2.19.

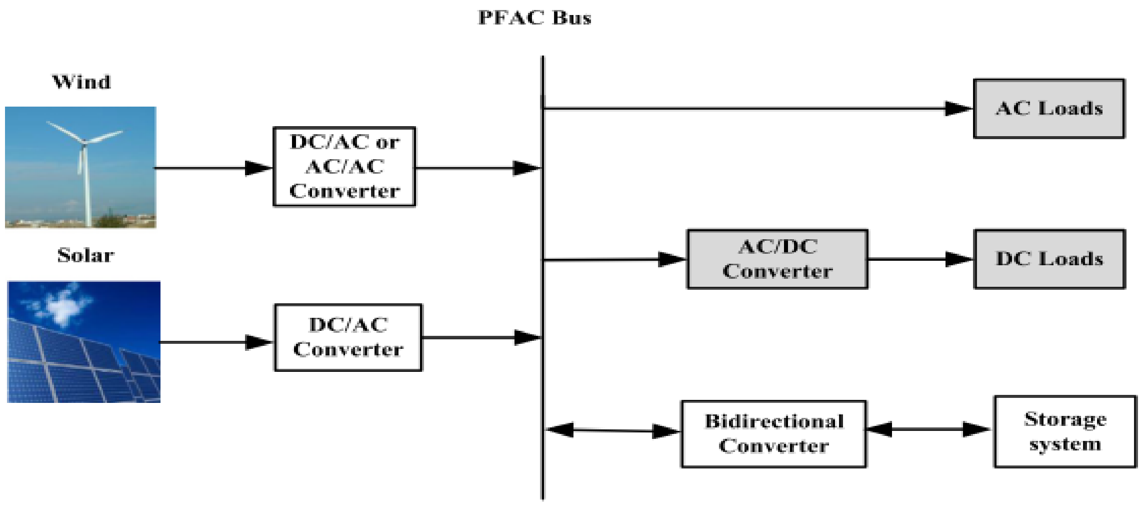


Figure 2.19: Schematic presentation of AC coupled configuration (Chauhan and Saini, 2014)

In this form of coupling, AC loads connect directly to the PFCA bus where DC connect via an AC/DC converter. A bidirectional converter links the storage system to the bus and similarly as with the DC coupling, no synchronization of system components is required here. Regarding the HFCA, the different energy sources are connected to a HFCA bus and such coupling is extensively used in high frequency loads such as sub marine, airplanes and space station applications (Chauhan and Saini, 2014).

2.10.3 Hybrid DC-AC coupled configuration

This configuration make use of both PFCA and DC bus to integrate all the energy sources whereby DC power source are coupled to DC bus, DC loads served from DC bus through a DC/DC converter using the right interfacing circuits. This is illustrated in figure 2.20 below.

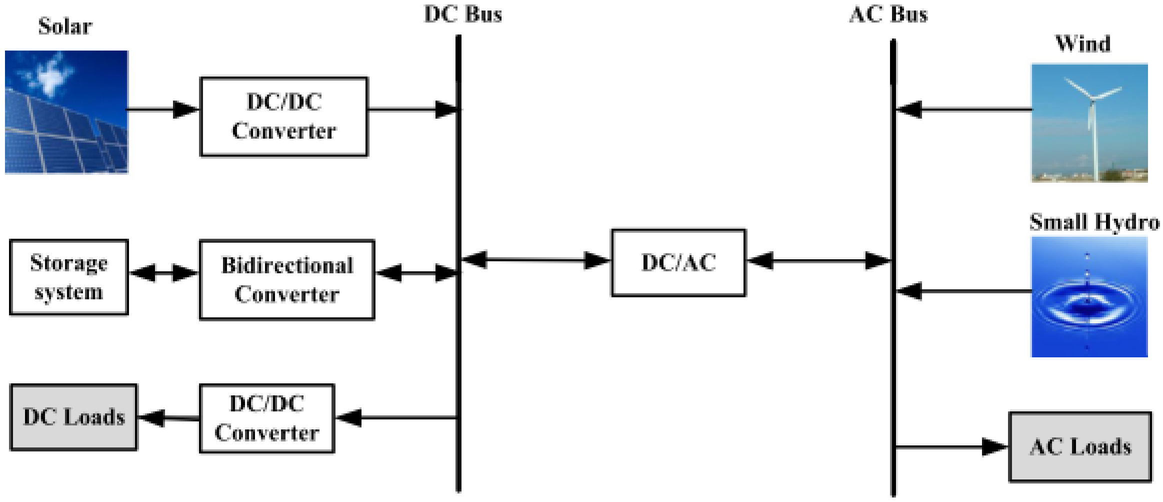


Figure 2.20: Representation of a Hybrid coupled configuration (Chauhan and Saini, 2014)

PFCA energy sources can be directly connected to the AC bus without the use of interfacing circuits and they served all AC loads. Such direct connections avoid inverters use and it associated conversion energy losses. This coupling configuration has high energy efficiency, reliability and reduced cost the DC or AC coupling but are however very complex in terms of energy management and control (Chauhan and Saini, 2014).

2.11 Criteria for optimal sizing of hybrid energy systems

Optimal system sizing ensures system operation with high reliability and at lowest cost. The evaluation of optimal hybrid system combination to meet the load is most often achieved in terms of power supply reliability and power supply economics (Kaabeche and Ibtiouen, 2014). With respect to economics, parameters such as the net present cost (NPC), levelized cost of energy (LCOE), annualised cost of system (ACS), payback period (PBP), internal rate of return (IRR) and so on are considered. System reliability (arising from intermittency of some renewable sources) evaluation enables the perfect understandings of the system ability to meet the required load demand over a given time period. Here, indicative parameters such as loss of power supply probability (LPSP), expected energy not supply (EENS), energy index ratio (EIR), level of autonomy (LA) are used (Chauhan and Saini, 2014). These evaluation indices according to Chauhan and Saini, (2014) are elaborated upon in the next section.

2.11.1 Economic Criteria

2.11.1.1 Levelised cost of energy (LCOE)

LCOE evaluates the system taking into account all recurring and non-recurring costs throughout the lifespan of the project. It is the ratio of the total annualised system cost (ACS) to the annual electricity production (E_{Total}) in kWh. Mathematically,

$$\mathrm{LCOE} = \frac{\mathrm{ACS}}{\mathrm{E_{Total}}} \quad \text{Equation 27}$$

2.11.1.2 Annualised system cost (ACS)

ACS is the sum of the annualised cost (capital, replacement and maintenance) of all the system components.

$$\mathrm{ACS} = \mathrm{Annualised(capital + replacement + maintenance)\ cost} \quad \text{Equation 28}$$

2.11.1.3 Net present cost (NPC)

It represents the system life cycle cost and consist of all incomes and outlay (cost) that occurs throughout the project life, including future cash flows discounted back to present. It takes into consideration the system initial capital cost, components replacement costs, maintenance and fuel cost, and components salvage (the net worth of the remaining system components after the system operation life) during the project life (Dalton et al., 2008; Chauhan and Saini, 2014). The NPC is opposite in sign to the net present value (NPV) of the system. NPC can be calculated as shown in equation 27 and 28.

$$\mathrm{NPC} = \frac{\mathrm{TAC}}{\mathrm{CRF}} \quad \text{Equation 29}$$

$$\mathrm{NPC} = \frac{\mathrm{TCO}(1+\mathrm{i})^{\mathrm{N}}}{1+\mathrm{ROI}} \quad \text{Equation 30}$$

Where,

TAC = total annualised cost (sum of annualised cost of all system components) and CRF = capital recovery factor given by:

$$\mathrm{CRF} = \frac{\mathrm{i}(1+\mathrm{i})^{\mathrm{N}}}{(1+\mathrm{i})^{\mathrm{N}}-1} \quad \text{Equation 31}$$

Where,

TCO = total capital outlay (sum of capital, replacement, operation and maintenance cost), i = annual inflation rate, N = project life (years), ROI = return on investment or the market discount rate (MDR).

The salvage value of the system (S) is computed as:

$$S(\$) = C_{rep} \frac{R_{rem}}{R_{comp}} \qquad \text{Equation 32}$$

Where,

C_{rep} = component replacement cost, R_{rem} = the remaining life of component (t) and R_{comp} = life time of component (t).

2.11.1.4 Internal rate of return (IRR)

The internal rate of return, also known as the return on investment (ROI) or time adjusted rate of return is the true interest yield of the system during the project life. This is evaluated by setting the project NPV value to zero and then compute the discount rate.

2.11.1.5 Payback period (PBP)

This is the time period during which the initial investment (cash outflow) of the system is expected to be recovered from the investment generated cash inflow.

$$\mathrm{PBP} = \frac{\text{Initial investment}}{\text{Cash flow per period}} \qquad \text{Equation 33}$$

2.11.2 System reliability analysis

2.11.2.1 Loss of power supply probability (LPSP)

LPSP refers to the fraction of the system energy deficiency that is required by the load or the probability that there will be insufficient power supply when the system will be unable to meet the required load demand.

$$\mathrm{LPSP} = \frac{\sum_{t=1}^{T} \mathrm{LPS}(t)}{\sum_{t=1}^{T} P_{Load}\, \Delta t} \qquad \text{Equation 34}$$

Where,

LPS(t) = loss of power supply at t hour, $P_{Load}(t)$ = Load demand at t hour.

For hybrid solar/wind/battery system, LPS(t) is computed as in equation 37.

$$\mathrm{LPS}(t) = (P_{Load}(t) - P_{Wind}(t))x\Delta t - (P_{PV}(t)x\Delta t + SOC(t-1) - SOC_{min})x\eta_{INV} \qquad 35$$

Where,

$P_{Wind}(t)$ = wind power output, $P_{PV}(t)$ = PV array output, SOC(t-1) = battery previous state of charge, SOC_{min} = minimum state of charge and η_{INV} = inverter efficiency.

2.11.2.2 Expected energy not supplied (EEN)

This is the expected energy not supplied to the load during conditions when load demand exceeds generation. EEN is evaluated in kWh and is given by:

$$\mathrm{EENS} = \sum_{k=1}^{8760} \mathrm{LxD} \qquad \text{Equation 36}$$

Where

L = average annual load demand (kW), D = duration (h) when load is not meet.

2.11.2.3 Level of Autonomy (LA)

This refers to the time fraction during which the required load can be effectively meet and depends on the number of hours of load loss (H_{LOL}) and the number of operation hours (H_{Total}).

$$\mathrm{LA} = 1 - \frac{H_{LOL}}{H_{Total}} \qquad \text{Equation 37}$$

2.11.2.4 Renewable energy fraction

This refers to the fraction of the total annual energy production of the systems that comes from the renewable energy sources and is calculated by dividing the amount of annual renewable power production by the total annual energy production (Dalton et al., 2008; Dekker et al., 2012). The higher the renewable energy fraction, the better and reliable the system.

2.12 Hybrid system control strategies

The control strategy for hybrid systems with only battery and without diesel generators are often very simple. Excess power from the system charges the battery and when the load exceeds the renewable energy supply, the battery discharges to supply the load with the deficiency from the system. In systems with battery storage and diesel generator together, control becomes very complex. Here, it is apparently very important to determine the charging mode of the battery and to decide which component (battery or generator) will be prioritised in load supply when there is insufficient power supply from the renewable sources or there is increase in power demand (Bernal-Agustín and Dufo-López, 2009). According to Bernal-Agustín and Dufo-López (2009), Barley and colleagues proposed three basic control strategies for systems with diesel and battery using a PV/diesel/battery system. They considered an hour interval for constant system parameters, ideal batteries without considering losses or the influence of the life span cycles. These strategies were:

- Zero-charging (Load Following diesel). Here, diesel generators will never be used for battery charging, giving a Setpoint of the State of Discharge (SOC_Setpoint) of 0%.
- Full cycle-charge, where the batteries are charged to full capacity whenever the diesel generator is on, giving a SOC_Setpoint of 100%.
- Predictive control, where battery charging depends on demand prediction and renewable power generation expectations. Here, renewable energy losses tend to decrease.

With theses, Barley and colleagues proposed a Zero-charge and Full cycle-charge strategy whereby the optimal SOC_Setpoint was to be between 0 and 100% in order to reduce the total operation cost of the system. This approach was improved by Barley and Winn in 1996 with the inclusion of new parameters and are now control strategies of tool such as HOMER, HOGA and HYBRID2. In this case, four control strategies were proposed

- Frugal dispatch, whereby in situations where the net demand is higher than L_d, the diesel generator and if lower, the batteries are used. Critical dispatch power (L_d) refers to the value at as from which the net energy is more profitable when supplied by the diesel system than when supplied by the battery that have previously been charged by the diesel system. The net energy refers to the difference between the charging energy demand and the energy supplied by renewable sources.
- Load Following: the diesel system never charges the battery.
- SOC_Setpoint: the diesel generator is under full operation for batteries charging until full SOC_Setpoint is reached.
- Operation strategy: the diesel system operates at a minimum time at maximum power to charge the batteries.

2.13 Hybrid system energy management strategy

Energy management in hybrid systems are usually done as follows (Kaabeche and Ibtiouen, 2014):

- When the hybrid system power generation exceeds the load requirement, the excess power is stored in the battery and the charging state of the battery at that hour is computed.
- When the load requirement exceeds the system power generation, the energy stored in battery is used to meet the excess load and the battery new state of charge (discharge) is computed.

In systems with diesel generators, when the battery state of charge decreases to minimum (E_{Bmin}), the generator is turns on and operates at rated power. In this case, part of the energy from diesel generator is used to meet the excess load demand (equation 38) and the remainder (equation 39) used to charge the battery.

$$E_{gen}(t) = E_L(t) - [E_{gen}(t) + E_B(t-1) - E_{Bmin}]\eta_{Inv} \qquad \text{Equation 38}$$

$$E_B(t) = E_{Bmin} + \left(E_{rated,\ gen.} - E_{gen}(t)\right)\eta_B.\eta_{Conv} \qquad \text{Equqtion 39}$$

Where: $E_{gen,\ rated}$ is the rated diesel generator capacity and η_{Conv} is the converter efficiency.

3 CHAPTER THREE: RESEARCH METHODOLOGY AND DATA COLLECTION

3.1 Study area

Cameroon is a central African country located at the Gulf of Guinea, bordered to the west by Nigeria, north by Chad, east by Central African Republic and to the south by Gabon, Congo and Equatorial Guinea. The climate of Cameroon varies within the terrain from semi-arid and hot in the north to tropical in the coast. The terrain is diverse and varies from plains in the north, to mountains in the west, coastal plains in the southwest and to dissected plateau in the Center (CIA, 2017). Various weather and environmental conditions (mean air temperature, mean relative humidity, mean rainfall, mean dew point etc.) varies within the country with some area with very high values and some with extremely low values. The choice of Cameroon for this study is due to the low deployment of renewable energies in the country (except large hydro) and the use of mostly conventional grid extensions and diesel generations for rural electrification in the country. This study involves the entire country, divided into three geographical zones (fig. 3.1): North consisting of the Adamawa, North and Far North regions; Centre-South consisting of the centre, South, Littoral, West and East regions and West, consisting of the North West and South West regions of Cameroon. The load assessment was conducted in Bambalang, a remote village in the North-West region of Cameroon (West zone of the study area). With respect to the choice of site for load assessment and approximations, very few research studies so far are reported in literature concerning renewables in West zone. The regions have the least electricity access in the country, power is very unreliable even in urban centres. There is no power generation facility in these regions and power is mainly supplied from French Cameroon (Center – South zone). Power outages are very frequent and often last for days or even weeks and the people here are used to such conditions. They mainly rely on candles, kerosene lamps and firewood or charcoal for lighting as electricity is unreliable. This is a major hindrance to learning and business activities in this part of the country.

3.1.1 Climate and surface meteorology

The climate of Cameroon is tropical with a humid south and a dry north. The coastal plains are hot and humid with a short dry season and covers over 150 km from the Gulf of Guinea. The southern plateau unlike the coastal plains has a less humid climate and is mainly covered by the equatorial rainforest. The country has an average annual rainfall of 4,060 mm along the coast, 3000 mm in the semi-arid northwest and up to 8000 mm on the slopes of Mount Cameroon. The average temperature in the north is 32°C, 25°C in the south and 21°C in the Plateau; with the dry season in the north covering the months of October to April. The mean annual sunshine hours in the country is 3000 hours with a mean solar irradiation intensity of 240 W/m^2 and the solar irradiance varies with the terrain with the highest value in the north and least in the south (Ngnikam et al., 2009; Tansi, 2011). In general, Cameroon represents all the major geographical, vegetation and climatic characteristics of Africa (coastal, mountains, deserts, savannah and rainforest regions) and is most oftenly referred to as "Africa in miniature".

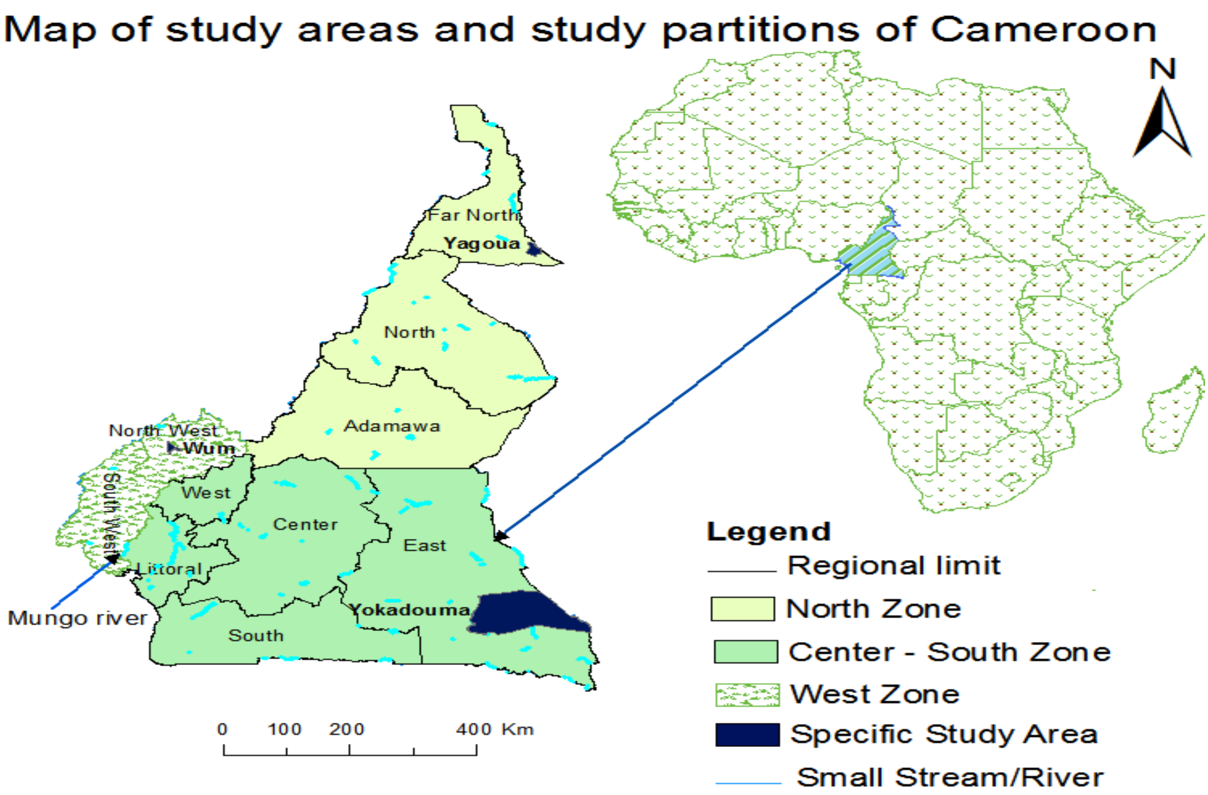


Figure 3.1: Location map of study areas

3.2 Data collection and methods

3.2.1 Resource assessment

Renewables energy resource assessment was done through detailed literature search and review of relevant and recent research works in the Cameroon, Africa and in the world. Mostly, research journal articles and publications were used. Also, government, NGO and Inter-Governmental Organisation websites, international organisations (IEA, IRENA, World Bank, CIA etc.) publications and reports were consulted for this assessment.

3.2.2 Technology selection

Based on the resource assessment and renewable energy resource availability in the different study geographic zones of Cameroon, the following hybrid Systems are selected for simulation and comparison of performances in the different zones. These systems are: PV/wind/battery, PV/wind/diesel/battery, PV/diesel/battery, Wind/diesel/battery, PV/diesel/small hydro/battery, PV/wind/small hydro/battery, PV/wind/small hydro, Wind/diesel/small hydro/battery. After simulation and optimization, these systems will be ranked according to their performances in each zone.

3.2.3 Electrical load estimation

The electrical load requirement of the village was done through field survey of household energy consumption patterns in the village and by approximation using typical remote village appliance (energy efficient appliances), typical village energy usage durations and the average household size for the community. It was assumed that all the village households are of the same size and household consumption and durations are the same. Field survey demonstrated that the household size varies from three family members (medium) to seven members and the house size varies from three rooms and a living room to four rooms and a living room. In this study, an average family size of five members and house size of four rooms and a living room is chosen and taken to be same for all village households. Also, a total of 500 households (2500 persons) is considered. The load for a single household was calculated and the total village load obtained by multiplying it to the total number of households. Businesses, hospital and community consumptions were also computed and added. The village electrical load is divided into the following categories: domestic (household) load (lighting, radio, TV, etc.); commercial load (flour mills, small businesses) and community load (nursery and primary school lighting, computers, printers, photocopiers, health clinic load: microscope, vaccine refrigerator, computer, printer, radio, TV, photocopier). Community load are of two types; primary and deferral loads. Primary loads are those that must be meet immediately (lighting, cooking, radio, etc.) whereas deferral loads can be meet within a given time period (water pump, etc.), the exact timing not very important. In this study, field survey also revealed that the village will not need any deferral load, maybe in the future for community water pumping.

3.2.3.1 Village load description

The village electrical load is divided into the following categories: domestic (household) loads, commercial and community loads. Village field survey showed that the village has one nursery school, 2 primary school, one secondary school, one hospital clinic, approximately 500 households, about 50 small businesses and 5 electric community flour mills. The Nursery school has two classrooms and one office. Each classroom is intended to have 4 bulbs and the office 2 bulbs. There is one 1kW electric heater for tea making in the morning, an office radio and one external bulb. Each primary school have 6 classrooms and one office. Each classroom for proper lighting is intended to installed with 4 internal bulbs. The office has one internal and external bulb and a radio. The Secondary school has 5 classrooms with 3 offices, each classroom requiring 4 bulbs. The offices have three 60 W desktop, one central printer and photocopier. The community health clinic has 5 wards and 2 offices; 8 bulbs per ward, a bulb per office, 5 external bulbs, an 80 W vaccine refrigerator (24-hours/day), two 20 W microscope working daily except on Sundays, one 5 W radio and a 1 kW water heater. The bulbs in the wards work from 6:00 pm – 12:00 pm; 4:00 am – 6:00 am daily and the wards make use of sunlight lighting during the day except on emergency cases. The Community flour mills (1 kW mill) work from 5:00 pm – 6:00 pm daily. Each household home size consists of 4 rooms, a living room, and an external kitchen, each containing one bulb and one external bulb, one 5W radio and a 60 W TV. The Small businesses all intend to have one internal bulb, one external bulb and a 5W radio. On weekends, the health clinic is working. All external bulbs at the offices in schools operate. Also, the Mills are working, household TV and radio have increased operation time. All the bulbs used are 9W compact fluorescent lamps or LED, photocopier 75 W and printer 60 W. A detailed description of the operation time of all the above appliances are appliances are found in appendix 1 and 2.

3.2.3.2 Village load calculation

Based on the above description of the energy use patterns and nature of appliances in the village, the village daily primary load is estimated to be approximately 100 kWh/d (35.17 kWh peak). Detailed of this load estimation is shown in appendix 1. The load was calculated by multiplying the power rating (W) of each appliance by the total number of appliance used daily and the result multiplied by the number of daily usage hours (h) of each of the appliances. Then, the power consumption of each individual appliances was then summed up to get the overall power consumption or load. The village hourly daily load profile is illustrated in figure 3.2.

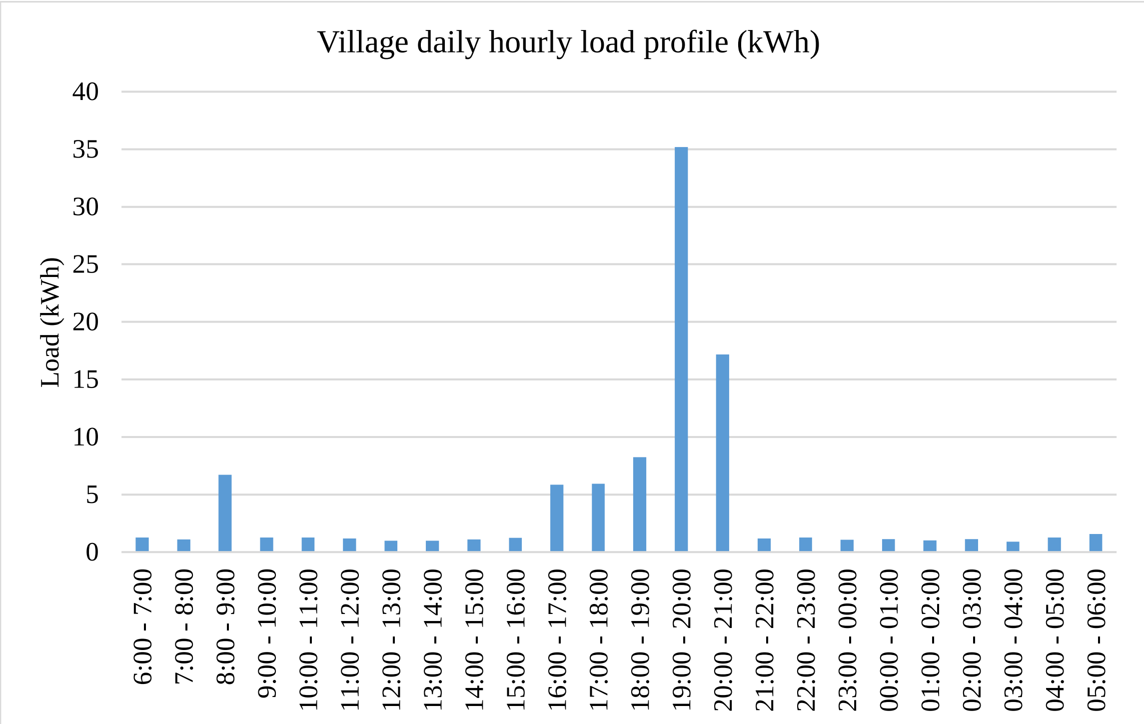


Figure 3.2: Village daily load profile

3.2.4 Solar radiation data of study zones

The mean monthly global horizontal ground Solar radiation data (table 3.1) of five representative (meteorological station) sites in the three study zones of Cameroon (North: Garoua Boulai, Ngounderé, Poli, Mokolo and Yagoua; Center – South:

Abong Bang, Batouri, Edéa, Kribi and Yokadouma; West; Akom, Bamenda, Fontem and Wum), was obtained from NASA Surface Meteorology and Solar Energy website (NASA Surface Meteorology and Solar Energy, 2017). This website provides mean monthly solar radiation data of the sites over a period of 22 years (1983-2005). To obtain these data, the exact location of the site in terms of latitude and longitude is required and this was obtained from RetScreen’s Cameroon meteorological stations. The above sites are chosen based on the level of radiation data (high) and their remoteness as the target population in this study are the rural populations. Climate and environmental weather conditions at the sites (temperature, relative humidity and clearness index) and all other weather stations in Cameroon were also obtained from the site and are show in appendix 2.

Table 3.1: Global horizontal solar radiation data of study zones representative sites.

Global mean monthly horizontal ground radiation of study areas (kWh/m2/day)													
North Zone													
Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Mean**
Garoua Boulai (5.9ºN, 14.6ºE)	6.34	6.42	5.89	5.5	5.07	4.68	4.38	4.5	4.78	4.8	5.58	6.06	**5.32**
Ngounderé (7.3ºN,13.6ºE)	6.48	6.74	6.53	5.83	5.42	5.01	4.67	4.66	4.84	5.25	6.16	6.27	**5.64**
Poli (8.5ºN,13.2ºE)	6.28	6.54	6.51	6.1	5.65	5.3	4.88	4.78	5.09	5.66	6.21	6	**5.74**
Mokolo (10.8ºN, 13.3ºE)	5.94	6.36	6.55	6.24	5.87	5.42	4.98	4.75	5.23	5.71	6.09	5.82	**5.74**
Yagoua (10.4ºN,115.2ºE)	5.76	6.3	6.62	6.33	6.03	5.58	5.04	4.87	5.35	5.79	5.91	5.65	**5.76**
Center – South Zone													
Abong Bang (4.0ºN, 13.2ºE)	5.86	6.01	5.6	5.29	4.83	4.36	4.2	4.34	4.62	4.56	5.04	5.54	**5.01**
Batouri (4.4ºN, 14.4ºE)	6.03	6.1	5.65	5.45	4.93	4.53	4.24	4.33	4.66	4.66	5.15	5.72	**5.11**
Edéa (3.8ºN, 10.1ºE)	5.31	5.36	5.07	4.88	4.58	4.01	3.53	3.35	3.69	3.86	4.46	5.04	**4.42**
Kribi (2.9ºN, 9.9ºE)	5.41	5.57	5.2	4.92	4.51	3.9	3.94	3.98	3.82	3.82	4.7	5.11	**4.56**
Yokadouma (3.5ºN, 5.1ºE)	5.87	5.86	5.51	5.32	4.9	4.5	4.34	4.25	4.56	4.54	4.92	5.59	**5**

West Zone													
Akom (2.8ºN, 10.6ºE)	5.12	5.13	4.92	4.65	4.34	4	3.91	3.71	3.77	3.71	4.13	4.78	**4.34**
Bamenda (6.0ºN, 10.2ºE)	6.3	6.35	5.83	5.34	5.07	4.62	4.29	4.26	4.48	4.74	5.65	6.08	**5.24**
Fontem (5.5ºN, 9.9ºE)	5.81	5.77	5.35	4.99	4.68	4.32	3.86	3.58	4.09	4.32	4.88	5.48	**4.75**
Wum (6.4ºN, 10.1ºE)	6.3	6.35	5.83	5.34	5.07	4.62	4.29	4.26	4.48	4.74	5.65	6.08	**5.24**

The average monthly clearness index (the fraction of solar radiation at the top of the atmosphere that reaches a particular location on the earth surface, provides useful information on the amount of solar radiation reaching the earth surface as well as atmospheric condition changes (Adaramola et al., 2014a; Adaramola et al., 2014b). It varies between June to August (rainy season) where it has relatively low values, to peak between October to February (dry season) with relatively high values. The various weather conditions on basis of the clearness index (K_T) are as follows: heavily overcast weather ($K_T \leq 0.4$), partly overcast weather ($0.4 \leq K_T \leq 0.6$) and clear weather $K_T \geq 0.7$). The diffuse components of global solar radiation increases with increase in global radiation but decreases with the clearing of the partly cloudy weather conditions in partly overcast weather conditions (Adaramola et al., 2014b).

3.2.5 Wind speed data of study zones.

The wind speed data at 10 m above ground level (table 3.2) of five representative (meteorological station) sites in the three designated study zones of Cameroon was obtained from NASA Surface Meteorology and Solar Energy website (NASA Surface Meteorology and Solar Energy, 2017). This website provides 10 years mean monthly wind speed data (1983-1993) of the sites. To obtain these data, the exact location of the site in terms of latitude and longitude is required and this location coordinates was obtained from RETScreen meteorological stations. The above sites are chosen based on the level of wind speed (high) and their remoteness as the target population in this study are the rural populations.

Table 3.2: wind speed data at 10 m of study zones representative sites.

Wind Speed (m/s) at 10m above ground level													
North													
Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Mean**
Garoua Boulai (5.9ºN, 14.6ºE)	2.84	3.01	3.1	3.18	3.02	2.75	2.6	2.58	2.39	2.45	2.57	2.77	**2.77**
Ngounderé (7.3ºN,13.6ºE)	3.41	3.44	3.73	3.87	3.63	3.14	2.9	2.81	2.62	2.83	3.17	3.52	**3.25**
Poli (8.5ºN,13.2ºE)	3.62	3.59	3.93	4.05	3.74	3.17	2.92	2.8	2.63	2.89	3.33	3.74	**3.36**
Mokolo (10.8ºN, 13.3ºE)	4.01	3.93	4.32	4.47	4.08	3.41	3.17	3.02	2.8	3.14	3.67	4.16	**3.68**
Yagoua (10.4ºN,115.2oE)	4.21	4.13	4.53	4.68	4.26	3.56	3.29	3.13	2.89	3.27	3.86	4.4	**3.85**
Center - South													
Abong Bang (4.0ºN, 13.2ºE)	2.2	2.37	2.25	2.13	1.88	1.76	1.76	1.81	1.76	1.67	1.69	1.87	**1.92**
Batouri (4.4ºN, 14.4ºE)	2.29	2.48	2.37	2.24	1.95	1.8	1.76	1.78	1.74	1.64	1.7	1.91	**1.96**
Edéa (3.8ºN, 10.1ºE)	1.71	1.85	1.47	1.23	1.22	1.5	1.75	1.87	1.73	1.33	1.22	1.31	**1.51**
Kribi (2.9ºN, 9.9ºE)	1.8	1.99	1.51	1.31	1.45	1.9	2.33	2.46	2.25	1.71	1.47	1.49	**1.8**
Yokadouma (3.5ºN, 5.1ºE)	2.02	2.28	2.1	1.9	1.58	1.49	1.42	1.45	1.47	1.33	1.35	1.56	**1.65**
West													
Akom (2.8ºN, 10.6ºE)	1.62	1.81	1.35	1.14	1.21	1.49	1.79	1.94	1.8	1.36	1.22	1.26	**1.49**
Bamenda (6.0ºN, 10.2ºE)	2.5	2.53	2.58	2.46	2.4	2.33	2.14	2.17	2.04	1.95	2.16	2.33	**2.29**
Fontem (5.5ºN, 9.9ºE)	2	2.04	1.89	1.63	1.6	1.86	1.88	1.98	1.81	1.48	1.55	1.64	**1.78**
Wum (6.4ºN, 10.1ºE)	2.5	2.53	2.58	2.46	2.4	2.33	2.14	2.17	2.04	1.95	2.16	2.33	**2.29**

3.2.6 Solar, wind and other weather data at study zones representative sites.

From the solar and wind resource data presented above, three locations (one from each zone) are chosen as representative of these zones. These sites are: Yagoua in the North, Yokadouma in the Center – South and Wum in the West Zone. They are chosen based on their weather data profiles especially wind data as its very low in the country and also the level of development in these areas. The solar, wind and environmental data (relative humidity, temperature and clearness index) of these sites are shown in table 3.3. Based on the mean annual values of the clearness index of Yagoua, Yokadouma and Wum which are 0.58, 0.50 and 0.52 respectively, the weather conditions at Yagoua, Yokadouma and Wum are described as being partly overcast both monthly and annually.

Table 3.3: Weather data of study zones representative sites

Zones representative site solar, wind and other weather conditions													
North Zone (Yagoua: 10.4^{o}N, 15.2^{o}E, 311m)													
Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Mean**
Solar radiation (kWh/m^2/d)	5.76	6.3	6.62	6.33	6.03	5.58	5.04	4.87	5.35	5.79	5.91	5.65	**5.76**
Wind Speed (m/s)	4.21	4.13	4.53	4.68	4.26	3.56	3.29	3.13	2.89	3.27	3.86	4.4	**3.85**
Clearness Index (K)	0.65	0.65	0.64	0.6	0.57	0.54	0.48	0.46	0.52	0.59	0.65	0.65	**0.58**
Relative Humidity (%)	16.1	13.3	21.4	40.5	55.1	65.9	75.7	76.9	69.2	45	22.5	18.6	**43.5**
Air temperature (^{o}C)	27.2	29.1	32.2	31.9	29.9	27.6	25.5	25.1	26.2	28.8	29.6	27.8	**28.4**
Center - South Zone (Yokadouma: 3.5^{o}N, 15.1^{o}E, 562m)													
Solar radiation (kWh/m^2/d)	5.87	5.86	5.51	5.32	4.9	4.5	4.34	4.25	4.56	4.54	4.92	5.59	**5**
Wind Speed (m/s)	2.02	2.28	2.1	1.9	1.58	1.49	1.42	1.45	1.47	1.33	1.35	1.56	**1.65**
Clearness Index (K)	0.6	0.57	0.52	0.51	0.49	0.46	0.44	0.42	0.44	0.44	0.5	0.58	**0.5**
Relative Humidity (%)	52.3	56.3	69.4	72.1	70.8	67.6	61.8	67.9	74.7	74.9	71.6	60.2	**66.7**
Air temperature (^{o}C)	25.1	25.6	25.1	25	24.9	24.4	24.5	24.1	23.6	23.7	23.9	24.5	**24.5**
West Zone (Wum: 6.4^{o}N, 10.1^{o}E, 1101m)													
Solar radiation (kWh/m^2/d)	6.3	6.35	5.83	5.34	5.07	4.62	4.29	4.26	4.48	4.74	5.65	6.08	**5.24**
Wind Speed (m/s)	2.5	2.53	2.58	2.46	2.4	2.33	2.14	2.17	2.04	1.95	2.16	2.33	**2.29**

Clearness Index (K)	0.67	0.63	0.56	0.51	0.49	0.46	0.42	0.41	0.43	0.47	0.59	0.66	**0.52**
Relative Humidity (%)	34.5	39.5	64.7	78.6	81.1	83.6	84.5	84.2	84.9	81.6	69.4	44.1	**69.3**
Air temperature (ºC)	22.8	23.4	22.5	21.6	21.3	20.3	19.4	19.4	19.7	20.1	20.3	21.8	**21**

3.2.7 Flow rate of Mungo river

The flow of the Mungo river is selected to represent the flow of small hydro schemes in remote localities of Cameroon. The mean monthly flow rate of the Mungo river as shown in table 8 is taken from the study of Nfah et al. (2008).

Table 3.4: Mean monthly flow rate of river Mungo (Nfah et al., 2008)

Monthly mean flow rate of Mungo river (m^3/s)													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Flow rate	46	42	55	88	114	170	263	321	343	276	162	75	163

3.2.8 Diesel fuel price

The diesel fuel price in Cameroon according to the global market price is $0.95/l (575.00 CFA per litre) as of April 24, 2017 (GlobalPetrolPrice.com, 2017). However, due to taxes, regulations and minor state subsidies on petroleum products, local distributors (Total, Tradex, etc.) sell at 600 FCFA per litre ($0.99/l). In this study, the local diesel price of $0.99/l will be used. As Cameroon is a net exported and importer of petroleum products, diesel prices in the country is vulnerable to world price fluctuations. To investigate the effect of diesel price on hybrid energy system optimal performance and electricity cost, the local diesel price of $0.99/l will be varied from the range $0.50/l - $1.50/l, at an interval of $0.20. It should be noted that in rural areas and during periods of fuel scarcity, diesel fuel price is relatively higher than the above and prices of $1.00/l and above is likely to represent fuel price in rural areas with inclusion of transport and price during fuel scarcity. [$1.00 = 610.00 FCFA).

3.3 Hybrid systems components, characteristics and price estimations

The hybrid systems considered in this study will consist of the following components: PV module, wind turbine, micro-hydro turbine, diesel generator, battery, converters, charge controllers, an inverter, and a mini-grid transmission and distribution system.

The components of each system will be chosen based on the system composition and configuration. The cost information of solar PV module, wind turbine, micro-turbine, diesel generator, inverter and battery are obtained from local suppliers and where absent, the manufacturers and foreign retailers' prices will be used. A detailed specifications and price estimations of these components are as shown below. All the systems considered in this study will have different lifespan based on manufacturer's specification and the project life is taken as 25 years.

3.3.1 PV modules specifications

The PV modules will be installed on a fixed axis at an angle equivalent to the latitude of the site for maximum solar energy or radiation capturing and at a south facing orientation. There will be no tracking system for cost related constraints. The cost of a solar PV modules is dependent on factors such as the size of panel, type of technology (mono or polycrystalline), the brand manufacturer, the retailer and country in particular. The PV system will be the major contributor of the hybrid systems based on the resource potential of Cameroon and will be expected to meet a maximum load of 100 kWh/d. In this study, the CS6P-250P Canadian Solar 250 W polycrystalline PV module with 60 polycrystalline cells is selected. The detailed specification of this module and the I-V characteristics of the module at various insolation and temperature are shown in table 3.5 and figure 3.3 respectively (Canadian Solar, 2014). The life time of this module is 25 years.

Table 3.5: Technical specifications of CS6P-250P Canadian Solar module

PV module specifications	
Manufacturer	Canadian solar
Mechanical data	
Cell type	Polycrystalline
Cell arrangements	60 (6x10)
Dimensions (mm)	1638x982x40
Weight (kg)	18.5
Electrical data	
Nominal Max. Power at STC (P_{max})	250W
Optimum Operating Voltage (V_{mp})	30.1V
Optimum Operating Current (I_{mp})	8.30A

Open Circuit Voltage (V_{oc})	37.2V
Short Circuit Current (I_{sc})	8.87A
Module efficiency	15.54%
Operating Temperature	-40 °C~+85 °C
Maximum system voltage	600V/1000V
Max Fuse Rating	15A
Power Tolerance	0~+5%
Temperature Characteristics	
Temp. Coefficient (P_{max})	-0.43%/°C
Temp. Coefficient (V_{oc})	-0.34%/°C
Temp. Coefficient (I_{sc})	-0.065%/°C
Nominal Operating Cell Temperature	45±2°C

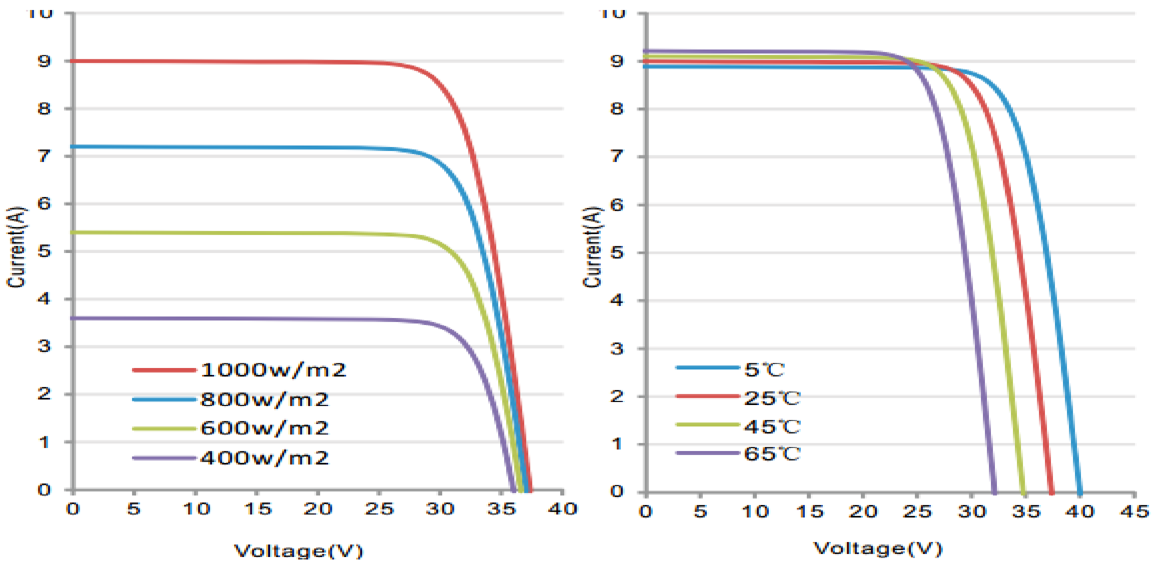


Figure 3.3: I-V characteristics of CS6P-250P Polycrystalline Canadian Solar module

The cost of this module in the Cameroonian market (Maguysama Technologies) as of June 12, 2017 is 168000.00 FCFA ($276.00) which is equivalent to $1.104/W. The installation cost of this module in Maguysama Technologies is 12500.00 FCFA ($20.00). This gives a total module cost of $296.00 ($1.18/W) and a replacement cost of $0.00, as the project life equals the lifespan of the modules. The PV derating factor to compensate for reduction in efficiency of PV modules arising from temperature increases, dust accumulation and wiring energy losses is taken to be 0.8 (PV derating factor typically ranges from 0.7-0.8 for high temperatures (Adaramola et al., 2014b). The ground reflectance (fraction of incident solar radiation on the ground that is reflected back to space) ranges from 20-70% (Adaramola et al., 2014b) depending on the ground nature at the location of study. In the study, ground reflectance is assumed to be the minimum (20%). This PV module will be mounted on a fixed axis oriented at an angle above the ground equivalent to the latitude at the site and facing south with an azimuth angle of zero.

3.3.2 Wind Turbine

The wind speed at 10 m in Cameroon as shown in table 10 ranges from around 1.42 – 4.4 m/s, lower than the cut-in speed of most wind turbines expect for some few areas in the Far North region of Cameroon. As such, low wind speed (cut-in speed) turbines is ideal for this study. Wind turbines are rare to find in the Cameroonian market due to the very limited wind potentials and applications in the country. As such, the Chinese Angel-500 model low wind speed turbine produced by Foshan OUYAD Electronics in Western China with a rated power of 500 W, low start wind speed of 1.5 – 2.0 m/s and a rated wind speed of 10m/s is chosen (https://ouyad.en.alibaba.com/). The turbine will be designed for a load range of between 70 – 80 kWh/d. More details of the technical specification of this turbine are shown in table 3.6.

Table 3.6: specification of Angel-500 low speed wind turbine

Property	Specification
Brand name/model no.	OUYAD/Angel-500
Rated power (W)	500
Rated voltage (V)	24/12
Low start wind speed (m/s)	1.5 – 2.0
Start-up wind speed	2.0
Rated wind speed	10.0
Number of blade	3(5pcs)
Rotor diameter (m)	1.44
Security wind speed (m/s)	35

This turbine has a lifespan of 20 years but it will be replaced after 13 years for security and performance reasons. The capital cost is $308.00 ($0.77/W), installation cost 10% of capital cost ($30.80) and replacement cost $308.00 (same as capital cost). This gives a total capital cos of $338.80. The annual operation and maintenance cost is considered to be 10% of capital cost ($30.80). The hub of the turbine is taken as

10m above ground level, same as the height of wind speed are measurement.

3.3.3 Micro hydro turbine

The specification and all other relevant data for the micro-hydro turbine to be used here is taken from the study of Nfah et al. (2008b).They modelled different off-grid systems for remote areas of Cameroon using the flow rate of the Mungo river, an 18 kW cross-flow turbine at a head of 13 m and a design flow rate of 200l/s with a turbine-generator efficiency of 70%, giving an output power of 17.85 kW. Also, a 300 mm diameter and 18.5 m length steal pipe was used with an evaluated head loss of 2.82%. The effects of stream flow rate variations on the hybrid systems cost of energy will be evaluated using flow rate range from 190-210l/s at 5l/s interval. The capital cost of 18 kW micro-hydro turbine (turbine and generator), replacement cost, operation and maintenance cost and fixed system cost from this same study are given as $10,000, $5,000, $500/yr. and $8,800 respectively (1Euro = 1.1USD).

3.3.4 Diesel generator

The diesel generator system is usually used as a backup system, mostly in periods of low power output from other energy generators in the hybrid system so as to ensure system reliability and effectiveness in meeting full load demand. In some case, it is assumed to indirectly play the role of the battery as storage system. They are usually sized to meet peak load demand (Adaramola et al., 2014a, Adaramola et al., 2014b) and are mainly used when the other energy sources in the hybrid system fails to meet the required load demand (Al-Badi, 2011). In this study, a peak load of 66 kWh is observed. Diesel generator capacities in the Cameroonian market ranges from zero to 12 kV and higher capacities requires importation on command. The Kohler 10 kW/12.5 kVA, model number 10REOZDC generator (Kohler Power, 2014) is chosen for meeting the peak load and the excess power of 14 kW will be used for spinning and/or operational reserve to be stored in batteries for later use, in expectation of changes in system's electrical load. The efficiency and fuel consumption patterns of Kohler 10 kW diesel generator are shown in figure 3.4 a and b. From figure 23(a), the values of a (intercept) and b (slope) are given as 0.03 L/hr/kW and 0.0352 L/hr/kW respectively. Table 3.7 shows a detailed technical specification of this generator (Kohler Power, 2014). The price of a 10 kW/12.5 kVA diesel generator in Cameroon is approximately 2.5 million FCFA ($4,098.00), equivalent to $409.80/kW. The minimum installation cost, assumed 10% of the initial capital cost is given as $409.80. Thus, the total capital cost of the diesel generator(s) is $4,508.00. The operating and maintenance cost of this generator model is taken as $0.02/h, each generator assumed to have a lifetime of 25000 hr. The life time of this diesel generator will also be considered to be equivalent to that of the project and as such the replacement cost of the diesel generator will be zero dollars.

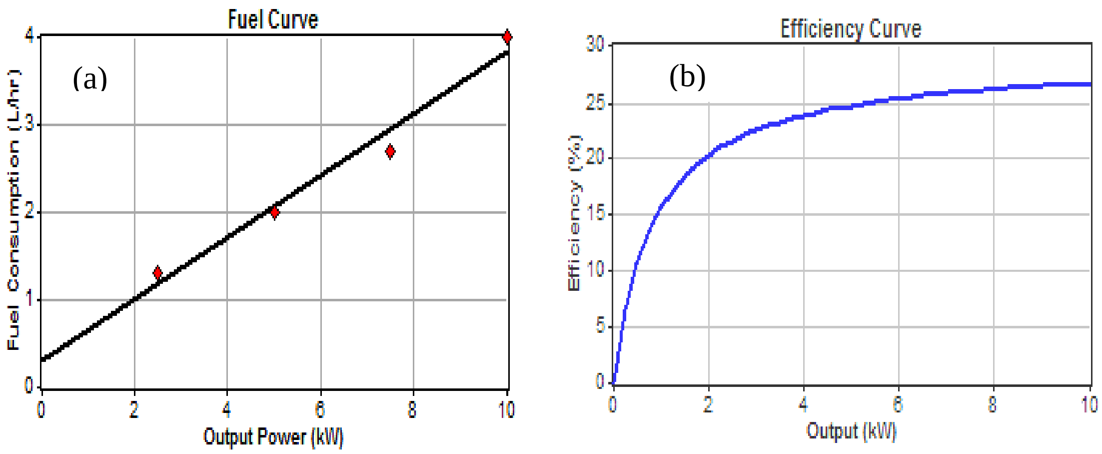


Figure 3.4: Fuel consumption curve (a) and efficiency (b) of Kohler 10 kW diesel generator

Table 3.7:Technical specification of 10REOZDC Kohler 10 kW diesel generator

Properties	Specifications
Standby max. Power	10 kW/12.5 kVA
Fuel consumption at 100%	4.0 l/hr, 1.1 g/h
Efficiency (Alternator)	0.82
Power factor	0.8
Frequency	60 Hz
Voltage	120/240 V
Phase	3

3.3.5 Battery

Generally, battery is used to store excess power from renewable energy systems necessary to meet power demand when the energy generators (PV, wind etc.) are not producing enough power. In this study, the 12V True Front Access C&D Technology battery TEL12–200TFA model Valve Regulated Lead Acid battery (VRLA) of 196Ah nominal capacity, at 1.80V End Point Voltage (EPV), 10 hours discharge rate (C10) at 25ºC, 10^{+} years lifetime, 90% efficiency is selected (C&D Technologies, 2012). The capital cost of this battery at Maguysama Technologies Cameroon is 196000.00 FCFA ($321.00) and replacement cost $321.00 and the operation and maintenance cost is taken as $10.0 yearly. The battery will be required to meet a peak load of 35.1 kWh at 60% depth of discharge when fully charged. It is assumed that changes in temperature will have no effect on the battery performance. Table 3.8 Shows the detailed technical specifications of this battery (C&D Technologies, 2012).

Table 3.8: Technical specification of TEL12-200TFA battery (C&D Technologies, 2012)

Properties	Specification
Nominal capacity at 10hr rate	196Ah,
Nominal voltage	12VDC
Efficiency	90%
lifespan	12
weight	60.2 kg
Dimensions	(559x125x310) mm

3.3.6 Inverter/converter

As hybrid energy systems consist of both AC and DC systems, and the load comprises mainly of AC appliances which cannot use directly the energy form (current) generated by the energy generator, an inverter or a converter is needed to convert the electrical current from DC to AC or AC to DC, that is compatible to the required energy form. In Africa for example, most energy appliances operate with AC. As such, DC current from systems such as PV needs to be converted into AC before it can be used to run various appliances. In hybrid systems, inverters maintain the flow of a single form of current into the load system by converting all current types from the different energy generators into a single current form that is required as output current. As a precaution, chosen inverters in any study should be capable of withstanding the maximum AC loads and the total capacity should be at least 10% higher than the nominal AC load requirement for the system (Agarwal et al., 2013). In this study, the PV inverter is required to meet a peak PV power of 20 kWp (100 kWh/d load, 48V PV system, 5 hours of daily sunshine) and a peak current of 417A. An Inverter capacity between 25 - 30 kW will be preferable here. The 5 kW Power Star W7 Inverter is selected (ENF Solar, 2017). Table 3.9 shows the technical specifications of this inverter.

Table 3.9: Technical specifications of 5 kW Power Star W7 inverter (ENF Solar, 2017)

Property	Specification
Rated power	5 kW
DC Input	
Battery Voltage	24/48V
Start Voltage (min)	10/12/20V for 24/40/48V
Max. charging current	70/35A
AC Output	
Voltage	230VAC
Phase/waveform	Single phase/sinewave
Frequency	50Hz ± 0.3Hz
Power factor	0.9 – 1.0
Efficiency - line/battery mode	95%/88%

The capital cost of inverters depends on the capacity, size and type (pure sinewave or modified sinewave). The capital and replacement cost of a 5 kW Power Star W7 Inverter in Cameroon is 60000.00 FCFA ($984.00), lifetime of 12 years (assumed) and a line efficiency 95%. The yearly maintenance cost of this inverter is taken as $10.00.

3.3.7 The Mini-grid system

Field survey in this village demonstrates that the village population is sparsely distributed and each group of close or dense settlement makes up a quarter. The village topography as well is not uniform with forest, hills and valleys as well as with tall trees. All these demonstrate that a single isolated mini-grid will not be suitable for the village. Instead the village load will be divided into clusters or groups, each group representing the load and profile of a quarter and different mini-grids will be design for the different load profile of each quarter. Thus, multiple mini-grid will be used. The capital cost of mini-grid systems depends on: the electricity distribution and voltage levels, the spatial distribution and the number of household within the area to be covered by the mini-grid system. In this study, the cost of the mini-grid systems will not be taken into consideration but is expected to be a low voltage mini-grid composed of mostly local and indigenous materials as components to minimize the cost.

3.4 Hybrid System simulation operational reserve and capacity shortage fraction

HOMER simulation ensures the system operating capacity is sufficient to supply both the primary load and operational reserve (load necessary to maintain system operation during any sudden increase/decrease in load demand). In this study, the operating reserve will be necessary to meet the load demand arising from changes in the system peak electrical load and from changes in parameters such as water flow rate, solar radiation, wind speed, diesel fuel price fluctuations etc. This reserve will be taken as 10% of hourly load as recommended by Adaramola et al. (2014a) and other researchers. In case the simulation is unable to produce sufficient power to meet both the load and operating reserve, HOMER will indicate a capacity shortage as a shortfall in production. The range of acceptable shortfall reported by Adaramola et al. (2014a) is 0.5-5.0% and in this study, a maximum annual allowable shortfall of 2% will be taken. Summarily, capacity shortfall fraction refers to the fraction of total load plus the operational reserves that the system fails to supply whereas the operational reserve (spinning reserve) is the additional reserve capacity that the system requires in order to account for sudden increase in electrical load demand or decrease in the renewable power output of the system (Dalton et al., 2008).

3.5 Economic input parameters and other simulation constraints

The life span of this project or hybrid system is taken as 25 years. The interest (Commercial bank rate) and inflation rates in Cameroon are 12.5% (December, 2016) and 2.4% (2016) respectively (CIA, 2017) and the computed annual real interest rate from Fisher expression 9.5%. The inflation rate will be taken as 3% instead of the indicated 2.4% in 2016. The effect of interest rate on the energy output and cost will be investigated with a ±5% variation of interest rate about the nominal interest rate at ±1% interval. Based on the above input economic data (system component cost, discount or interest rate, project life span), HOMER optimization ranks the different system configurations based on the lowest net present cost value and the Levelised cost of energy. Revenue from this mini-grid system will involve electricity sells to households and cost related to salvage value at the end of the project.

Table 3.10: Summary of HOMER input parameters

	PV	Wind turbine	Micro hydro turbine	Diesel generator	Battery (Ah)	Inverter
Capacity kW	0.320	0.5	18	100	1150	20
Capital cost ($)	266	338	11000	17930	635	3079
Replacement cost ($)	265	308	5500	17930	635	3079
O § M cost ($/yr)	10	30.8	1100	0.02/hr	15	100
Lifetime (yr)	25	15	25	25000hr	12	12

3.6 Hybrid system optimization procedure

The objective functions (decision functions) and constraints balancing is used to proper explain hybrid system optimization. The objective functions (economic and reliability indices: LCOE, NPC, ACS, PBP, LPSP, EENS, LA, Renewable fraction) discussed from equation 24-34 are used. The system investment cost, operation and maintenance costs, replacement costs, unmet energy demand cost with the exclusion of salvage make up the objective function (Hosseinalizadeh et al., 2016) and primarily, the optimum system will be chosen based on minimum cost (LCOE and NPV) with supporting contributions from other decision parameters. The system component specifications as described in section 3.3 to 3.5 will be used in the simulation. Various sensitivity variables are used to better refine the best system.

4 CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This chapter summarizes the simulation results obtained with Homer software for all the nine hybrid systems (scenarios) at Wum, Yokadouma and Yagoua, representing the West, Center-South and North study zones. The implementation priorities of the systems at each site based on economics and sustainability are given and we conclude with a performance and resilience analysis for the best economic and sustainable system in Wum.

4.2 Presentation of the results of environmental factors affecting the systems

Various environmental factors or conditions affected the performances of energy and hybrid system. These factors are: solar radiation, wind speed, clearness index, air temperature, humidity, dust etc. In this section, we look at the trends and impacts of these weather conditions across the country and especially at the study sites.

4.2.1 Variations in solar radiation and wind speed in Cameroon

Solar radiations and wind speed varies throughout the country. Consequently, the monthly energy output from solar and wind differs from one location to the other. The mean annual global solar radiation varies from 4.27 kWh/m^2/day in Douala to 5.81 kWh/m^2/day in Mora and mean annual wind speed varies from 1.37 m/s in Akonolinga to 3.9 m/s in Mora (fig. 4.1). The global solar radiation data are relatively low between the months of June-September (peak rainy season) compared to the months of October-February (typical dry season period). These periods are characterised by overcast and heavy cloud cover. Also, as fig. 4.1 indicates, the wind potential of Cameroon as reported in literature are relatively low and hence are not recommended for large scale utilization. Only the northern part of the country has relatively high wind speed (3.9 m/s in Mora) at 10 m above ground level but are still very far below the cut-in speed of most turbines (3.5-4.5 m/s). Thus, only turbines with relatively very low cut-in speed are recommended for use in Cameroon. From these curves and trends, the best recommended place for solar and wind energy installations in Cameroon is Mora in the north of the country.

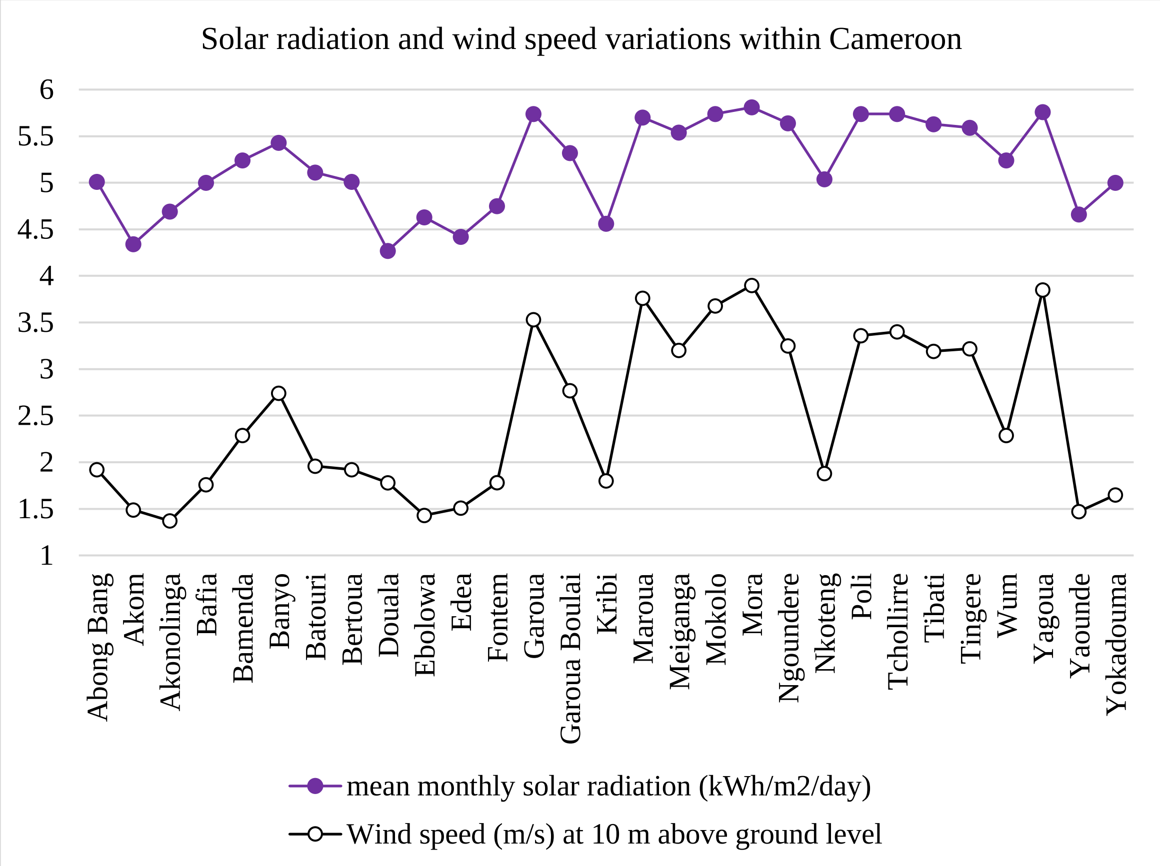


Figure 4.1: Trends in solar radiation and wind speed potentials of Cameroon

4.2.2 Trends in weather parameters at the representative study sites

A plot of these weather parameters at the study sites are as show in fig. 4.2 and fig. 4.3. Solar radiation varies at all the study sites from January to December, with relatively high values between December to March (peak dry season) and relatively low values between July to September (peak rainy season). The different sites have different peak months depending on the weather conditions in the area: March (Yagoua), December (Wum) and January (Yokadouma); with a least radiation in August at all the sites. Monthly wind speed trend variation is similar to that of solar radiations. However, the wind speeds at Yagoua is better than for Wum and Yokadouma, giving Yagoua (north zone) a better place for wind energy installation in Cameroon. This is explained by the relatively high temperatures in the North zone than in the West and Center-South zones. The clearness index at the sites ranges from 0.4 to 0.7. This means that, during the whole year, a clear sky corresponds to all the studied sites with Yagoua having clearer skies than Wum and Yokadouma.

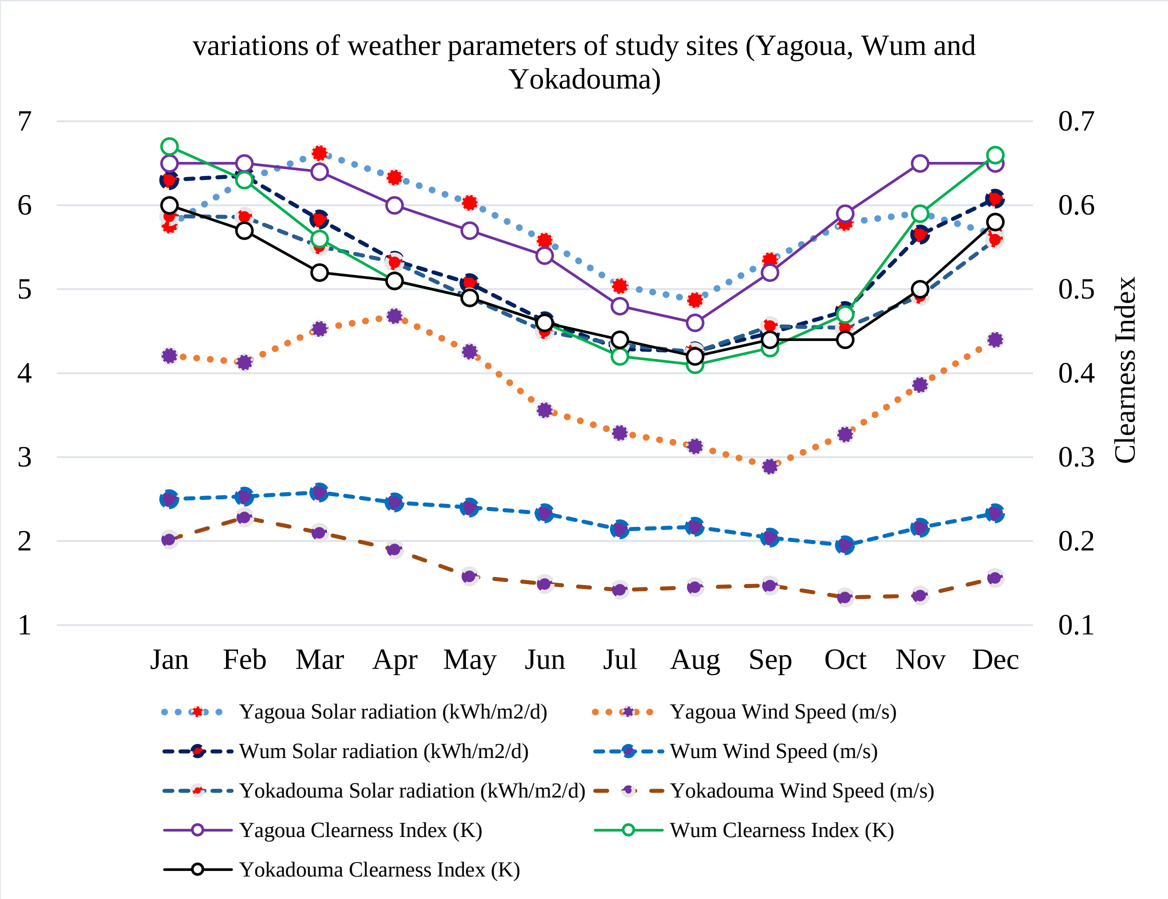


Figure 4.2: Variations of weather parameters of study sites

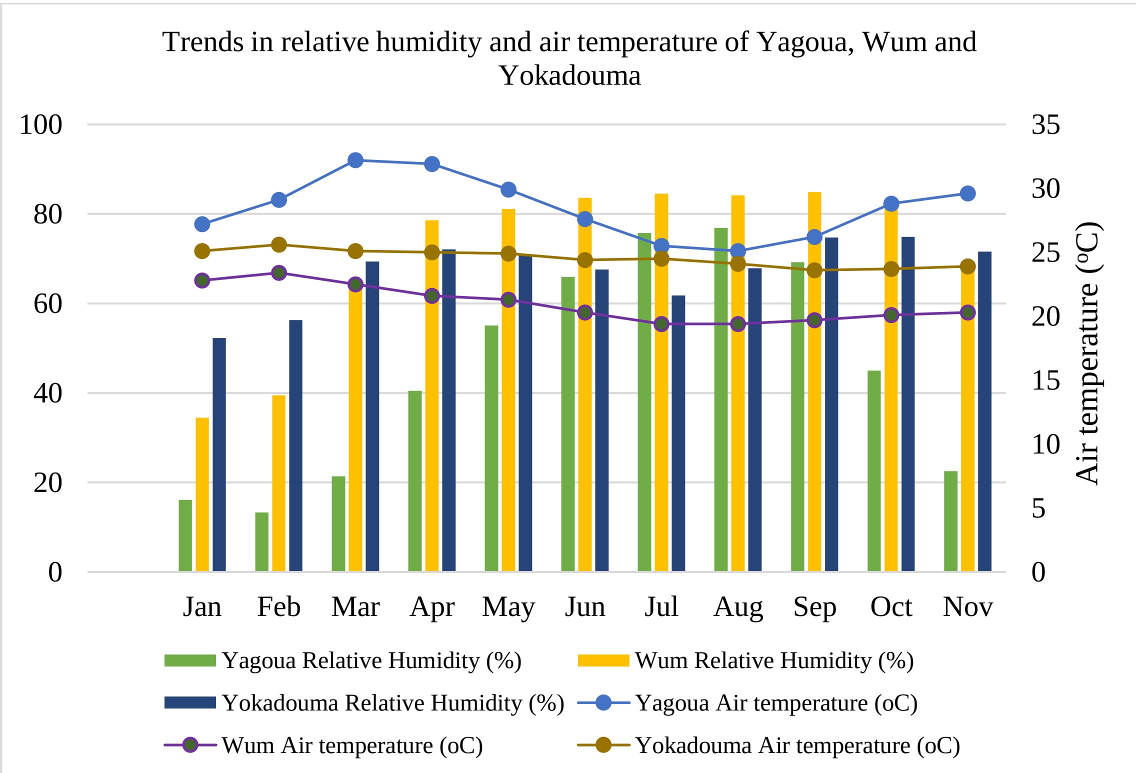


Figure 4.3:Trends in relative humidity and air temperature of study sites

The trends in air temperature and relative humidity in the studied sites behaves differently. The highest temperature is observed in Yagoua during the month of March and the lowest is recorded in Yokadouma in July and August. Monthly temperature variations are more prominent in Yagoua whereas Wum and Yokadouma has an almost constant monthly temperature. From these, we see that there is need for the control the effect of extreme temperature on the performance (output) of solar modules in Yagoua than for Wum and Yokadouma. The trends in relative humidity at the sites show that Wum is more humid throughout the year than Yokadouma and Yagoua (least). These reduces the performance of PV systems at these sits and hence the overall system performance.

4.2.3 Trends in village energy consumption

Village load assessment gave an estimated daily load of 100 kWh/m^2/d with a peak of 35.17 kWh between 7-8 pm in the evening (fig. 4.4). At this time, almost all the villagers are back home and almost all the appliances too are running. In this study, weekend loads are assumed to be the same as for working days. This assumption is based on the fact that there will be a redistribution of usage hours at different hours of the day on weekends where some hours will have less load and other more and so on. The usage durations of some appliances such as TV also increases on weekends as most children will be at home on weekend and a few will have to assist their parents in the farms.

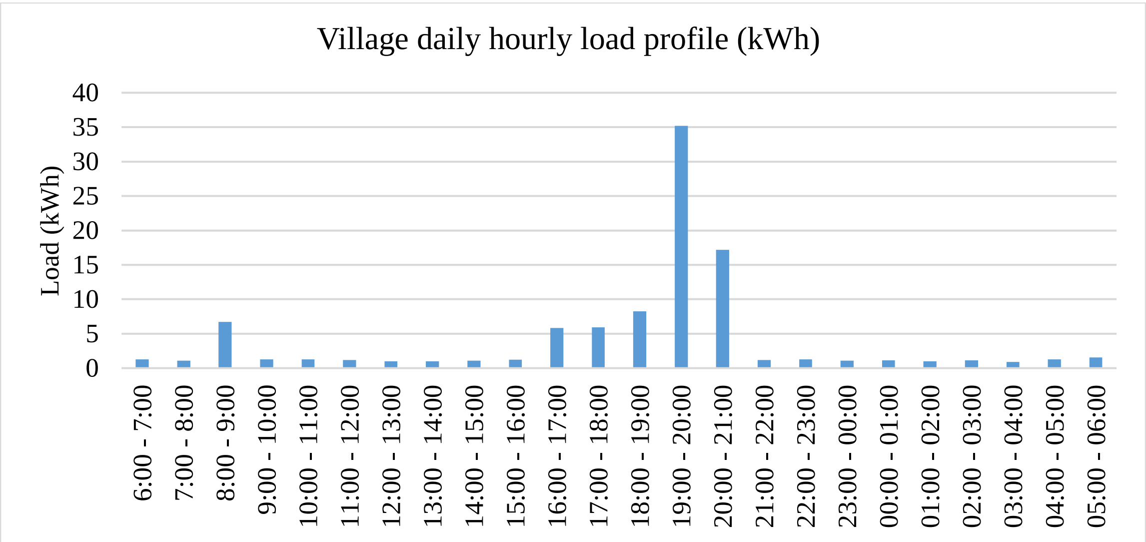


Figure 4.4: Village energy consumption patterns

4.3 Presentation of optimization results

All the various systems components characteristics (inputs) and economic constraints are introduced into HOMER and the software runs repeatedly several times to display a list of feasible systems. Optimization results are displayed in ascending order of their net present cost from the top to bottom with the most feasible system (least NPV) that suitably meets the load and the modeller input constraints at the top. The optimization results are usually presented as categorized or overall. The overall result displayed all the possible and affordable system compositions based on their NPV and the categorized result/table displayed all the least cost-effective combinations from among all the systems setup. After HOMER simulation and optimizations, the most feasible systems are chosen solely based on the NPV. The systems technical feasibilities are determined based on: low cost of energy, high renewable energy fraction, low excess power generation, low capacity shortage and less diesel fuel consumption. These variables are equally used in the comparisons of various systems apart from technical feasibility checks.

4.3.1 Systems optimization scenarios

HOMER simulations display feasible energy system combinations for detailed analysis. The simulation time and complexities depends on the design parameters and the number of potential values involved. The following simulation and optimization scenarios (table 4.1) are proposed for detailed analysis to find the most optimum or the best system. The system with the least NPC and cost of energy, least capacity shortage and excess power production, higher renewable energy fraction and lowest fuel consumption at each study site would be chosen as optimum. All the scenarios were optimized using the same data set.

Table 4.1: Proposed study and optimization scenarios

Proposed system	Scenario
PV/wind/battery	A
PV/wind/diesel/battery	B
PV/diesel/Battery	C
PV/Wind/diesel/small hydro/battery	D
PV/wind/small hydro/battery	E
PV/small hydro/battery	F
PV/diesel/small hydro/battery	G
Wind/diesel/small hydro/battery	H
Wind/small hydro/battery	I

The architecture of HOMER simulation for this study considers all the six different components in a single model in order to design and select the best economic system composition. Figure 4.5, shows a schematic representation of the hybrid system design with all the components (technologies) under consideration.

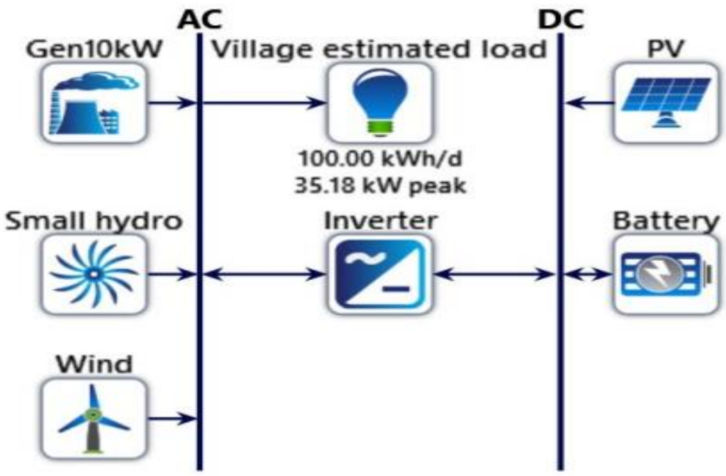


Figure 4.5: Hybrid system HOMER design

Input constraints such as: minimum renewable fraction of 40%, maximum annual capacity shortage of 2%, operating reserve as percentage of hourly load of 10%, operating reserve as percentage of solar and wind output of 10%, were used in order help HOMER refine the most economic feasible system.

4.3.2 Scenario simulation and comparison

After HOMER simulation of the various scenarios with the same criteria and constraints, the categorised simulation results at the various study sites (Yagoua, Wum and Yokadouma) we displayed as shown in figure 4.6. The categorized optimization result presents the various feasible energy system configurations with least NPC and COE with the system with the lowest COE place at the top. The above nine design scenarios comparison was done based on the following parameters: low COE, low NPC, low capacity shortage, low excess power production, high renewable energy fraction, low fuel consumption and so on. In addition to these parameters, constraints such as maximum annual capacity shortage of 10%, minimum renewable fraction of 40%, current diesel price of \$0.99, a primary load of 100 kWh/m^2/d, maximum annual capacity shortage of 2%, system operating reserve of 10% (as percentage of load in current time step and as percentage of peak annual load) and 10%, 10% as percentage of solar and wind output respectively. A maximum renewable energy penetration threshold of 40% was used. Economic constraints such as: nominal discount rate of 12.5%, inflation rate of 3% and system life of 25 years was equally used. These comparisons were concluded with the use of star diagrams in a multicriteria decision making approach to select the best systems at each site based on 10 design parameters. Not all the nine scenarios are feasible at all the study sites due to resource constraints. Scenario H and I are only feasible in Yagoua where wind resource potential is relatively high.

Export... Site: Wum

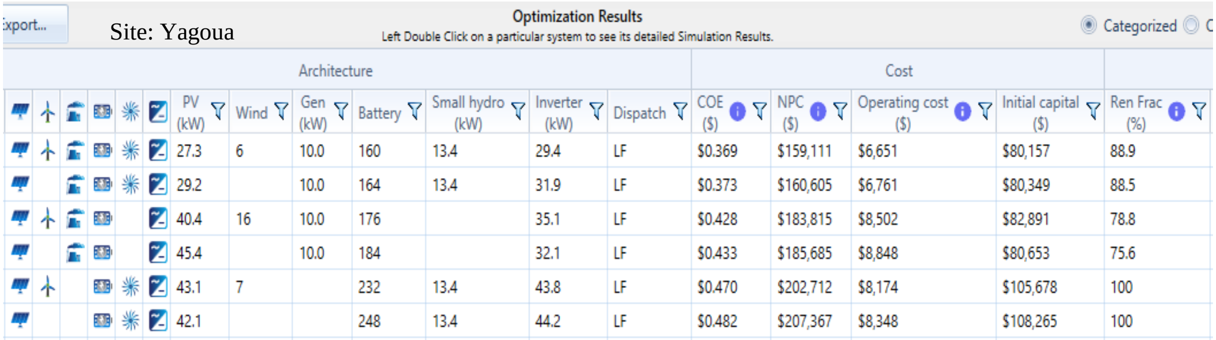
Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Categorized

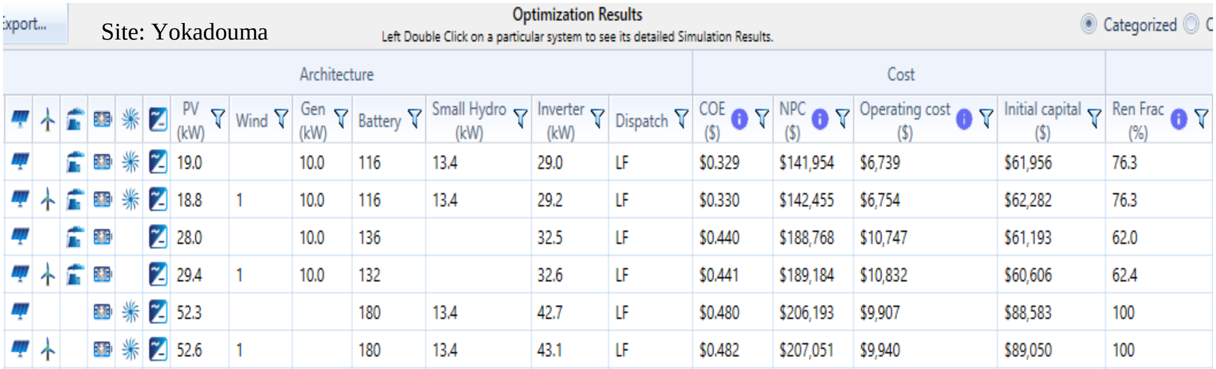
Architecture							Cost				
PV (kW)	Wind	Gen (kW)	Battery	Small hydro (kW)	Inverter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
26.0		10.0	164	13.4	32.1	LF	$0.369	$158,525	$6,646	$79,629	88.5
26.5	1	10.0	164	13.4	31.1	LF	$0.370	$159,415	$6,700	$79,877	88.3
60.8		10.0	188		40.6	LF	$0.461	$197,263	$9,268	$87,245	79.2
63.9	13	10.0	172		32.3	LF	$0.467	$200,479	$9,677	$85,601	74.9
49.7			236	13.4	42.3	LF	$0.476	$205,053	$8,357	$105,844	100
44.3	1		244	13.4	43.9	LF	$0.481	$207,091	$8,365	$107,797	100

Figure 4.6: Categorized optimization results of Wum



PV (kW)	Wind	Gen (kW)	Battery	Small hydro (kW)	Inverter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
27.3	6	10.0	160	13.4	29.4	LF	$0.369	$159,111	$6,651	$80,157	88.9
29.2		10.0	164	13.4	31.9	LF	$0.373	$160,605	$6,761	$80,349	88.5
40.4	16	10.0	176		35.1	LF	$0.428	$183,815	$8,502	$82,891	78.8
45.4		10.0	184		32.1	LF	$0.433	$185,685	$8,848	$80,653	75.6
43.1	7		232	13.4	43.8	LF	$0.470	$202,712	$8,174	$105,678	100
42.1			248	13.4	44.2	LF	$0.482	$207,367	$8,348	$108,265	100

Figure 4.7: Categorized optimization results of Yagoua



PV (kW)	Wind	Gen (kW)	Battery	Small Hydro (kW)	Inverter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
19.0		10.0	116	13.4	29.0	LF	$0.329	$141,954	$6,739	$61,956	76.3
18.8	1	10.0	116	13.4	29.2	LF	$0.330	$142,455	$6,754	$62,282	76.3
28.0		10.0	136		32.5	LF	$0.440	$188,768	$10,747	$61,193	62.0
29.4	1	10.0	132		32.6	LF	$0.441	$189,184	$10,832	$60,606	62.4
52.3			180	13.4	42.7	LF	$0.480	$206,193	$9,907	$88,583	100
52.6	1		180	13.4	43.1	LF	$0.482	$207,051	$9,940	$89,050	100

Figure 4.8: Categorized optimization results of Yokadouma

Based on the respective scenarios, the follow arranged scenario optimization results were obtained for each of the study location. The selection of the scenario optimization result was done through filtering of the overall optimization result using the following criteria: PV array contribution greater than 60 kW, maximum number of units of wind turbines (greater than 20 units), restricted capacity of genset to 10 kW, minimum size of battery bank (number of batteries) and lowest cost of energy. These results together with other parameters will form the basis of our comparison and references will be mad mostly to these tables.

Table 4.2: Wum filtered scenario optimization result

Wum	Architecture							Cost				System			
Scenario	PV (kW)	Wind	Gen (kW)	Battery	Small hydro (kW)	Inverter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)	Cap Short (kWh/yr)	Unmet load (kWh/yr)	CO2 (kg/yr)
A	101.0	23	0	332	0	53.0	LF	0.694	300073.1	12750.4	148716.2	100.0	357.5	95.1	0
B	84.2	28	10	168	0	44.2	LF	0.520	224369.2	10767.5	96550.7	76.2	450.0	162.3	10570.4
C	88.2	0	10	272	0	44.3	LF	0.564	244077.5	10331.7	121431.9	98.3	156.2	68.8	692.3
D	67.3	34	10	332	13.4	35.3	LF	0.689	298380.8	12036.0	155504.1	98.7	0	0	583.8
E	67.3	23	0	332	13.4	53.0	LF	0.674	292050.3	11903.7	150743.9	100.0	56.5	15.1	0
F	101.0	0	0	332	13.4	42.4	LF	0.689	298709.5	12625.7	148833.1	100.0	1.5	0.0	0.0
G	67.3	0	10	168	13.4	44.2	LF	0.443	191704.1	8308.8	93072.5	91.4	93.0	35.1	3852.4
H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.3: Yagoua filtered scenario optimization result

Yagoua	Architecture							Cost				System			
Scenario	PV (kW)	Wind	Gen (kW)	Battery	Small hydro (kW)	Inverter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)	Cap Short (kWh/yr)	Unmet load (kWh/yr)	CO2 (kg/yr)
A	101.0	34	0	332	0.0	53.0	LF	0.708	306746.1	12998.4	152445.2	100.0	50.9	12.7	0.0
B	101.0	34	10	332	0.0	35.3	LF	0.710	307800.7	13000.3	153476.4	97.5	0.0	0.0	1120.8
C	101.0		10	332	0.0	35.3	LF	0.663	287334.0	12247.2	141950.4	97.4	7.5	2.3	1182.6
D	67.3	11	10	332	13.4	35.3	LF	0.656	284347.0	11510.6	147707.1	98.8	0.0	0.0	552.6
E	67.3	34	0	332	13.4	35.3	LF	0.677	293145.9	11974.8	150996.1	100.0	716.6	0.0	0.0
F	101.0	0	0	332	13.4	42.4	LF	0.689	298709.5	12625.7	148833.1	100.0	0.0	0.0	0.0
G	101.0	0	10	332	13.4	35.3	LF	0.696	301672.8	12612.7	151950.4	98.8	0.0	0.0	568.2
H	0.0	222	10	264	13.4	23.4	LF	0.746	322070.4	12043.1	179109.0	96.6	590.5	120.8	1318.9
I	0.0	185	0	384	13.4	76.8	LF	0.887	380865.9	14301.3	211098.1	100.0	730.7	341.8	0.0

Table 4.4: Yokadouma filtered scenario optimization result

Yokadouma	Architecture							Cost				System			
Scenario	PV (kW)	Wind	Gen (kW)	Battery	Small hydro (kW)	Inverter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)	Cap Short (kWh/yr)	Unmet load (kWh/yr)	CO2 (kg/yr)
A	101.0	34	0	224	0.0	53.0	LF	0.737	318268.4	16889.5	117777.2	100.0	523.3	142.4	0.0
B	101.0	34	10	224	0.0	35.3	LF	0.646	280041.2	13582.3	118808.4	70.3	0.0	0.0	9695.8
C	101.0	0	10	224	0.0	35.3	LF	0.604	261575.8	12997.7	107282.4	70.0	0.0	0.0	9783.4
D	67.3	23	10	224	13.4	35.3	LF	0.558	241686.4	10494.6	117107.1	79.9	0.0	0.0	6544.5
E	67.3	34	0	224	13.4	53.0	LF	0.583	252450.6	11174.1	119804.9	100.0	142.5	45.9	0.0
F	101.0	0	0	224	13.4	53.0	LF	0.593	256935.0	11851.3	116251.2	100.0	73.4	14.8	0.0
G	67.3	0	10	224	13.4	35.3	LF	0.526	227831.7	9984.3	109310.1	79.8	0.0	0.0	6585.8
H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4.3.2.1 Cost of energy

With reference to figure 4.9, with details from table 4.2 to 4.4, scenario G is the most economic feasible system for Wum with a COE of \$0.443/kWh; followed by scenarios B, C, E, D, F, A. The scenario ranking for Yagoua and Yokadouma, in order of increasing COE are: D, C, E, F, G, A, B, H, I and G, D, E, F, C, B, A respectively. Based on COE, scenario D and G are the most feasible hybrid system for Yagoua and Yokadouma with a COE of \$0.656 and \$0.526 respectively. Scenarios H and I are infeasible in Wum and Yokadouma due to low wind potential at the sites.

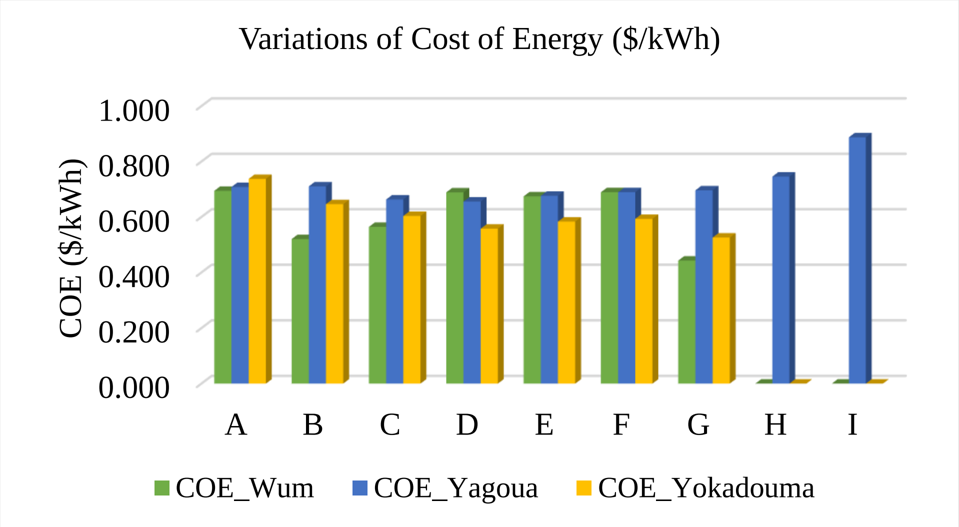


Figure 4.9: Scenario comparison of COE for Wum, Yagoua and Yokadouma

4.3.2.2 Total Net Present Cost

Referring to figure 4.10 (with details from table 4.2 to 4.4), the scenarios rankings in ascending order of NPC are: G, B, C, E, D, F, A; D, C, E, F, A, B, G, H, I and G, D, E, F, C, B, A for Wum, Yagoua and Yokadouma respectively. This show that the optimum system set-ups or configurations at the respective sites with least NPC are G, D and G with NPC $191,704.1, $284,017.2 and $227,831.7 respectively. Scenarios H and I are infeasible in Wum and Yokadouma as a result of very low wind speeds.

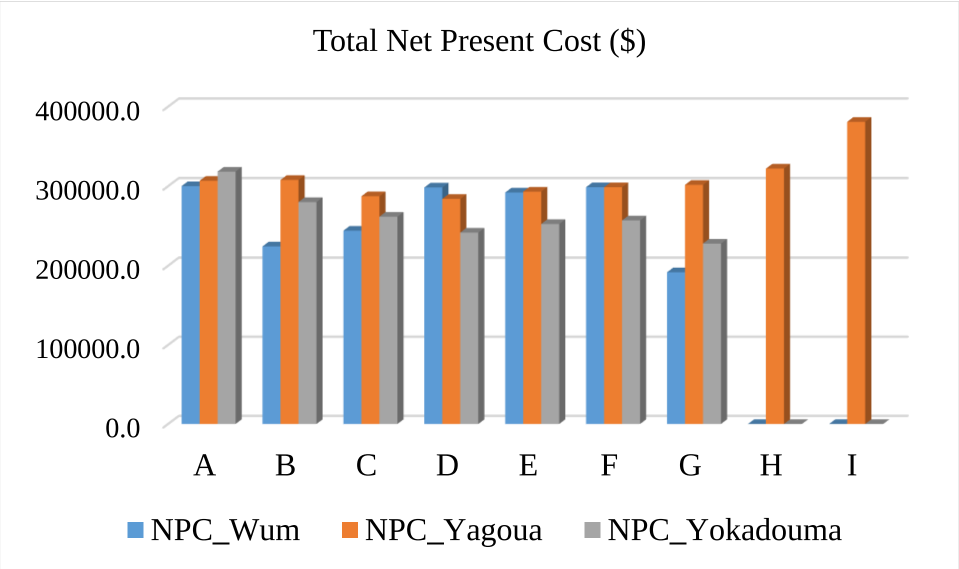


Figure 4.10: Total Net Present Cost scenario comparison of Wum, Yagoua and Yokadouma

4.3.2.3 Diesel fuel consumption

In the systems design considerations, the size of the diesel genset was restricted to 10 kW to serve mainly as additional storage and to limit emissions as well as to increase renewable penetrations. Systems with diesel components are compared for fuel consumption as depicted in figure 4.11 (details from table 4.2 to 4.4). The greatest fuel use scenario in the country corresponds to Yokadouma followed by Wum and Yagoua. This is because of very low solar and wind resource potential at Yokadouma. On the other hand, Yagoua has highest solar and wind potential in the country with least fuel consumption. This is because energy demand is provided by solar and wind, with very little from diesel. Wum unlike Yokadouma have relatively high fuel consumption especially with scenario B and G due to low wind potentials as well. Scenarios A, E, F, I and H with zero emissions are systems without a generator component. The systems rankings in order of decreasing fuel consumptions are: C, B, G, D; B, G, C, D; H, D, C, B and G for Yokadouma, Wum and Yagoua respectively. Thus, the systems with the least fuel consumptions at the respective locations are D, D and G. They are recommended for environmental reasons (protection).

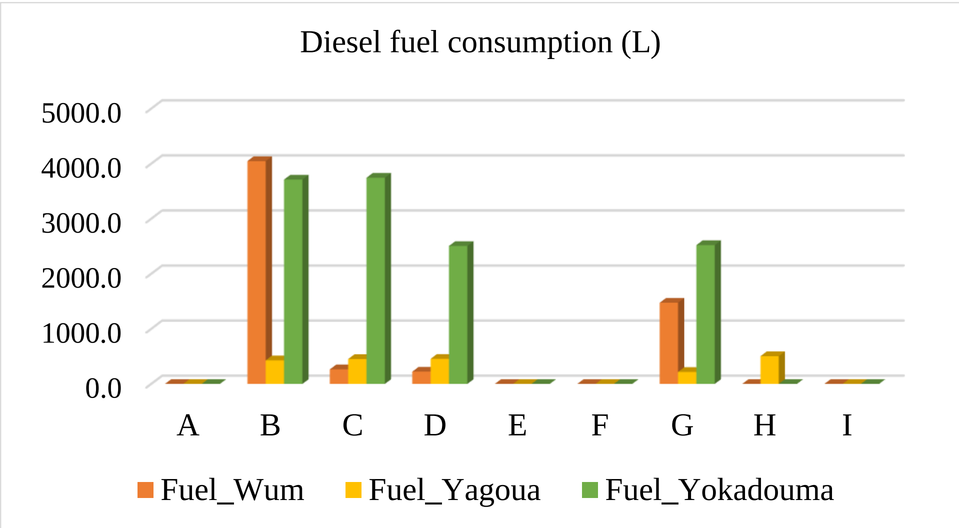


Figure 4.11: Diesel consumption scenario comparison for Wum, Yagoua and Yokadouma

4.3.2.4 Renewable fraction

All the systems have renewable energy fraction between 60-100% indicating a high penetration of renewables in the designs. Four configurations: A, E, F and I have 100% renewable fraction (fig. 4.12). These demonstrate the feasibilities of pure renewable hybrid systems in powering remote locations in Cameroon. The choice of the best system based on renewable fraction is bound to be biased as high system cost, battery size, energy cost will serious affects the realisation of such system. Thus, other parameters need to be used to refine these systems. In order of decreasing renewable fraction, the scenarios are classified thus: A, E, F, I, D, C, G, B; A, E, F, I, G, B, D, C, H; A, E, F, D, G, B, C for Wum, Yagoua and Yokadouma respectively.

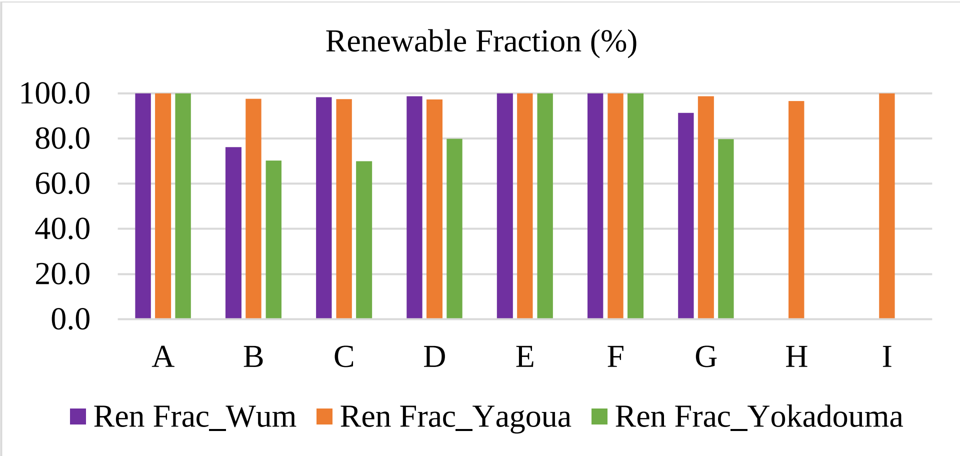


Figure 4.12: Renewable fraction scenario comparison Wum, Yagoua and Yokadouma

4.3.2.5 Capacity shortage

The design of the systems restricted the minimum annual capacity shortage to 2% for all the scenarios. This was to ensure systems reliability. Looking at the performances of the various systems (fig. 4.13) with regard to the shortages recorded, wind energy systems in Yagoua have much shortages. This is mainly due to fluctuations in wind speeds and directions, cloud covers and PV module power losses due to high temperatures in the northern regions of Cameroon. Most of the scenarios at the various sites recorded zero shortage and this shows the high performance and reliability of the systems. The scenario rankings are: D, F, E, G, C, A, B; B, F, G, C, D, A, H, E, I; B, C, D, G, F, E, A for Wum, Yagoua and Yokadouma respectively and in increasing order.

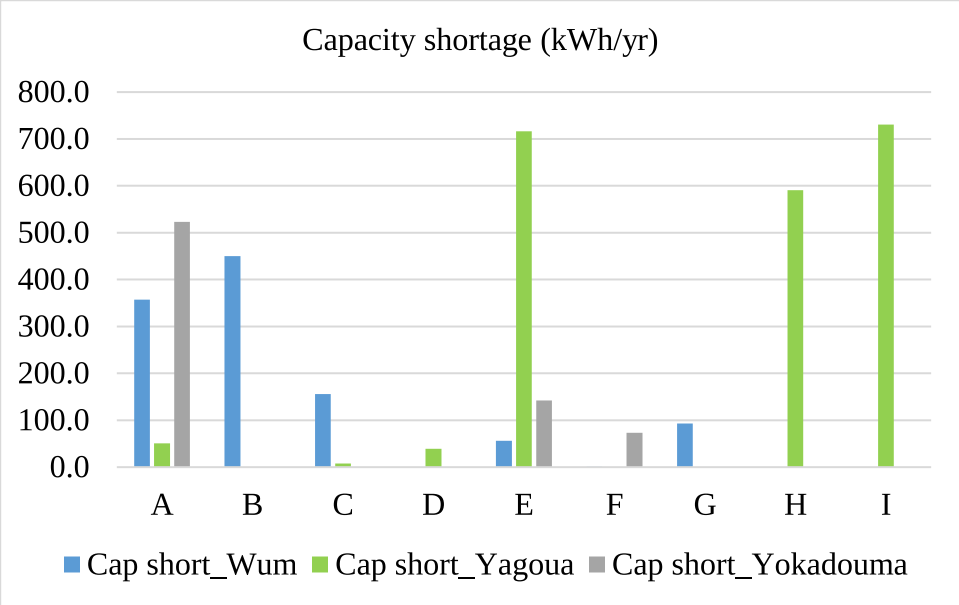


Figure 4.13: Capacity shortage scenario comparison for Wum, Yagoua and Yokadouma

4.3.2.6 Excess electricity production

Excess electricity results when the renewable systems generate more energy than expected or when the battery bank is fully charged and can no longer accept further power. The power produced at these periods are wasted. The trends in excess generations at the various study locations are shown in figure 4.14. The highest excess is observed in Yagoua (scenario G), due to high losses under extreme cell and air temperatures and the least in still in Yagoua (scenario D) due to the synergistic effects of the various system components in meeting deficits from each system component. It should be noted that systems with higher excess productions are favourable in another sense and the excesses will be able to accommodate future increase in demand. This will however, cause additional system cost to purchase additional storage facilities. High excess is also accounted for by the 10% hourly operating reserve, wind and solar output reserve and the minimum capacity shortage constraints. Based on excess production alone, the scenarios are ranked as follows: Wum (C, B, A, E, D, G, F), Yagoua (D, I, H, C, A, B, E, F, G) and Yokadouma (A, C, B, E, G, D, F), in ascending order.

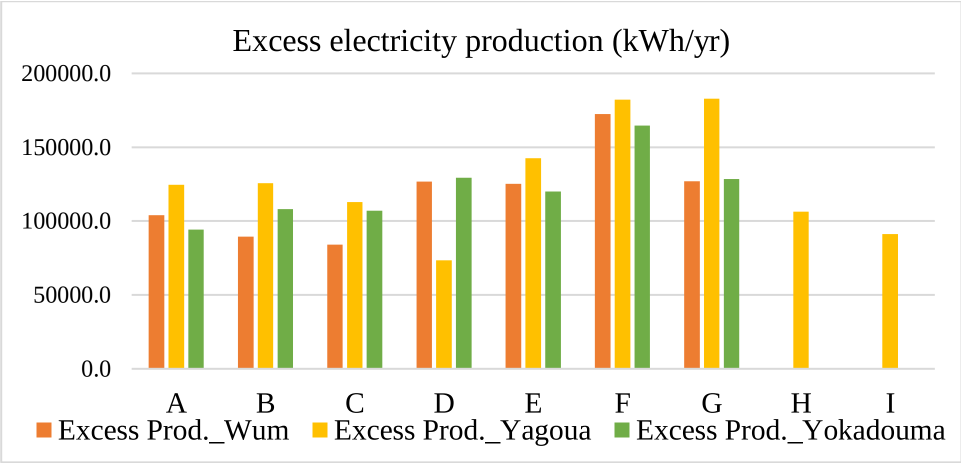


Figure 4.14: Excess production scenario comparison in Wum, Yagoua and Yokadouma

4.3.2.7 Excess unmet load

Unmet load gives an indication of systems supply reliability as it gives the yearly power deficiency of energy systems. The lesser the unmet load, the more reliable and preferable the system. This is accounted for in the design by the maximum annual capacity shortage (2%) which restricts the excess unmet load to minimum. Figure 4.15 shows the trends in unmet load of the different design scenarios. Based on this parameter, scenario D will be the best system for Yagoua and Yokadouma and scenario G for Wum. The overall ascending rankings are: Wum (D, F, E, G, C, A, B), Yagoua (B, E, F, G, C, A, D, H, I), and Yokadouma (B, C, D, G, F, E, A).

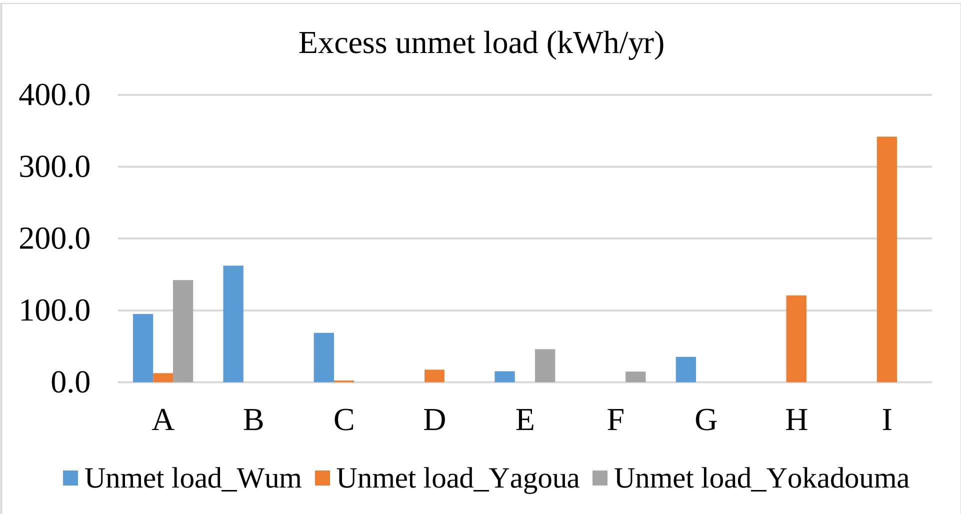


Figure 4.15: Excess unmet load scenario comparison for Wum, Yagoua and Yokadouma

4.3.2.8 CO_2 emissions

CO_2 emissions result from systems with diesel gensets and the magnitude depends on the level of diesel fuel consumption of the system. CO_2 emissions adversely affect the environment, health, natural ecosystems, causes climate and weather variations with associated risks. As the energy sector emits the highest percentage of global CO_2 emissions, systems with low emission values are advisable to ensure a sustainable environment and future. The emissions from genset coupled hybrid systems in Wum, Yagoua and Yokadouma are depicted in figure 4.16. This figure shows emission values for scenarios B, C, D, G, and H; with the least emissions recorded in scenario G (Yagoua) and the highest in scenario B (Wum). The ranks are: D, C, G, B (Wum); G, D, C, B, H (Yagoua) and D, G, B, C (Yokadouma), in increasing yearly CO_2 emission values.

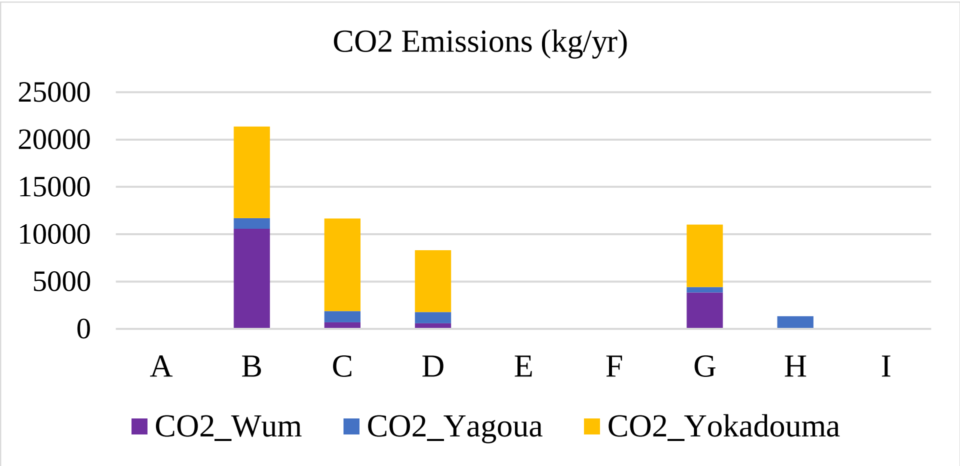


Figure 4.16: Scenarios CO_2 emissions in Wum, Yagoua and Yokadouma

4.3.2.9 Initial installation cost

The initial installation cost of renewable systems plays a fundamental role in the economic feasibilities and affordabilities of those systems. Looking at a remote community with limited household incomes, high systems cost will be unaffordable for them, except subsidized by the government or international organisations. High capital cost of renewables is a major hindrance to renewable deployment in a country like Cameroon where there are no laws, policies, regulations and incentives on renewables. Figure 4.17 compares capital cost of the study scenarios. Based on this, the least cost set-ups are G, C and C for Wum, Yagoua and Yokadouma respectively.

Arranging these systems in increasing capital cost gives: Wum: G, B, C, F, A, E, D; Yagoua: C, D, F, E, G, A, B, H, I and Yokadouma: C, G, F, D, A, B, E.

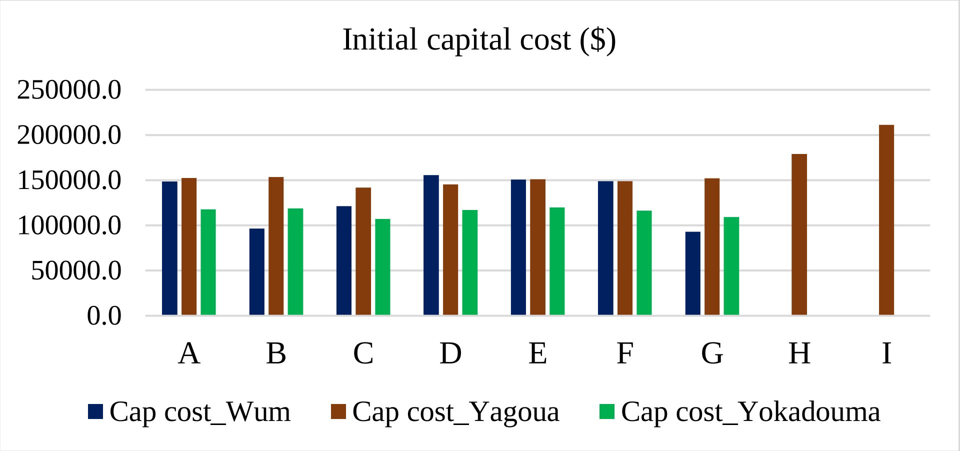


Figure 4.17: Scenarios initial capital cost comparison for Wum, Yagoua and Yokadouma

4.3.2.10 Operations and maintenance cost

Systems with high maintenance cost will be highly unsustainable for the community since the income levels of the community dwellers is relatively low. Based on these, scenario G and D (figure 4.18) are the most economic feasible system at all sites and the respective scenarios: G for Wum and Yokadouma and D for Yagoua.

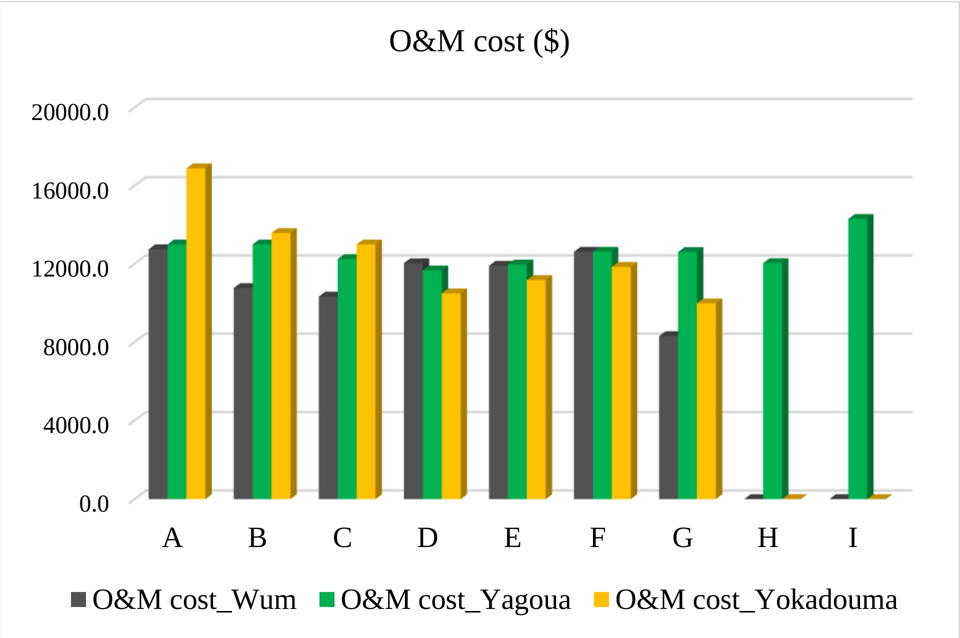


Figure 4.18: Scenarios operating and maintenance cost for Wum, Yagoua and Yokadouma

4.3.3 Selection of overall best scenarios

It was shown that system ranking depends on applied criteria. As such, a more appropriate way to select the best system is required. In this regard, the multicriteria decision making approach will be solicited and used to choose or select the most suitable system from the different scenarios and sites. A star diagram and a multicriteria bar chart will be solicited. The criteria to be considered are: total net present cost (low), COE (low), renewable fraction (high), capacity shortage (low), diesel fuel consumption (low), CO_2 emissions (low), excess unmet load (low), excess production (low), initial capital cost (low) and operation and maintenance cost (low). Two approaches were used to select the optimum system and perform the overall systems ranking. In the first approach, the selection is based on the systems economic performance using the above 10 criteria. The second approach is based on systems externalities, impact analysis and sustainability. The overall best system and ranking was chosen based on externalities and sustainability for reasons that the negative impacts of certain systems out weights the benefits from the low economic feasibilities. Maintenance free systems are preferable for remote communities. Furthermore, the most essential is not only to improve energy access in remote localities, it is very plausible to improve energy access in a way that the local environment is protected, health and living standards of community dwellers is improved, protects the natural ecosystem and mitigate climate change and associated risks.

4.3.3.1 Star diagram and bar chart comparison of Wum's scenarios

Taking into consideration all the design criteria, the economic performances of the scenarios at Wum are shown in figure 4.19. Here, the scenarios performance parameters are ranked on a scale of 0-100 in a star-like manner, making the ranking more convenient. Figure 4.20 represents the same criteria comparison but in a bar chart to give more evident and clarity on the comparison. Based on figure 4.19 and 4.20, the economic ranking of the scenarios is: G, B, C, E, F, D, A. Scenario G is the overall best system that reliably satisfy the load and satisfactorily meet all constraints and conditions set by the designer. Based on externalities and systems sustainability, the scenarios classification is: E, F, A, D, C, G, B. Thus, the most preferable system in Wum (based on externalities and sustainability) is scenario E (PV/wind/small hydro/Battery) and scenario G (PV/diesel/small hydro/Battery) based on economics.

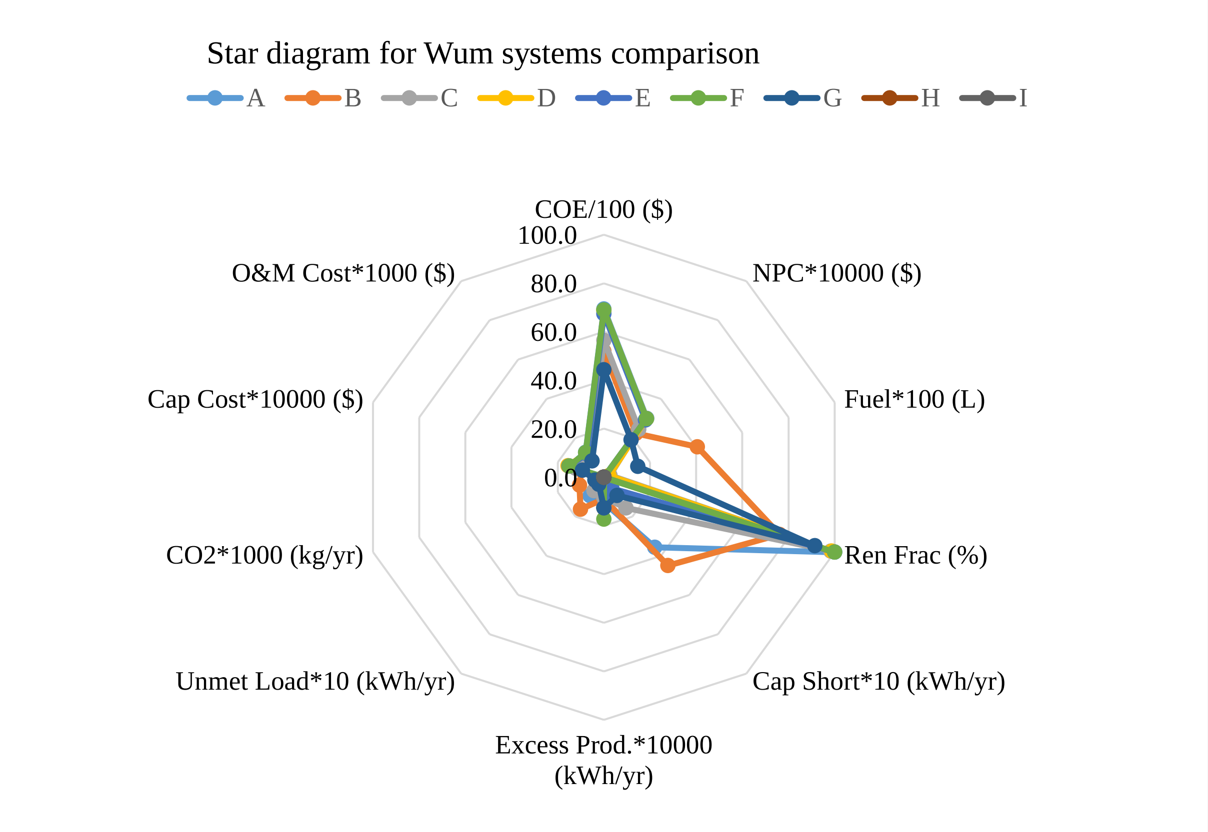


Figure 4.19: Scenarios Star diagram for Wum

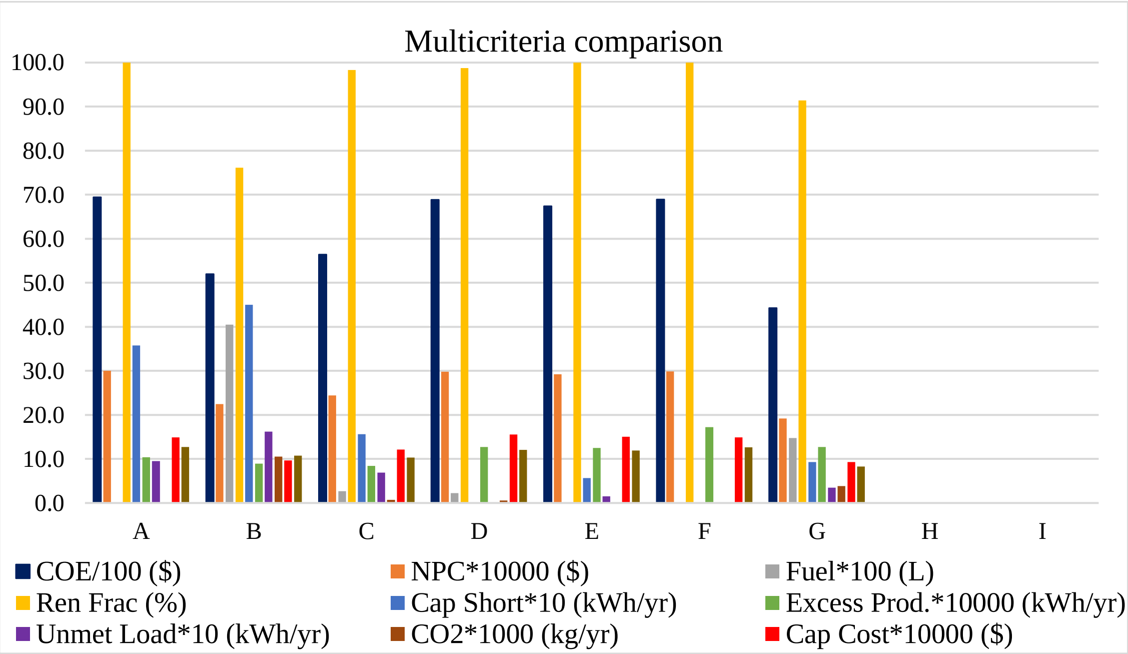


Figure 4.20: Scenarios bar chart for Wum

4.3.3.2 Star diagram and bar chart comparison of Yagoua's scenarios

With reference to figure 4.21 and 4.22, the economic ascending ranking of the scenarios is: D, C, E, F, G, A, B, H, I; with scenario D (PV/Wind/Diesel/Small hydro/Battery) being the most economically and technically feasible system. Ranking the scenarios in terms of externalities and sustainability, we have E, F, A, I, G, B, C, D, H. This gives scenario E (PV/wind/small hydro/Battery) as the most feasible in the rank.

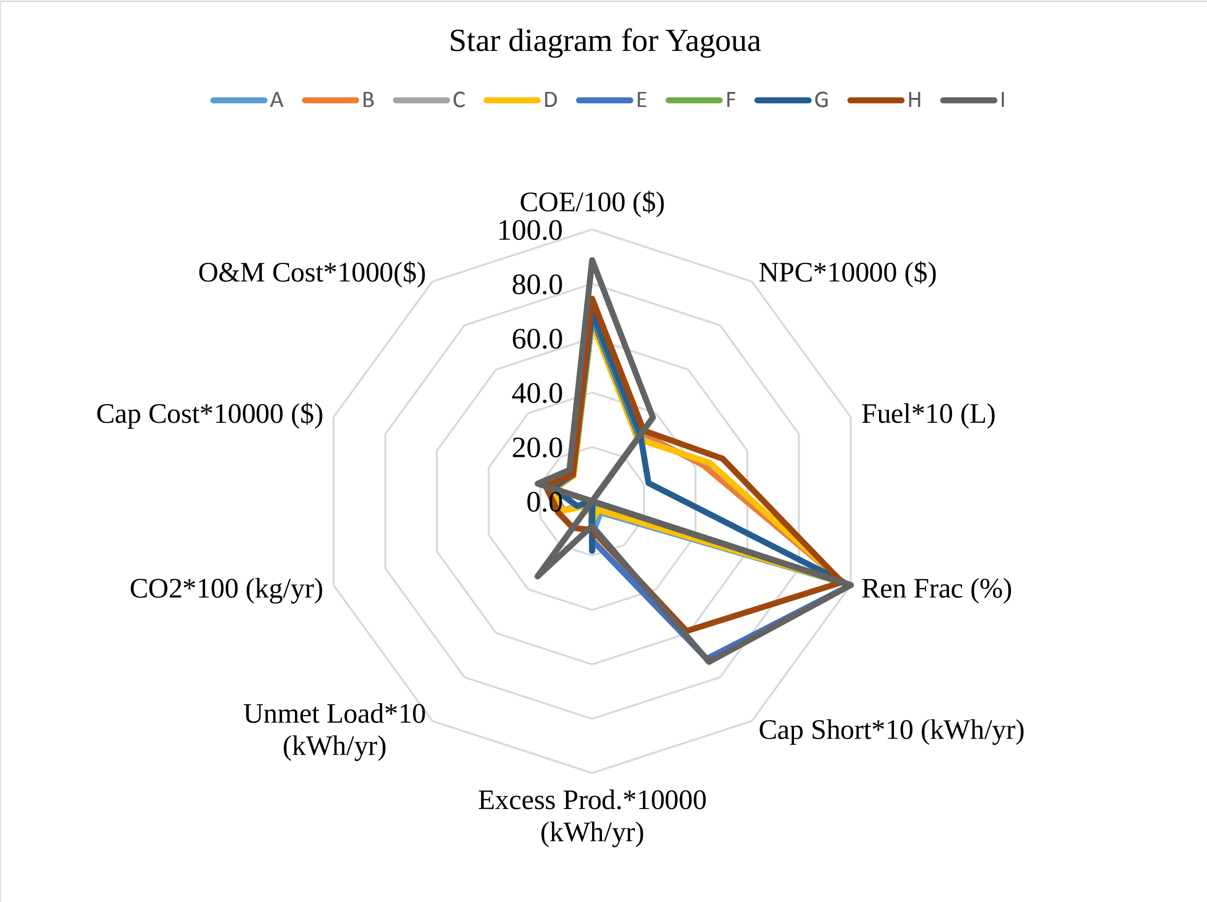


Figure 4.21: Scenario star diagram of Yagoua

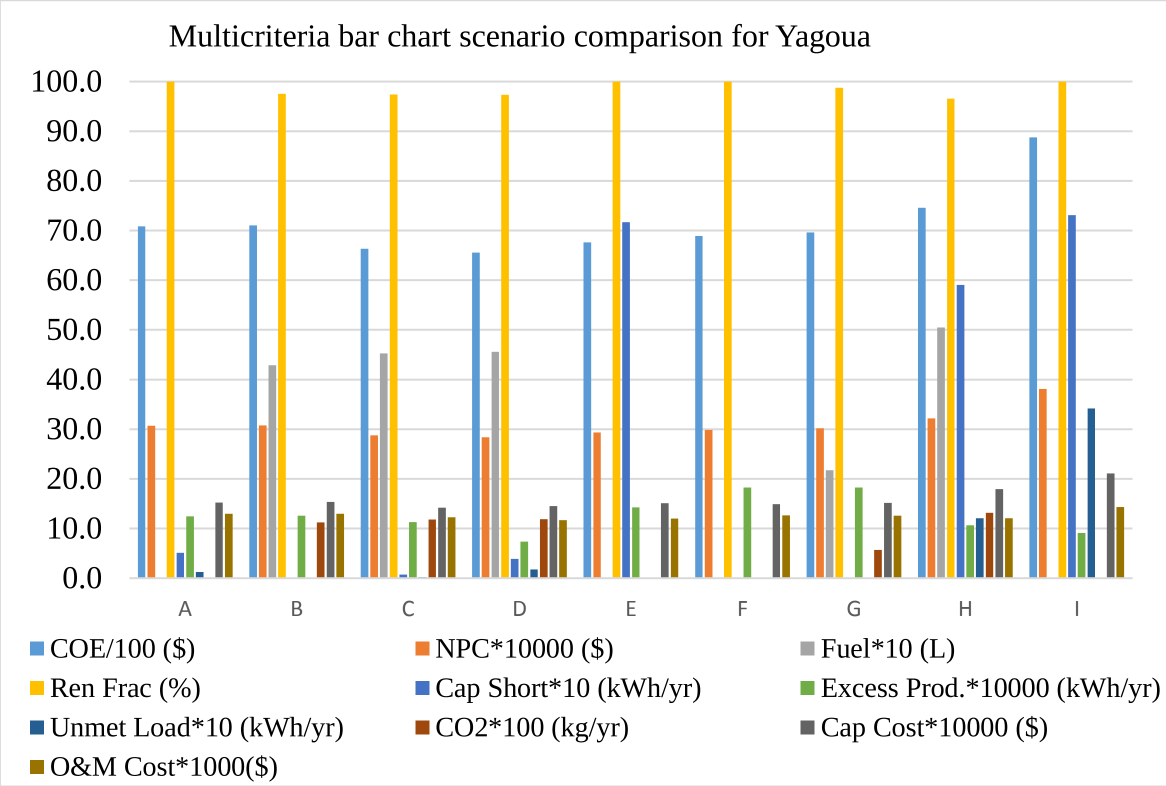


Figure 4.22: Scenarios bar chart comparison for Yagoua

4.3.3.3 Star diagram and bar chart comparison of Yokadouma's scenarios

Referring to figure 4.23 and 4.24, the techno-economic classification of the scenarios is: G, D, E, F, C, B, A. In this case, scenario G (PV/diesel/small hydro/Battery) is the most cost-effective system. If the systems are ranked taking into consideration their externalities and sustainability, we have E, F, A, G, E, D, C, B and scenario E (PV/wind/small hydro/Battery) emerges as the best-case scenario. Scenario H and I are not feasible in Yokadouma as seen in the figures.

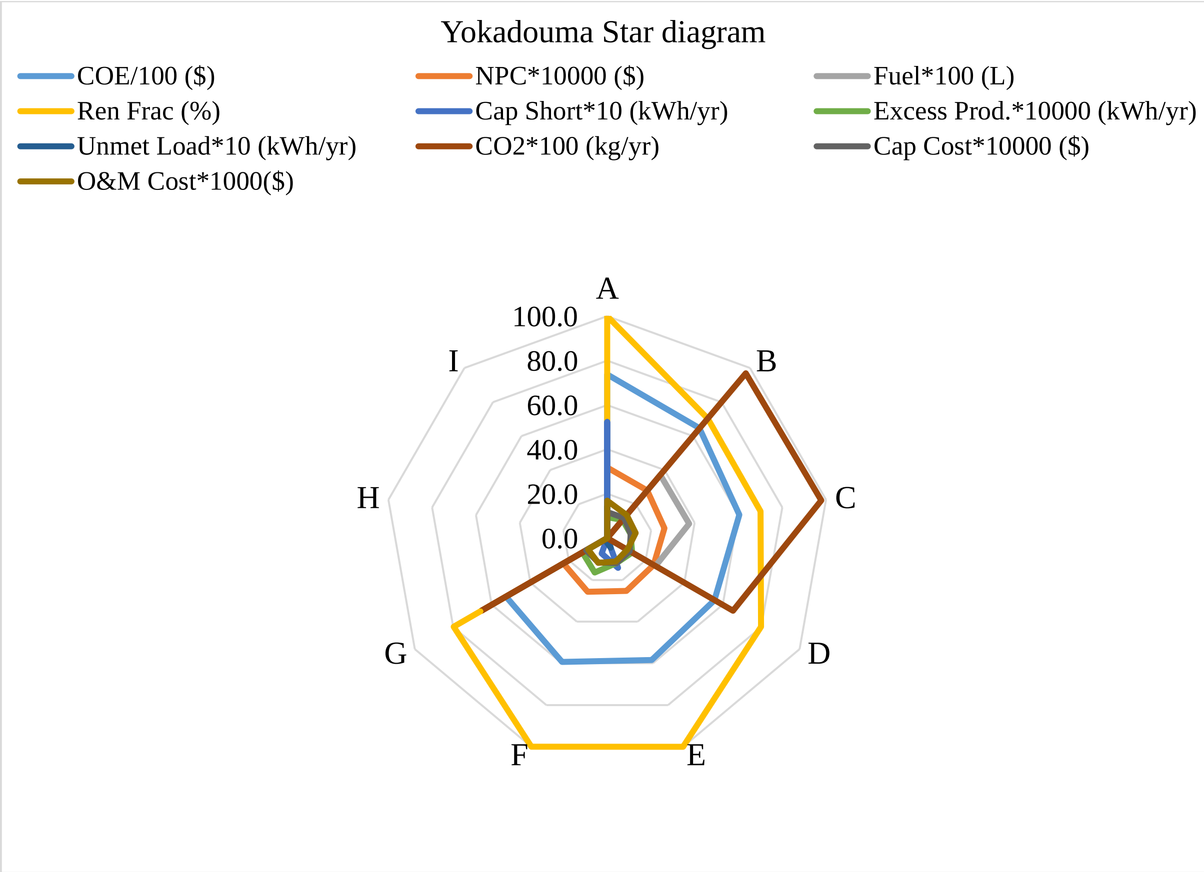


Figure 4.23: Scenarios star diagram comparison for Yokadouma

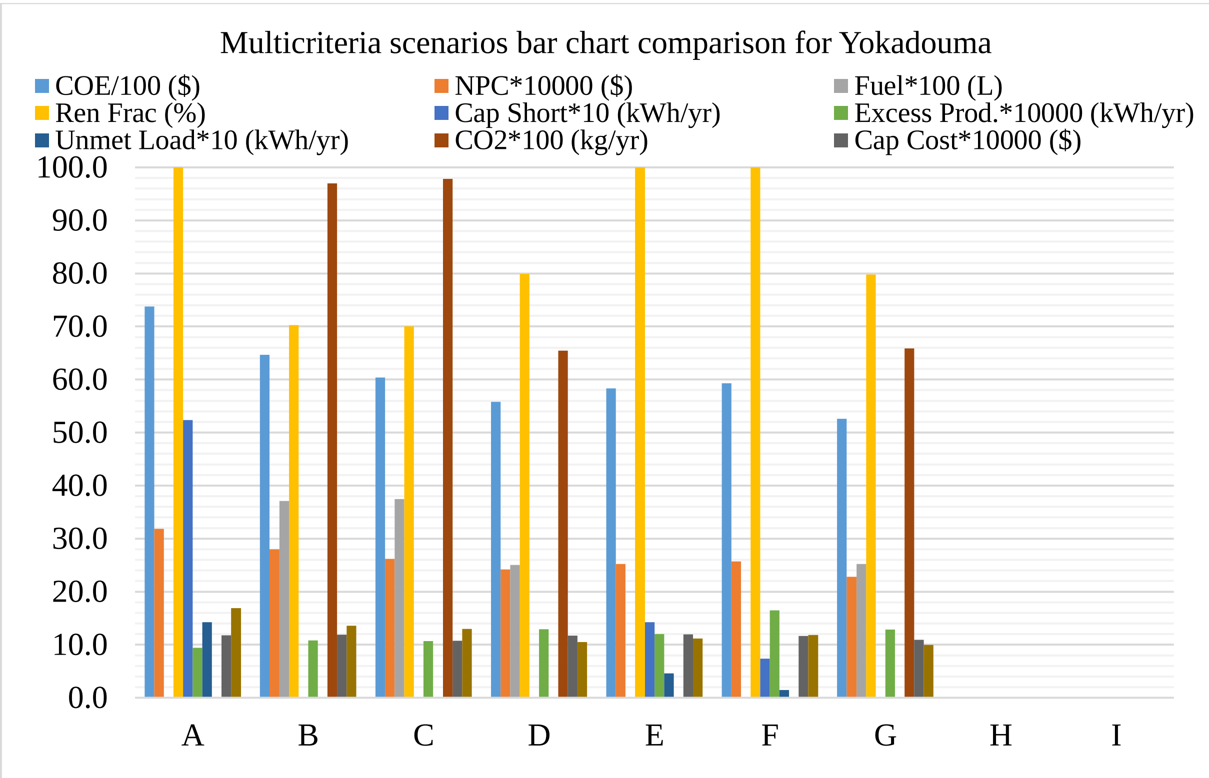


Figure 4.24: Scenario bar chart comparison for Yokadouma

4.3.4 Selection of best system for Cameroon

Based on the analysis made in section 3.3.3 to select the best system at each site, the following conclusions (table 4.5) were obtained.

Table 4.5: Summary of site scenarios ranking

Site	Selection basis	Scenario ranking	Best scenario	Optimum scenario set-up
Wum	economic	G, B, C, E, F, D, A	G	PV/diesel/small hydro/ battery
	externalities and sustainability	E, F, A, D, C, G, B	E	PV/wind/small hydro/battery
Yagoua	economic	D, C, E, F, G, A, B, H, I	D	PV/wind/diesel/small hydro/battery
	externalities and sustainability	E, F, A, I, G, B, C, D, H	E	PV/wind/small hydro/battery
Yokadouma	economic	G, D, E, F, C, B, A	G	PV/diesel/small hydro/ battery
	externalities and sustainability	E, F, A, G, E, D, C, B	E	PV/wind/small hydro/battery

From table 4.5, on the economic basis alone, scenarios G, D and G are the most cost-effective systems in Wum, Yagoua and Yokadouma respectively. Scenario D and scenario G in Wum differs only by the wind component in D. Thus, in the absence of wind, it can be conveniently concluded that scenario G is the most feasible techno-economic hybrid renewable energy system for Cameroon irrespective of the location throughout the country. On the other hand, scenario E is the most feasible system in terms of externalities, impact analysis and sustainability in Wum, Yagoua and Yokadouma respectively. Hence, with much certainty, Scenario E is the most feasible hybrid renewable energy system for Cameroon, under this consideration. Thus, scenario G and E are the two most feasible hybrid renewable energy system for Cameroon and are capable of operating reliably at all locations in the country. However, the system composition and the cost of energy varies from one location to another due to renewable resource, weather and climate variations throughout the country. The next section presents the optimization analysis of scenario E and G, using resource data of Wum as the country representative. The choice of Wum is due to limited studies on renewables reported in West Cameroon.

4.3.5 Optimization analysis of the most feasible sustainable scenario for Cameroon

The optimization process was carried out using HOMER Pro 3.9.2 (64-bits) software on a 4GB RAM, 1.80GHz processor and 64-bits laptop. All the systems have the same design architecture (fig. 4-5), the same input constraints, same sensitivity parameters and only the renewable resource input varies at the different study sites. A total of 383,807 simulations were performed in Wum by HOMER in a 60-minute time step optimization. Out of these simulations, 136,670 were feasible, 247,137 were infeasible due to capacity shortage constraint and 29,087 were infeasible due to minimum renewable energy. The design parameters and constraints took into consideration the system operating reserve in order to account for future load increment, although considered in load assessment and equally to ensure system reliability. Parameters such as: COE, NPC, operating cost, Initial cost, renewable fraction, capacity shortage, unmet load, CO_2 emissions, excess electricity, annual production, annual fuel consumption; were carefully chosen among others to ensure HOMER presents the best analysis and breakdown of the various economic feasible scenarios. The best-case scenario for Cameroon (section 4.3.4) were chosen considering economics alone as well as considering systems externalities and sustainability as another major aspect.

4.3.5.1 Optimization analysis of scenario E (PV/wind/small hydro/battery) of Wum

The optimized scenario result (table 4.2) display the set-up E with 67.3 kW of PV panel, 23 units of Wind Turbines of 0.5 kW each, 13.4 kW of Small hydro, 332 batteries (83 strings of 4 series 12V batteries) and 53 kW of bi-directional inverter. A total capacity of 55 kW inverter will be used and this will require 11of the 5 kW Power Star W7 inverter stipulated in this study. Monthly variations in electrical power production from this configuration is displayed in figure 4.25. The contribution of solar is almost constant throughout the year whereas small hydro is at its peak in the months of July to October (peak rainy season in Cameroon). Wind power contribution is almost negligible with minor contributions in every month except for the months of July and August and with an annual production of 1,702 kWh/yr. Small hydro contribution to the system is zero in the months of January, February, March and December probably due to very low stream flows, far below the design flow rate. However, for the months of April to November, the contribution is very significant and almost overshadows solar and wind from July to October.

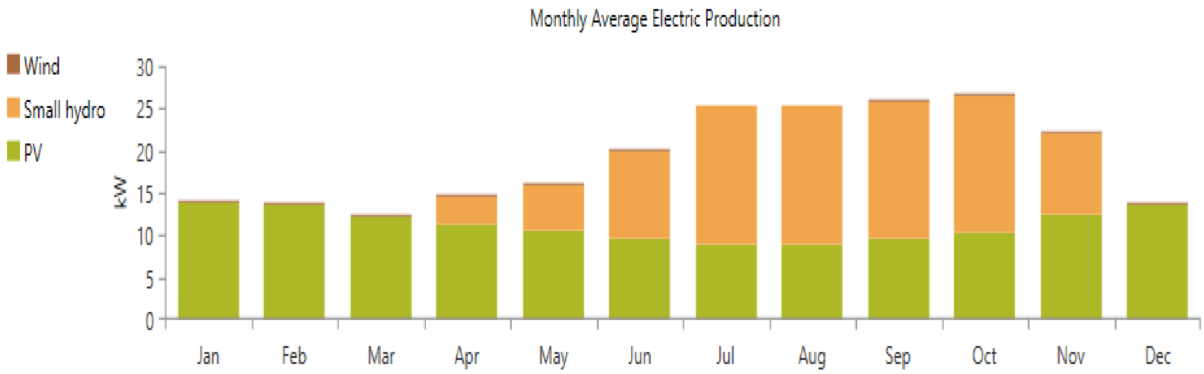


Figure 4.25: Monthly distribution of power production in scenario E in Wum

The overall annual electricity production by sources from the hybrid system is 168,661 kWh/yr (fig. 4.26). Small hydro accounts for 40.8%, solar PV with 58.2% and wind only 1%. The low contribution of wind results from the very poor wind potential in the area with an average speed of 2.3 m/s.

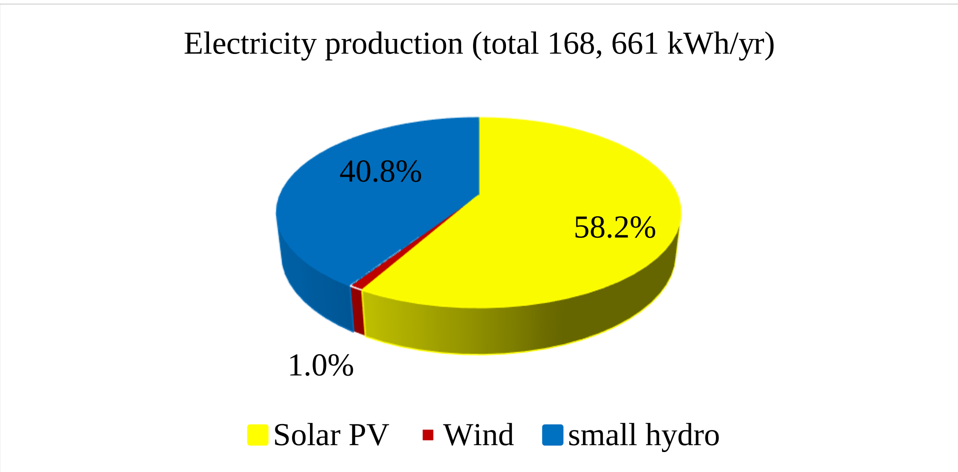
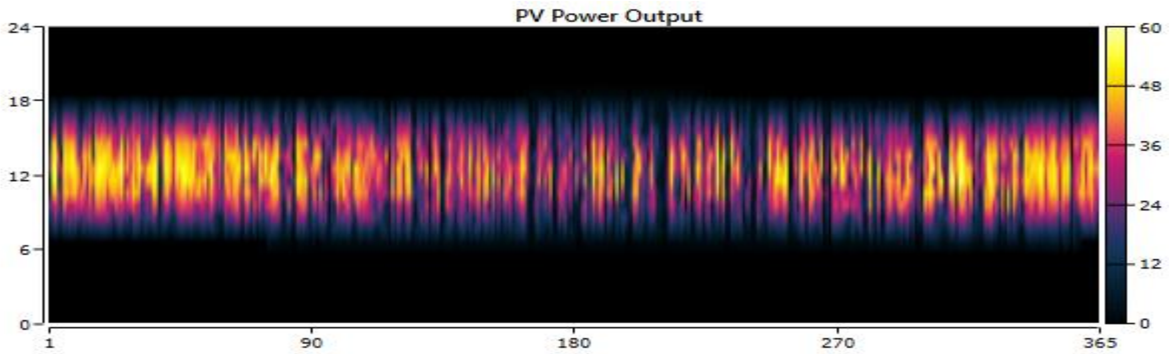


Figure 4.26: Share of electricity production of scenario E

All the power generated by the hybrid system is consumed by the primary AC load. There is no deferral load. Out of the total energy produced by the system, 36,485 kWh/yr are consumed by the AC load. The system produces an excess of 125,336 kWh/yr (74.3%), 15.1 kWh/yr (0.04%) of electrical load unmet and a capacity shortage of 56.5 kWh/yr (0.16%). The magnitude of the excess power produced by the system (high) indicates that the system is capable of accommodating future expansions in demand (increase in the number of households, small businesses expansions, increase household appliances and usage durations, as well as the connection of neighbouring villages). However, harnessing these excess powers requires additional cost which will be translated into an increase in energy cost of the system. The yearly performance of the of the system PV array is depicted in figure 4.27 and it characteristics in table 4-6. With a rated capacity of 67.3 kW and a capacity factor of 16.7%, the PV array produced a total of 63,758 kWh/yr; giving a LCOE of 0.0411 $/kW. From figure 4.27, PV power production begins around 6:00 am in the morning and ends around 6:00 pm in the evening, with peak production at noon. This performance scheme varies with days of the week, month and season of the year. The figure also shows that there will be production nearly the whole year with some few days or periods of overcast (back strips). The monthly variations of the PV arrays production (fig. 4.27b) show a decrease in PV output from March to October. This is the rainy period in the country which is usually characterised by clouds. The months of December, January and February (peak dry season) registered high PV output. Maximum PV output occurs during this dry season period when the skies are clear. The minimum output occurs mostly in the rainy season.



Legend: y-axis = time of the day (hr); x-axis = days of the year; surface = PV production (kW).

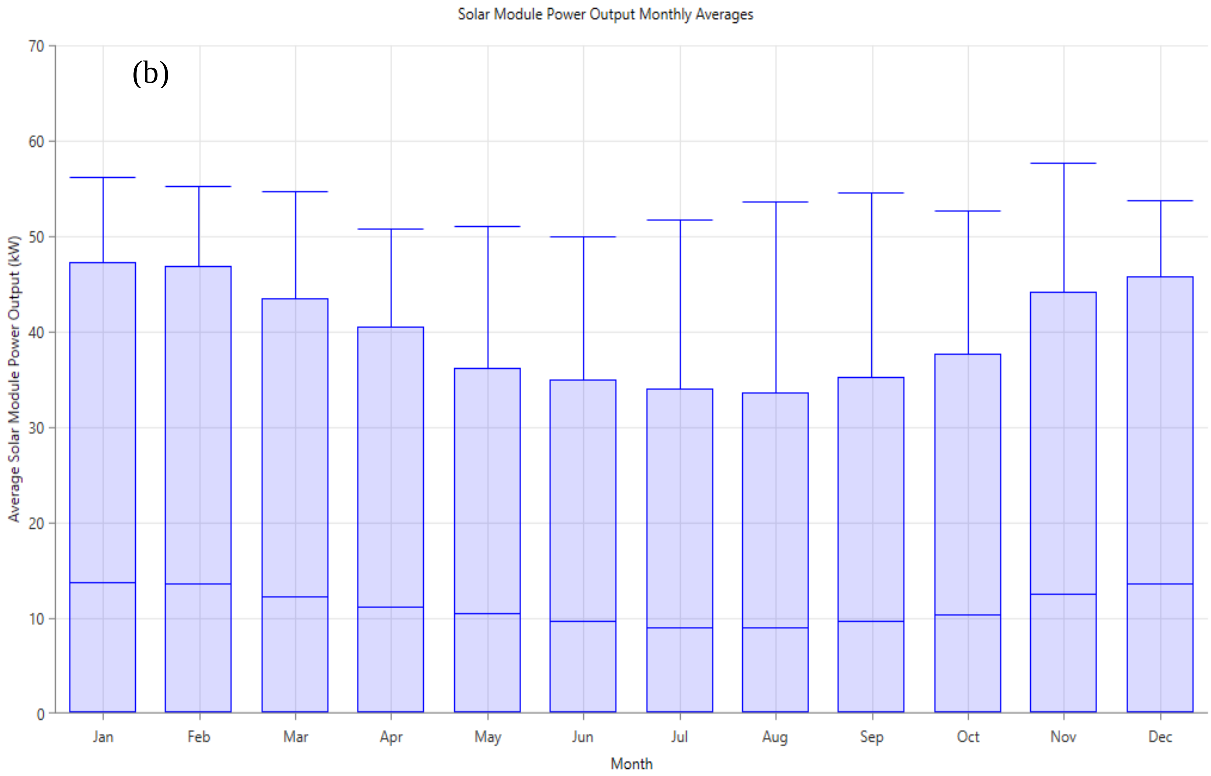


Figure 4.27: Yearly performance of PV array

Table 4.6: System PV array characteristics

PV array characteristics		
Quantity	Value	Unit
Rated Capacity	67.3	kW
Mean output	11.2	kW
Mean output	263	kWh/d
Capacity factor	16.6	%
Total production	98,108	kWh/yr
Min./Max output	0/57.8	kW
PV penetration	263	%
Operation hours	4,363	hrs/yr
Levelized cost	0.0411	$/kWh

The wind power output of this system is very low and production takes place all day long (fig. 4.28). The 23 wind turbines have a yearly rated capacity of 69 kW, a capacity factor of 0.282% with 8,760 hours of operation per year and a maximum output of 4.36 kW during maximum speed periods. The turbines produced a total of 1,702 kWh/yr and this gives a LCOE of 0.691 $/kW.

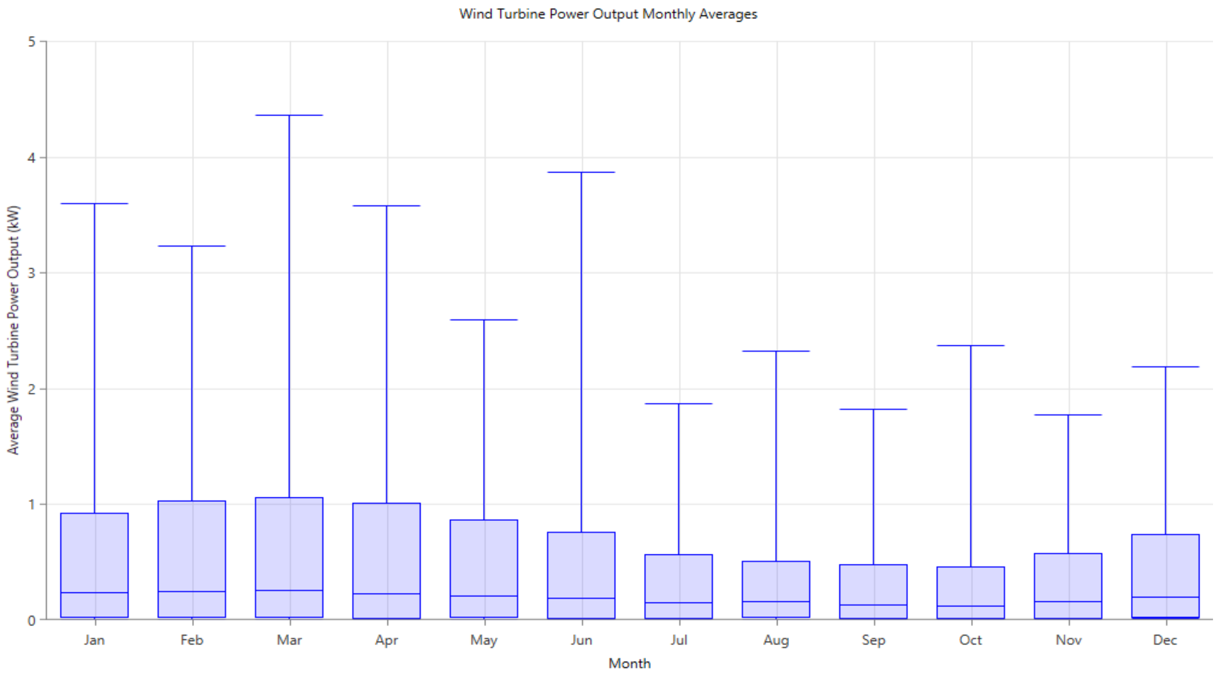
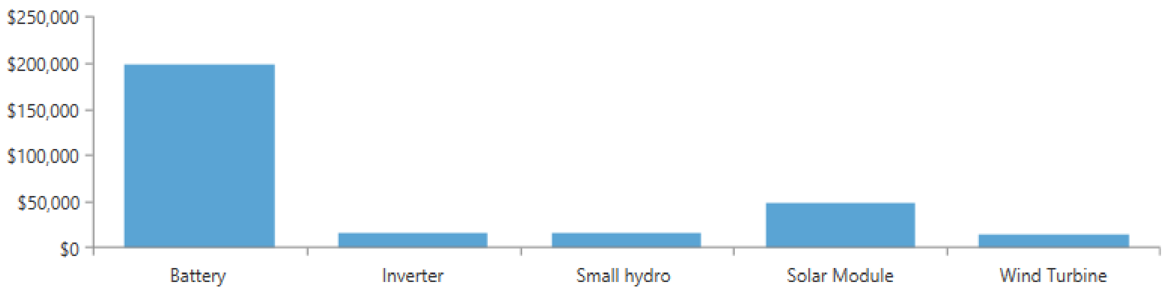


Figure 4.28: Monthly wind power output

The system NPC of the system by components is summarized in fig. 4.29. This cost breakdown shows that more than half of the system cost ($197,513) is used by the storage system (battery bank), followed by the solar modules ($47,916. Thus, reducing the system storage capacity will adversely reduce the overall cost of the system and hence make the system energy more affordable. The percent cost breakdown of the net present cost of the individual system components are shown in fig. 4.30.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery	$106,572.00	$70,409.14	$39,411.02	$0.00	($18,878.52)	$197,513.63
Inverter	$10,430.40	$6,891.07	$1,258.30	$0.00	($1,847.68)	$16,732.10
Small hydro	$10,000.00	$0.00	$5,935.39	$0.00	$0.00	$15,935.39
Solar Module	$15,944.53	$0.00	$31,971.99	$0.00	$0.00	$47,916.53
Wind Turbine	$7,797.00	$4,680.20	$2,730.28	$0.00	($1,254.88)	$13,952.60
System	$150,743.93	$81,980.41	$81,306.99	$0.00	($21,981.08)	$292,050.25

Figure 4.29: System NPC breakdown by components

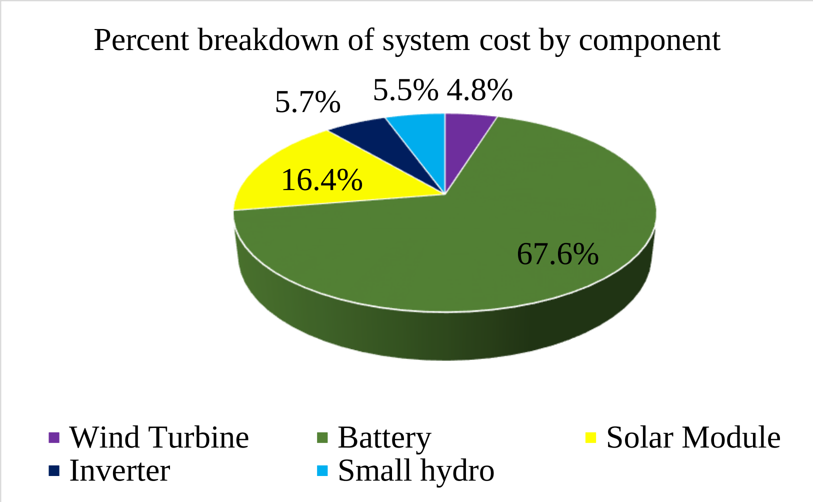


Figure 4.30: Percent breakdown of system component cost

From the above cost analysis, it is clear that reducing the number of batteries will adversely reduce the systems cost. Thus, other storage options (cheap) need to be explore for this system. As a temporal measure, the use of fuel cell system to replace the battery bank should be encourage even though fuel cells are very expensive. Also, the cost of wind turbines occupies 4.8% ($13,952) of the total net present cost and the overall wind output is only about 1% (1,702 kWh/yr) of the total system output. Hence, it will also be advisable to reduce the number of wind turbines to minimum or totally eliminate the wind component of the system to make the system more affordable.

4.3.5.2 Optimization analysis of optimum economic feasible system (scenario G)

Scenario G, as indicated in table 4.2 of the filtered scenario results consist of 67.3 kW of PV panel, 10 kW diesel generator connected in a load following dispatch strategy, 13.4 kW of Small hydro, 168 batteries (42 strings of 4 series 12V batteries) and 44.2 kW of bi-directional inverter. As such, a total capacity of 45 kW inverter will be used and this will require 9 of the 5 kW Power Star W7 inverter chosen for this study. The connection of the inverters shall be done in parallel strings based on the final system implementation strategy to be used. The yearly electrical power output from this system set-up is illustrated in figure 4.31, with diesel contributions in the months of January, February, March and December (peak dry season when water levels are low). The diesel generator is automatic and supplies whenever there is supply deficit from PV and small hydro. Thus, it serves as an additional storage for the facility. Solar has a fairly constant monthly and yearly generation with a slight decrease from the months of April to October (rainy season with low radiation values due to cloud covers, rainfalls and overcast conditions). Generations from the small hydro peaks in the months of July to October (peak rainy season in Cameroon), with no contributions for the months of January, February, March and December due to low stream flows as water levels decreases with the dry period.

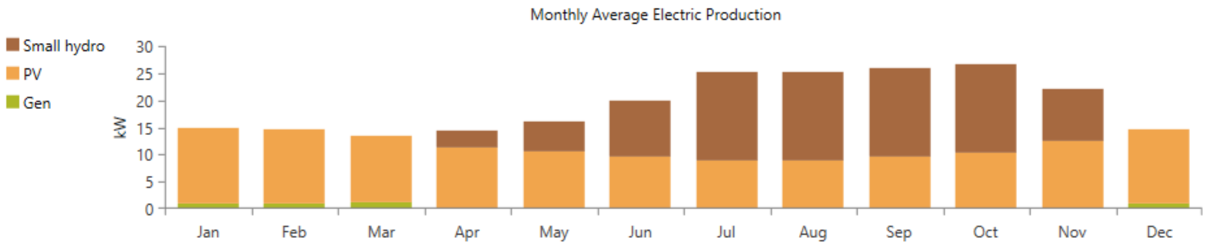


Figure 4.31: Electrical power generation of scenario G

This hybrid renewable power system produces an annual electricity of 170,095 kWh/yr (fig. 4.32), of which solar accounts for 57.7% (98,108 kWh/yr), small hydro 40.5% (68,851 kWh/yr), and only 1.84% (3,135 kWh/yr) from the genset. The genset size as earlier mention is restricted to 10 kW in this study and it only plays the role of a complimentary storage facility.

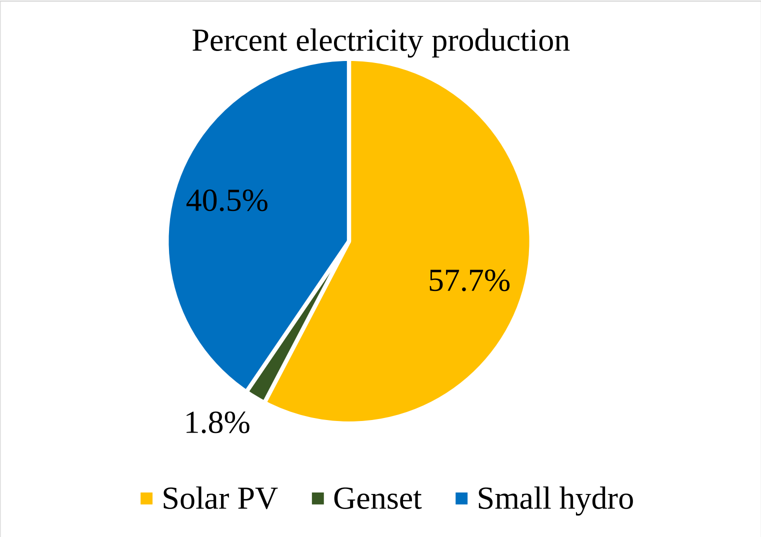


Figure 4.32: Percent share of electricity generation from scenario G

All the power generated by the hybrid system is consumed by the primary AC load (36,485 kWh/yr) with no deferral load. The system produces 74.7% excess power, registered 0.096% of electrical unmet load and a capacity shortage of 0.255%. Similar to the case of scenario E above, the amount of excess power produced by this system is high and can sustain future demand increases (increase in the number of households, small businesses expansions, increase household appliances and usage durations, as well as the connection of neighbouring villages). However, harnessing these power excesses will incurs additional cost which will increase the energy cost of the system. The performance of the system PV array is depicted in figure 4-33 with a decrease in PV output from March to October. With a rated capacity of 67.9 kW, mean output of 11.2 kW, maximum output of 57.8 kW and a capacity factor of 16.6%, the PV array produced a total of 98,108 kWh/yr with 4,363 hours of operation; giving a LCOE of 0.0411 $/kW and a PV penetration of 269%.

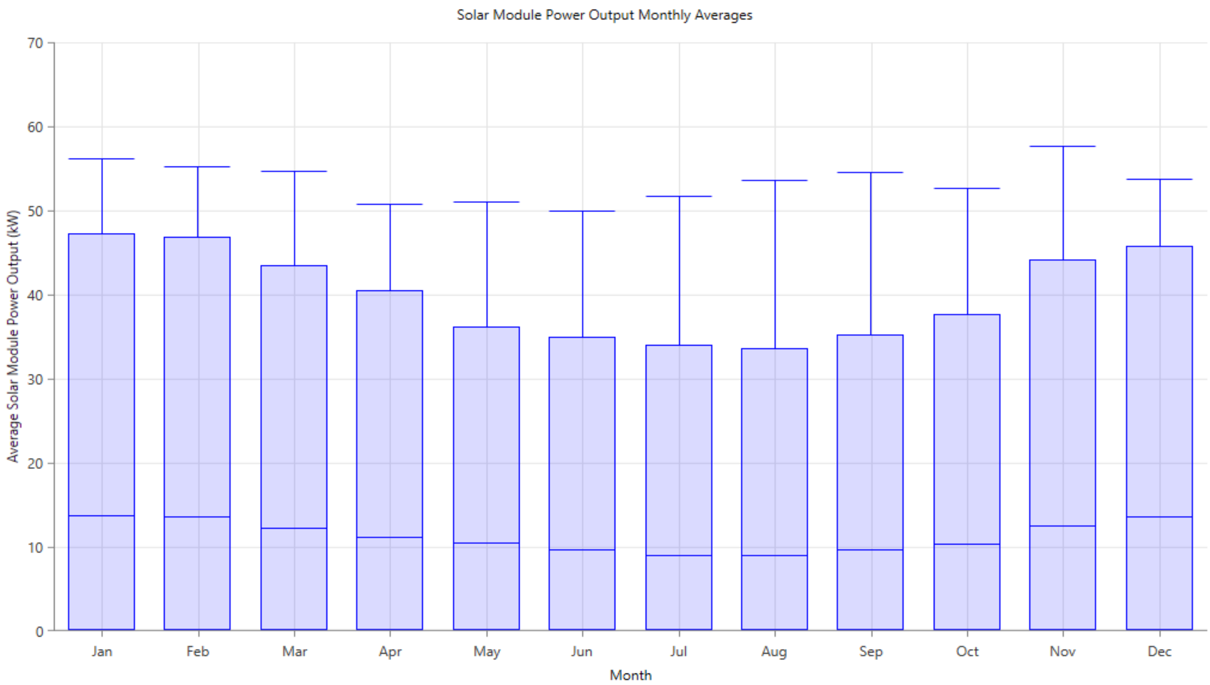


Figure 4.33: Solar modules monthly output averages of scenario G

The diesel power output from this system as displayed in figure 4.34, show no output for the months of May to November as solar and small hydro can adequately meet the load during these periods. The generator with an annual operation time of 1,204 hours, 248 starts, 3.58% capacity factor and with 20.8 years operational life generates a total of 3,135 kWh/yr with a mean/maximum output of 2.6/10 kW. It consumes a total of 1,475 L of fuel yearly (14,510 kWh/yr of fuel energy input) with an electrical efficiency of 21.6% and with a fixed generation cost of 0.424 $/hr and an annual power output of 3,135 kWh/yr. With a rated capacity of 10 kW and a highest output of 4.0 kW (March), the diesel genset operates under its nominal capacity throughout it operational life and this will result in enormous power losses and an overall decrease in the system efficiency.

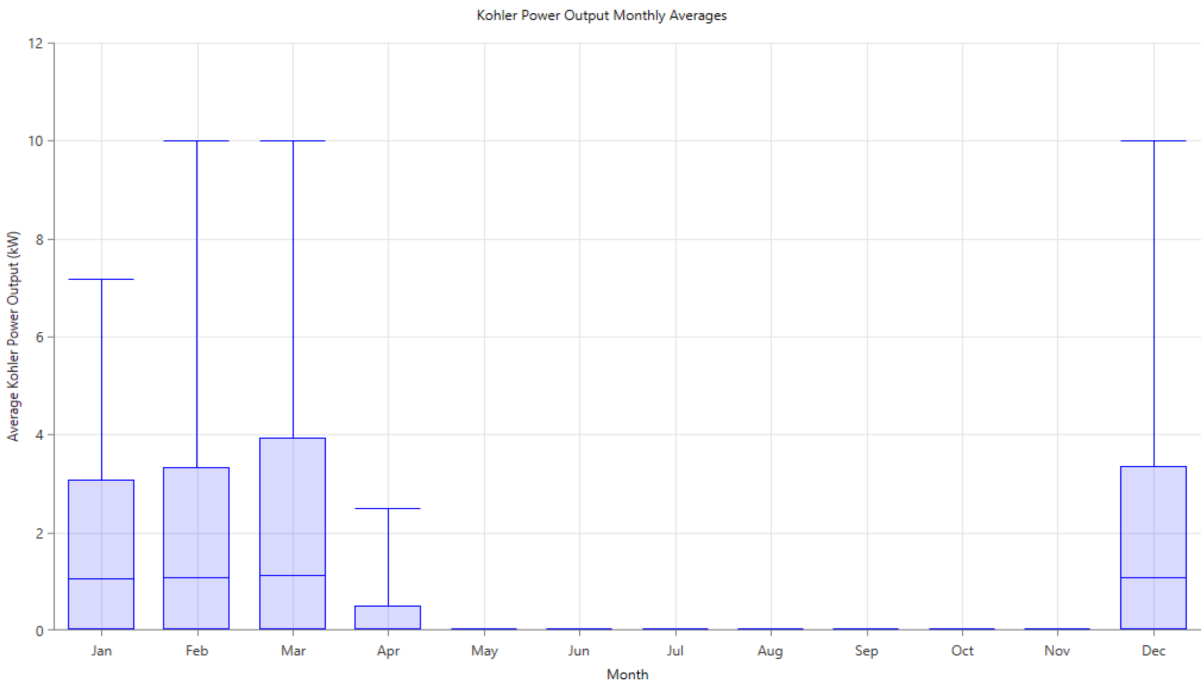
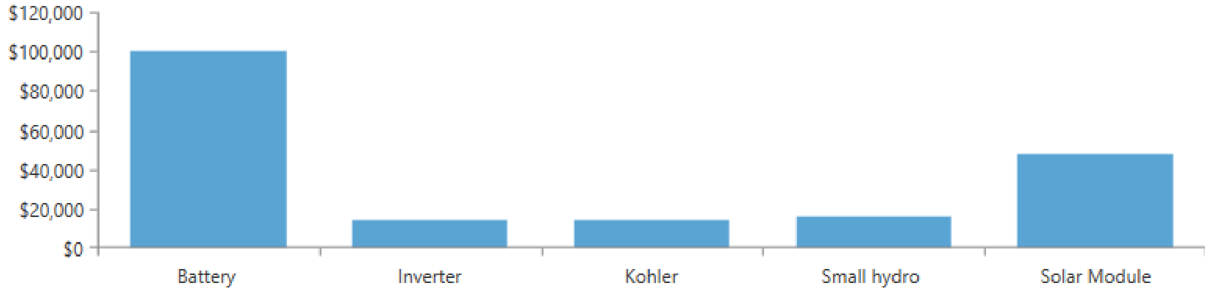


Figure 4.34: Monthly diesel output from scenario G

This system worth a total net present cost of $191,704, giving an energy cost of $0.443 and an operational cost of $8,308. The system NPC breakdown by components is summarized in fig. 4.35. This cost breakdown shows that more than half of the system capital cost ($99,946) is consumed by the storage system, followed by the solar modules ($47,916), small hydro ($15,935), diesel genset ($13,962) and the inverter ($19,943). Thus, reducing the system storage system will remarkably reduce the overall cost of the system and hence make the system energy more affordable. The breakdown of the net present cost of the system components in percentage is shown in fig. 4.36.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery	$53,928.00	$35,628.72	$19,942.93	$0.00	($9,552.99)	$99,946.66
Inverter	$8,692.00	$5,742.56	$1,048.59	$0.00	($1,539.73)	$13,943.42
Kohler	$4,508.00	$1,046.27	$285.85	$8,752.35	($630.37)	$13,962.09
Small hydro	$10,000.00	$0.00	$5,935.39	$0.00	$0.00	$15,935.39
Solar Module	$15,944.53	$0.00	$31,971.99	$0.00	$0.00	$47,916.53
System	$93,072.53	$42,417.55	$59,184.75	$8,752.35	($11,723.09)	$191,704.09

Figure 4.35: Scenario G system NPC breakdown by components

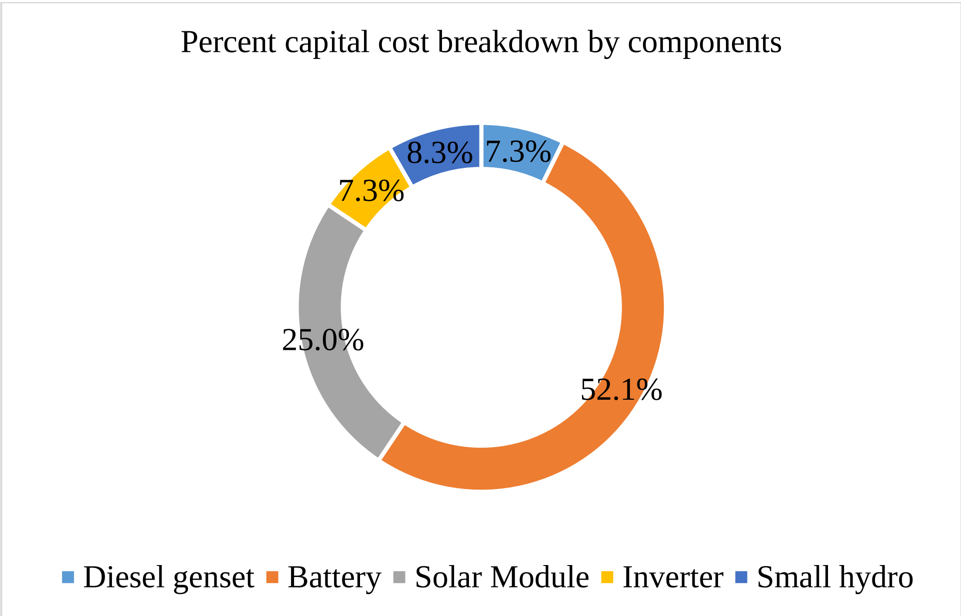


Figure 4.36: Percent breakdown of system component cost

Likewise, with scenario E and from the above cost analysis of scenario G, reducing the storage system will remarkably reduce the systems and energy cost. Thus, cheaper storage options need to be explore. Also, the performance of the diesel generator is not welcoming. It works below capacity and this affects the system performance, cost and cost of energy. If need be, it can be programmed to operate at maximum capacity or it should be completely removed from the system and replaced with cheap storage options or other power generation sources. The generator uses 7.3% ($13,962) of the capital cost but produces only 1.8% (3,135 kWh/yr) of the annual system output. Thus, not economically favourable for the system.

4.4 Comparison of the COE of scenarios with grid electricity cost in Cameroon

Grid electricity rates in Cameroon depends on the various consumer classes grouped into residential, business, industrial and large-scale users. Also, the nature of connections: low, medium and high voltage connection lines are also considered. In this study, we will compare the tariff of residential consumers of low voltage lines with the energy cost of the various hybrid power system. With domestic consumers, electricity rates depend on the consumer's monthly consumption. Consumption less or equal to 110 kWh cost 50 FCFA/kWh ($0.08/kWh); consumption between 111 to 400 kWh cost 79 FCFA/kWh ($0.13/kWh); between 401 to 800 kWh cost 94 FCFA/kWh ($0.15/kWh) and finally between 801 to 2000 kWh cost 99 FCFA/kWh ($0.16/kWh) (https://eneocameroon.cm/index.php/en/clients-particuliers-vos-factures-et-paiement-en/clients-particuliers-vos-factures-et-paiement-tarifs-delectricite-en). Comparison of these prices to the scenarios energy costs (fig. 4.9), shows that the cost of energy from the hybrid renewable energy system are far higher, irrespective of the consumption range. This is mainly due to high capacity factor and efficiency of hydropower generation (main power source of Cameroon). However, hydropower extensions to remote and isolated localities are often very expensive with lengthy delays of implementation. This makes grid extensions unfavourable for such localities, whose energy cost will be roughly similar to those of off-grid systems. Hence, off-grid hybrid renewable energy systems despite the high capital and energy cost are still interesting for sustainably powering isolated locations worldwide and especially in Cameroon.

4.5 Sensitivity analysis

Sensitivity analysis is aimed to check and evaluate the resilience the optimum system performances to changes in selected input parameters. This gives a blue print of the system reliability. Thus, in this section, interplay of some input parameters is performed to see the changes they will induce on the system performance and specifications. This enables the prediction of the effects of input uncertainties over the project life. The dependence of small hydro design flow rate, interest rate, PV capital cost multiplier and diesel fuel price, were analysed. The optimum economic hybrid power system (scenario G: PV/diesel/small hydro/battery) is only capable of supplying the load if it can accommodate changes in input parameters (especially the four parameters above) without such changes affecting the system power output and cost. The impacts design flow rate, interest rate, PV capital cost multiplier and diesel fuel price on the system COE, NPV and others, were analysed using surface and line plots. Figure 4.37 illustrates the impacts of discount rate and design flow rate on the system NPC and COE.

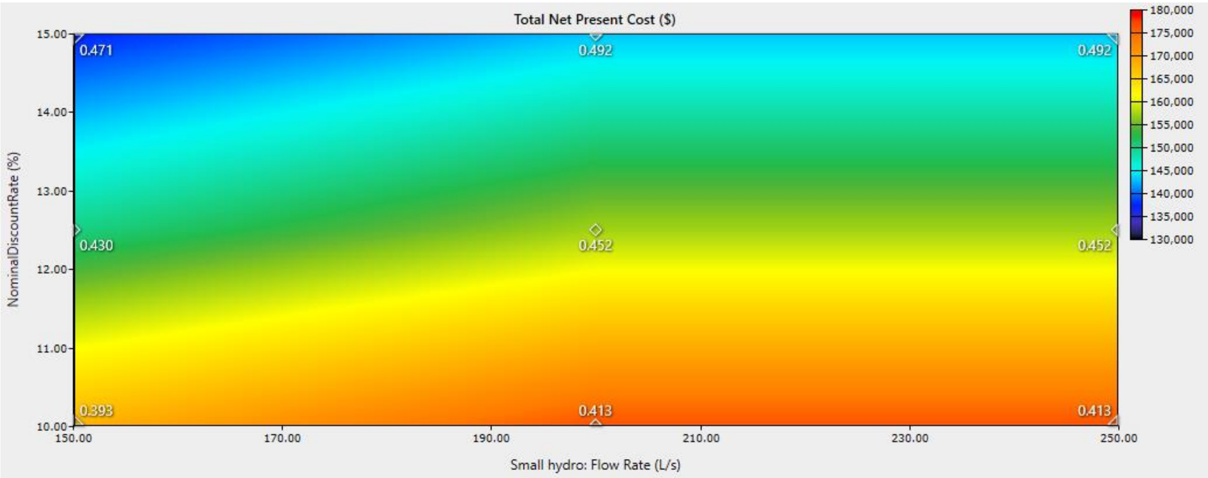


Figure 4.37: Effects of variations in small hydro flow rate and nominal discount rate on the COE and NPV.

In figure 4.37, other sensitivity variables: PV capital cost multiplier and diesel fuel price are kept constant at 0.2 and 0.99 $/L respectively. All the other design constraints (minimum renewable energy fraction of 40%, maximum capacity shortage of 2%, system operating reserve of 10%, system load of 100 kWh/d, etc.) are also kept constant. The surface of the surface plot represents the NPC ($) while the COE ($) is superimposed on the surface. As the discount rate increases from 10% to 15% (at 150 l/s design flow rate), the system's energy cost rises from $0.393 to $0.471 while the NPC drops from about $160,000 to $135,000. Thus, a high discount rate will make the system's energy very expensive and unaffordable by the community dwellers despite the more economic feasibility of the system with decrease in net present cost. More specifically, when the system design discount rate drops from 12.5% to 10%, the COE drops whereas the NPC increases and when it increases from 12.5% to 15%, the cost of energy will increase and the NPC falls. This shows that the discount rate effects on the COE antagonises it effects on the NPC of the system. With respect to the flow rate of the small hydro scheme and at 10% discount rate, an increase in the flow rate from 150 l/s to 250 l/s will cause a rise in energy cost from $0.393 to $0.413 while the NPC from $160,000 to $170,000. Hence, both the COE and NPC of the system will rise and fall as the flow rate rises above 200 l/s and falls below 200 l/s. This implies that low design flow favours both the economic feasibility of the system as well as energy affordability. Thus, if need be, the system design flow rate be decrease from 200 l/s as this will assure the contribution of small hydro throughout the year in the system energy output. Small hydro registers zero contribution for the months of December, January, February and March as the stream flow is far below the turbine's design flow. The effects of diesel fuel price and PV capital cost multiplier on the system COE and NPV are as shown in figure 4-38. The other chosen sensitivity variables: discount rate and flow rate are kept constant at 12.5% and 200 l/s respectively. The system design constraints as explained above are also maintained constant. Also, this surface plot presents the total NPC on the plot's surface and the COE superimposed.

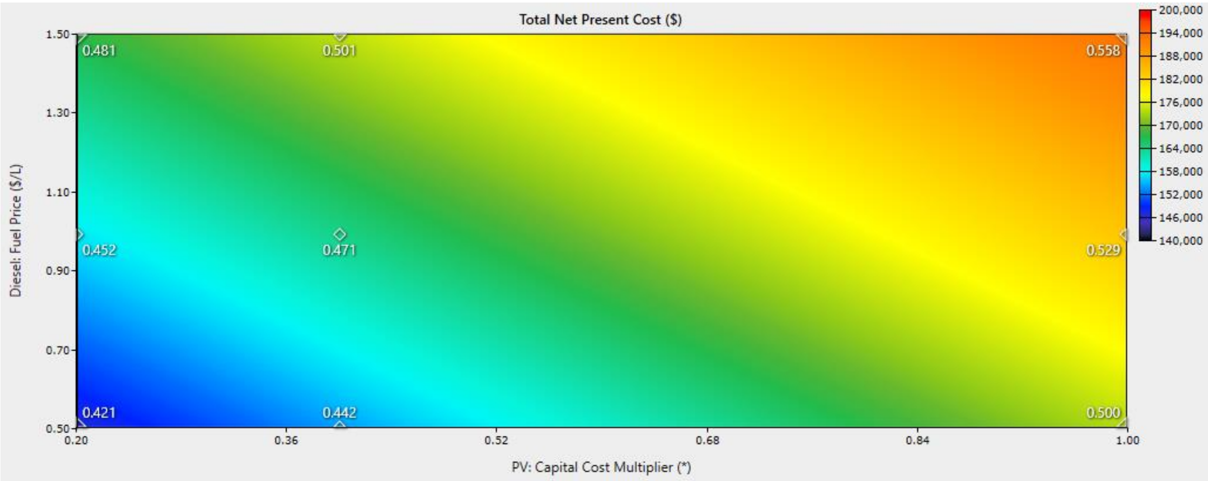


Figure 4.38: Impacts of diesel fuel price and PV cost multiplier on COE and NPV of system

In this case, when the diesel fuel price increases from $0.5/l to $1.5/l, the system COE rises from $0.421 to $0.481 while the NPC moves from about $146,000 to $170,000.

This increase in fuel price will adversely hinders the system energy affordability and economic feasibility. As such, diesel systems are not cost effect in remote localities with diesel price hikes. On the other hand, if diesel fuel can be purchased in bulk in the cities at medium cost and stored in the village for use, the system will be relatively affordable. This is with regards to the operations and maintenance cost for the system. Looking at the PV capital cost multiplier, an increase in this variable from 0.2 to 1.0 will results in an increase in the total NPC from $146,000 to $182,000; while the COE will rise from $0.421 to $0.500. All these changes occur at $0.5/l diesel fuel price. Thus, an increase in the capital cost of the PV component of the system will case the system unaffordable by the locals except otherwise subsidized by the state or local and international NGOs. Apart from the effects of the sensitivity variables on the COE and NPC, the effects of these variables on the PV and battery capacity were also investigated. This was done to evaluate the impacts of battery and PC capacity on the overall cost of the system, considering the facts that these two components' cost covers three quarter of the overall system cost. Thus, reducing their capacities in a way that will not affects the performance of the system will enhance the overall affordability by the locals and economic feasibilities of the system. Figure 4.39 displays the trends of diesel fuel price and PV capital cost multiplier on PV and battery capacity; the PV capacity on surface and battery capacity superimposed.

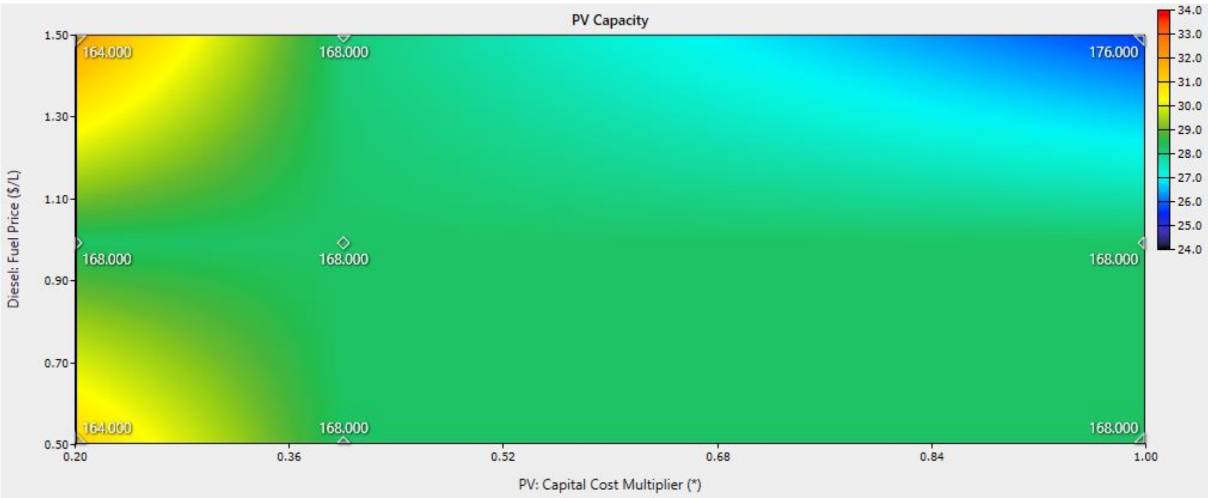


Figure 4.39: Effects of fuel price and PV cost multiplier on the system PV and battery capacity

This figure shows that increase or decrease in PV cost multiplier has no effect on the battery size as it remains constant at 168 and on the cost of the system. However, the PV capacity drops from 31-28 kW as PV cost multiplier moves from 0.2-1.0. PV capacity drop by 3 kW and this will reduce the PV capital cost and hence the system cost by $3,552. As the diesel fuel price increases from $0.5/l-$1.5/l, the battery size increases from 164 to 168 (at fuel price $0.99/l) and then falls to 164. Thus, the number of batteries drops by 4 units as fuel price falls to $0.5/L and this lowers the system cost by $1,284. The PV capacity drops from 31-28 kW likewise which decreases the system cost by $3,552. Similarly, when we evaluate the impacts of flow and discount rate on PV and battery capacities (fig. 4.40), the battery size increases by 8 units from 160-168 as flow rate increase from 150-250 l/s. This increases the system cost by $2,568. Also, the PV size falls from 29.1-28.4 kW with this rise in flow rate. On the side of discount rate, the battery and PV capacity remains constant at 160 units and 29.1 kW respectively as discount rate rises from 10-15%. Thus, no effect on the system cost.

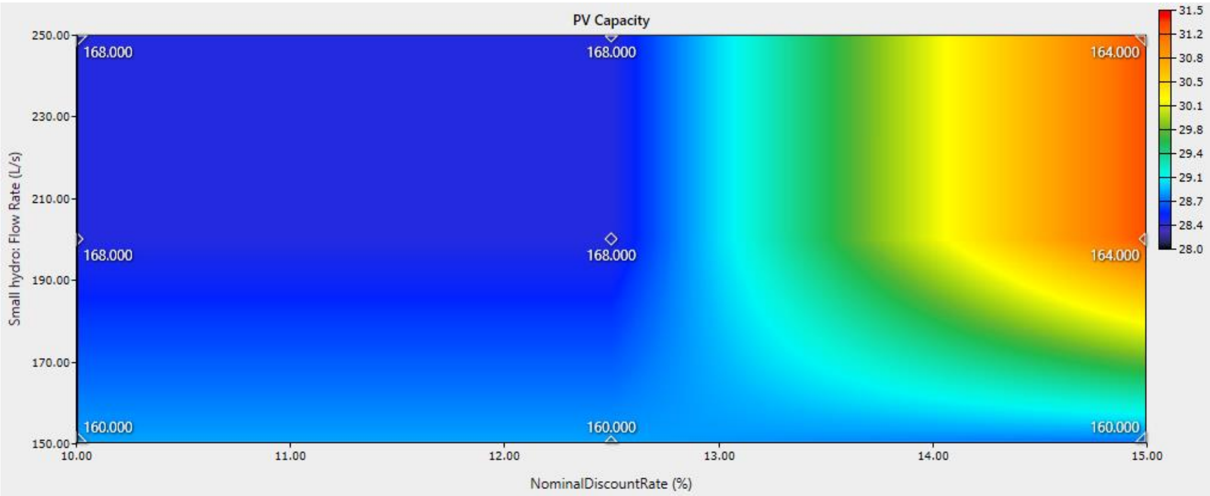


Figure 4.40: Impacts of discount and flow rate on system PV and battery sizes

To conclude, the effects of flow rate, discount rate, fuel price and PV capital cost multiplier on PV and battery capacities are not very much significant. Changes in these parameters will not impact much on the system cost and hence energy affordability for the village dwellers.

5 CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The aim of this study was to investigate the feasibilities of different hybrid renewable energy systems for the purpose of rural electrification of remote communities in Cameroon. Due to the diverse nature of the country with different climatic and energy resource potentials, the country was subdivided into three blocks or zones which represent all the climate zones of the country in the study. The analysis is performed using HOMER Pro version 9.9.2 (64-bits) together with satellite meteorological data of wind, solar radiation, air temperature, humidity, clearness Index etc. from weather stations at the various study sites and throughout the country. Two approaches: economic feasibility and, externalities and sustainability were used compare and rank the systems at the sites. Ten design parameters were used to scrutinised each of the above approach in order to select the best system which satisfactorily meet all the expectations of the parameters. The results obtained demonstrate that the optimum systems at each site varies, evident from the climate variations. In the west zone, the optimum system is a PV/diesel/small hydro/battery, with 67.3 kW PV, 10 kW diesel, 13.4 kW small hydro, 332 units of battery, 53 kW inverter and a load following dispatch strategy; giving a COE of 0.443 $/kWh. In the Center-South zone, the best economic feasible system is a PV/diesel/small hydro/battery system but with a composition consisting of 67.3 kW PV capacity, 10 kW generator, 13.4 kW small hydro, 224 units of battery, 35.5 kW of bi-directional Inverter and a load following generator dispatch strategy. This system gave an energy cost of 0.526 $/kWh. The best economic feasible system in the North zone was found to be a 67.3 kW PV, 11 units of wind turbines, 10 kW of diesel generator, 13.4 kW small hydro, 332 units of battery, 35.5 kW of bi-directional inverter and a load following generator dispatch mode. This gave a COE of 0.656 $/kWh. With respect to externalities, impact analysis and sustainability, PV/wind/small hydro/battery is the most feasible system in all the study sites with COE $0.674/kWh, $0.677/kWh, $0.583/kW for Wum, Yagoua and Yokadouma respectively. The COE obtained are far higher than the grid energy cost (0.08$/kWh). Considering systems supply reliability and the cost of long distance grid extensions to remote localities, these off-grid systems are more attractive for rural electrification than grid connections. They are also recommended for environmental reasons compared to isolated diesel systems. This is so because grid energy is mainly from hydropower with very high capacity factors and efficiencies compared to renewables. Hence, under these circumstances, these off-grid hybrid systems are not attractive for powering rural areas for cost reasons. However, considering systems supply reliability, ease of implementation, less transmission cost and losses, ease of local maintenance and the reduce cost of long distance grid extensions to remote localities, these off-grid system will be far more attractive for rural electrification than grid connections. They are also recommended for environmental reasons compared to isolated diesel systems. Cameroon.

5.2 Recommendation

- This study uses satellite datasets from meteorological stations at the various study sites. Future studies should consider using measured ground data for more precision.
- The design flow rate of the small hydro system in future studies should be reduced to around 150 l/s to allow contribution from small hydro all year round. This will also reduce the capacity of the other system components and hence the overall cost of system and energy.
- The diesel genset should be design to operate at full capacity in order to reduce the system cost.
- The wind resource of Cameroon is very low. As such, systems with wind components are not advisable for economic reasons.
- HOMER optimization involves complex simulation, optimizations and sensitivity analyses. Thus, in complex system designs (systems with many components), it is recommended to use high capacity and processors computers.

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APPENDICES

Appendix 1 : Village load estimation

Village daily Load estimation								
Load Category	block/ section	Appliances	Quantity	Watts (W)	Usage hr/d	Usage hr/d	Wh/d (AC load)	Total category Load /d
Nursery School	Classroom (02)	Bulbs	4	9	8:00-10:00	2	72	
	1 Office	Bulbs	2	9	8:00-10:00	2	36	
		External bulbs	1	9	18:00-6:00	12	108	
		Electric heater	1	1000	8:00-8:30	0.5	500	
		Radio/charger	1	5	8:00-1:00	5	25	741
Primary School (02)	6 Classroom	CR Bulbs (4)	48	9	7:00-09:00	2	864	
	2 Office	bulb-IN	2	9	7:00-09:00	2	36	
		bulb-EX	2	9	18:00-6:00	12	216	
		Radio/charger	1	5	7:00-14:00	7	35	1151
Secondary School (01)	5 Classrooms	bulbs (4)	20	9	7:00-09:00	2	360	
	3 Offices	bulbs (2)	6	9	7:00-9:00	2	108	
		Office bulb-EX	3	9	18:00-07:00	13	351	
		office desktop	3	60	9:00-12:00	3	540	
		Printer	1	60	8:00-10:00	2	120	
		Photocopier	1	60	10:00-11:00	1	60	1539
Health Clinic	5 Wards	bulbs (8)	40	9	18:00-12:00	6	2160	
			40	9	4:00-7:00	3	1080	
	2 Offices	bulbs (2)	4	9	19:00-7:00	12	432	
		bulbs-EX	5	9	18:00-6:00	12	540	
		Vaccine refrigerator	1	80	24hrs	24	1920	
		microscope (2)	2	20	9:00-11:00	2	80	
		radio/charger	2	5	11:00-17:00	6	60	
		Electric heater	1	1000	5:00-6:00	1	1000	
			1	1000	18:00-19:00	1	1000	8272
Community Load		Flour mills (5)	5	1000	8:00-9:00	1	5000	
			5	1000	16:00-18:00	2	10000	15000
Households (500)	4 rooms	bulb (1)	2000	9	20:00-21:00	1	18000	
	1 living room	bulb (1)	500	9	18:00-21:00	3	13500	
	1 kitchen-EX	bulb (1)	500	9	19:00-21:00	2	9000	
	External lighting	bulb-EX	50	9	18:00-21:00	3	1350	
		Radio/charger	150	5	6:00-9:00	3	2250	
			150	5	15:00-21:00	6	4500	
		TV	90	60	19:00-21:00	2	10800	59400
Small businesses (50)	50	bulb	50	9	18:00-21:00	3	1350	
		Bulb-EX	50	9	18:00-21:00	3	1350	
		Radio/charger	20	5	7:00-9:00	2	200	
			20	5	17:00-21:00	4	400	3300
				Safety load		10%*89406		8940.3
				Total load		**98343.3**		**100 kWh/d**

Appendix 2: Weather data (solar radiation, wind speed, clearness index, relative humidity, temperature) of all meteorological stations in Cameroon

Weather data of Cameroon													
Solar radiation (22 years average), clearness index (22 years average), wind speed (10 years average at 10m, humidity (22 years average) and air temperature (22 years average) at location elevation													
Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Abong Bang	(Latitude, Longitude, Elevation): (4ºN, 13.2ºE, 114m)												
Solar radiation (kWh/m2/d)	5.86	6.01	5.6	5.29	4.83	4.36	4.2	4.34	4.62	4.56	5.04	5.54	5.01
Wind Speed (m/s)	2.2	2.37	2.25	2.13	1.88	1.76	1.76	1.81	1.76	1.67	1.69	1.87	1.92
Clearness Index (K)	0.61	0.59	0.53	0.5	0.48	0.44	0.42	0.42	0.44	0.44	0.52	0.59	0.5
Relative Humidity (%)	48.9	53.3	71.5	76.3	76.5	77.7	76.8	78.8	80.8	79.1	74.6	58.5	71.1
Air temperature (ºC)	27.4	27.9	27.2	26.9	26.7	25.8	25.1	25.1	25.2	25.6	25.7	26.5	26.2
Akom	2.8ºN, 10.6ºE, 316m												
Solar radiation (kWh/m2/d)	5.12	5.13	4.92	4.65	4.34	4	3.91	3.71	3.77	3.71	4.13	4.78	4.34
Wind Speed (m/s)	1.62	1.81	1.35	1.14	1.21	1.49	1.79	1.94	1.8	1.36	1.22	1.26	1.49
Clearness Index (K)	0.52	0.5	0.46	0.45	0.43	0.41	0.4	0.36	0.36	0.36	0.41	0.49	0.43
Relative Humidity (%)	81.4	81.9	82	82.8	83.5	83	80.6	81	84.2	85.2	84.7	83.1	82.8
Air temperature (ºC)	23.7	24	24.5	24.6	24.4	23.5	22.8	22.9	23.1	23.3	23.5	23.6	23.7
Akonolinga	3.8ºN, 12.2ºE, 634m												
Solar radiation (kWh/m2/d)	5.3	5.45	5.21	4.99	4.59	4.29	4.24	4.18	4.48	4.33	4.42	4.93	4.69
Wind Speed (m/s)	1.59	1.72	1.56	1.35	1.14	1.14	1.29	1.49	1.46	1.27	1.18	1.33	1.37
Clearness Index (K)	0.53	0.53	0.49	0.48	0.46	0.44	0.43	0.41	0.43	0.42	0.44	0.51	0.46
Relative Humidity (%)	74	75	77	77.2	77.9	77.1	73.8	75.6	79.9	80.7	79.5	76.7	77
Air temperature (ºC)	24.2	24.7	25.1	25.3	25	24.2	23.7	23.8	23.8	23.9	24	24	24.3
Bafia	4.8ºN, 11.2ºE, 543m												
Daily horizontal radiation (kWh/m2/d)	5.73	5.86	5.45	5.19	4.93	4.61	4.33	4.37	4.63	4.55	4.97	5.46	5
Wind Speed (m/s)	2	2.12	1.92	1.75	1.62	1.69	1.78	1.86	1.77	1.55	1.53	1.67	1.76
Clearness Index (K)	0.59	0.57	0.52	0.49	0.49	0.47	0.43	0.43	0.44	0.44	0.51	0.58	0.5
Relative Humidity (%)	61	63.8	77.5	81.5	81.6	83.2	82.7	83.1	84.7	83.7	79.6	68.1	77.6
Air temperature (ºC)	24.2	24.8	24.2	24	23.8	22.8	22	22.1	22.3	22.6	22.9	23.6	23.3
Bamenda	6ºN, 10.2ºE, 1122m												
Solar radiation (kWh/m2/d)	6.3	6.35	5.83	5.34	5.07	4.62	4.29	4.26	4.48	4.74	5.65	6.08	5.24
Wind Speed (m/s)	2.5	2.53	2.58	2.46	2.4	2.33	2.14	2.17	2.04	1.95	2.16	2.33	2.29
Clearness Index (K)	0.67	0.63	0.56	0.51	0.49	0.46	0.42	0.41	0.43	0.47	0.59	0.66	0.52
Relative Humidity (%)	34.5	39.5	64.7	78.6	81.1	83.6	84.5	84.2	84.9	81.6	69.4	44.1	69.3
Air temperature (ºC)	22.6	23.3	22.4	21.5	21.2	20.1	19.3	19.3	19.6	20	20.2	21.7	20.9

Banyo	6.8ºN, 11.8ºE, 1116m												
Solar radiation (kWh/m2/d)	6.43	6.57	6.05	5.51	5.29	4.87	4.43	4.47	4.71	4.96	5.85	6.17	5.43
Wind Speed (m/s)	2.85	2.92	3.06	3.09	2.99	2.77	2.58	2.56	2.38	2.4	2.6	2.8	2.74
Clearness Index (K)	0.68	0.66	0.58	0.52	0.51	0.48	0.44	0.43	0.45	0.49	0.61	0.67	0.54
Relative Humidity (%)	27.8	30.7	56.2	74.6	78.3	81.1	82.6	82.8	82.7	77.8	60.1	35.9	64.4
Air temperature (ºC)	23.3	24.2	23.6	22.2	21.6	20.6	19.7	19.7	20	20.4	21.1	22.6	21.6
Batouri	4.4ºN, 14.4ºE, 656m												
Solar radiation (kWh/m2/d)	6.03	6.1	5.65	5.45	4.93	4.53	4.24	4.33	4.66	4.66	5.15	5.72	5.11
Wind Speed (m/s)	2.29	2.48	2.37	2.24	1.95	1.8	1.76	1.78	1.74	1.64	1.7	1.91	1.96
Clearness Index (K)	0.62	0.6	0.54	0.52	0.49	0.46	0.43	0.42	0.45	0.45	0.53	0.6	0.51
Relative Humidity (%)	44.2	49.5	69	74.4	74.4	74.5	72.6	75.9	78.7	77	71.8	53.8	68.1
Air temperature (ºC)	25.2	25.6	24.7	24.4	24.1	23.3	22.8	22.7	22.7	22.9	23.2	24.3	23.8
Bertoua	4.6ºN, 13.7ºE, 691m												
Solar radiation (kWh/m2/d)	5.86	6.01	5.6	5.29	4.83	4.36	4.2	4.34	4.62	4.56	5.04	5.54	5.01
Wind Speed (m/s)	2.2	2.37	2.25	2.13	1.88	1.76	1.76	1.81	1.76	1.67	1.69	1.87	1.92
Clearness Index (K)	0.61	0.59	0.53	0.5	0.48	0.44	0.42	0.42	0.44	0.44	0.52	0.59	0.5
Relative Humidity (%)	48.9	53.3	71.5	76.3	76.5	77.7	76.8	78.8	80.8	79.1	74.6	58.5	71.1
Air temperature (ºC)	24.3	24.8	24.1	23.9	23.6	22.7	22.1	22.1	22.2	22.5	22.6	23.5	23.2
Douala	4.1ºN, 9.7ºE, 406m												
Solar radiation (kWh/m2/d)	5.41	5.36	4.88	4.55	4.37	3.91	3.41	3.04	3.44	3.7	4.3	5.05	4.27
Wind Speed (m/s)	1.95	2.04	1.75	1.47	1.46	1.84	2.12	2.23	2.02	1.55	1.45	1.56	1.78
Clearness Index (K)	0.56	0.53	0.46	0.43	0.43	0.39	0.34	0.29	0.33	0.36	0.44	0.53	0.42
Relative Humidity (%)	73.9	76.2	82.2	84	84.8	85.9	85.5	85.7	86.9	86.8	84.2	78.6	82.9
Air temperature (ºC)	24.1	24.4	24.2	24.3	24.1	23.2	22.4	22.3	22.6	22.9	23.3	23.7	23.4
Ebolowa	2.9ºN, 11.1ºE, 501m												
Solar radiation (kWh/m2/d)	5.3	5.36	5.19	4.93	4.61	4.25	4.16	4.04	4.26	4.18	4.38	4.97	4.63
Wind Speed (m/s)	1.6	1.77	1.46	1.25	1.17	1.32	1.53	1.71	1.63	1.32	1.2	1.3	1.43
Clearness Index (K)	0.53	0.52	0.49	0.47	0.46	0.44	0.43	0.4	0.41	0.4	0.44	0.51	0.46
Relative Humidity (%)	78.8	79.6	80.2	80.6	81	80.8	78.2	78.9	82.6	83.5	82.7	80.8	80.6
Air temperature (ºC)	23	23.4	23.8	24	23.8	22.9	22.3	22.4	22.5	22.7	22.9	22.9	23
Edéa	3.8ºN, 10.1ºE, 242m												
Solar radiation (kWh/m2/d)	5.31	5.36	5.07	4.88	4.58	4.01	3.53	3.35	3.69	3.86	4.46	5.04	4.42
Wind Speed (m/s)	1.71	1.85	1.47	1.23	1.22	1.5	1.75	1.87	1.73	1.33	1.22	1.31	1.51
Clearness Index (K)	0.54	0.52	0.48	0.47	0.45	0.41	0.36	0.33	0.35	0.37	0.45	0.53	0.44
Relative Humidity (%)	79.5	80.6	82.5	83.5	84.2	84.9	83.4	83.9	86	86.3	84.8	82.2	83.5
Air temperature (ºC)	24.2	24.6	24.8	25	24.8	23.9	23.2	23.2	23.3	23.6	23.9	24	24.1
Fontem	5.5ºN, 9.9ºE, 1080m												

Solar radiation (kWh/m2/d)	5.81	5.77	5.35	4.99	4.68	4.32	3.86	3.58	4.09	4.32	4.88	5.48	4.75
Wind Speed (m/s)	2	2.04	1.89	1.63	1.6	1.86	1.88	1.98	1.81	1.48	1.55	1.64	1.78
Clearness Index (K)	0.61	0.57	0.51	0.47	0.46	0.43	0.38	0.35	0.39	0.42	0.5	0.59	0.47
Relative Humidity (%)	59.2	63.9	79	83.8	84.5	86.4	86.7	86.2	87.2	86.3	81.4	68	79.5
Air temperature (ºC)	21.2	21.5	21	20.8	20.7	19.8	18.9	18.9	19.2	19.6	19.8	20.4	20.1
Garoua	9.3ºN, 13.4ºE, 332m												
Solar radiation (kWh/m2/d)	6.07	6.36	6.5	6.24	5.78	5.37	4.93	4.83	5.16	5.7	6.17	5.93	5.74
Wind Speed (m/s)	3.82	3.78	4.13	4.28	3.93	3.3	3.05	2.92	2.73	3.03	3.52	3.97	3.53
Clearness Index (K)	0.67	0.65	0.63	0.59	0.55	0.52	0.48	0.46	0.5	0.58	0.67	0.68	0.58
Relative Humidity (%)	17.7	16.1	31.1	56.7	69.6	76.7	80.1	80.3	76.9	61.4	28.9	20.4	51.5
Air temperature (oC)	26.5	28.3	30.2	29	27.2	25.6	24.5	24.4	25	26.3	28.1	27.1	26.8
Garoua Boulai	5.9ºN, 14.6ºE, 866m												
Solar radiation (kWh/m2/d)	6.34	6.42	5.89	5.5	5.07	4.68	4.38	4.5	4.78	4.8	5.58	6.06	5.32
Wind Speed (m/s)	2.84	3.01	3.1	3.18	3.02	2.75	2.6	2.58	2.39	2.45	2.57	2.77	2.77
Clearness Index (K)	0.66	0.64	0.56	0.52	0.5	0.47	0.44	0.44	0.46	0.47	0.58	0.65	0.53
Relative Humidity (%)	32.5	38.1	64.9	76	76.2	77.4	77.7	79.4	79.6	75.7	65.1	41.8	65.5
Air temperature (ºC)	24.9	25.4	24.1	23.4	23	22.1	21.3	21.3	21.6	22	22.5	24.1	23
Kribi	2.9ºN, 9.9ºE, 21m												
Solar radiation (kWh/m2/d)	5.41	5.57	5.2	4.92	4.51	3.9	3.94	3.98	3.82	3.82	4.7	5.11	4.56
Wind Speed (m/s)	1.8	1.99	1.51	1.31	1.45	1.9	2.33	2.46	2.25	1.71	1.47	1.49	1.8
Clearness Index (K)	0.55	0.54	0.49	0.47	0.45	0.4	0.4	0.39	0.36	0.37	0.47	0.53	0.45
Relative Humidity (%)	82.4	82.7	82.7	83.8	84.6	82.8	80.8	81.6	84.4	85.5	85.7	84	83.4
Air temperature (ºC)	25.4	25.8	26.1	26.2	25.9	25	24.3	24.3	24.5	24.8	25.1	25.3	25.2
Maroua	10.6ºN, 14.3ºE, 394m												
Solar radiation (kWh/m2/d)	5.61	6.24	6.56	6.31	5.96	5.5	5.03	4.84	5.34	5.7	5.85	5.56	5.7
Wind Speed (m/s)	4.11	4.04	4.42	4.58	4.18	3.49	3.23	3.07	2.84	3.21	3.77	4.26	3.76
Clearness Index (K)	0.63	0.65	0.63	0.59	0.56	0.53	0.48	0.46	0.51	0.58	0.65	0.64	0.58
Relative Humidity (%)	17.2	14.2	22.5	44.3	59.2	70.1	78	78.2	72.3	48.5	23.1	19.4	45.8
Air temperature (ºC)	25.9	27.9	30.9	30.5	28.7	26.5	24.7	24.5	25.4	27.7	28.6	26.6	27.3
Meiganga	6.5ºN, 14.3ºE, 1023m												
Solar radiation (kWh/m2/d)	6.5	6.76	6.33	5.67	5.25	4.88	4.59	4.63	4.9	4.93	5.93	6.31	5.54
Wind Speed (m/s)	3.22	3.34	3.57	3.74	3.59	3.21	2.99	2.92	2.69	2.85	3.07	3.32	3.2
Clearness Index (K)	0.69	0.68	0.6	0.54	0.51	0.49	0.45	0.45	0.47	0.49	0.62	0.69	0.55
Relative Humidity (%)	24.8	27.5	53.9	72.3	75.2	77.6	79.8	80.8	79	72.1	51.6	31.8	60.7
Air temperature (oC)	24	25	24.5	23.2	22.6	21.6	20.6	20.6	21	21.5	22.8	23.7	22.6
Mokolo	10.8ºN, 13.3ºE, 628m												

Solar radiation (kWh/m2/d)	5.94	6.36	6.55	6.24	5.87	5.42	4.98	4.75	5.23	5.71	6.09	5.82	5.74
Wind Speed (m/s)	4.01	3.93	4.32	4.47	4.08	3.41	3.17	3.02	2.8	3.14	3.67	4.16	3.68
Clearness Index (K)	0.67	0.66	0.63	0.59	0.56	0.52	0.48	0.45	0.5	0.58	0.67	0.67	0.58
Relative Humidity (%)	18.8	15.8	25.1	49.7	64.6	75	80.5	80	75.8	54.4	25	20.8	49
Air temperature (oC)	23.6	25.6	28.6	28.1	26.5	24.5	23.1	23	23.7	25.2	26.3	24.3	25.2
Mora	11ºN, 14.1ºE, 301m												
Solar radiation (kWh/m2/d)	5.59	6.29	6.67	6.56	6.29	5.86	5.27	4.98	5.52	5.77	5.74	5.35	5.81
Wind Speed (m/s)	4.29	4.21	4.59	4.74	4.32	3.6	3.33	3.17	2.92	3.31	3.91	4.48	3.9
Clearness Index (K)	0.64	0.66	0.65	0.62	0.59	0.56	0.5	0.47	0.53	0.59	0.64	0.63	0.59
Relative Humidity (%)	18.3	15.1	18.5	35.7	50.9	64.3	76.1	76.6	67.6	40.1	21	19.9	42.2
Air temperature (oC)	25.1	27	30.9	31.9	30.4	28	25.7	25.4	26.6	29.1	28.7	26	27.9
Ngounderé	7.3ºN, 13.6ºE, 933m												
Solar radiation (kWh/m2/d)	6.48	6.74	6.53	5.83	5.42	5.01	4.67	4.66	4.84	5.25	6.16	6.27	5.64
Wind Speed (m/s)	3.41	3.44	3.73	3.87	3.63	3.14	2.9	2.81	2.62	2.83	3.17	3.52	3.25
Clearness Index (K)	0.7	0.68	0.62	0.55	0.52	0.49	0.46	0.45	0.46	0.52	0.65	0.69	0.57
Relative Humidity (%)	21.3	21.4	42.9	66	73.9	78	80.8	81.7	79.1	70.7	42.1	26.4	57.2
Air temperature (ºC)	23.8	25.3	25.9	24.5	23.4	22.2	21.2	21.1	21.5	22.1	23.7	23.8	23.2
Nkoteng	4.5ºN, 12ºE, 671m												
Solar radiation (kWh/m2/d)	5.81	5.95	5.55	5.19	4.82	4.48	4.38	4.5	4.75	4.59	5.01	5.5	5.04
Wind Speed (m/s)	2.12	2.27	2.13	2	1.81	1.72	1.76	1.85	1.79	1.69	1.68	1.84	1.88
Clearness Index (K)	0.6	0.58	0.53	0.49	0.48	0.45	0.44	0.44	0.45	0.45	0.51	0.58	0.5
Relative Humidity (%)	55.3	58.4	74.6	78.6	78.9	80.4	79.9	80.9	82.6	81.2	77	63.9	74
Air temperature (ºC)	23.8	24.4	23.9	23.7	23.5	22.5	21.8	21.8	22	22.4	22.5	23.1	22.9
Poli	8.5ºN, 13.2ºE, 401m												
Solar radiation (kWh/m2/d)	6.28	6.54	6.51	6.1	5.65	5.3	4.88	4.78	5.09	5.66	6.21	6	5.74
Wind Speed (m/s)	3.62	3.59	3.93	4.05	3.74	3.17	2.92	2.8	2.63	2.89	3.33	3.74	3.36
Clearness Index (K)	0.68	0.66	0.62	0.58	0.54	0.52	0.47	0.46	0.49	0.57	0.67	0.67	0.58
Relative Humidity (%)	18.6	18.1	36.5	60.8	71.8	77.1	79.8	80.5	77.5	66.4	34.7	22.2	53.9
Air temperature (ºC)	26.2	27.9	29.3	28	26.4	25.1	24.1	23.9	24.4	25.3	26.9	26.6	26.2
Tchollirre	8.5ºN, 14.2ºE, 404m												
Solar radiation (kWh/m2/d)	6.23	6.54	6.51	6.16	5.67	5.26	4.92	4.81	5.12	5.6	6.17	5.99	5.74
Wind Speed (m/s)	3.66	3.64	3.98	4.12	3.78	3.21	2.96	2.83	2.65	2.92	3.37	3.8	3.4
Clearness Index (K)	0.68	0.66	0.62	0.58	0.54	0.51	0.48	0.46	0.49	0.56	0.66	0.67	0.58
Relative Humidity (%)	18	17.1	33.7	57.7	68.7	75	78.8	79.5	75.9	61.9	31.5	21.4	51.8
Air temperature (ºC)	26.4	28.2	29.8	28.5	26.9	25.4	24.2	24.1	24.6	25.8	27.4	26.8	26.5
Tibati	6.5ºN, 12.6ºE, 933m												

Solar radiation (kWh/m2/d)	6.45	6.64	6.32	5.75	5.51	5.13	4.71	4.79	5.04	5.19	5.96	6.26	5.63
Wind Speed (m/s)	3.19	3.3	3.53	3.71	3.58	3.19	3	2.95	2.71	2.86	3.04	3.28	3.19
Clearness Index (K)	0.68	0.66	0.6	0.54	0.54	0.51	0.46	0.46	0.48	0.51	0.63	0.68	0.56
Relative Humidity (%)	25.4	27	52.6	73.1	76.9	79.5	81.5	82.3	81.3	75.6	54.8	32.7	62.1
Air temperature (ºC)	24.4	25.5	25	23.5	22.8	21.8	20.8	20.9	21.2	21.6	22.6	24	22.8
Tingere	7.4ºN, 12.7ºE, 983m												
Soar radiation (kWh/m2/d)	6.42	6.65	6.41	5.75	5.4	4.98	4.63	4.59	4.82	5.18	6.09	6.23	5.59
Wind Speed (m/s)	3.39	3.4	3.69	3.82	3.6	3.1	2.88	2.81	2.61	2.82	3.14	3.48	3.22
Clearness Index (K)	0.69	0.67	0.61	0.54	0.52	0.49	0.45	0.44	0.46	0.52	0.65	0.69	0.56
Relative Humidity (%)	21.8	22.5	45.7	68.4	76	79.7	81.7	82.4	80.4	73.9	46.8	27.6	59.1
Air temperature (ºC)	23.4	24.9	25.2	23.9	22.8	21.7	20.7	20.6	21.1	21.5	22.7	23.3	22.6
Wum	6.4ºN, 10.1ºE, 1101m												
Solar radiation (kWh/m2/d)	6.3	6.35	5.83	5.34	5.07	4.62	4.29	4.26	4.48	4.74	5.65	6.08	5.24
Wind Speed (m/s)	2.5	2.53	2.58	2.46	2.4	2.33	2.14	2.17	2.04	1.95	2.16	2.33	2.29
Clearness Index (K)	0.67	0.63	0.56	0.51	0.49	0.46	0.42	0.41	0.43	0.47	0.59	0.66	0.52
Relative Humidity (%)	34.5	39.5	64.7	78.6	81.1	83.6	84.5	84.2	84.9	81.6	69.4	44.1	69.3
Air temperature (oC)	22.8	23.4	22.5	21.6	21.3	20.3	19.4	19.4	19.7	20.1	20.3	21.8	21
Yagoua	10.4ºN, 15.2ºE, 311m												
Solar radiation (kWh/m2/d)	5.76	6.3	6.62	6.33	6.03	5.58	5.04	4.87	5.35	5.79	5.91	5.65	5.76
Wind Speed (m/s)	4.21	4.13	4.53	4.68	4.26	3.56	3.29	3.13	2.89	3.27	3.86	4.4	3.85
Clearness Index (K)	0.65	0.65	0.64	0.6	0.57	0.54	0.48	0.46	0.52	0.59	0.65	0.65	0.58
Relative Humidity (%)	16.1	13.3	21.4	40.5	55.1	65.9	75.7	76.9	69.2	45	22.5	18.6	43.5
Air temperature (ºC)	27.2	29.1	32.2	31.9	29.9	27.6	25.5	25.1	26.2	28.8	29.6	27.8	28.4
Yaoundé	3.9ºN, 11.5ºE, 622m												
Solar radiation (kWh/m2/d)	5.43	5.49	5.2	4.97	4.65	4.26	4	3.98	4.26	4.13	4.56	5.12	4.66
Wind Speed (m/s)	1.72	1.86	1.56	1.34	1.21	1.35	1.53	1.67	1.6	1.31	1.22	1.34	1.47
Clearness Index (K)	0.55	0.53	0.49	0.48	0.46	0.44	0.4	0.39	0.41	0.4	0.46	0.53	0.46
Relative Humidity (%)	75.9	77.2	80.8	81.6	82	83.1	81.8	82.4	84.6	84.7	82.9	79.4	81.4
Air temperature (ºC)	22.4	22.9	23.2	23.4	23.2	22.2	21.4	21.5	21.7	21.9	22.1	22.2	22.3
Yokadouma	3.5ºN, 15.1ºE, 562m												
Solar radiation (kWh/m2/d)	5.87	5.86	5.51	5.32	4.9	4.5	4.34	4.25	4.56	4.54	4.92	5.59	5
Wind Speed (m/s)	2.02	2.28	2.1	1.9	1.58	1.49	1.42	1.45	1.47	1.33	1.35	1.56	1.65
Clearness Index (K)	0.6	0.57	0.52	0.51	0.49	0.46	0.44	0.42	0.44	0.44	0.5	0.58	0.5
Relative Humidity (%)	52.3	56.3	69.4	72.1	70.8	67.6	61.8	67.9	74.7	74.9	71.6	60.2	66.7
Air temperature (ºC)	25.1	25.6	25.1	25	24.9	24.4	24.5	24.1	23.6	23.7	23.9	24.5	24.5