MASTER THESIS

ENERGY TECHNOLOGY FOR SUSTAINABLE DEVELOPENT

DESIGN OF A HYBRID RENEWABLE ENERGY SYSTEM ISOLATED FROM THE POWER GRID IN A RURAL COMMUNITY IN ZAMBIA

AUTHOR: **AXELSSON, JOSEFINE**

SUPERVISOR: GÓMEZ NAVARRO, TOMÁS

SUPERVISOR: RIBÓ PÉREZ, DAVID

Academic Year: 2018-19

ACKNOWLEDGEMENT

I would like to take this opportunity to express my sincere gratitude to my supervisors Tomás Gómez Navarro and David Ribó Pérez, for their support and encouragement as well as their invaluable knowledge and guidance, throughout this thesis process.

RESUMEN

Zambia es un país en vías de desarrollo del sur de África. Sus tasas de electrificación urbana y rural son del 67.3% y 4.4% respectivamente. La diferencia entre el acceso a la electricidad de las zonas rurales y urbanas reside en la dispersión de su población rural. Por ello, los sistemas aislados son necesarios para electrificar estas áreas rurales que se encuentran lejos de la red eléctrica central. Este estudio pretende investigar sobre el diseño y viabilidad de un sistema híbrido de energías renovables en la comunidad rural de Mumbeji, ubicada al noroeste de Zambia. El potencial renovable y las curvas de carga de la comunidad han sido estimados en base a una búsqueda bibliográfica y posteriormente modelas en la herramienta informática HOMER Pro. Se ha realizado un análisis económico, medioambiental y social para evaluar la viabilidad del proyecto y los posibles riesgos asociados al mismo. La configuración óptima obtenida ha sido un gasificador de biomasa de 25 kW, 80 kW de energía solar fotovoltaica, un banco de baterías de una capacidad de 360 kWh y un inversor de 27 kW. El diseño y los costes de la red eléctrica y elementos adicionales han sido estimados también. Así, en HOMER se obtiene que el Coste Actualizado Neto del proyecto asciende a 382,000€. En caso de añadir la red y el resto de componentes, el coste asciende a 469,000€. Por tanto, el coste de la electricidad no es competitivo respecto a los precios actuales subsidiados por el estado. Se concluye que la viabilidad es la mayor barrera para la implementación del proyecto, que necesitará de algún subsidio para ser viable. El análisis social subraya la necesidad de involucrar a la comunidad desde el principio del proyecto para asegurar un diseño correcto y su viabilidad a largo plazo.

Palabras Clave: Sistemas híbridos de energía renovable; Simulación con HOMER; Sostenibilidad; Comunidades rurales aisladas; Zambia.

RESUM

Zàmbia és un país en vies de desenvolupament del sud d’Àfrica. Les seues taxes d’electrificació urbana i rural son del 67.3% y 4.4% respectivament. La diferència entre l’accés a l’electricitat de les zones rurals i urbanes resideix en la dispersió de la seua població rural. Per això, els sistemes aïllats són necessaris per a electrificar aquestes àrees rurals que es troben lluny de la xarxa elèctrica central. Aquest estudi pretén investigar al voltant del disseny i viabilitat d’un sistema híbrid d’energies renovables en la comunitat rural de Mumbeji, ubicada al nord-oest de Zàmbia. El potencial renovable i les corbes de càrrega de la comunitat han sigut estimades a partir d'una recerca bibliogràfica i posteriorment modelades en la ferramenta informàtica HOMER Pro. S'ha realitzat un anàlisis econòmic, mediambiental i social per avaluar la viabilitat del projecte i els possibles riscos associats al mateix. La configuració òptima obtinguda ha sigut un gasificador de biomassa de 25 kW, 80 kW d’energia solar fotovoltaica, un banc de bateries d’una capacitat de 360 kWh i un inversor de 27 kW. El disseny i els costos de la xarxa elèctrica i elements addicionals han sigut estimats també. Així, en HOMER s’obté que el Cost Actualitzat Net del projecte ascendeix a 382,000€. En cas d’afegir la xarxa i la resta de components, el cost ascendeix a 469,000€. Per tant, el cost de l'electricitat no és competitiu respecte als preus actuals subsidiats per l’estat. Es conclou que la viabilitat és la barrera més gran per a la implementació del projecte, que necessitarà algun subsidi per tal de ser viable. L’anàlisi social subratlla la necessitat d’involucrar a la comunitat des del principi del projecte per a assegurar un disseny correcte i la seua viabilitat a llarg termini.

Paraules clau: Sistemas híbridos de energía renovable; Simulación con HOMER; Sostenibilidad; Comunidades rurales aisladas; Zambia.

ABSTRACT

Zambia is a developing country in southern Africa with an urban electrification rate of 67.3% and a rural electrification rate of 4.4%. The difference in rural and urban access to electricity partly depends on its sparsely populated rural areas. Stand-alone energy systems are necessary in order to electrify these rural areas located far from the national grid. This study intends to investigate the optimal design and the feasibility of a renewable hybrid energy system in the rural community of Mumbeji, in the North-Western province of Zambia. Renewable energy potentials and demand load profiles have been estimated from literature studies and modelled in the software tool HOMER Pro. Economic, environmental and social assessments were performed to evaluate the feasibility and identify possible risks of a project. The optimal configuration found with the modelling tool consists of a 25 kW gasifier, 80 kW of PV modules, batteries with a total capacity of 360 kWh and a inverter of 27 kW. The design and costs of the power grid were estimated as well as the necessary additional system components. In HOMER, the system's Net Present Cost of the project is 382,000€. The addition of a grid and additional components make the total system cost 469,000€. Therefore, the cost of electricity of the system is not competitive compared to the country's current subsidised electricity tariffs. It can be concluded that the economic feasibility is the major challenge to the system's implementation. Thus, the system needs to be subsidised to be economically viable. The social analysis highlights that the participation and integration of the community from the start of project is crucial for a successful design and a long-term sustainability of the system.

Keywords: Hybrid Renewable Energy Systems; Simulation with HOMER; Sustainability; Isolated rural communities; Zambia.

Table of contents

List of Figures

List of Tables

Acronyms and Abbreviations

7NDP	7th National Development Plan
DRC	Democratic Republic of Congo
EDL	Economical Distance Limit
ERB	The Energy Regulation Board
FAO	the Food and Agriculture Organisation of the United Nations
GDP	Gross Domestic Product
GHG	Greenhouse Gas Emissions
ha	Hectare
HFO	Heavy Fuel Oil
HHV	Higher Heating Value
INDC	Intended National Determined Contribution plan
IRENA	the International Renewable Energy Agency
JICA	Japan International Cooperation Agency
ktoe	Kilotonne of Oil Equivalent
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
MACS	Maximum Annual Capacity Shortage
MDGs	Millenium Development Goals
MEWD	Ministry of Energy and Water Development under the government of Zambia
MOE	Ministry of Energy under the government of Zambia
NPC	Net Present Cost
O&M	Operation and Maintenance
PJ	Petajoule
PV	Photovoltaic
REA	Rural Electrification Authority
REF	Rural Electrification Fund
REMP	Rural Electrification Master Plan
SDGs	Sustainable Development Goals
SHS	Solar Home Systems
SREP	Scaling-up Solar Renewable Energy Programme
USD	United States Dollar
ZMW	Zambian Kwacha

1 Introduction

Zambia is a landlocked country in southern Africa, bordering a total of eight countries; Angola, Botswana, Democratic Republic of Congo (DRC), Malawi, Mozambique, Namibia, Tanzania and Zimbabwe. It is a country rich in natural resources, such as copper, cobalt, zinc, lead, coal emeralds, gold, silver, uranium, forest and hydropower[1]. Despite its resources, 54% are living in poverty and the overall access to electricity is 31.4%. Access to electricity is closely linked to development and is therefore crucial to lift Zambia out of poverty. Zambia's rural areas have a significant lower electrification rate compared to urban areas, and the government has therefore implemented an aggressive rural electrification plan, with the aim of increasing rural electrification rate from 3% in 2008 to 51% by 2030. Today, 10 years later, not much has changed, as the rural areas now have an electrification rate of 4.4% [2].

Another major challenge that Zambia is facing is climate change. The country is already experiencing extreme weather events such as flash floods, droughts and extreme temperatures[3]. Zambia is particularly vulnerable to droughts, since 95% of its electricity generation comes from hydropower and to increase energy security, the country needs to diversify its electricity sector. Besides from hydropower, renewable energy sources such as solar and biomass are plentiful in Zambia, allowing it to not only diversify its electricity sector with domestic resources, but to do so with renewable sources[2]. In addition, countries like Zambia, where the national grid and the power system still are limited, have an opportunity to leapfrog to a sustainable decentralised energy system.

This study aims to investigate the optimal configuration and feasibility of an off-grid hybrid renewable energy system for the rural community of Mumbeji, located in the North-Western province of Zambia. The initial steps of the study included estimating the community's demand load profile as well as the renewable energy potential at site, which was done through literature reviews and data collection. The optimal system design was then found using the software modelling tool HOMER Pro[4]. Subsequently, the economic, environmental and social feasibilities of the system were assessed.

2 Zambia

2.1 Background

2.1.1 Geography

Zambia is a landlocked country in southern Africa, formed in 1964 when it gained its independency from the United Kingdom, and was formerly known as Northern Rhodesia. Zambia has a total area of approximately 750,000 km^2, divided into 740,000 km^2 of land and 9,000 km^2 of rivers and lakes [1].

With a population of 16.5 million the country has a population density of 23 people/km^2 land area which makes it a relatively sparsely populated country (comparing to an average of 50 people/km^2 in Sub-Saharan Africa) [5]. 43% is urban population, and is particularly concentrated around the cities Lusaka, Ndola, Kitwe and Mufulira in the central parts, as can be seen in Figure 1. The population growth rate at almost 3% is the 10th highest in the world, due to the high fertility rate in the country (5.6 children/woman) [1].

Zambia is divided into nine administrative provinces; Central, Copperbelt, Eastern, Luapula, Lusaka, Northern, North-Western, Southern and Western as can be seen in Figure 1. The provinces consist of 72 districts, which further can be broken down to 1,286 wards, being the smallest administrative unit [6]. Zambia is a unitary state with a centralised power and the governance can be divided into two levels; national and local. The local governance consists of 109 local authorities, so called councils; 84 district or town councils, 4 city councils and 15 municipal councils [7].

Figure 1. Map of Zambia

Zambia is situated on a plateau with some hills and mountains, having a mean elevation of 1,138 meter above sea level, mainly varying between 1,000-1,350 m (lowest and highest point at 329 m and 2,301 m) [1]. The climate is tropical but relatively moderate due to the altitude. The rainy season stretches from November to April and is the main farming season. May to October are usually dry months with May to August being cooler and September and October hot months[8].

Approximately two thirds of Zambia's land is covered by forest and woodland, the majority being woodland and of the type Miombo [8]. The agricultural land use is around 32% where the majority of this land, 27%, is permanent pastures and 5% arable land. 1,560 km^2 are being irrigated, meaning around 4.3% of the arable land [1]. 47% of the total land is arable while only around 5% is being used, showing a potential of increasing the agricultural sector, which also is one of the aims stated in the country's National Development Plan. The aim is to increase the agricultural and manufacturing sectors' contribution to Gross Domestic Product (GDP) in order to reduce their dependency on their traditional exports and products such as cobalt and copper. However, it has not been very successful, since the agricultural sector's contribution has decreased with more than 70% from year 2000 to year 2014. In addition, due to poor rainfalls, agricultural outputs decreased significantly in 2015/2016 from the previous farming season 2013/2014. For instance, maize production decreased by 21.9%, barley by 75% and rice by 48.6% [9].

2.1.2 Economy

Natural resources are what mainly contribute to the country's GDP and socio-economic development and around 80% of Zambians depend directly on the forest and other natural resources for livelihood, especially the Zambians living in rural areas. Resources include copper, cobalt, zinc, lead, coal, emeralds, gold, silver, uranium, forest and hydropower [8]. The contribution to GDP per sector is shown in Figure 2. Cobalt and especially copper are the biggest export products which play a significant role in Zambia's economy, which in turn makes the economy vulnerable to external fluctuations. This is one of the reasons why the government of Zambia wishes to increase GDP contribution by other sectors such as the agricultural and manufacturing sectors [9].

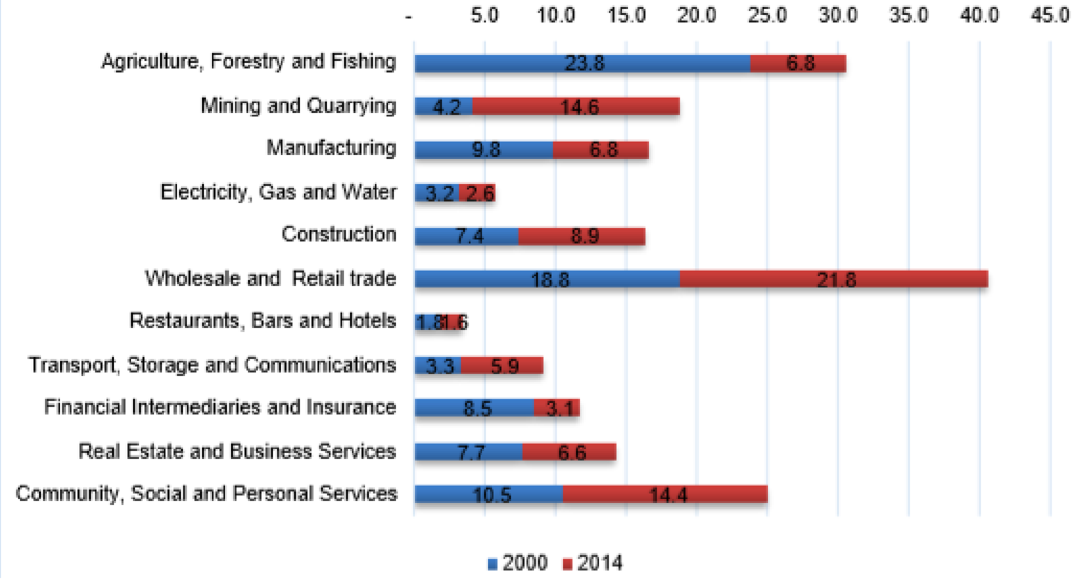


Figure 2. Contribution to GDP by Sector

Zambia has had a steady GDP growth rate until 2015 (averaging 5.8% 2000-2005 and 6.9% 2006-2015) and was during these years one of the fastest growing economies in the world. However, in contrast to the aim of expanding the agricultural and manufacturing sector, the GDP of these decreased from 23.8% to 6.8% and 9.8% to 6.8% respectively, while the mining sector increased from 4.2% to 14.6% [9]. When copper prices then fell during 2015, it effected Zambia's economy, decreasing to a GDP growth rate of 2.9% in 2015 and recovered slightly, to 3.4%, in 2017. Other factors affecting the drop of economy growth was a decreased power generation in 2015 and 2016 and depreciation of the Zambian kwacha (ZMW) [1]. Figure 3 shows the exchange rate of 1 United States Dollar (USD) to ZMW. In February 2019 1 USD converts to 11.925 ZMW [10].

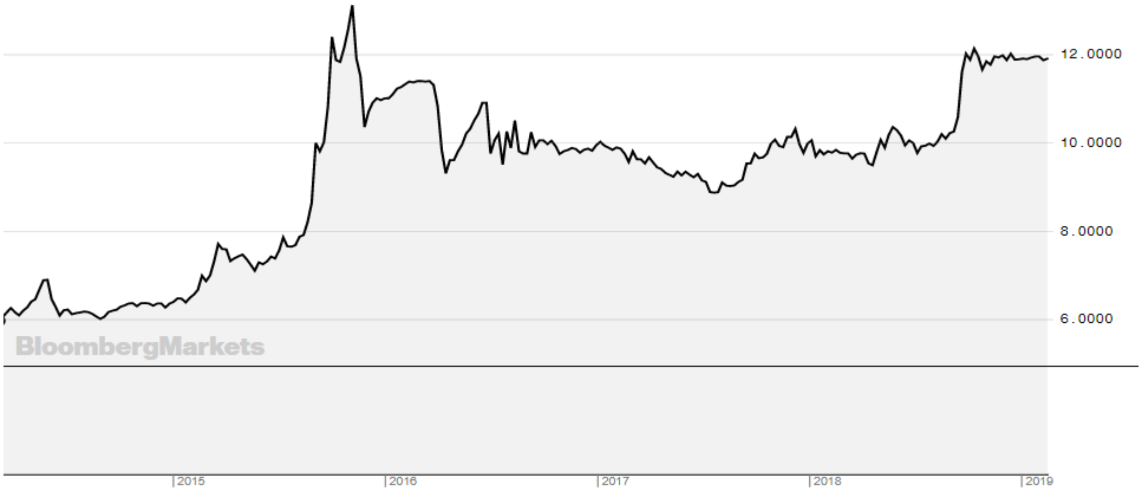
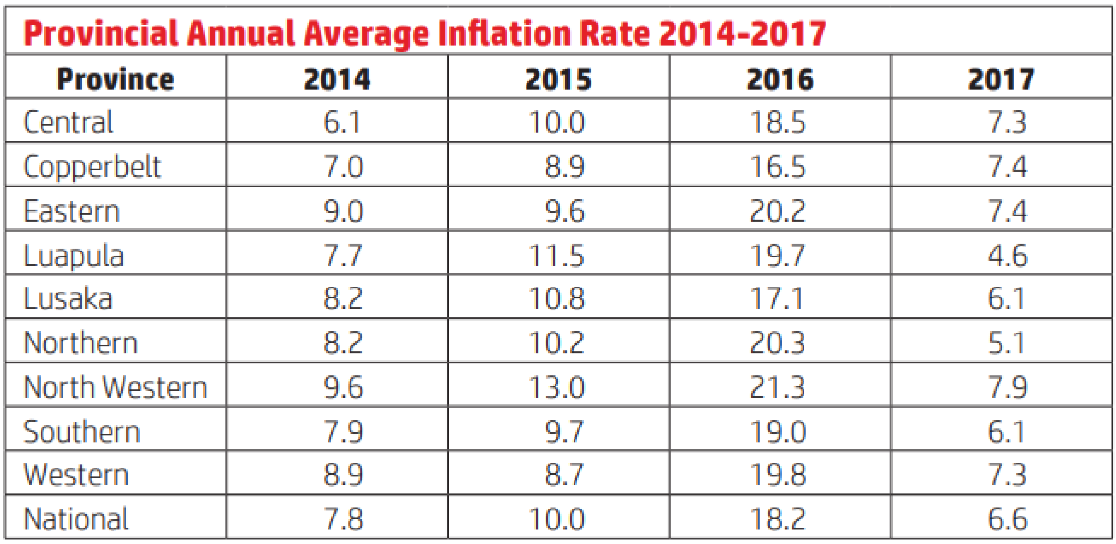


Figure 3. Exchange Rate of 1 USD to Zambian Kwacha (ZMW)

Zambia provincial annual average inflation rate from year 2014-2017 can be seen in Table 1 [11]. It can be seen that Zambia has a fluctuating inflation rate as well as significant variations from province to province.

Table 1. Provincial Average Inflation Rate 2014-2017



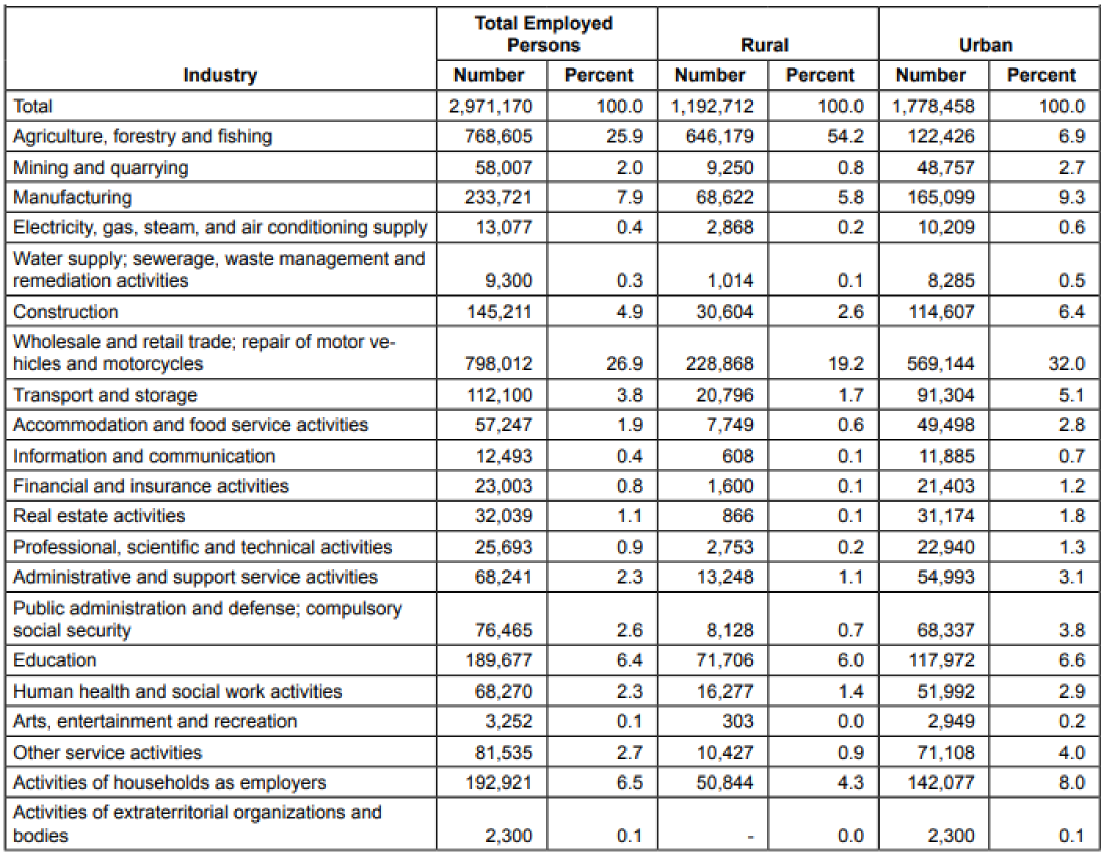
Provincial Annual Average Inflation Rate 2014-2017

Province	2014	2015	2016	2017
Central	6.1	10.0	18.5	7.3
Copperbelt	7.0	8.9	16.5	7.4
Eastern	9.0	9.6	20.2	7.4
Luapula	7.7	11.5	19.7	4.6
Lusaka	8.2	10.8	17.1	6.1
Northern	8.2	10.2	20.3	5.1
North Western	9.6	13.0	21.3	7.9
Southern	7.9	9.7	19.0	6.1
Western	8.9	8.7	19.8	7.3
National	7.8	10.0	18.2	6.6

2.1.3 Employment

Employed persons in Zambia accounts for approximately 18% of the population, a total of approximately 3 million people. Of these, 46% are employed in the formal sector, while the informal and household sectors employ 31% and 23%, respectively. The number and percentage distribution of employed persons by industry and rural/urban areas can be seen in Table 2. It can be seen that overall most people are employed in the wholesale and retail trade industry and in the agricultural industry (26.9% and 25.9% respectively). The wholesale and retail industry is the biggest employer in urban areas, followed by manufacturing (9.3%), household activities (8.0%), agriculture (6.9%), education (6.6%) and construction (6.4%). The largest sectors in rural areas are agriculture (54.2%) and the wholesale and retail trade industry (19.2%). Although the agricultural sector still is one of the biggest sectors, the employment is slowly moving from agricultural to non-agricultural sectors [12].

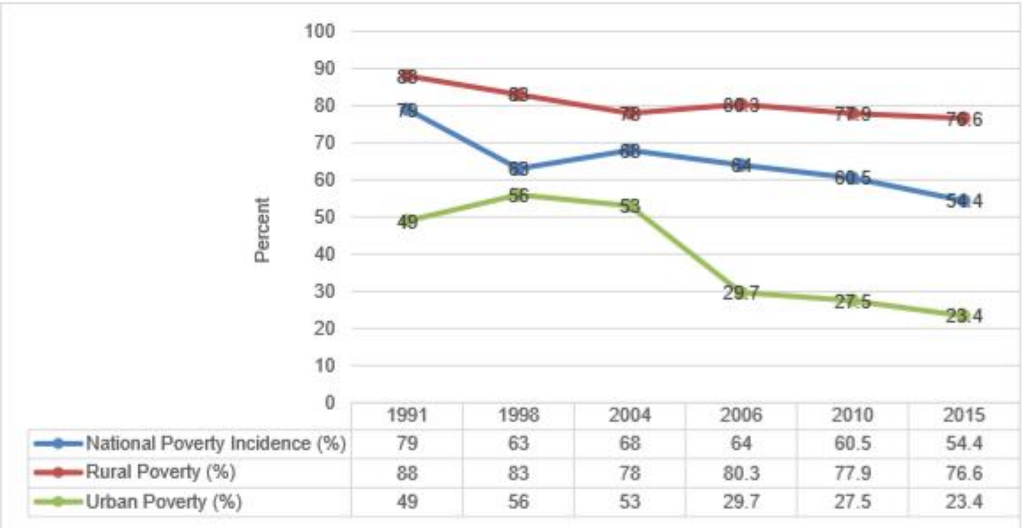
Table 2. Employment Distribution in Zambia by Industry and Rural/Urban Area, 2017



Industry	Total Employed Persons		Rural		Urban	
	Number	Percent	Number	Percent	Number	Percent
Total	2,971,170	100.0	1,192,712	100.0	1,778,458	100.0
Agriculture, forestry and fishing	768,605	25.9	646,179	54.2	122,426	6.9
Mining and quarrying	58,007	2.0	9,250	0.8	48,757	2.7
Manufacturing	233,721	7.9	68,622	5.8	165,099	9.3
Electricity, gas, steam, and air conditioning supply	13,077	0.4	2,868	0.2	10,209	0.6
Water supply; sewerage, waste management and remediation activities	9,300	0.3	1,014	0.1	8,285	0.5
Construction	145,211	4.9	30,604	2.6	114,607	6.4
Wholesale and retail trade; repair of motor vehicles and motorcycles	798,012	26.9	228,868	19.2	569,144	32.0
Transport and storage	112,100	3.8	20,796	1.7	91,304	5.1
Accommodation and food service activities	57,247	1.9	7,749	0.6	49,498	2.8
Information and communication	12,493	0.4	608	0.1	11,885	0.7
Financial and insurance activities	23,003	0.8	1,600	0.1	21,403	1.2
Real estate activities	32,039	1.1	866	0.1	31,174	1.8
Professional, scientific and technical activities	25,693	0.9	2,753	0.2	22,940	1.3
Administrative and support service activities	68,241	2.3	13,248	1.1	54,993	3.1
Public administration and defense; compulsory social security	76,465	2.6	8,128	0.7	68,337	3.8
Education	189,677	6.4	71,706	6.0	117,972	6.6
Human health and social work activities	68,270	2.3	16,277	1.4	51,992	2.9
Arts, entertainment and recreation	3,252	0.1	303	0.0	2,949	0.2
Other service activities	81,535	2.7	10,427	0.9	71,108	4.0
Activities of households as employers	192,921	6.5	50,844	4.3	142,077	8.0
Activities of extraterritorial organizations and bodies	2,300	0.1	-	0.0	2,300	0.1

2.1.4 Poverty

Despite a formerly steady economic growth, the poverty in Zambia remains relatively high, particularly in rural areas. This is mainly due to three reasons according to the ministry of National Development Planning; the first one being that economic growth has mainly occurred in capital-intensive industries such as mining, construction and transport, second one due to a geographical factor; that urban areas have experienced a bigger economic growth and the third one being the structure of economy, economic growth is not correlated to labour-intensive work such as in the agricultural sector, where poor tend to work. The national poverty has decreases from 79% in 1991 to 54.4% in 2015. Poverty in urban areas has decreased from 49% in 1991 to 23.4% in 2015 while in rural areas the poverty has decreased from 88% to 76.6% in the same period. The poverty trends by urban/rural population from 1991-2015 can be seen in Figure 4 [9].



	1991	1998	2004	2006	2010	2015
National Poverty Incidence (%)	79	63	68	64	60.5	54.4
Rural Poverty (%)	88	83	78	80.3	77.9	76.6
Urban Poverty (%)	49	56	53	29.7	27.5	23.4

Figure 4. Poverty Levels 1991-2015

The poverty distribution trends by poverty status (moderate/extreme) in Zambia is shown in Figure 5. Of the 54.4% living in poverty in 2015, 75% of these are living in extreme poverty (40.8% of total population) while 25% (13.6% of total population) are moderately poor [13].

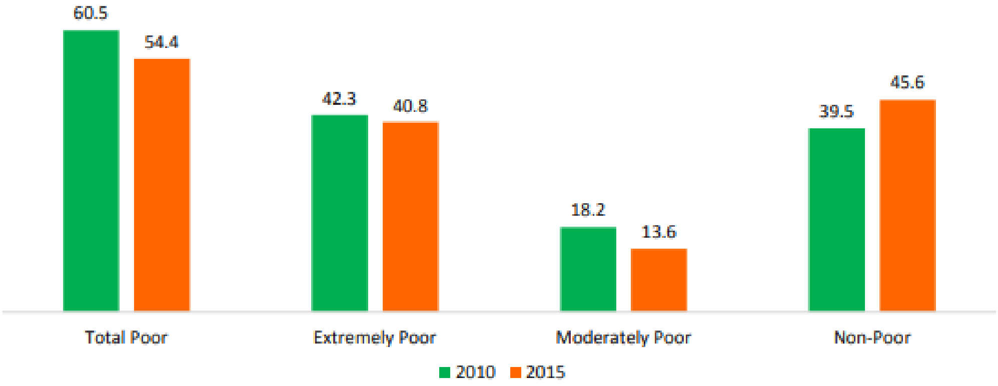


Figure 5. Poverty Trends by Poverty Status, 2010-2015

From Figure 4 and Figure 5 it is clear that rural poverty and extreme poverty are decreasing very slowly in Zambia. The rural poverty decreased by 11.4 percentage points in 24 years and urban by 25.6 percentage points during the same period. Besides, the extreme poverty decreased by 1.5 percentage points and moderate poverty by 4.6 percentage points during the last five years, despite all the efforts under the Millennium Development Goals (MDGs) programmes first, and the Sustainable Development Goals (SDGs) programmes now [13].

2.2 Energy Context

2.2.1 The Energy Sector

As mentioned in the introduction, access to safe and clean energy is crucial for the socio-economic development of a country. Currently, Zambia's energy use mainly derives from wood fuel, which represents 78% of the energy consumption. After wood fuel, electricity is the source contributing most to the energy supply with 11% of the total consumption, followed by oil products (10%) and coal (1%). The primary energy supply and consumption are shown by source in Figure 6. The division between sources is more or less the same for supply and consumption, only hydropower substituting the electricity in the supply chart. Zambia has a total annual energy supply of 11.0 ktoe (130 GWh) and a total final consumption of 8.8 ktoe (100 GWh) [14].

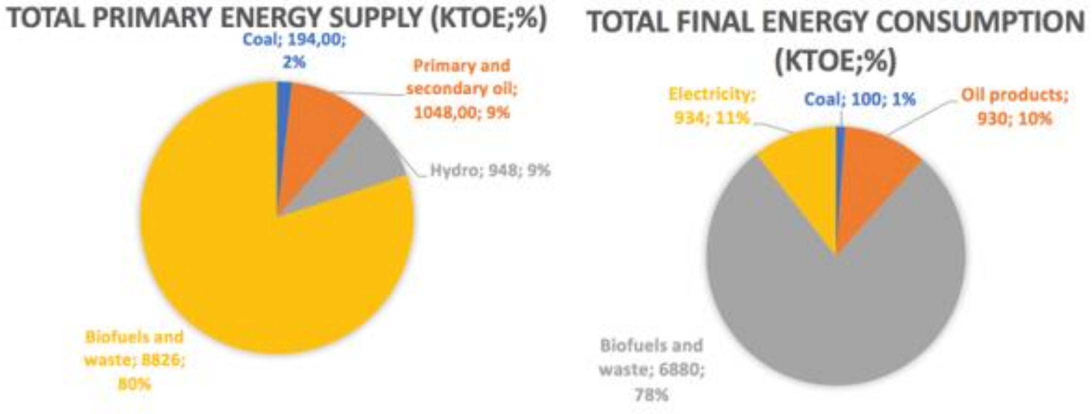


Figure 6. Annual Total Primary Energy Supply to the left and Total Final Energy Consumption to the right

To a large extent Zambia is energy independent. The only imports are oil products and some electricity. All oil products are being imported by the Government and Oil Marketing Companies (OMCs), either by road/train or via a 1'710 km pipeline from Dar es Salaam to INDENI Petroleum Refinery Limited (INDENI) in Ndola for processing. Finished petroleum products are imported by the OMCs by road or train from Tanzania, Mozambique or South Africa to various fuel depots owned by the Zambian government. Regarding petrol and diesel, 50% is being refined at INDENI in Ndola and 50% imported. The fuel price is mainly determined by two factors, the international oil prices and the exchange rate ZMW - USD [9]. As mentioned in the Introduction, Zambia is rich in renewable energy sources such as solar (thermal and photovoltaic), hydro (mini/micro), biomass (agricultural waste, forestry waste, industrial/municipal organic waste, animal waste and energy crops and products), geothermal and wind, but the usage of these sources remain low at the time being [15].

2.2.2 The Electricity Sector

The current overall access to electricity in Zambia is at 31.4%, 67.3% in urban areas and the rural electrification rate being as low as 4.4% [2]. The electricity access in each province is shown in Figure 7 [16].

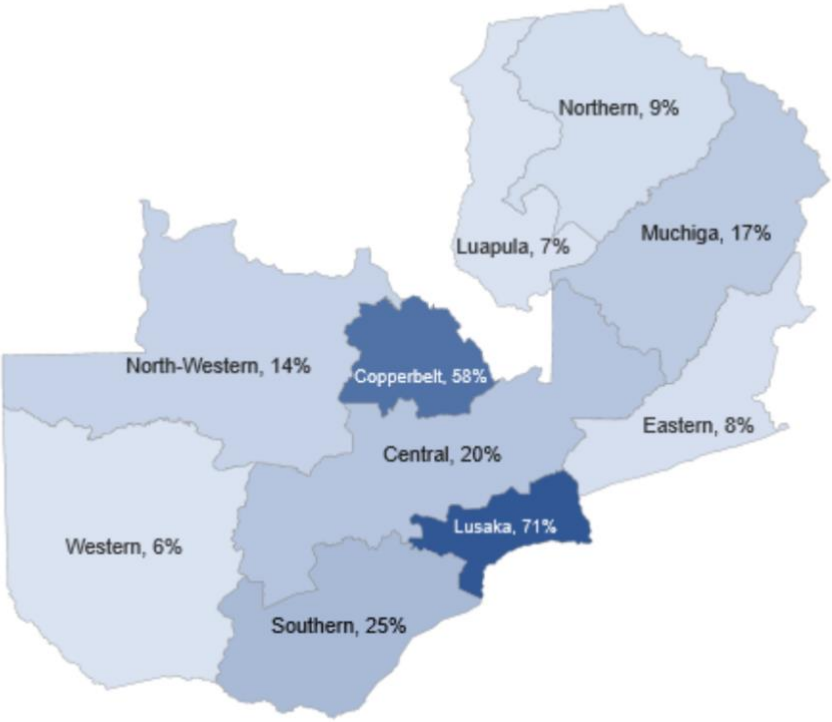


Figure 7. Access to Electricity by Province

The total electricity generation capacity installed was 2,892 MW in 2016 and is shown by technology in Figure 8. Hydropower is by far the most installed capacity, representing 83%, followed by coal (10%), heavy fuel oil (HFO) (4%), diesel (3%) and solar (1%) [17].

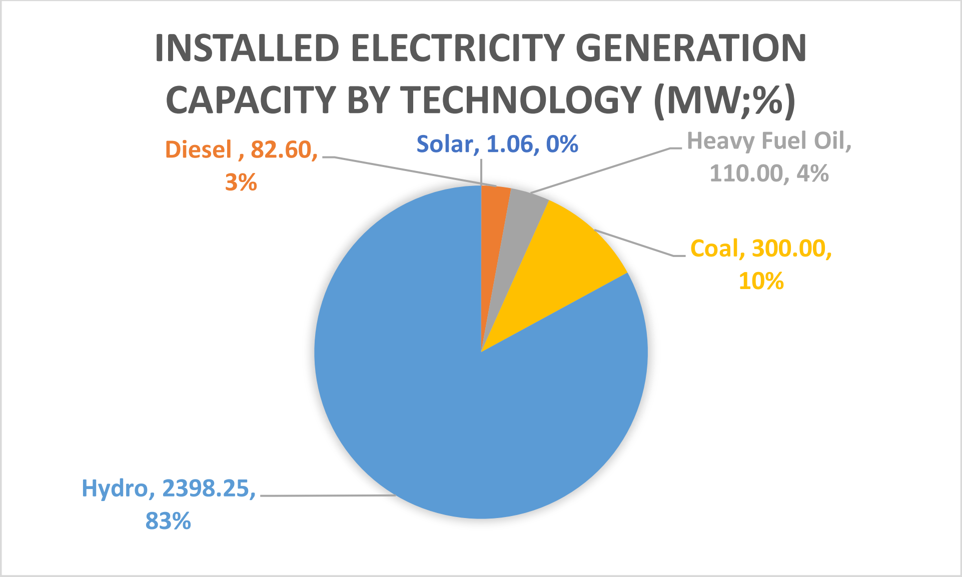


Figure 8. Installed Capacity by Technology

Installed capacity had an increase of 17.3% from 2015 to 2016 (from 2,411 MW to 2,827 MW) due to the installation of two new power plants; Maamba coal power plant (300 MW) and Itezhi-Tezhi hydropower plant (120 MW) [18]. The electricity consumption has since beginning of the 1980's been almost completely covered by hydroelectric sources (around 99%) [19]. Since year

2013, hydropower generation covered around 95% of Zambia's electricity consumption but had a significant drop in 2016 due to droughts, as can be seen in Figure 9 [18].

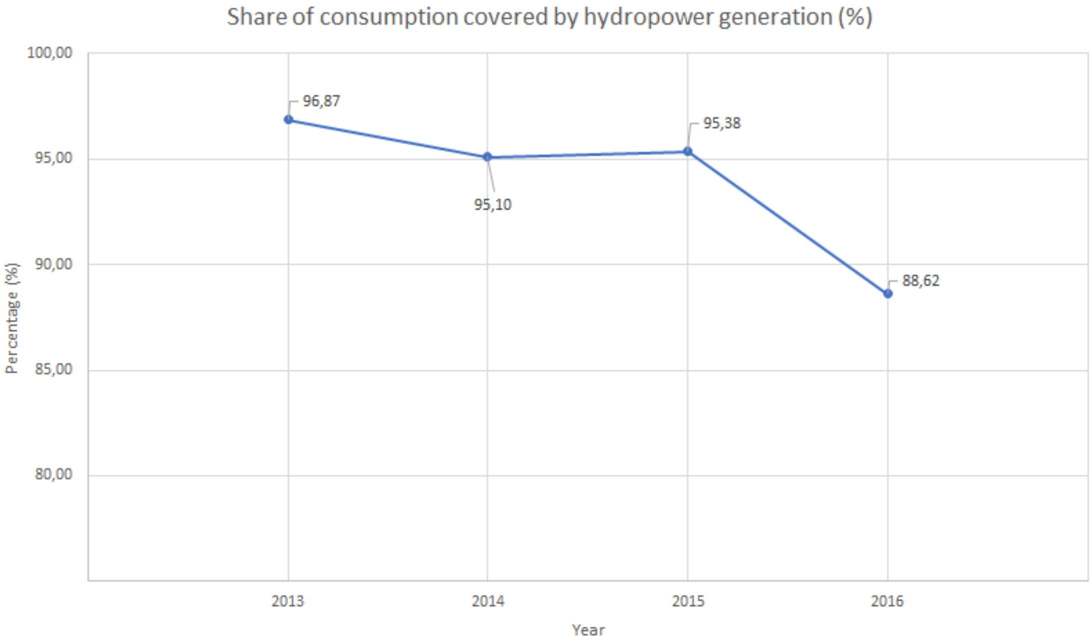


Figure 9. Electricity Consumption Covered by Hydropower Generation

All currently installed power plants, their capacity and the undertaker of the projects are listed in Table 3 [17].

Table 3. Installed Capacity 2018

Undertaking	Station	Machine Type	Installed Capacity (MW)
ZESCO Limited Generation Plants	Kafue Gorge	Hydro	990.00
	Kariba North	Hydro	720.00
	Kariba North extension	Hydro	360.00
	Victoria Falls	Hydro	108.00
	Lunzua River	Hydro	14.50
	Lusiwasi	Hydro	12.00
	Chishimba Falls	Hydro	6.00
	Musonda Falls	Hydro	10.00
	Shiwang'andu	Hydro	1.00
Itezhi-tezhi Power Corporation	Itezhi-tezhi	Hydro	120.00
Zengamina Generation Plants	Ikelengi	Hydro	0.75
Lusemfwa Generation Plants	Mulunguish	Hydro	32.00
	Lunsemfwa	Hydro	24.00
	Total Hydro		**2,398.25**
Maamba Collieries Limited	Maamba Power Plant	Coal	300.00
	Total Coal		**300.00**
Copperbelt Energy Generation Plants	Bancroft	Diesel	20.00
	Luano	Diesel	40.00
	Luanshya	Diesel	10.00
	Mufulira	Diesel	10.00
ZESCO Limited	Luangwa	Diesel	2.60
	Total Diesel		**82.60**
Ndola Energy Generation Plants	Ndola	Heavy Fuel Oil	110.00
	Total HFO		**110.00**
Copperbelt Energy Generation Plants	Solar Park	Solar	**1.00**
Rural Electrification Authority Generation Plants	Samfya	Solar	0.06
	Total Solar		**1.06**
	Grand Total		**2,891.91**

Currently planned projects are listed in Table 4. All the planned projects are hydropower plants ranging with capacity from 15 MW to 1,200 MW, with a joint capacity of 2,066 MW. Two of the projects have expected completion dates in 2019 (15 MW) and 2020 (750 MW), the remaining three projects' completion dates are yet to be announced [17].

Table 4. Planned Electricity Generation Projects

Project Name	Type	Owner	Capacity (MW)	Expected Completion Date
Kafue Gorge	Hydro	ZESCO	750	April, 2020
Chishimba Falls	Hydro	ZESCO	15	TBA
Batoka Hydro Power Project	Hydro	ZESCO	1,200	TBA
Luisiwasi Upper	Hydro	ZESCO	15	February, 2019
Luisiwasi Lower	Hydro	ZESCO	86	TBA

The total electricity generated in 2017 was 14,300 GWh with a total consumption of 11,700 GWh and export of 1,100 GWh. In general, the electricity generation has been increasing steadily every year but due to decreases in rainfall the electricity generation decreased in 2015 and 2016 as can be seen in Figure 10. However, in 2017 water levels improved and the generation increased by 23.3% from previous year, resulting in an electricity generation like the one before the droughts [11].

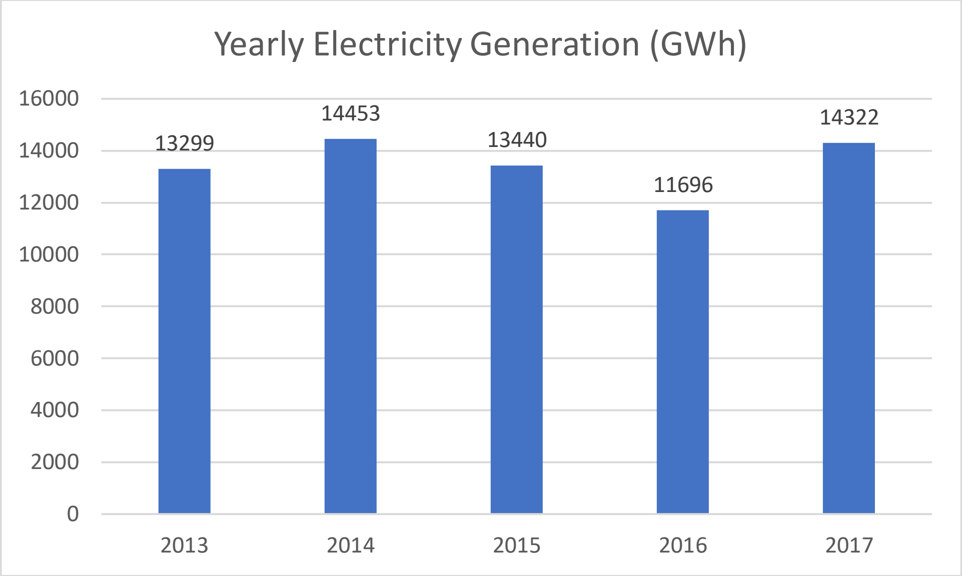


Figure 10. Yearly Electricity Generation

For the same period the electricity consumption only increased by 3.2%. This can be seen in Table 5 where the electricity consumption by sector is shown for the years 2015-2017. The consumption increased in the mining, domestic and quarries sectors while the consumption decreased in sectors such as manufacturing, trade and energy & water. The mining sector is the dominating consumer with a share of around 53% followed by the domestic sector of around 32% [11].

Table 5. Electricity Consumption by Sector

	Consumption (GWh)			Change (%)	Share (%)		
Sectors	2015	2016	2017	2017/2016	2015	2016	2017
Mining	5773,7	5916,4	6202	4,8	54,2	52,3	53,1
Domestic	3205,7	3716,8	3791,2	2,0	30,1	32,8	32,4
Finance & Property	477,1	545,9	581,7	6,6	4,5	4,8	5,0

Manufacturing	530,8	508,8	466,0	-8,4	5,0	4,5	4,0
Agriculture	260,4	241,1	243,8	1,1	2,4	2,1	2,1
Quarries	68,2	65,8	108,1	64,3	0,6	0,6	0,9
Trade	109,8	106,8	100,2	-6,2	1,0	0,9	0,9
Others	98,5	86,2	80,1	-7,1	0,9	0,8	0,7
Energy & Water	89,1	94,7	75,0	-20,8	0,8	0,8	0,6
Transport	33,4	30,6	29,3	-4,2	0,3	0,3	0,3
Construction	15,2	7,9	7,3	-7,6	0,1	0,1	0,1
Total	10661,9	11321	11684,7	3,2	100	100	100

Typically, the export of electricity in Zambia has been greater than the import, as can be seen in Figure 11. However, the export has decreased by 32.5% and import increased by 178.3% between 2015 and 2016 due to the lower hydropower generation in the country.

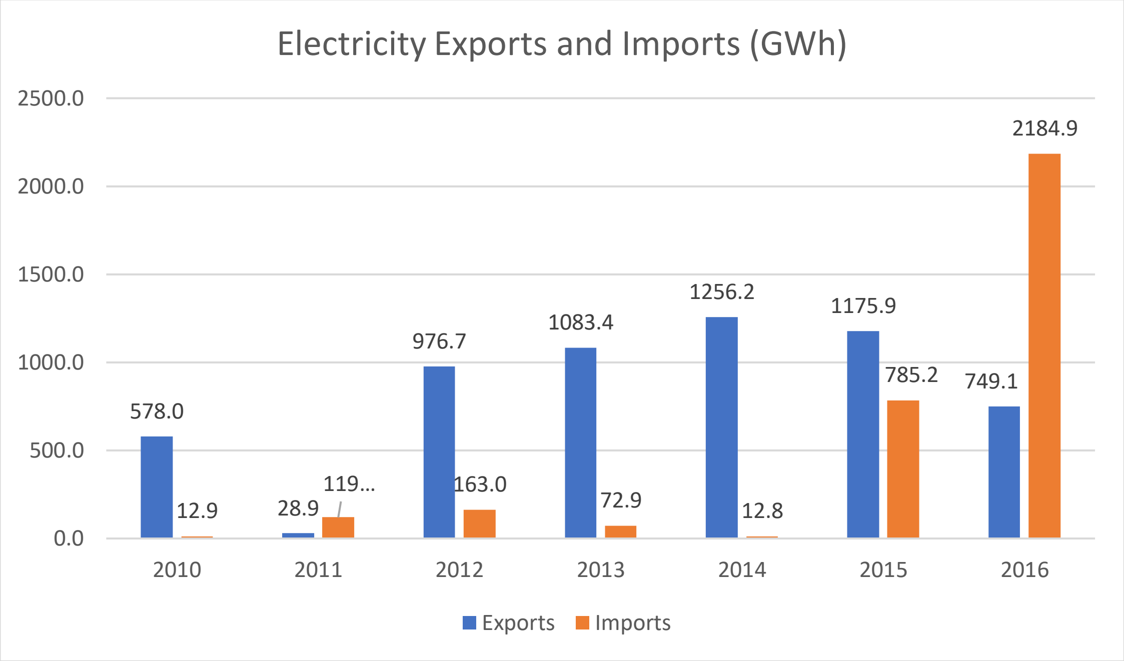


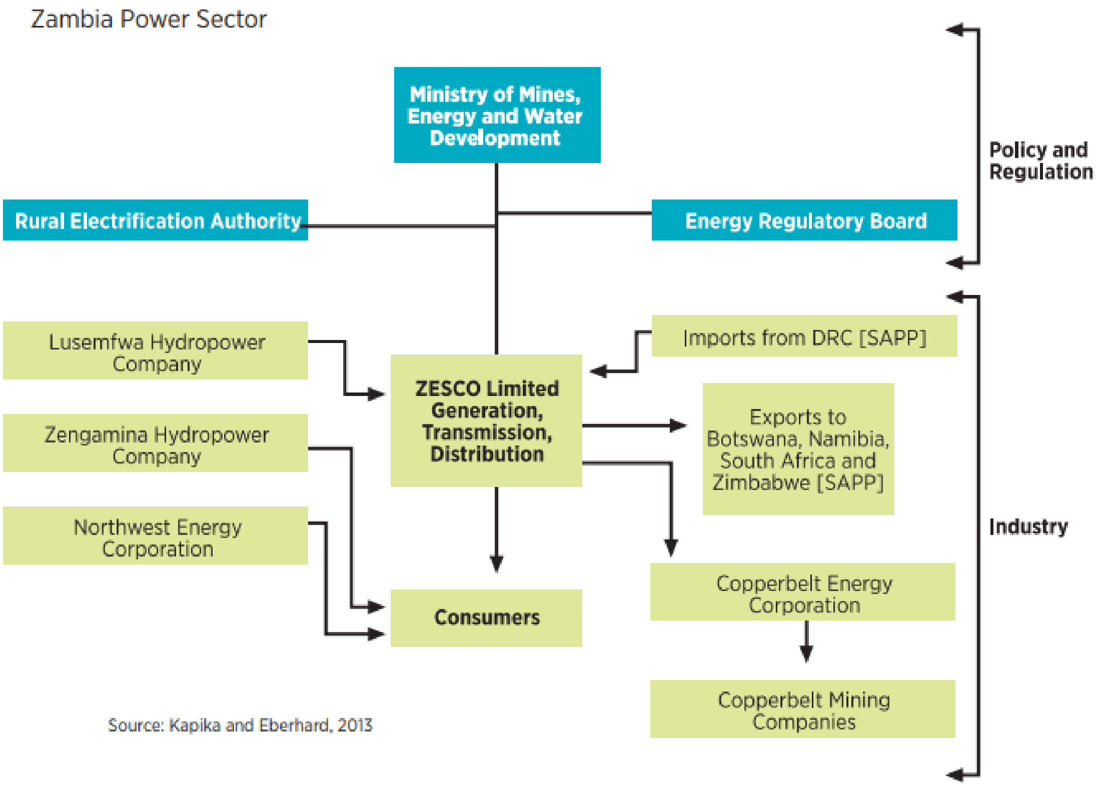
Figure 11. Electricity Exports and Imports

2.2.3 Administrative Structure of the Energy Sector

The main authority responsible for energy in Zambia is the Ministry of Energy (MOE) which is an institution under the government of the republic of Zambia. It was established in 2016, when the ministries were re-organised, from the former ministry of Energy and Water Development

(MEWD) [15]. The Rural Electrification Fund (REF) was established under MEWD in 1994 to foster rural electrification. This was done by introducing a sales tax on electricity of 3% that would fund electrification programmes. However, the rural electrification rate did not increase as planned and the Rural Electrification Authority (REA) was created in 2003 under MEWD as an independent administrator to control REF. REA's main purposes are to develop and implement electrification programmes with the help of REF, and monitor contracted projects so that they fulfil their obligations and meet set standards. The Energy Regulation Board (ERB) is another governmental institution that was founded in 1995 whose responsibilities include licensing power plants, regulating transmission, distribution and power tariffs and solving issues regarding these matters [6].

ZESCO Limited (ZESCO) is a vertically-integrated public power utility, managing generation, transmission and distribution and is responsible for 94% of the electricity generation. The remaining share of the electricity generation is provided by the Copperbelt Energy Corporation (CEC) (4%) and Lunsemfwa Hydropower Company (LHPC) (2%). CEC is a private power utility in the Copperbelt province with mining industries as their consumers. They own and control small gas power plants as well as transmission lines (66 kV and 220 kV) and are the main providers for the bigger industrial customers in the province, while smaller costumers are provided by ZESCO. LHPC is a private Independent Power Producer (IPP) and owns two hydropower plants (Mulungushi and Lunsemfwa) with a total capacity of 38 MW. In addition, there are two distribution utilities; Zengamina Hydropower Company (ZHPC) that distributes electricity from off-grid mini hydropower plants to rural mining communities and the Northwest Energy Corporation (NWEC) that distributes to rural mining communities from the national grid. A schematic of the power sector is shown in Figure 12 [20].



Source: Kapika and Eberhard, 2013

Figure 12. Administrative Structure of the Zambian Power Sector

2.2.4 The Grid

The Transmission Development Directorate (TD) is the organisation within ZESCO that is responsible for the development and maintenance of the transmission system. The grid has powerlines of voltages of 330 kV, 220 kV, 132 kV, 88 kV and 66 kV, while powerlines of 330 kV are the dominating, forming the backbone of the system. The distribution of power lines in terms of distance are shown in Table 6 while Figure 13 shows the current and planned grid network on a map. The 330 kV powerlines are built from the south where the major power plants are located (Kariba North and Kafue dams), up through Lusaka and the central province to the Copperbelt province where the major loads are due to mining activities [21]. Export is transported via high voltage lines to Zimbabwe, South Africa, Namibia, DRC and import comes from Botswana, Tanzania or DRC via low voltage lines. The distribution network consists of the distribution network of the national grid or isolated networks, that are fed by stand-alone diesel generators or small hydropower plants. Transmission losses were averaging 4.6% and distribution losses averaging 13.8% in 2011, with an estimation of total system losses of 13.1% [20]. Subtracting 2017's electricity consumption and exports from the generation, shows a decrease in losses to 10.5% in 2017 [11].

Table 6. Division of Power Lines by Distance

Distance (km)	Voltage (kV)
2241	330
1037	66
734	88
571	220
202	132

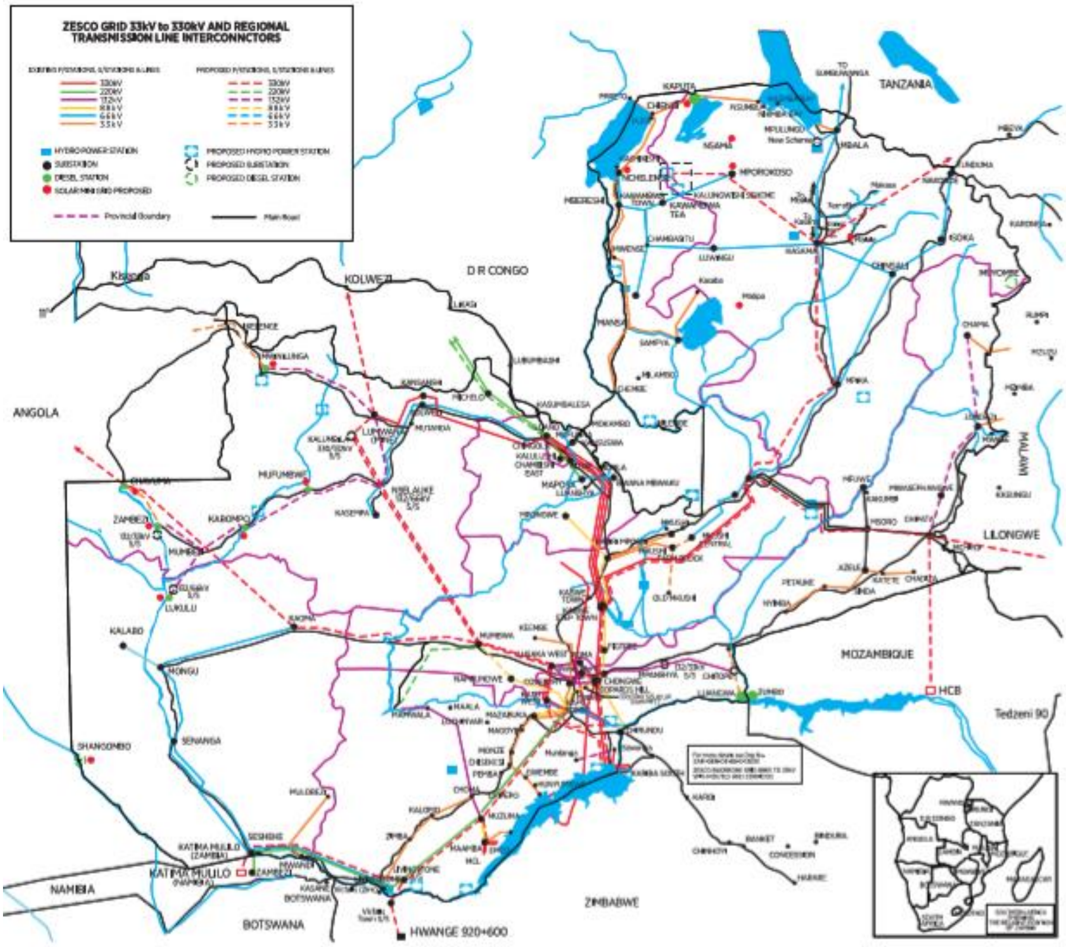


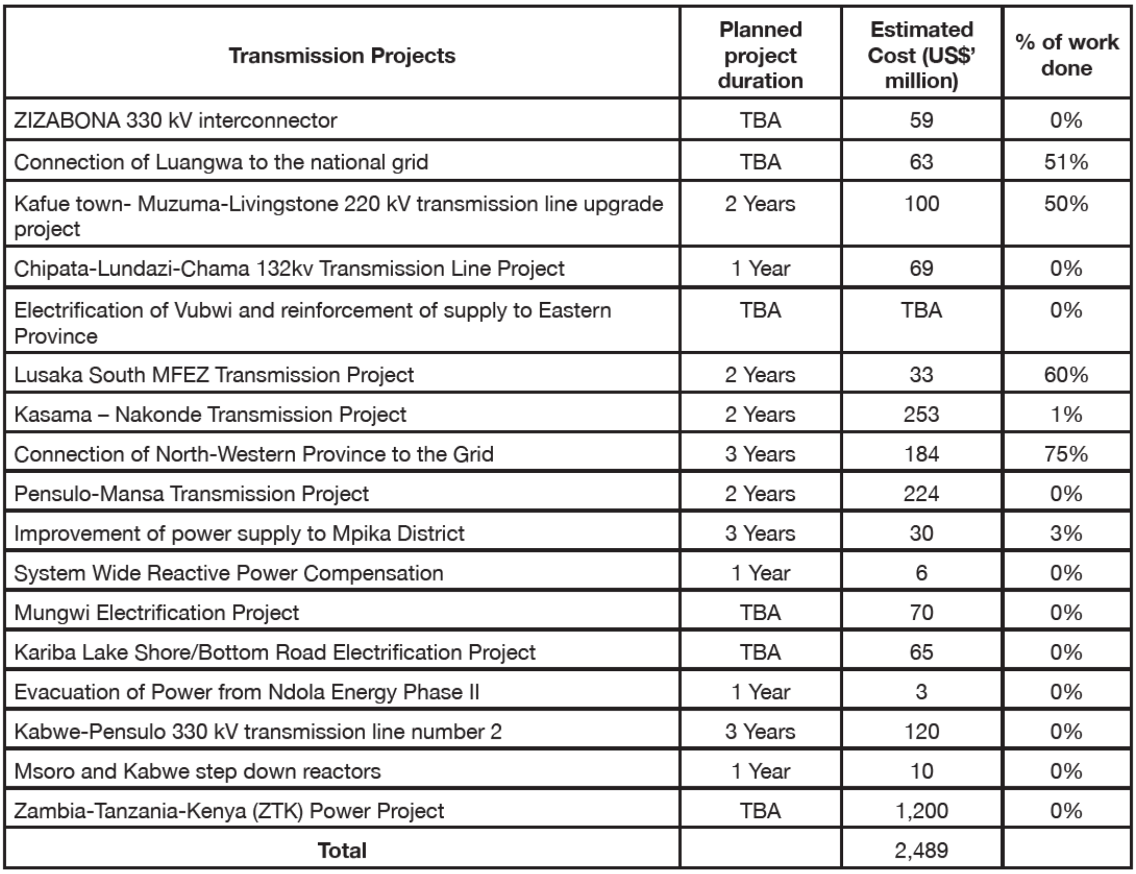
Figure 13. Zambia National Grid Network and Regional Interconnectors

TD is further divided into five technical departments, Transmission South (TS), Transmission North (TN), Transmission Development South (TDS), Transmission Development North (TDN) and Electro-Technical Services (ETS). TS and TN are responsible for operation and maintenance, ETS for metering and monitoring (SCADA) while TSN and TDN are responsible for expansion projects for the transmission system [21].

2.2.5 Planned and On-going Grid Projects

Current and planned transmission projects are shown in Table 7 together with planned duration, estimated cost and percentage of work done. A total of 17 projects are presented, of these, six projects are currently being executing and the remaining eleven are yet to be started. The total estimated cost of the projects is 2,849 million USD.

Table 7. Transmission Projects



Transmission Projects	Planned project duration	Estimated Cost (US$' million)	% of work done
ZIZABONA 330 kV interconnector	TBA	59	0%
Connection of Luangwa to the national grid	TBA	63	51%
Kafue town- Muzuma-Livingstone 220 kV transmission line upgrade project	2 Years	100	50%
Chipata-Lundazi-Chama 132kv Transmission Line Project	1 Year	69	0%
Electrification of Vubwi and reinforcement of supply to Eastern Province	TBA	TBA	0%
Lusaka South MFEZ Transmission Project	2 Years	33	60%
Kasama – Nakonde Transmission Project	2 Years	253	1%
Connection of North-Western Province to the Grid	3 Years	184	75%
Pensulo-Mansa Transmission Project	2 Years	224	0%
Improvement of power supply to Mpika District	3 Years	30	3%
System Wide Reactive Power Compensation	1 Year	6	0%
Mungwi Electrification Project	TBA	70	0%
Kariba Lake Shore/Bottom Road Electrification Project	TBA	65	0%
Evacuation of Power from Ndola Energy Phase II	1 Year	3	0%
Kabwe-Pensulo 330 kV transmission line number 2	3 Years	120	0%
Msoro and Kabwe step down reactors	1 Year	10	0%
Zambia-Tanzania-Kenya (ZTK) Power Project	TBA	1,200	0%
Total		2,489	

2.2.6 Electricity Tariffs

Historically electricity tariffs in Zambia have been very low and not cost-reflective, making investments in power projects less attractive. However, the government aim to increase the tariffs to be cost-reflective by 2021, in order to encourage investments in the electricity sector. In 2017 the domestic tariffs were increased with 75% and are shown in Table 8[1] [11].

Table 8. Electricity Tariffs

Customer Category		Tariffs
1. Metered Residential (Prepaid) (capacity 15kVA)		

---

[1] Prices were originally given in ZMW. An exchange rate of 1 ZMW= 0.078 USD has been used [74].

R1- Consumption up to 200kWh/month	USD/kWh	0.012
R2- Consumption above 201kWh/month	USD/kWh	0.069
	Fixed monthly charge (USD)	1.42
2.Commercial Tariffs (capacity 15 kVA)		
Commercial	USD/kWh	0.042
	Fixed monthly charge (USD)	7.52
3.Social Services		
Schools, hospitals, orphanages, churches, water pumping & street lighting	USD/kWh	0.038
	Fixed monthly charge (USD)	6.54

2.2.7 On-going Plans & Programmes

2.2.7.1 Vision 2030

Vision 2030 is a campaign launched in 2006 with the aim of Zambia transitioning from a low-income nation to a strong and dynamic middle-income nation by 2030. It's the first long-term written plan for the country and focuses on the socio-economic development of the country, with 7 key pillars; sustainable development, upholding democratic principles, respect for human rights, fostering family values, a positive attitude to work, peaceful coexistence and upholding good traditional values [22].

2.2.7.2 Seventh National Development Plan

The national development plans are building blocks of the Vision 2030. The seventh national development plan (7NDP) stretches from 2017 to 2021 and aims to achieve the goals outlined in Vision 2030 in order to meet the vision [9].

2.2.7.3 Rural Electrification Master Plan 2008-2030

The Rural Electrification Master Plan 2008-2030 (REMP) is a plan developed by the government in cooperation with Japan International Cooperation Agency (JICA), REA and MEWD. The aim of the plan is to increase access to electricity from 3% to 51% in rural areas by 2030. The government has targeted 1,217 rural growth centres to be electrified, through three means; extension of the national grid, installation of stand-alone electricity systems supplied by renewable energy sources such as mini-hydro power plants and biomass generation, and thirdly, installation of solar home systems (SHS) to a total cost of 1.1 billion USD. The plan states that off-grid solutions are necessary for the electrification of areas located far away from the national grid in Zambia. The plan suggests the possibility of micro-grids and where not even those are economically viable, a SHS. Although the focus lies on hydro and solar power the Zambian government has shown strong interest in the research and development of the exploitation of biomass and geothermal for electricity for remote areas [6].

However, it is underlined in REMP that in order to be able to expand the use of renewable energy, many issues have to be addressed, such as:

- Support is needed to subsidise private sector investment because of the high investment costs
- Improved technical skills
- Development of organisation and management for sustainable business enterprises
- Promoting the establishment of the market for equipment and materials

According to REA, the execution of the REMP is going slow, due to lack of financial support. The private sector participation is minimal and the financing of the electrification projects are mainly done by the government. So far, 3,401 km of grid extension has been done and the current rural electrification rate is at 4.4% [16].

2.2.7.4 Power Systems Development Master Plan (PSDMP)

Funded by and with the help of JICA, the formerly Ministry of Energy and Water Development (now Ministry of Energy) launched the Power Systems Development Master Plan, a least-cost expansion plan of generation, transmission and distribution. The plan stretches from year 2010-2030 and include expansion plans of 4,337 MW to the national grid of an estimated cost of 9.5 billion USD, 2.3 billion USD for transmission projects and 179.7 million USD for distribution projects [23].

2.2.7.5 The Renewable Energy Feed-in Tariff (REFiT) Strategy

The Renewable Energy Feed-in Tariff Strategy serves as a complemental plan to REMP and PSDMP which include plans of expanding large-scale hydropower to the country's fully potential (6,000 MW). These plans neglect the small-scale projects of up to 20 MW, and in addition, has large-scale hydropower suffered from recent droughts, showing the disadvantages of a non-diversified electricity sector. The Renewable Energy Feed-in Tariff Strategy is therefore a governmental power sector initiative with;

- A short-term aim of promoting private investments in small- and medium sized renewable energy projects of up to 20 MW
- A medium- and long-term aim of creating a diversified energy mix to be able to increase energy security

This will be done by promoting small- and medium sized renewable projects of up to 20 MW, ensuring cost-reflective tariffs by creating a transparent and competitive sector and removing technical and legislative barriers. The barriers hindering private investments in the sector today, as stated in the strategy plan, include [2]:

- Inadequate policy framework and policy measures to provide an effective Governmental framework for the objectives, principles, measures, mechanisms and scale for the uptake of private sector investments in the energy sector
- The need for clear guidelines, rules and regulations for operationalization of private sector involvement. This includes guidelines for long-term contracts, payment

guarantees, tariff calculations, grid connection procedures and costs, governmental priorities, tender procedures, etc.

- Non-cost reflective tariffs have contributed to the low uptake of private sector investments

2.2.7.6 Scaling-up Solar Renewable Energy Programme (SREP)

The Scaling-up solar programme is a programme with support of the World Bank that aims to scale-up the use of renewable energy sources. The World Bank will contribute with up to 40 million USD to the Zambian government to support investments in the private power sector. The government aims to add 600 MW of on-grid solar power in the coming 2-3 years and two projects has already been awarded to two companies; Enel Green Power of Italy (34 MW, expected finished beginning of 2019) and NEON S.A.S/First Solar (45 MW, under development) [24].

2.2.7.7 Zambia South to South Project on Technology Transfer

The Zambia South to South Project on Technology Transfer is a project between Zambia and China, in collaboration with UNDP with the aim of increasing the knowledge about solar and small-scale hydropower generation technologies. One of the main outcomes are to establish two centres of excellence; one on solar in the University of Zambia and one on small-scale hydropower at the Kafue Gorge Training centre.

2.2.7.8 Zambia's Intended Nationally Determined Contribution (INDC)

The Intended Nationally Determined Contribution (INDC) is an outcome of the Paris Agreement and states the nation's intended efforts to reduce their greenhouse gas (GHG) emissions and adapt to climate change [25]. The stated mitigation efforts of Zambia include a GHG emissions reduction of 47% (38,000 Gg CO_2eq[2]) by 2030, compared to base year 2010. The reduction efforts are estimated to cost 50 billion USD, of which 35 billion USD is expected to come from external sources and 15 billion USD from domestic sources. Three different programs have been implemented in order to achieve this mitigation; Sustainable Forest Management, Sustainable Agriculture and Renewable Energy and Energy Efficiency. The objective of the Renewable Energy and Energy Efficiency program is [26]:

- To promote the switching from conventional and traditional energy sources to sustainable and renewable energy sources and practices, and use of off grid renewable energy technologies for rural electrification as decentralized systems

And include following measures to be implemented:

---

[2] Charts and tables convert all greenhouse gas (GHG) emissions into CO_2 equivalents so they can be compared. Each GHG has a different global warming potential (GWP) and persists for a different length of time in the atmosphere. Thus, for example, the 100-year global warming potential (GWP 100a) compared to carbon dioxide methane (CH_4) is 25, i.e. releasing 1 kg of CH_4 into the atmosphere is about equivalent to releasing 25 kg of CO_2.

- Fuel switch (diesel/HFO[3] to biodiesel)
- Fuel switch (coal to biomass)
- Switch from existing isolated diesel to mini-hydro
- Introduce and increase blending of biofuels with fossil fuels and where possible substitution with biofuels
- Off grid renewable energy to non-electrified rural
- On grid expansion program to support economic growth and grid extension through inter-basin water transfer
- Grid extension to non-electrified rural areas

2.2.8 Previous Projects of Rural Electrification

Regarding earlier experience of rural electrification in Zambia, not much information has been found. However, several planned projects, but yet not implemented, have been found. For example, there are eight diesel mini-grids operated by ZESCO, which they plan to hybridise or replace with solar or hydro (as stated in Zambia's Intended Nationally Determined Contribution (INDC)) [20]. Another planned project, in Mwayne village in the Eastern province, consists of a 100 kW off-grid photovoltaic (PV) system with a battery bank of 230 kWh and a 25 kVA diesel generator for emergencies. The project is executed by Entiba Energy Zambia and to attract customers the electricity prices are thought to mirror Zambia's grid tariffs during daylight and only charge a higher tariff when the electricity is supplied by the batteries [27].

Only one already implemented mini-grid has been found. It is a 60 kW solar mini-grid in the rural fishing community Mpanta, located in the Luapula province. The community has approximately 6,000 inhabitants and 617 households. The REA has provided part of the investment cost while remaining costs have been financed through a loan facility agreement between the Development Bank of Zambia and the REA. The interest-free loan has been promoted by the United Nations Industrial Development Organisation (UNIDO) under the Global Environment Facility (GEF) agreement.

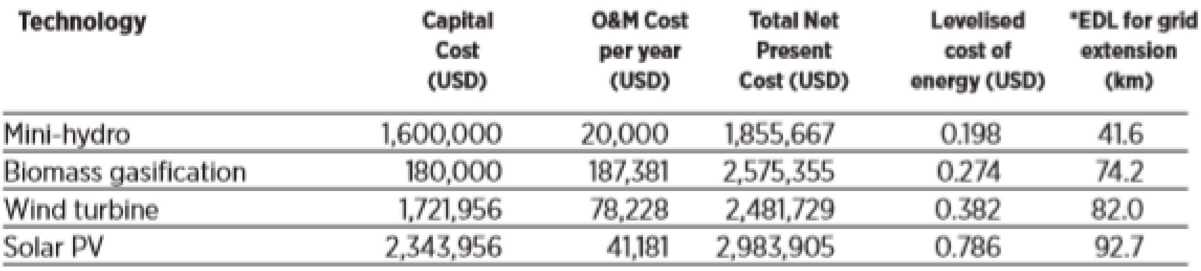
Besides, a study performed on a typical remote rural village with about 2,000 inhabitants, showed that similar sites throughout the country could be most cost-efficiently electrified by renewable based mini-grids rather than extending the national grid. The study found the Economical Distance Limit[4] (EDL) for various renewable technologies as can be seen in Table 9. For example, the EDL for solar PV was found to be 92.7 km, i.e. if the village is located farther than 92.7 km from the existing power line(s), it is more cost-efficient to electrify the village by a solar based mini-grid [20].

---

[3] Heavy Fuel Oil (HFO)

[4] The Economic Distance Limit is defined as the break-even point at which grid extension become less economically viable than decentralised alternatives.

Table 9. Economical Distance Limit per Technology.



Technology	Capital Cost (USD)	O&M Cost per year (USD)	Total Net Present Cost (USD)	Levelised cost of energy (USD)	*EDL for grid extension (km)
Mini-hydro	1,600,000	20,000	1,855,667	0.198	41.6
Biomass gasification	180,000	187,381	2,575,355	0.274	74.2
Wind turbine	1,721,956	78,228	2,481,729	0.382	82.0
Solar PV	2,343,956	41,181	2,983,905	0.786	92.7

2.2.9 Renewable Energy Potential

Renewable energy sources in Zambia include solar, hydro, wind, biomass and geothermal [15].

2.2.9.1 Hydropower

Zambia currently has 2,400 MW of hydropower installed while the estimated potential is another 6,000 MW. 2,000 MW of these are already planned projects, which are listed in previous section Table 4 [15].

2.2.9.2 Solar

Zambia has good potential for solar energy (thermal and PV), generating a potential of around 5.5 kWh/m^2/day. Despite great potential, solar power is very low in Zambia, mainly due to high investment costs. In SREP it is declared that Zambia targets to develop 600 MW of on-grid solar generation in the coming 2-3 years. Figure 14 show the global horizontal irradiation and PV power potential in Zambia [24].

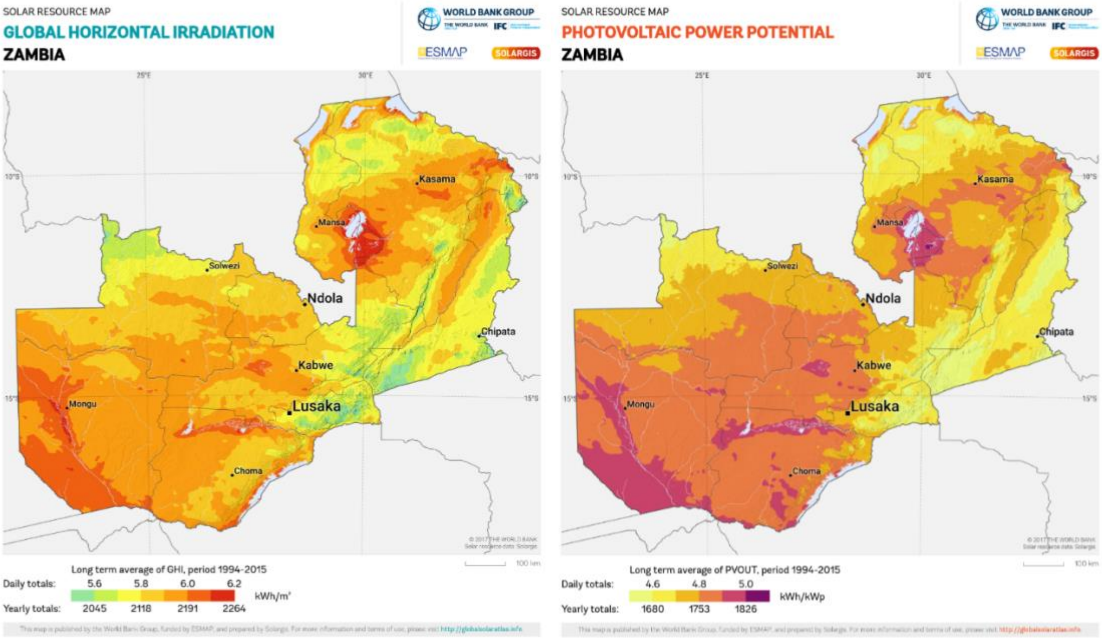


Figure 14.Left figure: Global horizontal irradiation, Right figure: Photovoltaic power potential

2.2.9.3 Wind

Zambia has an average wind speed of 3.2m/s at 10 m height, which make the wind potential in Zambia only suitable for smaller applications such as water pumping and irrigation. However, the Zambian government together with the World Bank are currently executing a wind resource measurement campaign through the Energy Sector Management Assistance Program (ESMAP), in order to assist stakeholders in wind projects with valuable data [6].

2.2.9.4 Biomass

Zambia has great potential for biomass, 66% of its land is covered by forest and today 80% of the energy supply derives from biomass. However, despite the great potential, Zambia has an increasing deforestation rate, currently at 250,000-300,000 ha/year, which must be taken into consideration to assure a sustainable use of biomass [8].

According to the report Bioenergy resource assessment for Zambia 2015, Zambia has a total bioenergy potential of 310 PJ/year (corresponding to approximately 86 TWh/year) and the biggest potentials are found in agricultural residues (198 PJ/year), forest residues (52 PJ/year) and livestock waste (27 PJ) [28].

The Zambian government and the Food and Agriculture Organisation (FAO) also made an estimation of the biomass potential in the country in 2010 and found a total potential of approximately 500 MW of electricity generation. The agricultural residues have a potential of 447 MW, forest residues 46 MW and municipal/industrial waste 4 MW [24].

2.2.9.5 Geothermal

At the moment, the geothermal potential in the country has not been fully investigated. Nevertheless, Zambia has at least 80 identified hot springs but financial resources and expertise are lacking for further investigation. One project with two turbines of 120 kW was started in collaboration with the Italian government in the Kapishya Hot Springs in the Northern Province in the 1980’s, but has never been operational since completed [24].

2.3 The Community

The community investigated in this study, Mumbeji, is one of thirteen wards in Kabompo district which, in turn, is one of the nine districts in the North-Western province, shown in Figure 15.

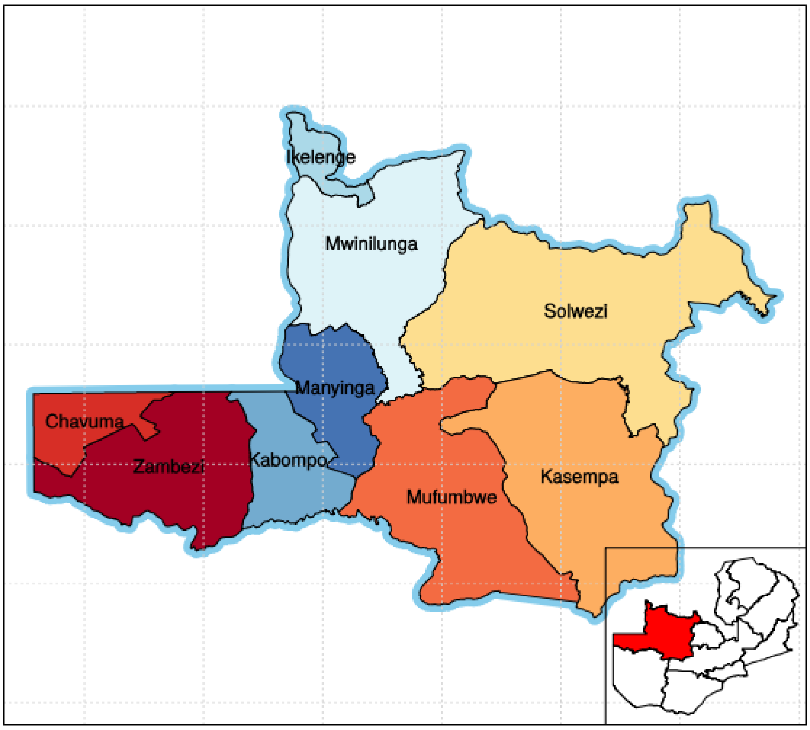


Figure 15. The North-Western Province in Zambia

The capital in the North-Western province is Solwezi. The province is the smallest in Zambia regarding inhabitants (900,000) and also the most sparsely populated (7.2 people/km^2 in 2018). According to the Zambian Central Statistical Office, Mumbeji ward has approximately 4,000 inhabitants and an area of 680 km^2, resulting in a population density of 5.83 persons/km^2 [5]. A satellite picture of the community studied in Mumbeji can be seen in Figure 16.

Figure 16. The Community in Mumbeji ward.

Kabompo district lies on a plateau of an elevation of 1,123 m above sea level. The average temperature can be seen in Figure 17. October is the hottest month of the year with an average temperature of 24.6 degrees Celsius while June is the coolest with an average temperature of 17.0 ºC. The rainy season occurs from November-March with January being the month with most precipitation (231 mm), which can be seen in Figure 18.

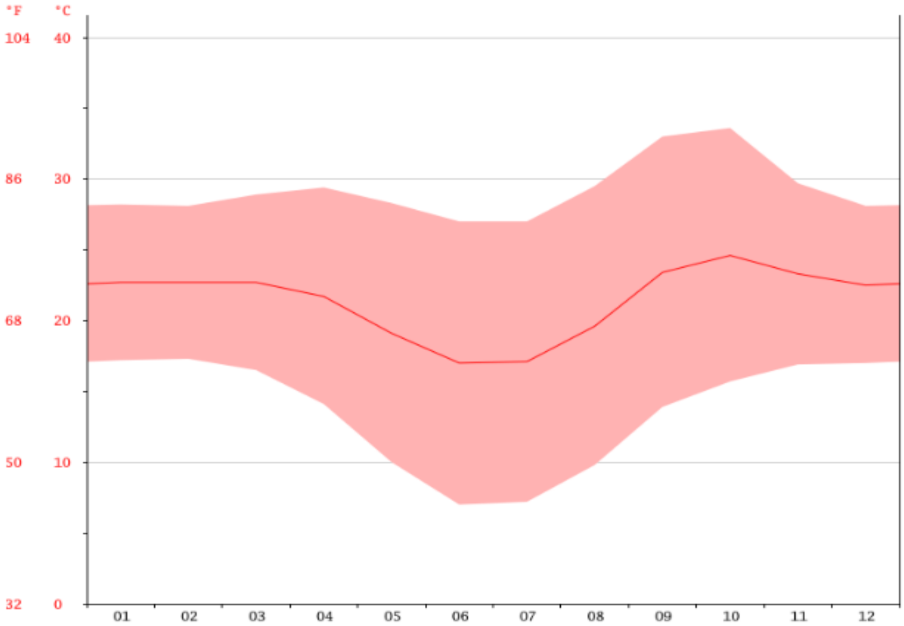
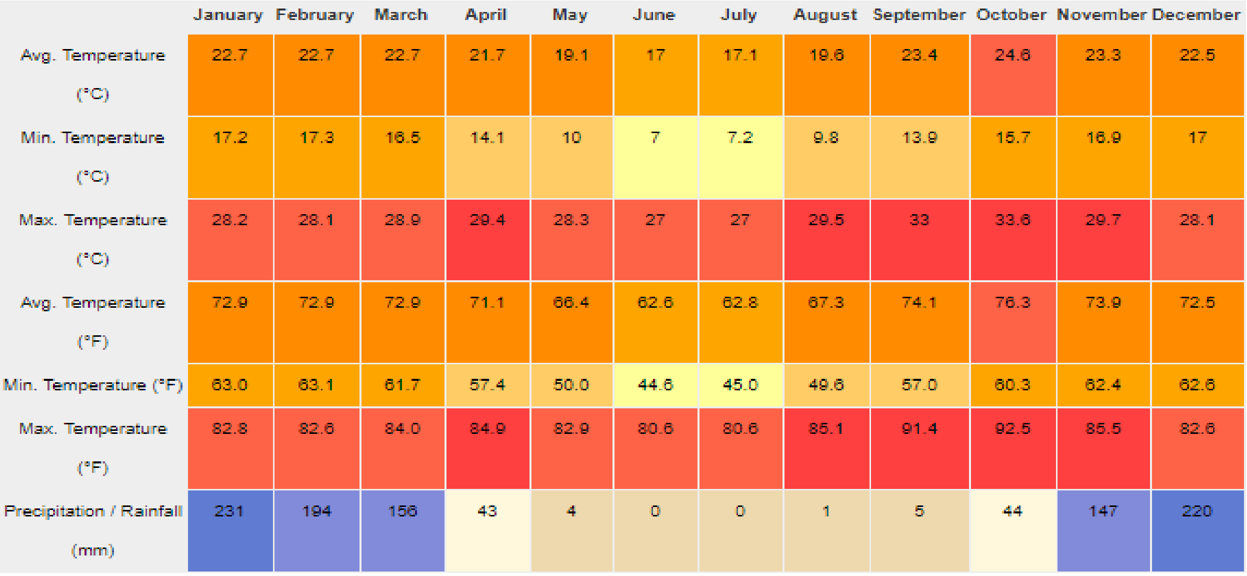


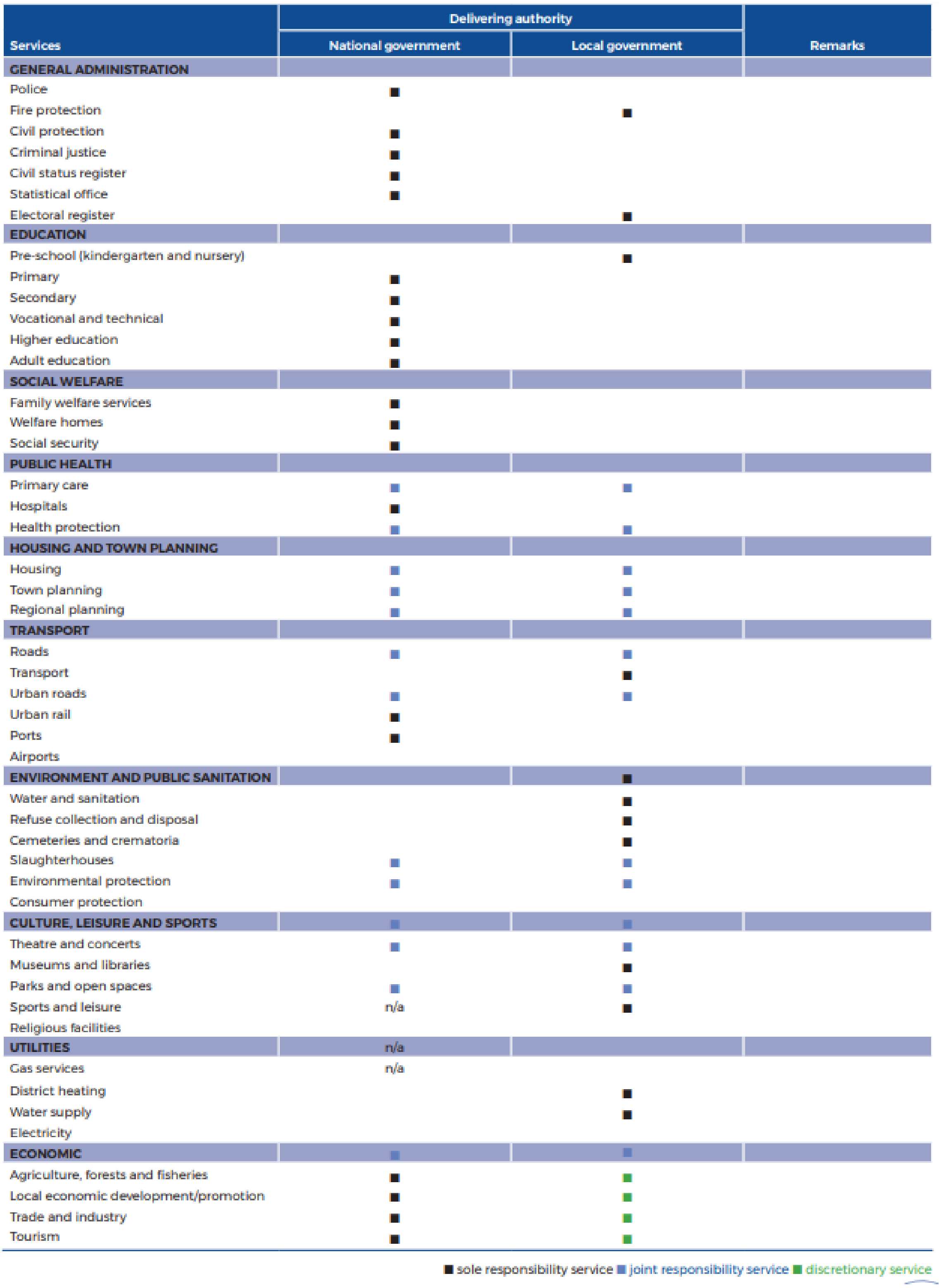
Figure 17. Average Temperature Kabompo



	January	February	March	April	May	June	July	August	September	October	November	December
Avg. Temperature (°C)	22.7	22.7	22.7	21.7	19.1	17	17.1	19.6	23.4	24.6	23.3	22.5
Min. Temperature (°C)	17.2	17.3	16.5	14.1	10	7	7.2	9.8	13.9	15.7	16.9	17
Max. Temperature (°C)	28.2	28.1	28.9	29.4	28.3	27	27	29.5	33	33.6	29.7	28.1
Avg. Temperature (°F)	72.9	72.9	72.9	71.1	66.4	62.6	62.8	67.3	74.1	76.3	73.9	72.5
Min. Temperature (°F)	63.0	63.1	61.7	57.4	50.0	44.6	45.0	49.6	57.0	60.3	62.4	62.6
Max. Temperature (°F)	82.8	82.6	84.0	84.9	82.9	80.6	80.6	85.1	91.4	92.5	85.5	82.6
Precipitation / Rainfall (mm)	231	194	156	43	4	0	0	1	5	44	147	220

Figure 18. Kabompo Weather Averages by Month

The minister of the north-western province is Nathaniel Mubukwanu. However, as mentioned earlier, the provinces exist only for administrative purposes. The local government in the north western province consists of 9 councils, so called town councils, one represented in each district. There are three types of councils in Zambia; city, municipal and town, town being the type represented in rural areas, where the inhabitants are fewer and the reliance on agriculture is higher. However, all councils have the same mandates and functions no matter the type. An overview of the distribution of responsibility between local and national government is shown in Figure 19. The members of the council don’t get paid by the national government, but are remunerated by allowances from their council [7].



Services	Delivering authority		Remarks
	National government	Local government	
GENERAL ADMINISTRATION			
Police	■		
Fire protection		■	
Civil protection	■		
Criminal justice	■		
Civil status register	■		
Statistical office	■		
Electoral register		■	
EDUCATION			
Pre-school (kindergarten and nursery)		■	
Primary	■		
Secondary	■		
Vocational and technical	■		
Higher education	■		
Adult education	■		
SOCIAL WELFARE			
Family welfare services	■		
Welfare homes	■		
Social security	■		
PUBLIC HEALTH			
Primary care	🟦	🟦	
Hospitals	■		
Health protection	🟦	🟦	
HOUSING AND TOWN PLANNING			
Housing	🟦	🟦	
Town planning	🟦	🟦	
Regional planning	🟦	🟦	
TRANSPORT			
Roads	🟦	🟦	
Transport		■	
Urban roads	🟦	🟦	
Urban rail	■		
Ports	■		
Airports			
ENVIRONMENT AND PUBLIC SANITATION		■	
Water and sanitation		■	
Refuse collection and disposal		■	
Cemeteries and crematoria		■	
Slaughterhouses	🟦	🟦	
Environmental protection	🟦	🟦	
Consumer protection			
CULTURE, LEISURE AND SPORTS	🟦	🟦	
Theatre and concerts	🟦	🟦	
Museums and libraries		■	
Parks and open spaces	🟦	🟦	
Sports and leisure	n/a	■	
Religious facilities			
UTILITIES	n/a		
Gas services	n/a		
District heating		■	
Water supply		■	
Electricity			
ECONOMIC	🟦	🟦	
Agriculture, forests and fisheries	■	🟩	
Local economic development/promotion	■	🟩	
Trade and industry	■	🟩	
Tourism	■	🟩	

■ sole responsibility service 🟦 joint responsibility service 🟩 discretionary service

Figure 19. Overview of the Distribution of Responsibility Between Local and National Government

There are 166,131 number of households in the North-Western province of which 69.6% are located in rural areas and 30.4% in urban areas. The average number of people per household is 5.4 people in rural areas and 5.1 people in urban [12].

The employment rate is 29.9% in the province (38.1% among men and 22.5% among women) which is similar to the overall employment rate in Zambia of 32.8% (41.7% among men and

24.7% among women). 24.9% of these are employed within the agricultural sector and 75.1% in the non-agricultural sector (specific employment data was not found for this sector) [12]. Poverty rate by province can be seen in Figure 20. The poverty rate is higher in the North-Western province (66.4%) than the average in the country (54.4%) but in the same range as other provinces with many rural areas [29].

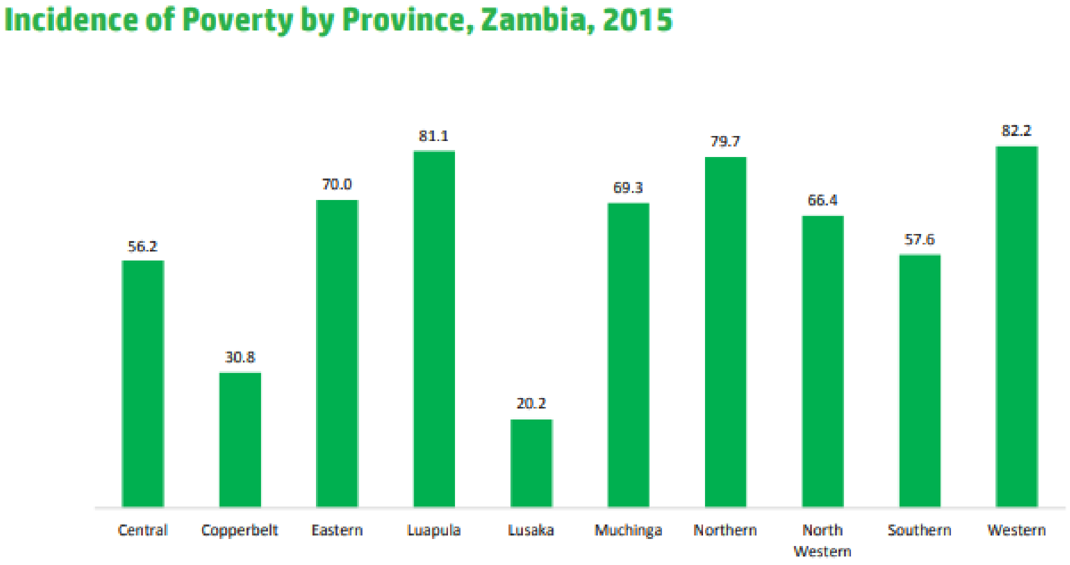


Figure 20. Poverty Rate by Province, 2015

3 Methodology

The first section describes the chosen modelling tool for this project, followed by a section describing how input data was collected and estimated.

3.1 HOMER Pro

HOMER Pro is a software modelling tool used to optimise and evaluate power system configurations, particularly microgrid configurations but can also be used for on-grid solutions. The software was developed in 1992 by the National Renewable Energy Laboratory (NREL) for the Department of Energy in the United States. It is the chosen modelling tool for this study since it's becoming the global standard in microgrid software and used worldwide [4].

The tool evaluates different power system configurations from input parameters such as costs, technical data and resource availability. The time period modelled is one year with a minimum time step of one minute. HOMER finds the configuration with the lowest total net present cost[5] (NPC). A sensitivity analysis can also be performed by the tool, to find out how a variation of a certain parameter effects the outcome, e.g. how an altered solar irradiance affects the results.

3.2 Data Collection

3.2.1 Households and Inhabitants

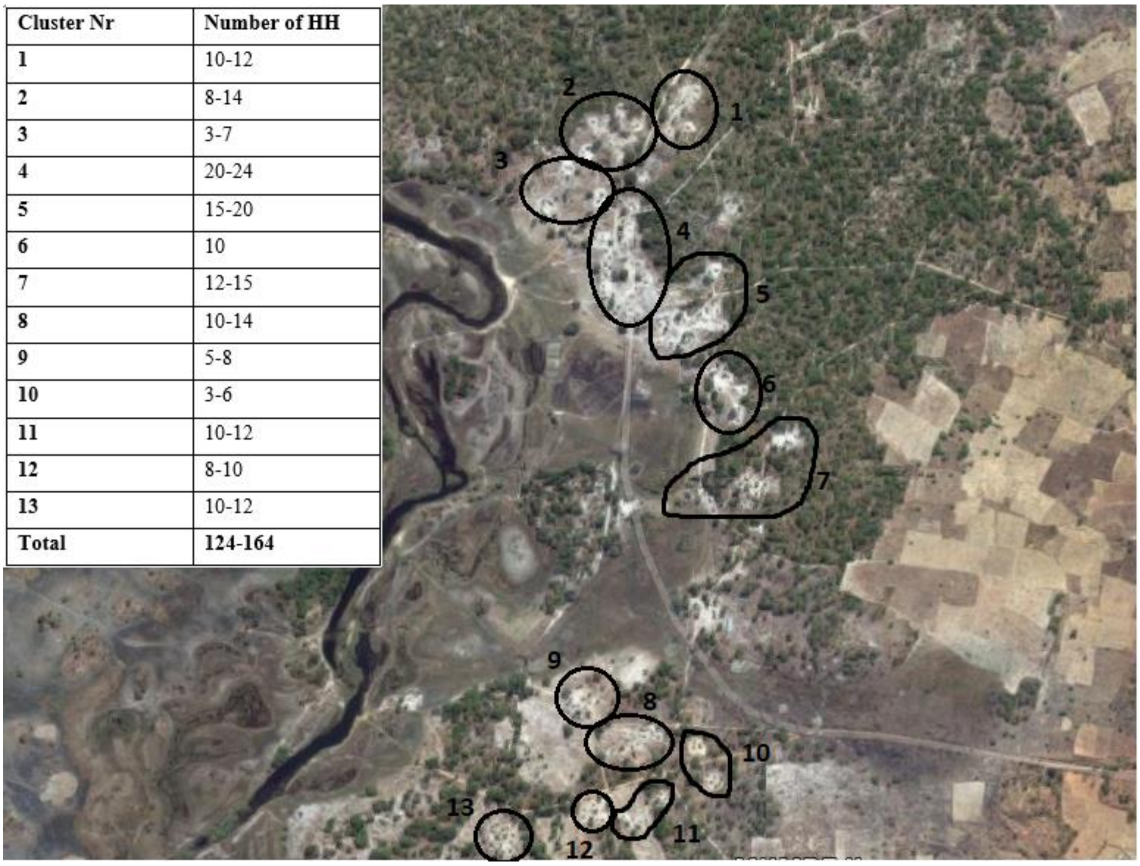
The geographical coordinates for the community are:

Latitude: -13.892º
Longitude: 23.646º

Number of inhabitants and households were estimated from satellite pictures using Google Maps. The number of households were estimated to 124-164 households as can be seen in Figure 21. An assumption of 5.4 people/household was made (the average household size for rural communities in the North-Western province), resulting in a total of 670- 886 inhabitants. The average number was used (144 households, 778 inhabitants) for further estimations.

---

[5] The total NPC condenses all the costs and revenues that occur within the project lifetime into a single lump sum in year-zero dollars, with future cash flows discounted back to year zero using the discount rate



Cluster Nr	Number of HH
1	10-12
2	8-14
3	3-7
4	20-24
5	15-20
6	10
7	12-15
8	10-14
9	5-8
10	3-6
11	10-12
12	8-10
13	10-12
Total	**124-164**

Figure 21. Households Estimation, Mumbeji

3.2.2 Renewable Energy Potential

Solar radiation as well as temperature data was retrieved as hourly data from the PVGIS-SARAH database for the location of Mumbeji (Lat -13.892º, Long 23.646º, Altitude 1054 m, GMT+02:00) from the online software tool Photovoltaic Geographical Information System (PVGIS) developed by the European Commission [30]. The average values of the ten most recent years available (2007-2016) was used and for leap years the data for the 29th of February was dismissed in order to get data for an identical time span. The average daily radiation can be seen in Figure 22. The collected hourly data started at local time 00.49 but when introduces to the modelling tool (HOMER) as 8760 values, the program reads it as local time 00.00, 01.00, 02.00 and so on. This means that there’s a displacement of 11 minutes for the temperature and radiation data which has been considered neglectable.

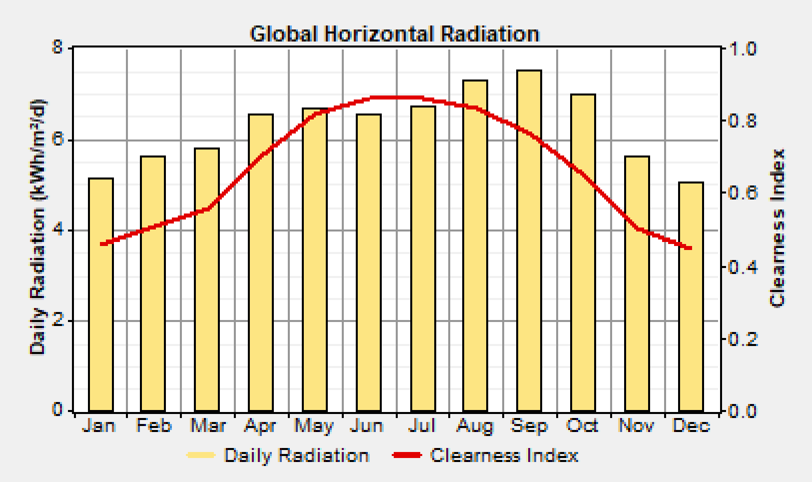


Figure 22. Average Daily Radiation (kWh/m2/day)

Temperature data is being considered in HOMER in regard to the efficiency of the PV panels. The average monthly temperature can be seen in Figure 23.

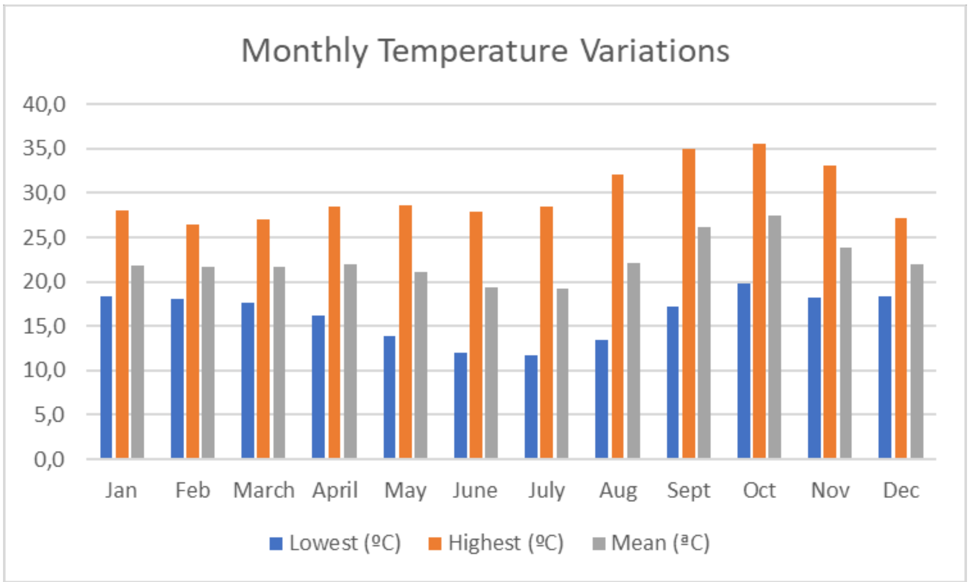


Figure 23. Average Monthly Temperature Variations

As previously mentioned, Zambia has great biomass potential and regarding biomass resources in Mumbeji, cassava waste has been considered as a suitable option, since approximately 60% of the agricultural yields in the North-Western province consist of cassava[6] and using biomass waste doesn’t require additional land use. In addition, cassava is a very promising crop when it comes to biomass energy. It contains a high amount of fermentable sugars (32.4% in fresh cassava and in dry matter 80.6%) and is the crop which yields most carbohydrates per hectare

---

[6] Data was only available for year 2001, 2003-2005 and 2007 and varied between 55-73% in these years

after sugar beet and sugar cane. It has a lower heating value (LHV) of around 16 MJ/kg [31]. It is also one of the most robust crops with no need of irrigation and low agrochemical input [32].

To estimate the available biomass in Mumbeji the ratio inhabitants in the community (800) to the rural population in the north western province was multiplied with the average production of cassava in the province. This gave a value of 0.365 tonnes per day. Comparing this to FAO's value of 5.8 tonnes per hectare and year in Zambia would mean that Mumbeji community cultivates 23 ha of cassava which seems reasonable in relation to satellite pictures of the area. Further, the ratio waste-useful crop varies depending on location and community. According to Veiga et al. [31] the ratio varies from 0.36 to 0.91 in Brazil where their studies on three types of cassava waste (seed stem, thick stalks and thin stalks) were conducted [31]. Using the lowest ratio gives a biomass potential of 0.13 tonnes per day.

Regarding hydropower, there is the Mumbeji river running alongside the community, as can be seen on the left side of the community in Figure 16. However, no data was found for any site-specific hydropower potential and neither was other relevant data such as water flow or precipitation data. To make an estimation was therefore considered too uncertain and this option was neglected. Geothermal potential was neglected due to the same reasons and also, that, despite a geothermal energy potential in Zambia, it has not yet been exploited and an implementation in the near future was therefore considered unfeasible. Due to the low wind potential in the country (wind averages of 3 m/s), wind power has also been neglected.

3.2.3 Technologies & Equipment Data

After evaluating the different renewable energy potentials at the location, it could be concluded that, with the data available, solar and biomass were the most feasible options. The technologies that were considered most appropriate for these resources in Mumbeji community are presented in this section, together with related data that was used as inputs in HOMER. The cost data used as inputs to HOMER are presented in this section, while total system costs and auxiliary components not introduced into HOMER are presented in next chapter. A report produced by the International Renewable Energy Agency (IRENA) on costs and markets for Solar PV in Africa was used as a reference as well as data from retailers [33]. The higher values on the cost ranges were used, to ensure that costs were not underestimated. The cost variations for different components of an off-grid mini-grid PV system (0-120 kW) in Africa according to the report by IRENA are shown in Table 10. Soft cost included project development/feasibility study cost, customer acquisition (sales and marketing costs), system design and procurement, subsidies (applications, fees, etc.), permitting (application for permitting), financing and contract (legal) fees, installation costs/civil works, interconnection, performance and warranty, commissioning cost and training and capacity building. Other hardware costs included racking, wiring and cables, monitoring system, duty and transportation cost and others such as transformer, protection devices, etc.

Table 10. Costs PV System (IRENA).

Component	Cost (USD/W)
PV module	0.8-2.8
Battery	0.1-4.1
Inverter	0.163-2.2
Other hardware	0.1-2.8
Soft cost	0.4-5.5

Excluding the batteries, the estimations made for PV panels and inverter resulted in a system cost of 5.2 USD/W. Looking at the off-grid PV systems investigated in IRENA's report, all systems of 80 kW or higher (except one), have a system cost lower than 3 USD/W, while the one exception has a system cost of approximately 5 USD/W.

3.2.3.1 Photovoltaic Technology

The most mature, competitive and commercially available solar technology is PV and was therefore the chosen technology. The models considered was the REC Peak Energy series, since it's a renowned manufacturer who offer high quality and reliability [34]. The input data for the PV panels in HOMER can be seen in Table 11. The lifetime and the efficiency are data from the manufacturer while the remaining are assumptions. The slope angle was set to be the same as the latitude (13.89º) and the azimuth angle to face north (180º) since the community is located in the southern hemisphere.

Table 11. Properties PV system HOMER

Output current	DC
Lifetime	25 years
Derating factor	85%
Slope	13.89º
Azimuth	180º
Ground reflectance	20%
Efficiency	15.8%

The capital cost for PV modules in Mumbeji's mini-grid was estimated to 3 USD/W, including installation and hardware costs associated to the PV modules (such as the ones described by IRENA). According to IRENA the soft costs and hardware costs together vary between 0.5-8.3 USD/W (0.4-5.5 USD/W and 0.1-2.8 USD/W respectively). Since these costs consider the whole system and PV costs have experienced a continuous decrease (the report considers the years 2011-2015) 3 USD/W was considered reasonable. Comparing to data from Spanish and European retailers, the costs for the REC Peak Energy Series PV modules vary between 0.5-0.8 USD/W [35][36]. Replacement cost was estimated to 10% lower than capital costs and operation and maintenance (O&M) costs to 1% of capital costs. Technical and mechanical data are shown in Table 12.

Table 12. Technical and Mechanical data, PV panels

Rated power	260 W
Nominal power voltage	30.7 V
Nominal power current	8.5 A
Efficiency	15.8%
Dimensions	1665 x 991 x 38 mm
Weight	18 kg

3.2.3.2 Batteries

Since solar energy is highly intermittent it's necessary to add some type of storage to the system to be able to meet the demand. Lead-acid batteries were chosen for this model, as they are the most common and economically competitive option for off-grid applications. The model used was Hoppecke 12 OPzS 1500 Ah with a capacity of 3 kWh. Hoppecke is a well-known battery manufacturer and are widely used for hybrid off-grid configurations. The battery has a lifespan of more than 1'500 life cycles, making it one of the most durable stationary batteries on the market [39]. Technical and mechanical data are shown in Table 13. Each battery has a nominal voltage of 2 V and will be modelled in strings with 24 batteries in each, resulting in strings of 48 V. The battery cost used was retail data, approximately 3'800 USD for 6 batteries [40].

Table 13. Technical and Mechanical data, Batteries

Nominal capacity	1,500 Ah
Nominal voltage	2 V
Round trip efficiency	86%
Min. state of charge	30%

Dimensions (L/W/H)	215 mm / 277 mm / 710 mm
Weight	76.4 kg

3.2.3.3 Inverter

PV modules and batteries provide electricity in direct current (DC) and for this reason an inverter is needed to convert the DC to alternating current (AC). The inverter considered was Sunny Tripower 25000TL, which has a high efficiency (up to 98.3%), a wide input voltage range and is compatible with many PV modules [41]. The inverter cost was set to the highest value from IRENA's report, 2.2 USD/W. Data from retailers for the considered inverter was found at as low as 0.13-0.17 USD/W but since the costs shall include installation, transportation, etc., 2.2 USD/W was set to avoid risks [42][43]. Technical and general data are shown in Table 14.

Table 14. Technical and Mechanical data, Inverter

Max. generator power	45,000 Wp
DC rated power	25,550 W
Max. input voltage	1,000 V
MPP voltage range	390 – 800 V
Output rated power (at 230 V, 50 Hz)	25,000 W
Feed-in phases/Connection phases	3 / 3
Max. efficiency	98.3%
Dimensions (W / H / D)	661 / 682 / 264 mm
Weight	61 kg

3.2.3.4 Biomass Gasification

One way to generate electricity from biomass is to gasify the biomass and then combust it. A gasifier using cassava waste was evaluated for this case study. Biodigestion was not considered, since cassava is a dry biomass, and there's no reliable continuous supply of water at site. Gasification is a thermo-chemical process that converts the solid biomass to a combustible gas, with a gasification agent that commonly is either air, oxygen, steam or carbon dioxide. The product gas, called syngas, is a mixture of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), ethane (C_2H_6), propane (C_3H_8) and tar, in quantities depending on the type of feedstock and operational factors [44]. The syngas can then be combusted to generate heat and electricity. In addition to being CO_2 neutral, another significant benefit is that it is always available (as long as there's feedstock available) and not an intermittent energy source like many other renewables. If the feedstock used is waste, then there's also not any additional land use needed. Lastly, local farmers can increase their income by selling biomass fuel or feedstock.

The downdraft gasifier Power Pallet PP30 with a capacity of 25 kW was considered appropriate for the power system, since the manufacturer, All Power Labs, is a global leader in small-scale gasification [45]. Technical and general data can be seen in Table 15. It has a fuel consumption of 1.2 kg biomass/kWh and a gasification ratio of 2-2.5 Nm^3/kg [46].

Table 15. Technical, Mechanical and General data, Biomass gasifier

Gasifier type	APL v5 Patented Multistage heat recycling downdraft gasifier
Power Rating (off-grid)	25 kW
Sound level at 7 meters	75 dB
Biomass consumption	1.2 kg/kWh
Runtime per hopper fill: approximate at 250 kg/m^3 feedstock density	5 kW: 12 hours 10 kW: 6 hours 15 kW: 4 hours 25 kW: 2.4 hours
Max. continuous operation before empty ash vessels	16 hours
Start-up time	10-15 minutes
Installed footprint (L / W / H)	1.778 / 1.42 / 2.24 m
Weight (main crate + hopper crate)	1,130 kg + 91 kg
Site Requirements	Ideally outdoor covered patio. Well ventilated, level floor, protected from rain and direct sun, 1.75m overhead clearance. If poor ventilation, a fireproof hood over the flare is required.

The properties of the syngas and the generator introduced into HOMER can be seen in Table 16. Martínez et al. [47] find the typical gasification ratio for wood to syngas in a downdraft biomass gasifier to be between 2-3 Nm^3/kg. The density 0.72 kg/m^3 gives a gasification ratio of 1.44-2.16 kg gas/kg biomass for 2-3Nm^3/kg and an estimation of 1.5 kg gas/kg biomass was therefore made. The minimum load ratio was set to the one given in the specification sheet of the PP30, 20%. The lifetime of the gasifier was not specified and therefore estimated to be 15,000 hours, as is the default value set by HOMER. In an economic feasibility study on small-scale biomass gasification done by Fracaro et al. [48] the useful lifetime of the gasifier was considered to be 10,000 hours while the engine-generator was estimated to 20,000 hours and 15,000 hours therefore seemed reasonable. With no possibility to do tests on the cassava waste in Mumbeji, data had to be sought from existing literature. According to a study done by Veiga et al. [31] cassava has physical and chemical characteristics similar to woody biomass (HHV[7], proximate analysis[8], elemental composition and TGA[9]). Veiga et al. [31] find the carbon content for cassava waste to be 44.12%, Pattiya [49] find it to be 51% and according to Commeh et al. [50] the carbon content for wood pellets is 44.5%. An estimation of the carbon content was therefore set to 44%. Molino et al. [44] have conducted a state-of-the-art on biomass gasification technology and found the LHV of syngas to range from 4-13 MJ/Nm^3. A density of 0.72 kg/m^3, as set by HOMER for biogas, gives an LHV of 5.56-18.06 MJ/kg. The LHV of the gas depends much on the gasification medium, for air it ranges between 4-7 MJ/Nm^3, steam 10-18 MJ/Nm^3 and oxygen 12-28 MJ/Nm^3. The working medium in the PP30 gasifier is air and the lowest value was applied to be precautious.

Table 16. Gasifier Input Data HOMER

Carbon content cassava	44 % (mass-based)
Gasification ratio	1.5 kg gas/kg biomass
LHV of syngas	4 MJ/kg
Marginal fuel consumption of generator	1.2 (kg/hr/kW output)
Lifetime gasifier (operating hours)	15’000 hours
Minimum load ratio	20%

The cost of the Power Pallet PP30 gasifier is approximately 50,000 USD with an additional cost of 3,950 USD for on-site commissioning and training services [51]. The replacement cost was set to 50,000 USD, excluding the on-site commissioning and training services, and O&M cost was estimated to 0.18USD/hr.

3.2.3.5 Biomass Feedstock

The gasifier has general feedstock requirements; an ash content lower than 5%, moisture content of less than 30% (dry weight) and a particle size between 1 and 4 cm [52]. The cassava

---

[7] Higher Heating Value (HHV) expresses the amount of heat released when combusting a fuel

[8] Proximate analysis includes ash content, volatile matter, moisture content and fixed carbon content

[9] Thermal gravimetric analysis (TGA) analyses the mass changes with temperature changes over time

waste can be divided into three parts – the leaves, the stalks and the rhizome. The cassava plant and its parts can be seen in Figure 24.

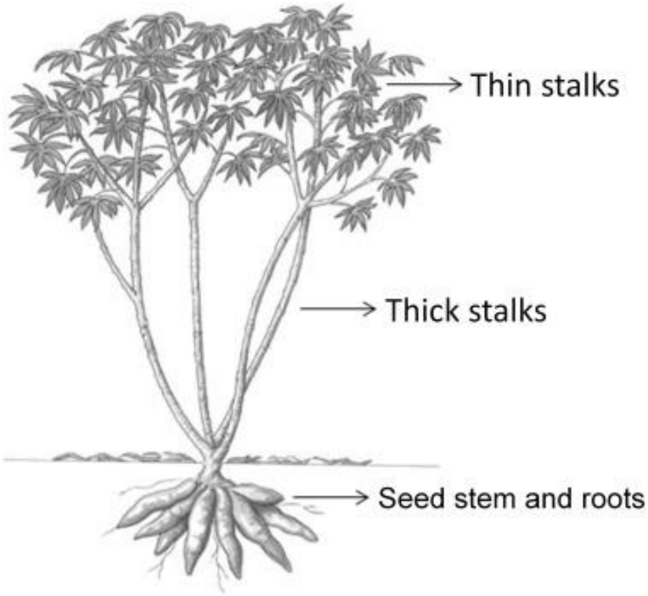


Figure 24. Cassava Plant

The ash content in cassava waste varies between 2.5-3.5% and therefore meets the requirements [31]. Kaewwinud et al. [53] investigate physical and mechanical properties of the stalks and divide the stalks into three parts; top, middle and bottom as the stalks are thicker at the bottom and thinner at the top. They also investigate the parts at different time stages; 0, 10 and 20 days after being harvested. When harvested they had a moisture content of 54.19%, after 10 days 43.05% and after 20 days 24.93%. Veiga et al. [31] find the moisture to vary between 52% and 75% when harvested, but in the proximate analysis the moisture content varies between 11-12%. It is not stated how much time has passed between harvest and the proximate analysis but due to the findings of Kaewwinud et al. [53] it's estimated that the waste needs at least 20 days of drying after harvest. After 20 days the mean diameter of the top stalks, middle stalks and bottom stalks is 2.093 cm, 1.840 cm, and 1.447 cm respectively. This means that potentially the entire stalk could be chipped into particles that fit the appropriate size of 1-4 cm. The only part that ever had a smaller diameter than 1 cm was the top stalk that ranged between 0.771 and 2.104 cm [53].

Veiga et al. [31] classify the waste parts into thin stalks, thick stalks and the seed stem. The seed stem is stalks that have been cut into 20 cm pieces and planted to reproduce the plant asexually. To be on the safe side, only the thick stalks have been considered usable as feedstock even though it seems that most of the stalks and the seed stem could be used as well. Therefore, the average ratio thick stalk/root was calculated from 10 different samples investigated in the report and gave a biomass potential of 95 kg/day which was the value used in the modelling. As much other data, the cost of the biomass feedstock is hard to estimate without doing on-site surveys. An article from August 2013 was found on the Zambian news site Lusaka Voice where it was stated that the price of fresh cassava roots at that time was 20 USD/tonne and of the sale price 94% were production costs [54].

In a cost analysis of biomass for power generation done by IRENA, costs range between 44-94 USD per tonne in the United States and include woodchips and pellets from local energy crops and local agricultural residues. In the same report IRENA also provides some data on costs in developing countries India and Brazil. Bagasse costs 11-13 USD/tonne in Brazil and 12-14 USD/tonne in India while woodchip has a cost of 71 USD/tonne in Brazil and rice husk 22-30 USD/tonne in India.

A cost of 50 USD per tonne biomass feedstock was used in HOMER, with a risk of overestimation since the feedstock is waste and much of the production costs are therefore already covered in the harvesting of cassava. However, a biomass cost of 25 USD or 50 USD per tonne doesn't have a significant impact on the costs in the model, since the biomass potential is limited to 35 tonnes yearly. To chip the stalks, an electric wood chipper of 7.5 kW, MHC-500 from Taizy, was found suitable in terms of capacity and appropriate sizes of the wood chips. The technical and mechanical data of the wood chipper can be seen in Table 17 [55] .

Table 17. Technical and Mechanical data, Wood chipper

Capacity	0.5 tonnes/hour
Power	7.5 kW
Power type	Electric
Weight	240 kg
Dimensions (L / W / H)	2.2 / 1.1 / 1.8 m
Speed (r/min)	480
Blade (pieces)	4

3.2.4 Demand Curve

To estimate the community's demand several assumptions was made. Firstly, the demand was divided into three categories; household demand, community demand and commercial demand and from there on estimated separately as explained in below sections. The methodology of forecasting demand for mini-grids presented by the German Climate Technology Initiative in the handbook *What size shall it be?* was followed [56]. Due to lack of data, ideally gained from on-site surveys, estimations were made from literature reviews.

3.2.4.1 Household Consumption

According to a research study done by Makashini et al. [57] on residential energy practices in Kitwe in central Zambia the most used electric appliances in informal settlements are television, fridge, non-energy saving light bulb, energy-saving light bulb, radio and DVD-player. These appliances are also the most common for the households in the 60 kW solar mini-grid project in Mpanta in northeast Zambia [58]. Less used appliances include fans, electric pressing iron, electric stove, electric kettle and battery powered lamps.

It’s worth mentioning that energy practices vary from settlement to settlement and furthermore, abovementioned results from the study in central Zambia is a mining area which is more industrialised than Mumbeji. However, the findings still give an indication of which appliances are being used in rural settlements. Therefore, these appliances were also assumed to be used in the community in Mumbeji. Assumptions of number of units per household (HH), average wattage per device and total wattage can be seen in Table 18.

Table 18. Household Consumption

Household Consumption	Units per HH	Total Units	Power (W)	Total power (W)
Lighting	3	432	20	8640
TV	0,3	43,2	150	6480
Radio	0,75	108	20	2160
Phone	2	288	10	2880
Fan	0,4	57,6	50	2880
Fridge	0,05	7,2	180	1296
Other appliances such as DVD player	0,1	14,4	43	619,2
Other appliances such as electric kettle, electric flatiron	0,05	7,2	1600	11520
Internet routers	1	144	6	864
Computer/lap tops (assuming 50% laptops 50% computers)	0,3	43,2	175	7560

Electric cooking and heating demand were neglected for several reasons. Firstly, the lowest temperature during the year is at 11.7ºC (see temperature data in Figure 17 in previous section) indicating that there’s no significant need for heating. Secondly, studies show that non-electrified communities rarely transit completely from traditional fuels to electric energy straight away, i.e. although given access to electricity the transition is gradual. Lastly, affordability can be an issue in rural communities, an initial high consumption can lead to debt, hence disconnection from the grid, which is what has happened in the 60 kW solar mini-grid in Mpanta village in Zambia [58]. A more feasible scenario could be to extend the power system as the demand grows once the incomes increase.

Prinsloo et al. [59] has performed a scoping exercise to find a universal load profile shape for domestic households in isolated off-grid rural African villages. Several load profile shapes used for cases in- and outside Africa are compared. They find that the load profile for traditional rural African villages has very similar characteristics, with two typical peak loads – one during early morning and one in the evening, the evening peak always being more prominent. A smaller peak around noon was often found in agricultural communities. The typical electrical load is represented by equation 1 as the power load as a function of time and shown in Figure 25. This curve was used as a reference when developing the demand curve for the household demand.

$$P_e = e[\sin(0.3409 - \sin(0.68039 * t) - 0.16801 * t)] \qquad \text{(Eq. 1)}$$

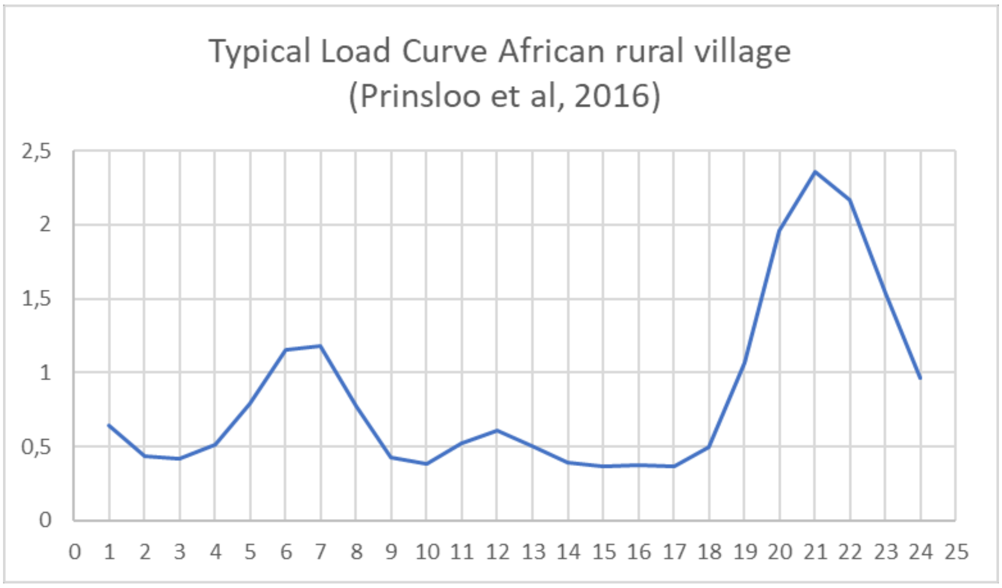


Figure 25. Typical Electrical Load Curve for Isolated Off-grid African Communities

The daily energy consumption per household is 1.52 kWh and a total domestic demand of 219.04 kWh per day. The estimated demand load profile can be seen in Figure 26

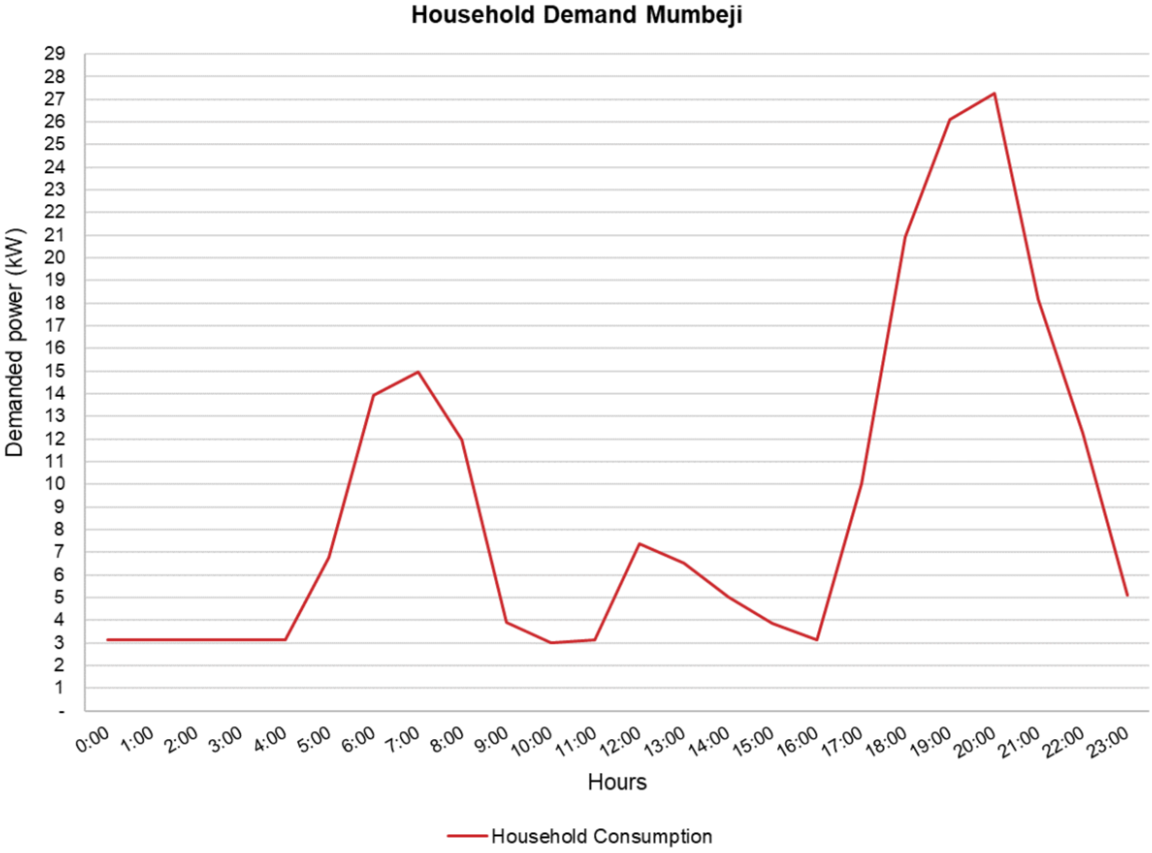


Figure 26. Estimated Demand Load Profile for Households in Mumbeji

3.2.4.2 Community Consumption

Information regarding communal buildings or services was not found and therefore an assumption was made that the community includes one school, a health care centre, a church and a town/police office. In addition, it was decided that street lightning will be installed.

Regarding street lighting it was assumed 3 lights per "cluster", meaning a total of 39 street lights. For the school, the church and the town/police office it was assumed that each entity had 4 rooms with 2 light bulbs per room. Detailed assumptions regarding appliances can be seen in Table 19.

Table 19. Community Consumption

Community Consumption	Units	Power	P. Total
Street lighting	40	80	3200
Fans	9	100	900
Lighting community buildings (church, school, police/town office)	24	20	480
Phones	9	10	90
Internet routers	3	6	18
Computers	8	175	1400
Printer	2	300	600
Tv + DVD player	2	193	386
Health care centre	-	-	-

Regarding the health care facility, a load profile shape from a rural Nigeran health care facility was used [60]. It consumed 19 kWh/day, which correspond to a medium sized health facility (60-120 beds). A small health facility (0-60 beds) was considered feasible for the community's 800 inhabitants, hence the load curve from the Nigerian health centre was scaled down by 50% [61]. The aggregated communal demand is 67.67 kWh/day and can be seen in Figure 27.

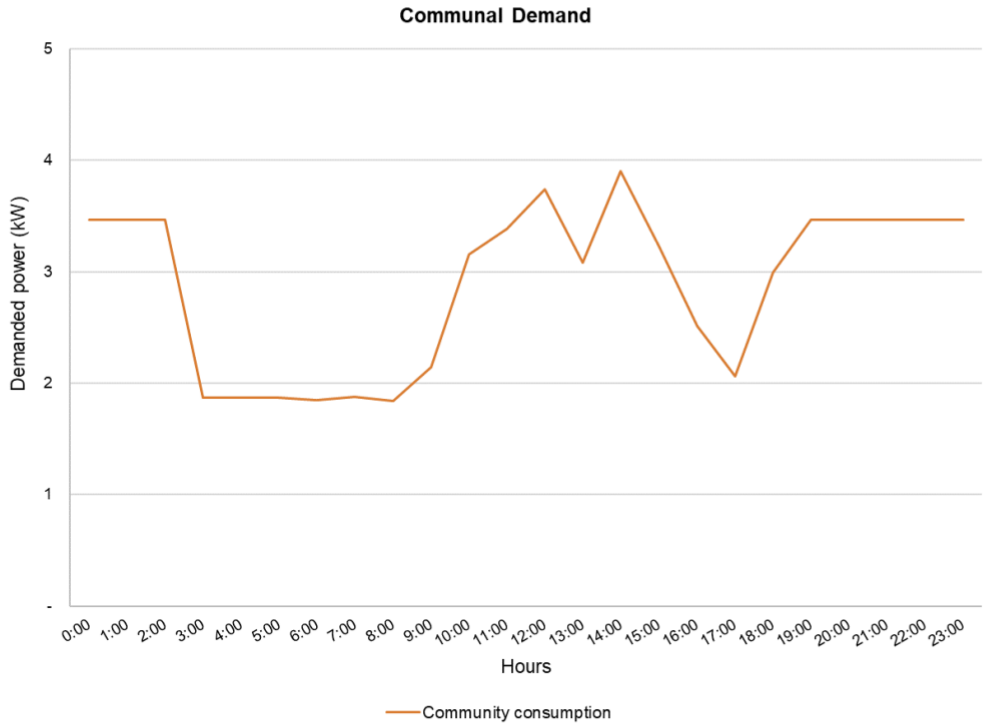


Figure 27. Estimated Demand Load Profile for Communal Services in Mumbeji

3.2.4.3 Commercial Consumption

Due to lack of data it was assumed that the community had two shops and two restaurants/bars with electric appliances as described in Table 20 and an aggregated load profile as shown in Figure 28 below. The load of the wood chipper for the biomass feedstock was also added here. The chipper has a capacity of 0.5 tonnes/hour. To chip the waste yield of a year would require approximately 70 hours. The load of the chipper was added as 1 hour per day, between 11 am and 12 pm in, in August and 2 hours per day, between 11 am and 1 pm in September, when the solar radiation is the highest. This resulted in a total demand of 24.89 kWh per day in August, 32.39 kWh per day in September and 17.39 kWh per day during the rest of the year.

Table 20. Commercial Consumption

Commercial consumption	Units per facility	Units	Power (W)	Total power (W)
Lighting (stores, bars)	2,5	10	20	200
Fans	1	4	100	400
Fridge	0,5	2	180	360
Laptops	1	4	75	300
Wood chipper	1	1	7500	7500

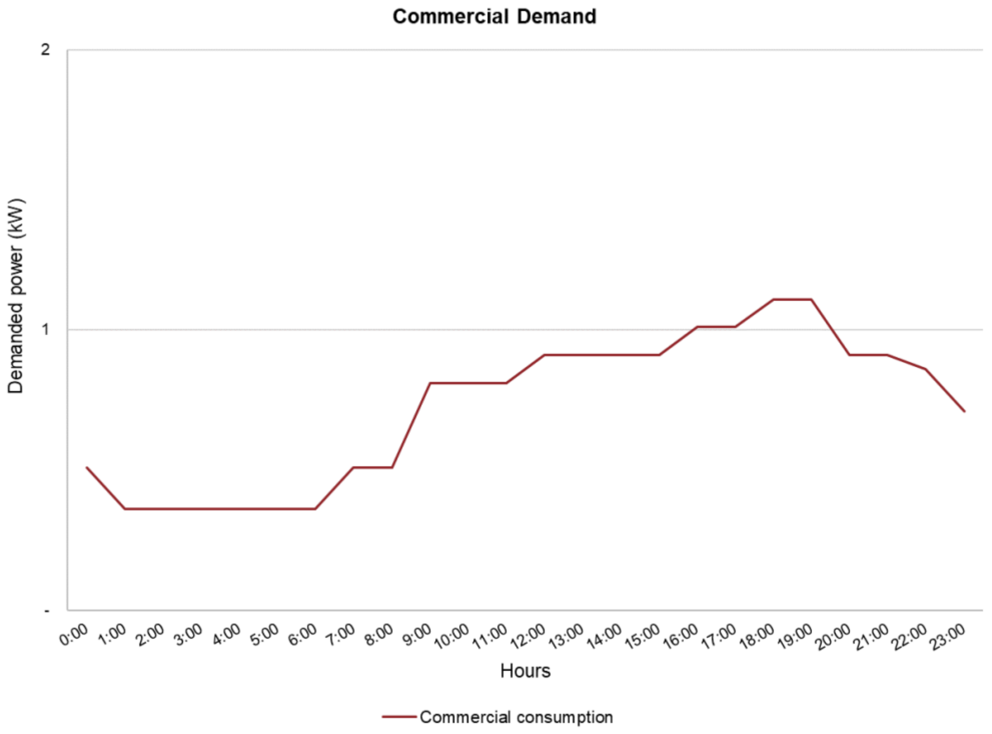


Figure 28. Estimated Demand Load Profile for Commercial Services in Mumbeji

3.2.4.4 Total Consumption

Figure 29 shows the three individual demand profiles and the total demand profile (green). The total demand is 304.10 kWh/day.

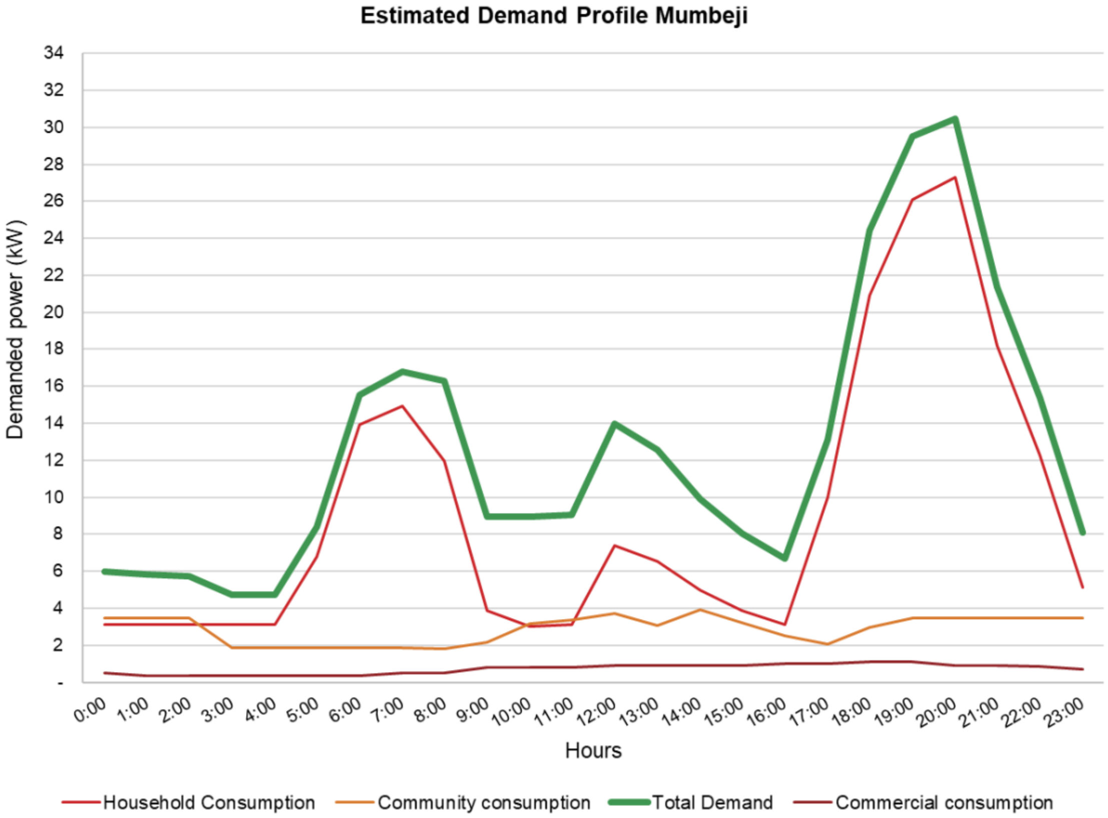


Figure 29. Estimated Total Demand Load in Mumbeji

4 Proposal for Rural Electrification

4.1 Simulations in HOMER

4.1.1 Modelling

The simulations in HOMER was done by first introducing the literature sought and estimated data, which resulted in an initial model that was further evaluated and modified by investigating how different technical parameters, and changing these parameters, impacted the model.

The researched data introduced to HOMER included the data explained in previous chapter, such as demand load curve, energy resources and cost data. In addition, a time step of 60 minutes was set, as for the estimated demand load, and a project life time of 25 years. Random variability was applied to the load curve to make it more realistic, 20% daily variability and 20% hourly variability was added. Figure 30 shows the initial daily load profile and the hourly load and seasonal profile with the added random variabilities.

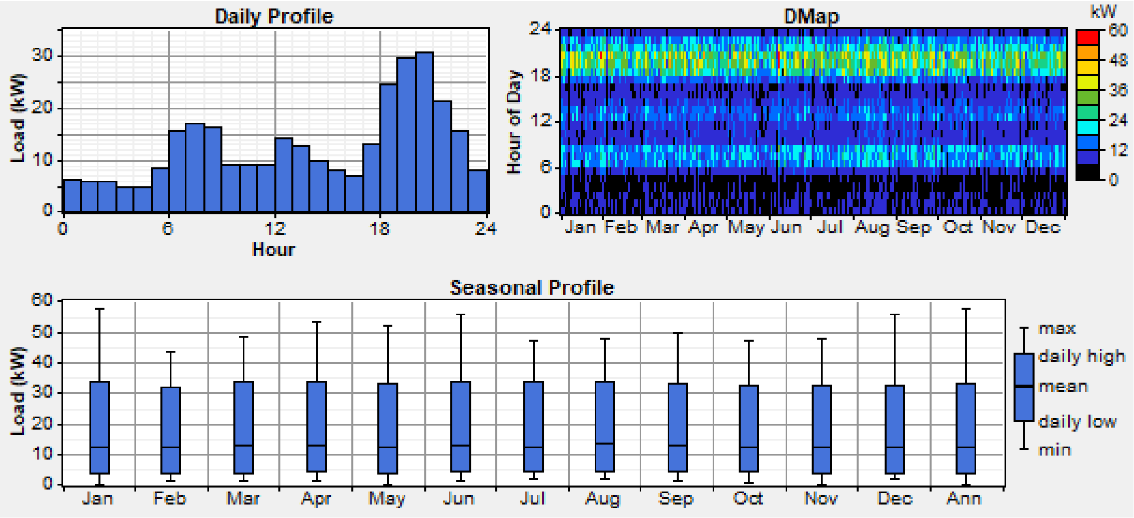


Figure 30. Daily Load Profile, Hourly Load Variation during the year and the Seasonal Load Profile

An initial discount rate of 8% was used and the first simulations were run. Technical parameters whose impact was explored in HOMER included the schedule of the gasifier, the dispatch strategy and maximum annual capacity shortage (MACS).

In the first simulations the gasifier had no schedule restrictions and could be turned on and off at any time. However, the gasifier was forced off between 10 pm and 7 am since it requires manual labour and maintenance. This maintenance is worth not overlooking as it includes refilling the hopper daily, emptying out char-ash and cyclone dust cans (daily to weekly), changing filter bags and cleaning the filter basin (weekly to monthly) [52]. Because of these maintenance requirements, it was considered desirable to use the gasifier as few hours as possible, and also at as few times as possible and not, for example, on scattered hours throughout the day. To decrease the number of hours used and the scattered hours, iterations of forcing the gasifier off/on at certain hours while changing the biomass feedstock price were explored. The biomass price was increased until a desired biomass consumption was reached, with a trade-off between the biomass consumption and other effects on the model, like installed capacities and costs. At 150 USD/tonne the feedstock consumption was 21.2 tonnes per year (58 kg/day, 1,199 hours of operation/year) while at 200 USD/tonne the feedstock consumption was at 5.37 tonnes per year (15 kg/day, 930 hours of operation/year). The biomass consumption was not significant lower with a feedstock cost of 250 as compared to 200 USD/tonne and was therefore kept at 200 USD/tonne.

To avoid that the gasifier was being turned on and off several times during the day, attempts were made of forcing the gasifier on at certain hours instead. It is not possible to set a minimum run time for the gasifier in HOMER, which, if possible, would've been done. Forcing the gasifier on, did decrease the scattered single-hour uses without increasing the biomass consumption, but the hours of operation increased. Increasing the biomass price further, as an attempt to push back the gasifier's hours of operation, did only lower the biomass consumption but not the hours of operation. No matter how the gasifier was forced on and off, it still resulted in a few scattered single-hour-uses. These were therefore considered neglectable, since they were relatively few. In real life the gasifier could be on for two hours instead of one when this occurred and charge the batteries with the surplus energy.

In addition, the price change on biomass also changed the size of the inverter, since a higher biomass price required more production from the PV modules and therefore demanding a larger inverter. At the trade-off at 200 USD/tonne, the inverter increased 10% in capacity but the biomass consumption decreased three times. This trade-off also led to small cost increases, due to the extra inverter capacity. Rising the biomass price also resulted in a better use of the batteries; with a lower price the batteries were fully charged most of the time while the higher price resulted in a more evenly distributed frequency of the state of charge. The frequency of state of charge can be seen to the left in Figure 31 for the lower biomass costs and for the higher costs to the right in the figure.

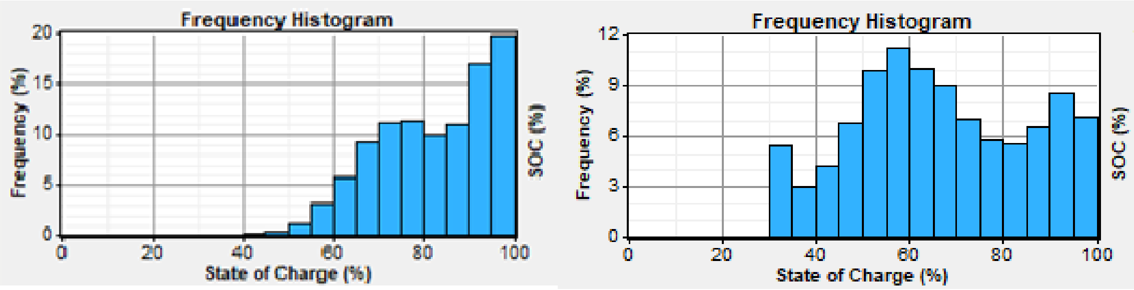


Figure 31. Frequency Histograms with a lower biomass feedstock price (left) and a higher biomass feedstock price (right)

In the case of no schedule restrictions for the gasifier, a MACS of 0% was not a problem, but had significant impact on the model when controlling the generator. Capacity shortage include not only the unmet load but also the unmet operating reserve. Forcing the gasifier to be off at night while accepting a MACS at 1-2% decreased the initial cost and NPC significantly, due to a decreased need of installed PV modules and batteries. The MACS was therefore set to 2%. Increasing the MACS to 3% had no impact on the model. In reality, in the occasion of blackouts, the gasifier could be switched on. It would be to a certain cost, but it would be up to the community.

Two dispatch strategies are available in HOMER; load following (LF) and cycle charging (CC). At LF, the generator produces just enough power to cover the demand when it runs, as opposed to CC, where the generator always runs at full power when running, to charge the batteries with surplus electricity. For the CC strategy, a setpoint state of charge can be applied, meaning that when the generator is running it doesn’t stop until the batteries are charged to a certain level. Different setpoints can be evaluated through a sensitivity analysis. Both strategies were made available for HOMER to find the optimal strategy, the CC with the option of different setpoints for state of charge (40-90% with steps of 10%) and the optimal solution was with the LF strategy. The setpoint state of charge had no impact on the results.

Operation and maintenance costs’ impacts were evaluated by increasing them (by 50% and 100%, 200%) and decreasing them (by 50% and 75%) for the gasifier, PV modules and the batteries but had no significant impact on the configuration or the costs (up to 3% on NPC) since the main costs lie in the installation costs and the O&M costs are relatively low. The only impact it had on the configuration was the size of the inverter, with higher O&M costs for the gasifier, the PV production increased, requiring a higher inverter capacity.

It’s also worth mentioning that the inclusion of the gasifier in the system was not completely obvious. The second most optimal solution of the model does not include the gasifier, but instead increased capacities of the PV modules and the inverter, the MACS increased from 0% to 2% and the NPC and initial costs increased with less than 10%. This shows that the gasifier is not particularly economically competitive with the PV panels but its competitiveness lies in its function as a back-up resource, since the MACS increased when not including the gasifier.

4.1.2 Results

The optimal power system for the community in Mumbeji was found to have the following configuration:

- 80 kW of PV panels
- 25 kW gasifier
- 120 batteries of 3 kWh, a total of 360 kWh
- Inverter of 27 kW

The yearly electricity production is 155,693 kWh. This production supplies a yearly load of 109,058 kWh and remaining produced electricity is excess electricity (24,531 kWh) and losses (15,386 kWh). There's an unmet load of 1.4% (1,537 kWh) and a capacity shortage of 1.6% (1,814 kWh). The PV modules stand for 95.7% (148,975 kWh) of the yearly production and the gasifier 4.3% (6,719 kWh) although the share changes over seasons, as can be seen in Figure 32. The PV production is noticeably bigger from April to October while the production from the gasifier is more or less the same throughout the year.

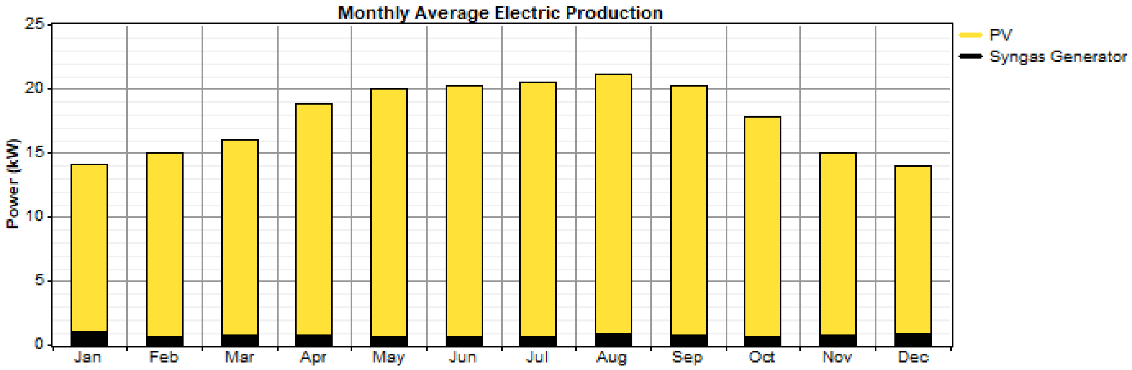


Figure 32. Monthly Average Electric Production

PV output ranges between 0-66.1 kW with a mean output of 17.0 kW and 408 kWh per day. Hours of operation are 4,252 hr/year which basically is all hours with sunshine during the year. The variation in PV output during the year can be seen in Figure 33. The highest power outputs (63-70 kW) are found from May to September around midday while the output rarely reaches more than 49 kW from November to January.

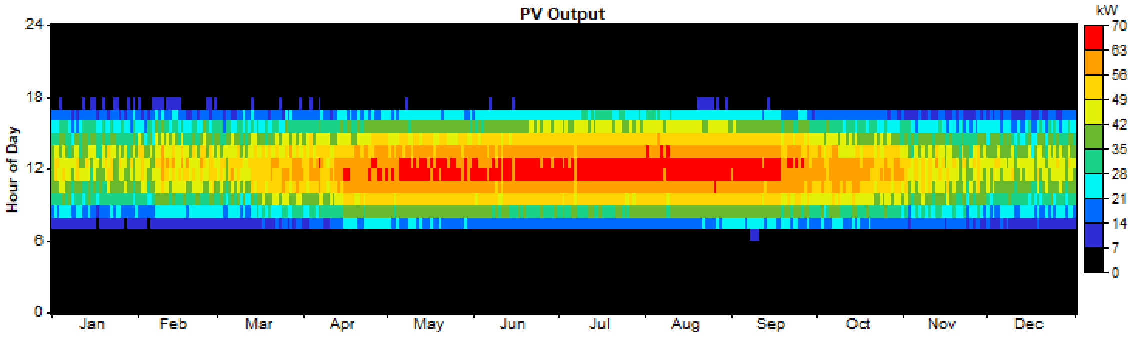


Figure 33. PV output

The schedule of the gasifier can be seen in Figure 34. It has a total of 930 hours of operation during the year and 426 starts, which mostly occur during the evening between 6 pm and 10 pm, particularly between 7 pm and 9 pm. From mid-November until mid-February, when PV output is lower, the gasifier is also often operating during the morning between 7 am and 9 am. It has a mean electrical output of 7.22 kW and a yearly fuel consumption of 5.37 tonnes. 426 starts per year means an average of 1.17 starts per day, or 1 start every day except every 5th day when it has 2 starts. At the same time, the mean output is approximately at 30% of rated capacity. The low mean output depends on a high fuel cost. In the real case, it might be possible to run the gasifier less hours but on higher capacity instead – if that is not possible due to the demand load, running the gasifier twice a day during the rainy season, mid-November to mid-February, would still be feasible.

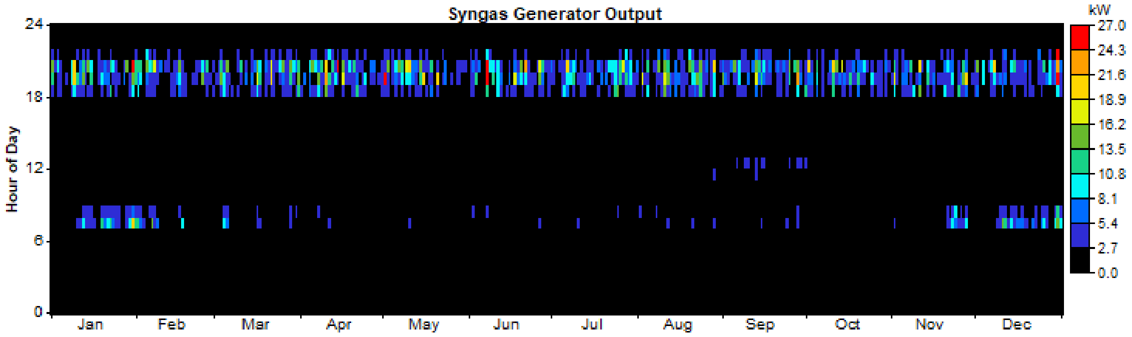


Figure 34. Gasifier Output

The battery bank consists of 5 strings in parallel, each string with a bus voltage of 48 V and storage capacity of 72 kWh, resulting in a total capacity of 360 kWh. The energy going in to the battery bank is 78,552 kWh per year and out 67,819 kWh, with losses of 10,495 kWh. The expected life time of the battery bank before replacement is needed is 8.43 years. The battery bank's state of charge during the year is shown in Figure 35. It can be seen that between 12 pm and 18 pm from April to November, the bank is fully charged most of the time, due to the high solar radiation during these months.

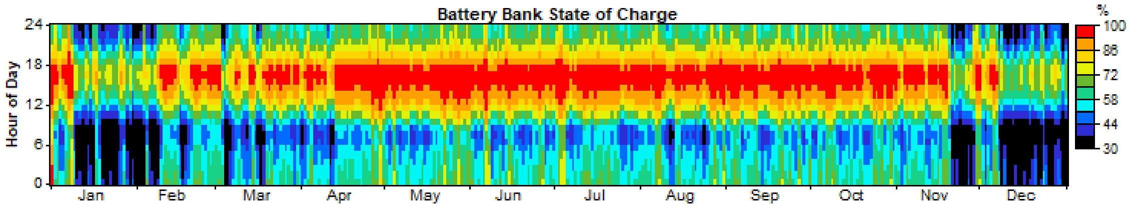


Figure 35. Battery Bank State of Charge

HOMER also displays the hourly behaviour of all the variables. In Figure 36 and Figure 37 below, two examples can be seen. The figures show the randomized demand and the response of the system: PV power generation, gasifier generation and the battery bank's state of charge.

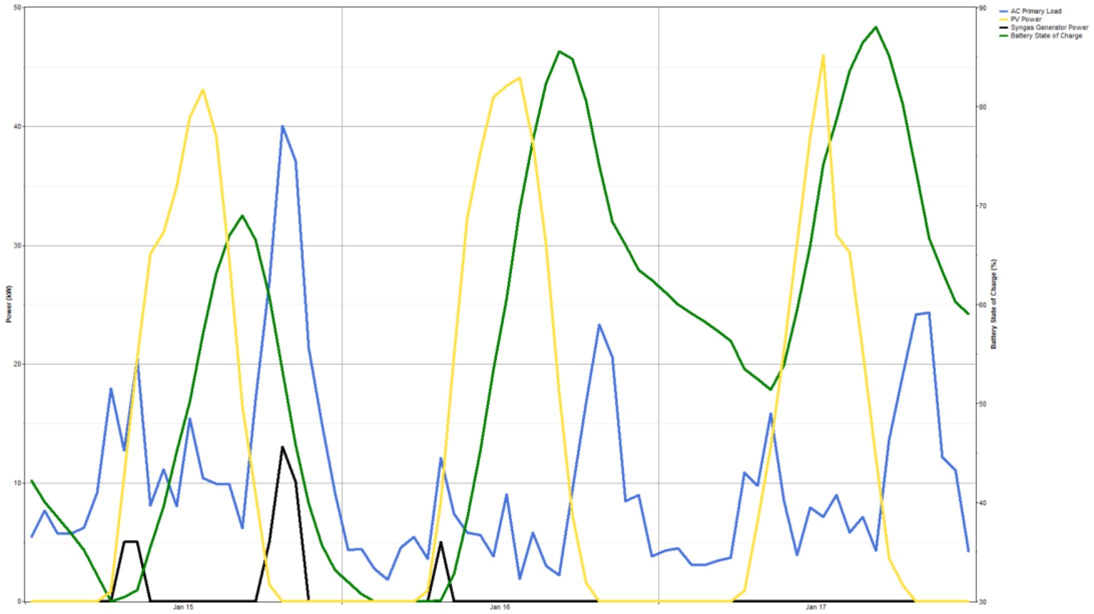


Figure 36. Demand Load (blue), PV Power (yellow), Gasifier Output (black) and Battery Bank State of Charge (green) during Jan 15th- Jan 17th.

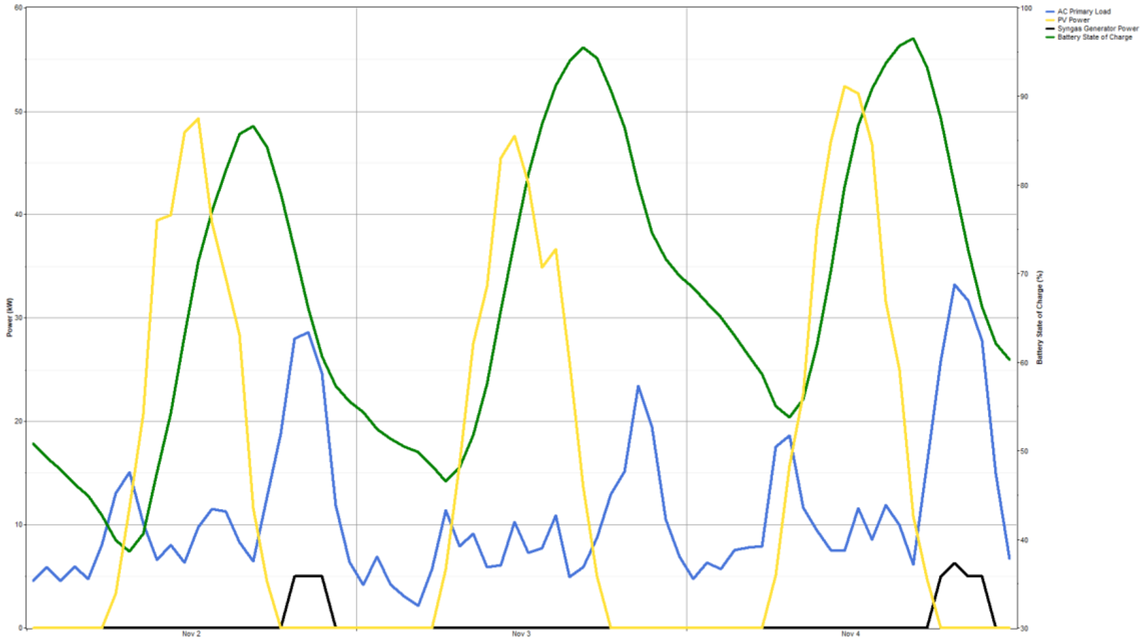


Figure 37. Demand Load (blue), PV Power (yellow), Gasifier Output (black) and Battery Bank State of Charge (green) during Nov 2nd - Nov 4th.

The EDL, referred to as the breakeven grid extension distance[10] in HOMER, was also evaluated in HOMER, using a capital cost of 6000 USD/km[11], an O&M cost of 160 USD/km and a grid power

---

[10] The breakeven grid extension distance is defined as the break-even point at which grid extension become less economically viable than the system in question

[11] Grid extension cost often used in literature is 5000 €/km, an estimation of 6000 USD/km was made [46].

price of 0.02USD/kWh. The result is a breakeven grid extension distance of 70.2 km as can be seen in Figure 38. Studying transmission lines maps of Zambia, an estimation of 140 km to the closest grid line can be made, which is a 66-kV line. The EDL found in HOMER is in the same range as the EDLs found in the study regarding EDLs for rural villages in Zambia, mentioned in the section Previous Projects of Rural Electrification. In that study, the EDL for solar PV was found to be 92.7 km and for biomass gasification 74.2 km.

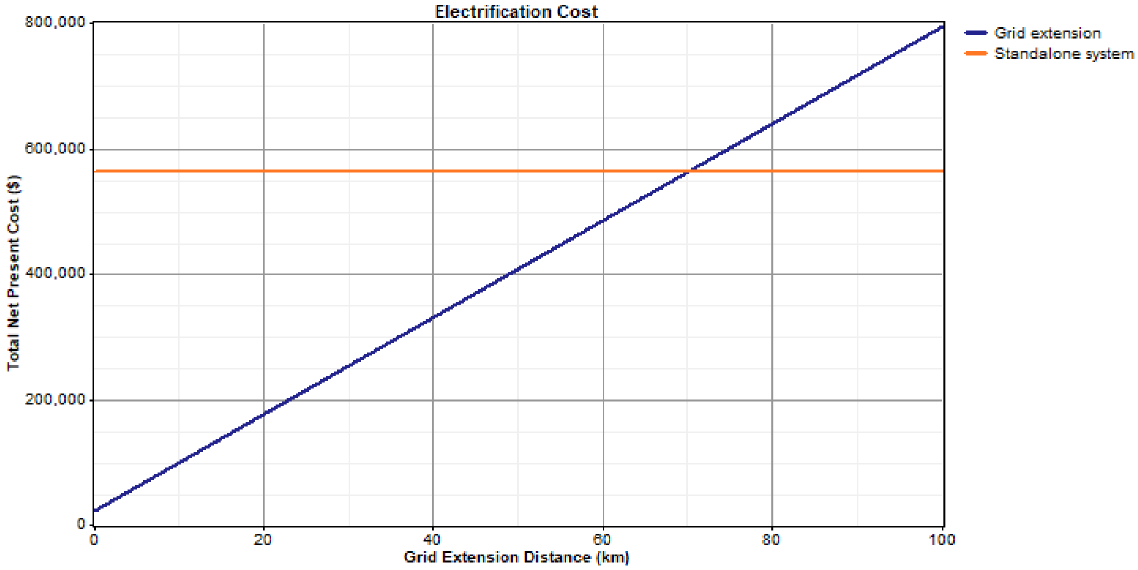


Figure 38. Breakeven Grid Extension Distance

4.2 System Design and Management

In addition to the power system found with HOMER software, there are several other aspects and components that have to be considered regarding the system's design. The grid network has to be designed; quantity and types of cables as well as where the power utility is best placed have to be decided. Auxiliary components not considered in HOMER include a power management system, the wood chipper and the storage needed for the biomass feedstock. Following sections describe how the design of the grid was performed and the management required for the power system.

4.2.1 Grid Network Design

To estimate the lengths and cross-sectional areas of the cables needed for the grid, a model of the grid network was made from studying satellite pictures and the distribution of households, which can be seen in Figure 39. A main power line was placed along what could be identified as the main road connecting the scattered community. Distribution lines were then placed from the main line to the clusters of households. The main power line has a length of 1,300 m and the distribution lines a total of 1,240 m. The main line and the distribution lines (the ones shown in Figure 39) have a voltage of 400 V while smaller cables with 230 V will be connected from the main/distribution lines to the individual households.

Cluster Nr	Number of HH	Line	Length (m)
Main line	-	-	1300
1	10-12	A	160
2	8-14	B	80
3	3-7	C	90
4	20-24	-	-
5	15-20	D	120
6	10	E	60
7	12-15	F	210
8	10-14	G	175
9	5-8	G	-
10	3-6	H	95
11	10-12	I	160
12	8-10	I	-
13	10-12	J	90
Total	124-164	-	2540

Figure 39. Grid Network Design

The power utility is best placed where the load is balanced, meaning where the load is equally large in both directions. For example, not in the end of the main power line, so it has to carry the entire load of the community from start to end point. Where to place the power utility was therefore decided by calculating in which point on the main line the load was equally large. An average load per household was assumed and a simultaneity factor calculated for each cluster, using equation 2, according to the Spanish standard ITC-BT-10. A Zambian standard was sought but not found, and the Spanish was considered viable since these standards are similar internationally.

$$K_S = (15.3 + (n - 21) * 0.5)/n \qquad \text{(Eq. 2)}$$

K_S = Simultaneity factor
n = Number of households

The average load per household was assumed to be 1 kW although the largest possible momentary demand is at 61.2 kW with the current estimated demand, meaning 0.425 kW per household. However, the load demand is estimated as an initial demand with basic appliances and might increase when incomes increase as earlier described. Therefore, the grid lines are designed for 1 kW per household to allow an increasing load demand and power generation, without the need to replace the grid. With the simultaneity factors and load per clusters, it was found that the power plant should be placed between cluster 5 and 6, close to cluster 6, as shown in Figure 39. To find appropriate cables, the voltage drop was calculated for different cross-sectional areas. First, the load on each distribution line was calculated using equation 3. The power factor (cos (φ)) was considered to be 1. Although the appliances include fridges, this reactive power was neglected, due to the relatively small energy consumption of these[12].

$$P = \sqrt{3} * U * I * \cos(\varphi) \qquad \text{(Eq. 3)}$$

P = Power (W)
U = Voltage (V)
I = Current (A)

The loads on every node and every distribution line can be seen in Table 21. The voltage drops between the nodes and on the distribution lines were then calculated using equation 4 and 5. Cables in copper were considered since they have a higher conductivity than aluminium, meaning lower voltage losses. Copper is generally more expensive but since it’s Zambia’s main export, the costs might be more competitive.

$$\Delta U = \sqrt{3} * I * R * \cos(\varphi) \qquad \text{(Eq. 4)}$$

$$R = \frac{\rho * l}{s} \qquad \text{(Eq. 5)}$$

---

[12] In addition, the household load of 1 kW is being used (instead of 0.425 kW) and a voltage drop of 5% is considered instead of the Zambian standard of 10%, and therefore the grid was considered robust enough to be able to neglect the small amount of reactive power.

ΔU = Voltage drop (V)
R = Resistance of the cable (Ω)
ρ = Resistivity of copper at 40ºC, $1.81 * 10^{-8}$ Ωm.
l = Length of cable (m)
S= Cross sectional area (m^2)

Table 21. Lengths (m) and Loads (kW) on Power Lines

Distribution Line	**L(m)**	**Max Load (kW)**
A	160	10,3
B	80	10,3
C	90	5
Main line, cluster 4	-	15,8
D	120	13,8
E	60	9,8
F	210	11,3
G	175	14,3
H	95	4
I	160	14,8
J	90	10,3
Total	1240	119,7
Main line	**L(m)**	**Max Load (kW)**
North of Power plant		
Power plant- Node 3	70	55,2
Node 3- Node 2	235	25,6
Node 2 - Node 1	65	20,6
South of Power plant		
Power plant - Node 4	30	64,5
Node 4 - Node 5	170	54,7
Node 5 - Node 6	430	43,4
Node 6 - Node 7	300	10,3
Total	1300	-

Finally, the voltage drops were calculated as a percentage of the line voltage, 400 V. A maximum voltage drop of 5 per cent was considered, although the Zambian standard allows a voltage drop of up to ±10% for voltages less than 11 kV (ZS 387-1: 2011). Cross-sectional area (A) of the cables and voltage losses are shown in Table 22. The voltage losses are shown as the losses in the specific line, as total losses from the power plant to the point of distribution and as a percentage from the power plant to point of distribution. The smaller 230 V cables are not considered in this calculation since the calculation is made to give an indication of required cables and costs, not exact numbers, and were therefore considered neglectable.

Table 22. Cross-Sectional Area and Voltage Drop of Power Lines

Distribution Line	A (mm2)	Voltage drop in line (V)	Total voltage drop (V)	Total Voltage drop (%)
A	10	4,28	11,22	2,81
B	4	5,35	12,29	3,07
C	4	2,92	9,03	2,26
D	10	4,30	6,69	1,67
E	10	1,53	2,41	0,60
F	16	3,85	8,97	2,24
G	16	4,06	17,69	4,42
H	16	0,62	14,24	3,56
I	16	3,85	17,47	4,37
J	10	2,41	17,44	4,36
Main line	**A (mm2)**	**Voltage drop in line (V)**	**Total voltage drop (V)**	**Voltage drop (%)**
North of Power plant				
Power plant- Node 3	70	2,39	2,39	-
Node 3- Node 2	70	3,72	6,11	-
Node 2 - Node 1	70	0,83	6,94	-
South of Power plant				-
Power plant - Node 4	95	0,88	0,88	-
Node 4 - Node 5	95	4,24	5,12	-
Node 5 - Node 6	95	8,51	13,63	-
Node 6 - Node 7	95	1,41	15,04	-

A summary of the quantity of each type of cable in regard to cross-sectional area is shown in Table 23 below.

Table 23. Quantities of Cables by Cross-Sectional Area.

Area (mm2)	Meters
4	170
10	430
16	640
70	370
95	930
Total	2540

4.2.2 Facilities & Land Use

As earlier mentioned, the farming season in the north-western province stretches from November to April, meaning the feedstock has to be stored to be able to be used throughout the year. This requires a dry storage facility to keep the stalks/chips in. Wood chips have a typical bulk density of 250-350 kg/m^3 [62]. Using a density of 250 kg/m^3, approximately 140 m^3 would be needed to store the entire yearly yield. Assuming that the waste can be stocked with a height of 2 m, a 70 m^2 storage facility is needed. The gasifier requires a total surface of approximately 13 m^2. The gasifier itself is 1.42 m wide and 1.83 m deep but an additional meter around the gasifier is needed, according to the manufacturer [52].

To estimate the required area for the PV panels, equation 6 was used. The solar irradiation used was 0.8 kW/m^2. Studying the solar data retrieved, the solar radiation reaches 0.6 kW/m^2 every day, and 0.8 kW/m^2 every day apart from a few days during the year. 0.6 kW/m^2 gives an area of 10.55 m^2/kW and 0.8 kW/m^2 gives 7.91 m^2/kW. Using the area of the PV panels (1.65 m^2 of 260 W) results in 308 PV panels for 80 kW, an area of 508.2 m^2, or 6.35 m^2/kW. An assumption of 8 m^2/kW was made and, in order to leave some space between panels to be able to clean them, an area of 8.5 m^2/kW was used, meaning a total area of 680 m^2 for the 80 kW PV panels.

$$P = A * I_S * \eta \qquad \text{(Eq. 6)}$$

P = Power (kW)
A = Area of PV panel (m^2)
I_S = Solar irradiation (kW/m^2)
η = Efficiency, 18%

The PV panels, gasifier and the storage facility together require 763 m^2. In addition, space for a control room, batteries, inverter and other equipment is needed. A total area of 850 m^2 was considered sufficient but studying satellite pictures it seems there is available area to add more PV panels and batteries if the demand load increases. A suggestion of where to place the power plant is shown in Figure 39. The dimensions of the surface area in the figure are 50x30 m^2, i.e. an area of 1500 m^2.

4.2.3 Management and Maintenance of Power Utility

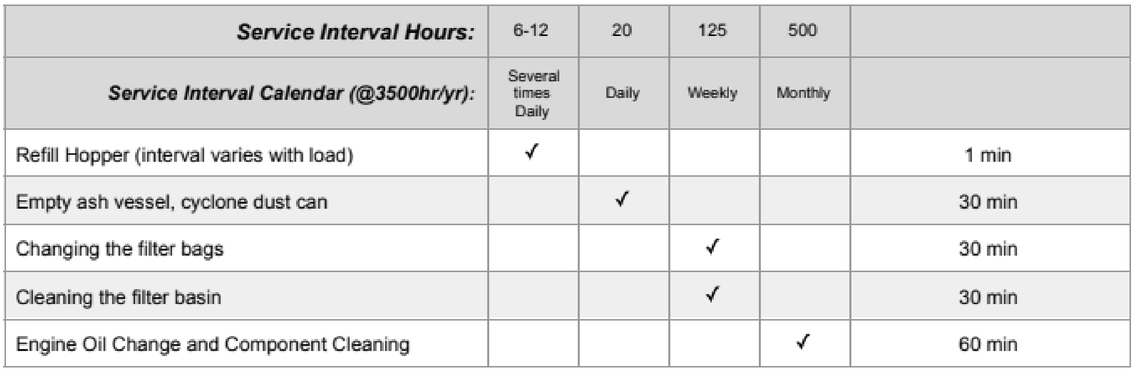
A power management device is needed to manage and coordinate the power flows between the system components in accordance with the demand load. The power generation from the PV panels and the gasifier needs to be directed to either feeding the grid or the batteries and the AC load from the gasifier needs to be converted to DC when charging the batteries. The battery inverter Sunny Island 8.0H is compatible with the batteries and is the chosen power management device due to its reliability and cost competitiveness. Relevant data is shown in Table 24. With a capacity of 6 kW per unit, 5 units are needed for the 120 Hoppecke 12 OPzS 1500 Ah batteries.

Table 24. Technical and General data, Sunny Island 8.0H

Rated power	6 kW
Battery DC input	48 V
Rated grid voltage	230 V
Battery capacity (lead-acid)	100 Ah – 10’000 Ah
Maximum efficiency	95.8%
Dimensions (W/H/D)	467mm/612mm/242mm
Weight	63 kg
Warranty	10 years

Aside from the gasifier, the manual labour requirements of the power plant are expected minimal, and are restricted to occasional cleaning and inspections of the components. The gasifier on the other hand, requires daily maintenance. The tasks are shown in Table 25 [52]. The hopper needs to be refilled while running and the char-ash and cyclone dust cans need to be emptied after using the gasifier. On a weekly basis, the filter bags need to be changed and the filter basin needs to be cleaned, and once a month the engine oil has to be changed and components cleaned. Assuming that the gasifier is running 3 hours every day, an operator is needed for 3.5 hours/day to monitor the gasifier, refill the hopper while running and empty ash and cyclone dust cans. The cleaning and changing of the filter basin and filter bags require an additional hour per week and the change of engine oil and component cleaning an hour a month.

Table 25. Maintenance Tasks of Gasifier



Service Interval Hours:	6-12	20	125	500	
Service Interval Calendar (@3500hr/yr):	Several times Daily	Daily	Weekly	Monthly	
Refill Hopper (interval varies with load)	✓				1 min
Empty ash vessel, cyclone dust can		✓			30 min
Changing the filter bags			✓		30 min
Cleaning the filter basin			✓		30 min
Engine Oil Change and Component Cleaning				✓	60 min

Regarding the feedstock of the gasifier, the steps of the process from harvesting the cassava to ready feedstock for the gasifier are shown in Figure 40. Once harvested, the cassava plants have to be washed and sorted into roots, useful waste and waste. The useful waste then has to be chipped into pieces of 1-4 cm and kept to dry before it’s ready to be used. Alternatively, the waste is kept to dry first and then chipped. What order to be used depends on what order results in the most appropriate moisture content and has to be investigated at site, which has not been possible for this study.

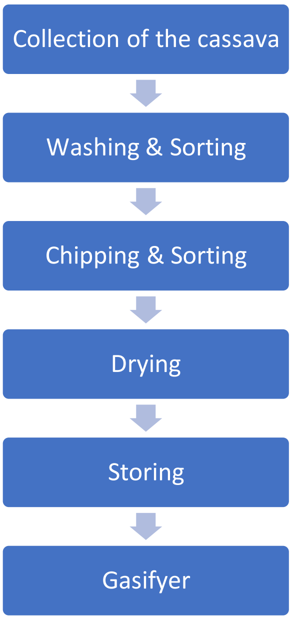


Figure 40. Process of Feedstock Production

4.3 Equipment & Costs

4.3.1 HOMER Configuration Costs

A summary of the total net present system costs from HOMER can be seen in Table 26. The total capital cost is 429,400 USD and the total NPC is 564,697 USD. The largest capital cost is the PV modules (55.9%), followed by the batteries (17.7%), the inverter[13] (13.8%) and the gasifier (12.6%). The capital costs are the major costs of the project (76% of NPC) as shown in Figure 41, followed by the replacement costs (16.6%). The yearly O&M cost is 12,675 USD while the yearly fuel cost is 1,074 USD. The fuel cost however, is calculated with a fuel price of 200 USD/tonne, which was used in HOMER to decrease the operational hours of the gasifier. A fuel cost of 50 USD/tonne results in 268.5 USD per year.

Table 26. Net Present Cost by Component and Type of Cost.

Component	Capital (USD)	Replacement (USD)	O&M (USD)	Fuel (USD)	Salvage (USD)	Total (USD)
PV	240000	0	25619	0	0	265619
Gasifier	54000	14450	1787	11475	-3285	78427
Batteries	76000	60502	6405	0	-372	142535
Converter	59400	18725	2882	0	-2891	78116
System	429400	93677	36693	11475	-6548	564697

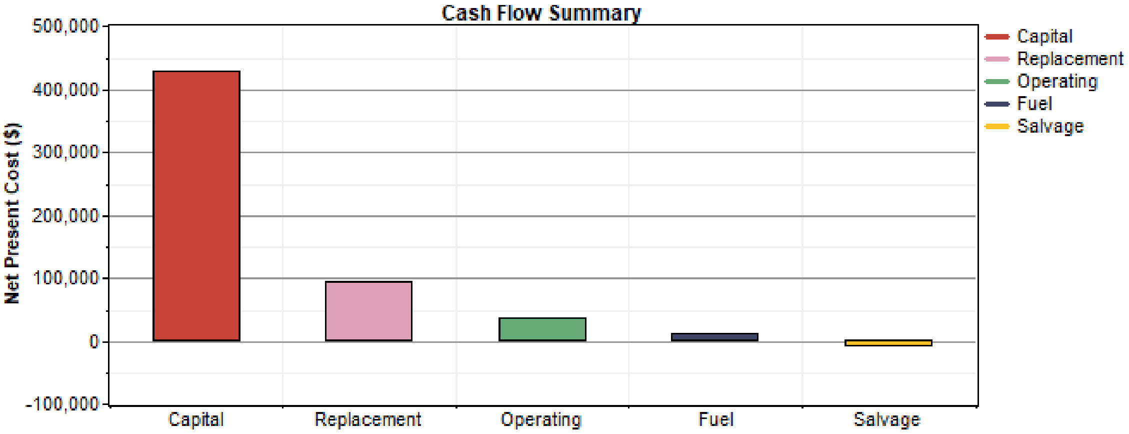


Figure 41. Cash Flow Summary of Net Present Cost by Type of Cost

The levelized cost of electricity[14] (LCOE) are shown in Table 27. The LCOE for PV is 0.167 USD/kWh while it's almost seven times as high for the gasifier, 1.14 USD/kWh. However, the

---

[13] In HOMER, the converter component models any device that converts power from AC to DC (rectifying) and DC to AC (inverting), and the inverter is therefore recognized as the converter in the results tables and results figures from HOMER

[14] HOMER defines the levelized cost of energy (LCOE) as the average cost per kWh of useful electrical energy produced by the system

fuel price for the gasifier was increased in HOMER in order to control the operational hours of it. Calculating the LCOE with a biomass fuel cost of 50 USD/tonne still results in a high LCOE for the gasifier, 1.02 USD/kWh. The overall LCOE for the power system is 0.485 USD/kWh.

Table 27. Levelized Cost of Electricity (LCOE) per Component

Component	**LCOE (USD/kWh)**
PV	0,167
Gasifier	1,14
System	0,485

Regarding the net present costs divided by component, the PV panels followed by the batteries are the highest costs, as can be seen in Figure 42.

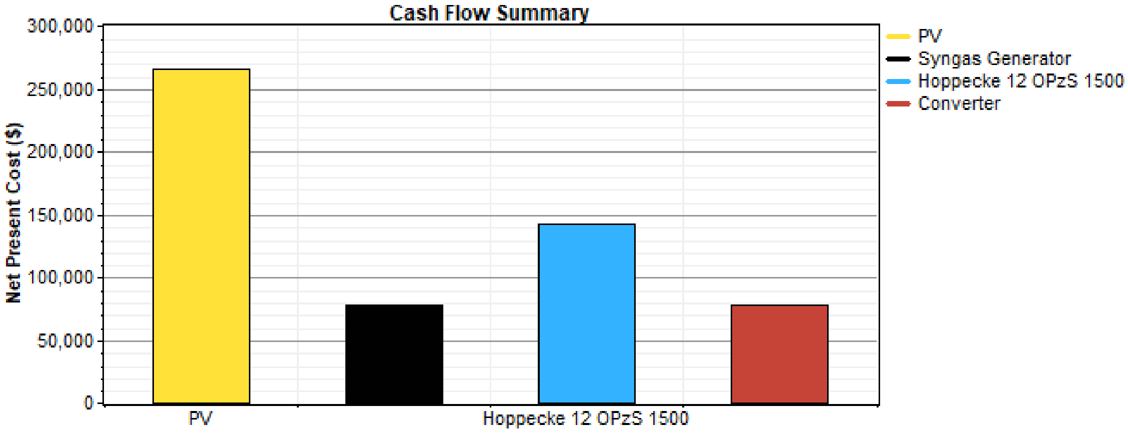


Figure 42. Cash Flow Summary of Net Present Cost by Component

The nominal cash flows by type of component and type of cost throughout the modelling period can be seen in Figure 43 and Figure 44, respectively. The PV panels have the highest NPC due to their installation costs, as can be seen in Figure 43. It is also shown that the high NPC of the batteries is due to their need of replacement twice during the time span. The gasifier needs to be replaced after approximately 16 years, with its lifetime of 15,000 operational hours.

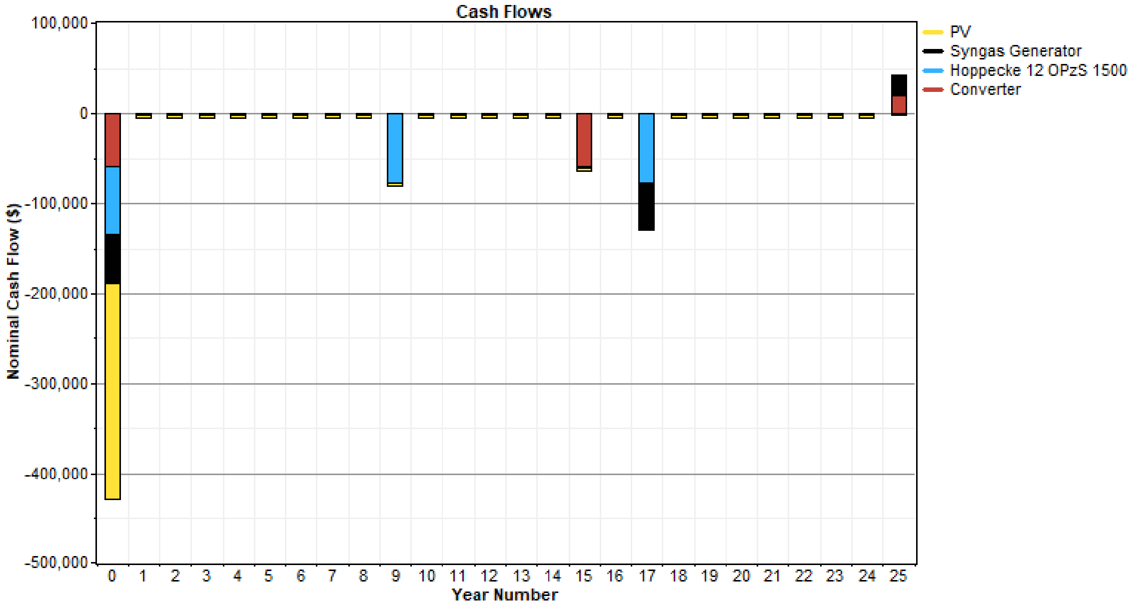


Figure 43. Cash Flows by Component

Studying Figure 44, it is clear that the operational cost accounts for a small yearly cost, while the big expenditures lie in the capital costs of year 0 and the replacement costs in year 9, 15 and 17. Of the NPC the operational costs accounts for 6.5%.

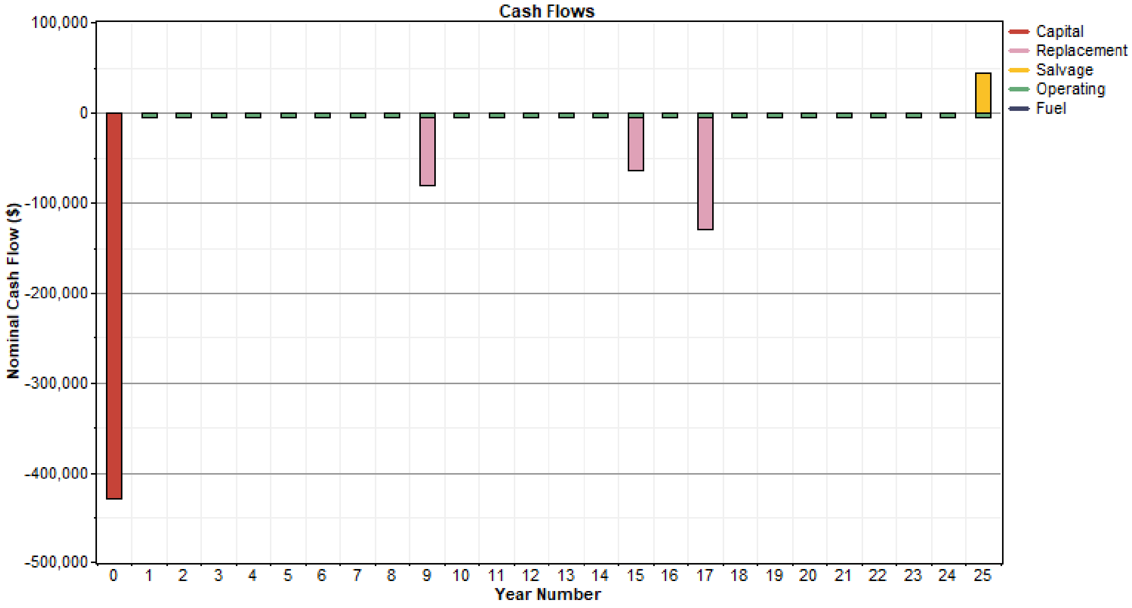


Figure 44. Cash Flows by Type of Cost

4.3.2 Additional Component Costs

In addition to the costs provided from HOMER there are the additional component costs in the system, which need to be considered. The additional components and costs include the battery inverter Sunny Island 8.0H, the wood chipper MHC-500, the storage facility, the land use and the cables. Sunny Island has an approximate cost of 3,000€ per unit [63]. The cost of the wood chipper is 885-1,770 €, 1,770 € was used [55]. Average costs of buying bare land and constructing factory buildings were retrieved from Zambia Development Agency [64]. The average cost of buying bare land in non-industrial zones was used for the land use estimation of 850 m^2. The costs ranged from 10-20 USD/m^2 depending on the region[15]. 10 USD per square meter was used since Mumbeji is a remote rural community which results in a total of 8,500 USD, approximately 7,500 €. The average construction cost of a factory with reinforced concrete structure was 390-450 USD/m^2. 390 USD per square meter was used and gives a construction cost of 39,000 USD for 100 m^2 (storage 70 m^2, control room etc 30 m^2), approximately 34,500€. However, a storage facility will most probably be able to be constructed by local labour and local resources to a fraction of that cost. Regarding power cables, the costs considered are for PVC insulated copper cables from the software CYPE[16] and can be seen in Table 28 [65]. Installation costs are assumed included in these costs, since they are Spanish and not Zambian. In addition, as mentioned earlier, copper is a big resource in Zambia, hence it should be significantly less expensive at site. Price rates were sought at the local manufacturer ZAMEFA but without success [66].

Table 28. Cost of Power Cables

Area (mm2)	Cost (€/m)	Meters	Cost (€)
4	0,63	170	107,1
10	1,61	430	692,3
16	2,5	640	1600
70	16,35	370	6049,5
95	21,47	930	19967,1
Total		**2540**	**28416**

4.3.3 Total Costs

A summary of the total capital cost is shown in Table 29. The total net present cost of the system is 589,800 €[17].

Table 29. Summary of Total System Installation Costs

	Units	€/unit	Total (€)
System HOMER	-	-	382,166
Battery inverter Sunny Island 8.0H	5	3,000	15,000
Wood chipper MHC-500	1	1,770	1,770
Cables	-	-	28,416

---

[15] 20 USD/ m^2 in Lusaka, 15 USD/m^2 in Kitwe and Ndola, 10 USD/m^2 in Livingstone

[16] Those costs may be higher than in Zambia but local costs could not be found

[17] Costs are given in USD in HOMER. An exchange rate of 1 USD = 0.89 € has been applied

Land (850m^2)	-	-	7,500
Facilities (100 m^2)	-	-	34,500
Total	-	-	469,352

5 Assessment

5.1 Economic

Moner-Girona et al. [67] published a paper comparing cost data for PV/hybrid mini-grid systems in Sub-Saharan Africa. In total 27 installed PV/hybrid mini-grid systems were analysed. They found a cost-trend related to the size of the generator of the PV/hybrid mini-grid, a decreasing cost per kW with increasing size of generator. Systems larger than 150 kWp had capital costs in the range of 4-6 €/Wp while systems smaller than 50 kWp had capital costs in the range of 8-14€/Wp. A capital cost in the range of 6-8 €/Wp could be interpreted for systems in the range of 50-150 kWp, as the system of this study. The configuration modelled in HOMER has equipment capital costs of approximately 3.64 €[18]/Wp, while the investment cost (including additional components' cost) gives a result of 4.47 €/Wp, meaning lower than the interpreted average cost of 6-8 €/Wp of the mini-grids studied by Moner-Girona et al. [67]. The paper investigates 6 mini-grid projects in particular, which all offer high-quality service 24 hours a day, have a high share of PV production, batteries with autonomy of 1-3 days and small genset back-up. The installation costs and LCOE of these systems can be seen in Table 30. The net present costs of these projects were not found. Studying this table, it can be concluded that the system investigated in this study has a lower installation cost but higher LCOE (0.43€/kWh18[18]) compared to these projects. The reason that the LCOE is lower for these projects is probably due to the fact that the soft costs were not included when calculating the LCOE, such as installation labour, transport, permitting fees & taxes and system design & project management. These costs were assumed included in the capital cost of 3 USD/W (approximately 2.7 €/Wp) for PV modules in HOMER, while the PV modules in the projects mentioned had an average cost of 0.83€/Wp.

Table 30. Installation Costs and LCOE of PV/hybrid mini-grids in Sub-Saharan Africa

Size (kW)	Installation cost (€/Wp)	LCOE (€/kWh)
27	15	0.41
30	11	0.33
40	8	0.30
43	8	0.22
49	11	0.25
312	4	0.25

---

[18] Costs are given in USD in HOMER. An exchange rate of 1 USD = 0.89 € has been applied

The average total installation cost of the projects was 8.33 €/Wp, meaning the cost of PV modules only consisted of 10%. The paper highlights that the variation of costs is wide, about 20% of the 27 projects had an installation cost lower than 5 €/Wp while about 20% had an installation cost higher than 12 €/Wp. Furthermore, the authors define one key challenge to be that PV and storage technologies undergo constant cost changes, meaning that published studies can be outdated within a few months of publication.

Comparing the LCOE of the mini-grid to the current electricity prices in Zambia, it is clear that the LCOE is, by far, not competitive to the cost of electricity from the grid. But it's also clear, that the main costs of the project consist of the capital cost (76%), and is the reason to the high LCOE. In other words, the LCOE is set as if the whole project was to be paid by the consumers. If the capital costs would be funded and/or subsidized, the electricity cost would be significantly lower, as the operational costs of the system represents 6.5% of NPC.

It's also worth mentioning, that the electricity tariffs in Zambia are not cost-reflective today. Governmental policy aims to make them cost-reflective by 2021 to encourage investments in the electricity sector. An increase of electricity tariffs together with funding on the investment costs could therefore make this project economically competitive.

The LCOE was calculated as if the capital costs of the system were to be disregarded and the biomass feedstock cost set to 50 USD/tonne. The LCOE would in that case be 0.104 USD/kWh, which is still not competitive to the low electricity costs in Zambia of approximately 0.012 USD/kWh. However, an LCOE of 0.104 USD/kWh would mean an average monthly expenditure of 4.74 USD per household. The 2015 Living Conditions survey report done by Central Statistical Office states that the lowest agricultural household income is among small scale agricultural households, and is an average of 54 USD[19] per month [29]. Using this income as an average in Mumbeji, would mean that the electricity expenditure would account for nearly 9% of the incomes.

In the 60 kW Solar mini-grid in Mpanta in central Zambia, the consumers are paying a fixed rate every month as showed in Table 31, which are claimed to be cost-reflective according to information from World Access to Modern Energy (WAME) [68] while a report from GET.invest [69] claims that the tariff does not cover the O&M costs.

Table 31. Tariff Structure for Mpanta Solar mini-grid.

Residential House	**Monthly Fixed Charge (USD[19])**	**Light Commercials**	**Monthly Fixed Charge (USD)**	**Social Services**	**Monthly Fixed Charge (USD)**

---

[19] Originally value in Zambian Kwacha (ZMW). An exchange rate of 1 ZMW=0.078 USD has been applied

Less than 3 rooms	2.34	1 roomed shop	4.68	Health centre	3.9
4 rooms	2.73	2 roomed shop	5.07	Primary schools	3.9
5 rooms	4.68	3 roomed shop	5.46	Churches	3.9
6 rooms	5.07				
7 rooms	5.46				

Charging households in Mumbeji like a 4 roomed-household in Mpanta would result in an electricity price of 0.060 USD/kWh, a 2-roomed shop 0.039 USD/kWh and a health centre/school 0.008 USD/kWh. Thus, the LCOE, without taking capital cost into consideration, is almost twice as high compared to what the residents in Mpanta is paying. Comparing the costs in Mumbeji to the costs of a 5-roomed house in Mpanta on the other hand, would mean costs in the same range.

Even though the economic feasibility of the mini-grid is critical, the results show that it's less expensive than connecting to the grid, since the EDL of this study is 70.2 km, between 74.2 and 92.7 km in a previous study and the closest grid to Mumbeji is estimated at a distance of 140 km.

5.2 Environmental

The environmental impacts of any product/service are inevitable and thus assessing environmental impacts, to a large extent, involves minimizing the impacts. This is often done by, firstly assessing the own environmental impacts and secondly, comparing the impacts to alternative products/services. The impacts can be categorised according to at what stage of the product's/service's life cycle they occur and the different stages are commonly divided into; extraction of resources, production, transport, use and disposal/recycling. The system modelled in this study implies several environmental impacts during its life cycle, which of the considered most relevant are listed in Table 32.

Table 32. Environmental Impacts of the System

Extraction	Emissions of GHG and toxics Exploitation of minerals
Production	GHG emissions
Transport	GHG emissions
Use	Noise Tar production from gasifier

Disposal/Recycling	GHG emissions during transportation and recycling Release of toxics to soil and water if placed in landfill

Since the cassava, the biomass feedstock, is continuously replanted, the sum of greenhouse gas (GHG) emissions are considered to be zero during the use stage of the gasifier. The focus of this assessment has been on global warming since it’s generally the biggest environmental impact of energy systems. For this reason, the impacts of the stages before and after the system is being used, will not be evaluated since they’re considered relatively equal for all energy system – in other words, the biggest difference in impacts between energy systems lie in the use stage.

Thus, the system modelled in this study was compared to three possible alternative scenarios, in terms of GHG emissions. The first scenario was the Business As Usual, evaluating the GHG emissions if the community would continue using the same energy sources as today. The second scenario is considering the expected GHG emissions if the energy demand would be supplied by a diesel generator instead of the hybrid mini-grid. Lastly, GHG emissions are calculated if the community was to be connected to the grid.

5.2.1 Business As Usual

The main source of energy for lighting in rural areas in Zambia is torch (71%), followed by solar (7%), candle (6%), open fire (4%), electricity (4%) and others (8%). Only 2% in rural areas use kerosene [16]. Therefore, an assumption was made that 75% of the households in Mumbeji use torches for lighting and 25% use candles.

According to United States Environmental Protection Agency (EPA)[20] a candle emits 7 g CO_2eq[21]/h on average. Assuming 5 candles per household being used 5 hours per day gives yearly CO_2eq emissions of 2.3 tonnes as seen in equation 7.

$$7\ g\,\frac{CO_2\text{eq}}{\text{hour}} * 5\,\frac{hours}{day} * 5\,\frac{candles}{HH} * 0.25 * 144\ HH * 365\,\frac{days}{year} = 2.3\ tonnes\,\frac{CO_2eq}{year} \qquad \text{(Eq. 7)}$$

During the lifecycle of an alkaline battery 70.2 g CO_2eq are emitted, according to the database of emission factors provided by the Intergovernmental Panel on Climate Change (IPCC) [70]. 3

---

[20] http://www.epa.ie/pubs/reports/air/airemissions/ghg/nir2018/Ireland%20NIR%202018.pdf

[21] Charts and tables convert all greenhouse gas (GHG) emissions into CO_2 equivalents so they can be compared. Each GHG has a different global warming potential (GWP) and persists for a different length of time in the atmosphere. Thus, for example, the 100-year global warming potential (GWP 100a) compared to carbon dioxide methane (CH_4) is 25, i.e. releasing 1 kg of CH_4 into the atmosphere is about equivalent to releasing 25 kg of CO_2.

batteries per household and week were assumed to be consumed by torches or other smaller electric devices, resulting in yearly CO_2eq emissions of 1.18 tonnes (Eq. 8).

$$70.2\ g\ CO_2eq * 52\ weeks * 0.75 * 144\ HH * 3\ \text{batteries/w/HH} = 1.18\ \text{tonnes}\ \frac{CO_2eq}{year} \qquad \text{(Eq. 8)}$$

Thus, the business as usual scenario emits 3.48 tonnes of CO_2eq per year.

5.2.2 Diesel Generator

The emissions from a diesel generator depend on several factors, such as type of generator, quality of fuel and operational conditions. Assuming a latest-technology generator under adequate conditions, the IPCC database estimate CO_2eq emissions of 840 g per kWh [70]. The community's yearly electricity consumption of 109,058 kWh, would thus result in 91.6 tonnes of CO_2eq per year (Eq. 9).

$$109058\,\frac{kWh}{year} * 840\ g\,\frac{CO_2eq}{kWh} = 91.6\ tonnes\,\frac{CO_2eq}{year} \qquad \text{(Eq. 9)}$$

Only replacing the biomass gasifier with a diesel generator, would result in 5.64 tonnes of CO_2eq per year (Eq. 10).

$$6719\,\frac{kWh}{year} * 840\ g\,\frac{CO_2eq}{kWh} = 5.64\ tonnes\,\frac{CO_2eq}{year} \qquad \text{(Eq. 10)}$$

5.2.3 Grid Connection

Zambia has an emission factor for grid electricity of approximately 3.55 g CO2eq/kWh [71]. Consuming the electricity from the national grid would therefore result in yearly GHG emissions of 0.39 tonnes of CO_2eq (Eq. 11).

$$109058\,\frac{kWh}{year} * 3.55\ g\,\frac{CO_2eq}{kWh} = 0.39\ tonnes\,\frac{CO_2eq}{year} \qquad \text{(Eq. 11)}$$

This is the alternative scenario with lowest global warming impact. However, it should be taken into consideration that Zambia's low emission factor for grid electricity is due to that 95% of their generation come from hydropower. If the electricity system and national grid is to be extended in order to supply Mumbeji and the rest of Zambia, the energy sources have to keep the high share of renewables for this emission factor to apply. Even if the environmental impact is low in this case, the economic aspect makes it less feasible than an off-grid installation.

5.3 Social

5.3.1 Social Impact of Access to Electricity

First of all, it must be highlighted that access to electricity is crucial for development, and therefore closely correlated to many of the UN's seventeen Sustainable Development Goals (SDGs);

Directly:
SDG 7 – Affordable and Clean Energy
SDG 13 – Climate Action

Indirectly:
SDG 1 – No Poverty

SDG 2 – Zero Hunger
SDG 3 – Good Health and Well-Being
SDG 4 – Quality Education
SDG 5 – Gender Equality
SDG 6 – Clean Water and Sanitation
SDG 8 – Decent Work and Economic Growth
SDG 10 – Reduced Inequalities
SDG 11 – Sustainable Cities and Communities

For the inhabitants of Mumbeji, access to modern energy could mean economic development since access to electricity foster economic activities, as explained by the last reports of the IEA[22]. For example, electricity enables higher productivity of agricultural outputs (irrigation, harvesting, sowing, processing products) and better services at local businesses (lights, fans, TV, refrigeration for shops and restaurants). Economic development can therefore reduce poverty and increase power. Economic development is also a result of better living standards achieved by electricity access, such as better education (lighting after dark) and better health care (refrigeration medicine, lighting). Modern energy can also facilitate daily chores like pumping water and cooking, which in turn, leads to a higher gender equality since these are chores traditionally performed by the women of the households. Communication and access to information will also improve with electricity access which in turn can increase power and level of education in the community. Finally, access to electricity would prevent inhabitants from migrating to other areas.

On a bigger scale, an energy system on renewable sources also implies resilience to climate change, preventing future climate migration, which is a possible future scenario for the inhabitants of Mumbeji. However, whether this is a potential scenario or not, first and foremost depend on the global development.

Not attaining access to electricity, would most likely keep Mumbeji in poverty, with continuous poor access to education, health care, information and communication. Having that said, the access to electricity can also imply negative effects. The opportunities of economic development, could happen to just benefit a small share of people, people that from the beginning have more power or people that gain more power through successful businesses for example. In turn, this can lead to larger poverty and gender gaps. Power and gender gaps can also occur if the involvement in the maintenance or usage of the mini-grid is uneven. If consumers won't be able to pay for their electricity consumption, they might be put in debt, aggravating their financial situation and increasing poverty and power gaps in the community.

A study done on the solar mini-grid in Mpanta, show that affordability was the main reason that now only 247 (55%) of initially 450 connected households are still connected. Other contributing factors were poor expectation management and lacking integration to socioeconomic dynamics.

---

[22] https://www.iea.org/oilmarketreport/reports/

The expectations on the services were higher than the final outcome (residents were expecting 24 h-service but in the end had 14 h-service). In addition, many residents were under the impression of free electricity which resulted in resentment of paying expensive electricity bills in the end. Residents also stated that they would've preferred a pre-paid metering system instead of the flat rates they're paying now. This show the importance of keeping an open dialogue and including the community throughout the development of the project.

5.3.2 Risk Assessment

Raisch, V. [72] evaluated the economic feasibility of rural mini-grids in Uganda and highlights the financial feasibility of mini-grids as a major challenge. A high level of subsidies is needed to make mini-grids financially feasible [72]. A review paper done on potential benefits and risk of PV hybrid mini-grid systems states the biggest risks to be incorrect system sizing due to load uncertainty, community integration, inappropriate business models, equipment compatibility and geographical isolation [73]. Further, as previously stated, the consumers' affordability of the electricity, due to poor expectation management and community integration, was the biggest issue in Mpanta solar mini-grid [58].

A qualitative risk assessment has been performed for the mini-grid in Mumbeji and is presented in Table 33. The probability, severity and overall risk have been assessed as either low (L), medium (M) or high (H).

Table 33. Qualitative Risk Assessment

Description of risk	Possible consequences	Probability	Severity	Overall Risk	Mitigation/ Prevention Action
Not appropriate pricing	Disconnection from grid Increased poverty Mini-grid put out of use	M	H	H	Expectation management Integrating community
Connection to national grid	The mini-grid can be connected to the national grid, maybe batteries will lose their purpose	L	L	L	-
Undersizing system due to load uncertainty	Blackout Uneven and unreliable electricity service Dissatisfied consumers	M	M	M	Include community in design process Use of design tools Load control Expectation management
Oversizing system due to load uncertainty	Increased costs Lower efficiency of system	M	M	M	Include community in design process

					Use of design tools Load control Expectation management
Inadequate system operation and maintenance	System/equipment failures, more frequent replacement of components needed	L	H	M	Capacity building in community
Equipment failure	System not working properly Financial/geographical difficulties replacing equipment	L	H	L	Invest in reliable and renowned manufacturer Equipment with warranty
Geographical isolation	Difficulties getting skilled technician and spare parts to the site	L	M	L	Capacity building in community
Overconsumption from some consumers	Black outs	M	L	L	Expectation management Capacity building
Safety	Harm to the operators/users	L	M	L	Capacity building Disseminate Information
Meteorological[23]	System failure, replacement costs increase	L	H	L	Install lightning arrester
Decreased production of cassava	Higher dependency on solar resource	L	M	L	-

---

[23] Lightning hit the system in Mpanta solar mini-grid several times, destroying one of the charge controllers. The lower capacity of the system led to a 14 h-service of electricity instead of previous 24 h-service

5.3.3 Stakeholder Analysis

To be able to identify the key stakeholders of the project, different stakeholders and their influence and interest in the project was evaluated. The analysis is presented in Figure 45 and described below.

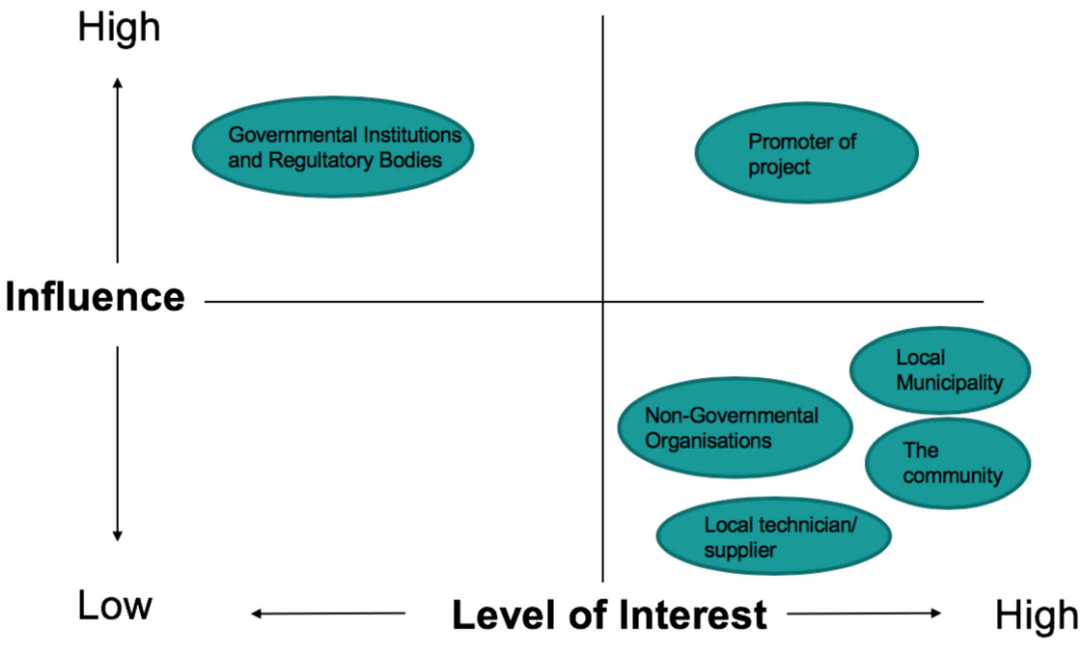


Figure 45. Stakeholder Analysis

5.3.3.1 Promoter of Project

The promoter of the project could be a governmental institution, an intergovernmental organisation or aid organisation. Being the promoter, they have high interest and high influence on the project, which make them a key stakeholder. In order to have an impact on the project, it's necessary to work closely with them.

5.3.3.2 The Community

The community, or the consumers, have high interest in the project but not as much influence. It's of importance to keep the community involved and engaged in the implementation of the project – if not, the project risks to be abandoned or not maintained properly.

5.3.3.3 Local Technician/Supplier

The local technician and supplier have low influence, but will have a high interest if they are inhabitants of the community.

5.3.3.4 Local Municipality

The local municipality will have a high interest in the project, but low influence since the project would be funded and executed by institutions/organisations not related to the community themselves.

5.3.3.5 Governmental Institutions and Regulatory Bodies

High influence since their policies, framework and regulations highly affect the project, but they don’t have any interest in the project on project-level. However, due to their high impact on the project, it’s wise to try and involve them in the project since they are highly influential.

5.3.3.6 Non-Governmental Organisations

Non-Governmental Organisations (NGOs) have a high interest in the project since this kind of projects are closely linked to their work and activities. However, they have a low influence on the project.

6 Discussion & Conclusions

Despite many efforts[24], Zambia is still facing severe challenges today. After many years of steady GDP growth, and unsuccessful plans of economic diversification, a falling copper price hit Zambia's economy hard in 2015. In the same way, the droughts in 2015 and 2016 hit the electricity sector hard and demonstrated just how vulnerable the electricity system and the country are to climate change. A possible way to diversify Zambia's power generation is by expanding their coal and diesel power generation capacity, and may seem tempting in a short-term perspective, due to lower investment costs and continuous supply. However, the long-term effects, dependency on external conditions and climate change, can be devastating for the country.

The same crossroads is appearing in the economic sector. Being a developing country rich in resources there's an extensive risk that these resources are overexploited in a short period of time in pursue of rapid growth and development. A convenient and beneficial solution in the short-term might be to expand the mining sector further, but will place Zambia in an even more vulnerable position. It is therefore of great importance that Zambia mobilises its funds and resources to promote economic diversification as well as a diversified electricity sector, in order to strengthen its independency and be able to ensure steady development. Electrifying rural farming communities like Mumbeji with decentralised energy systems, such as the one evaluated in this study, could help Zambia to both diversify the electricity sector and their economy as their aim is to increase the agricultural sector.

Diversifying the electricity sector by renewable energy sources has its challenges, including financial, technical and social challenges. In this study, the optimal design and feasibility of an off-grid hybrid renewable energy system for the rural community of Mumbeji were investigated. The study showed that the optimal configuration consists of:

- 80 kW of PV modules
- 25 kW gasifier
- 120 batteries of 3 kWh, a total of 360 kWh
- Inverter of 27 kW

Regarding the configuration of the system it must be mentioned that cassava waste as a feedstock for the gasifier has not been tested before. Even though general feedstock requirements match with the characteristics of cassava waste, the cassava has to be pretested with the gasifier before implemented. In addition, a gasifier with smaller capacity could be sufficient and this option should be explored if the project was to be implemented. Capital cost and fuel consumption are very similar in terms of costs per watt peak, but if a smaller capacity would be sufficient, the LCOE, capital costs and NPC would be lower.

---

[24] Vision 2030, National Development Plans, Rural Electrification Master Plan, SDGs, MDGs, etc.

Furthermore, the configuration of the system is a result of the demand load and the available energy resources. Knowing the energy potential and demand load profile is therefore crucial when designing an energy system in order to not under- or oversize the system. Undersizing will lead to black outs and unreliable supply whereas over sizing will result in higher costs, risking disconnecting costumers. The demand of a community is highly site-specific and therefore, on-site surveys and studies are crucial to be able to map energy potentials, energy consumptions and energy behaviour. The demand may (and most probably will) vary depending on the day of the week and also depending on the season. During the cooler season (June and July) heating may be necessary during the night, which has not been considered in this study. Due to limitations in time and resources to do site visits, the demand curve had to be estimated from literature and general cases, resulting in a simplified demand curve with less accuracy. However, even when on-site surveys are made to estimate demand load profiles, there's an extensive risk of mis-estimating it, since it's hard for the consumer to estimate his/her electricity consumption when he/she never has had access to electricity before.

The site visits are not only crucial for mapping the demand load and energy resources, but to involve the local community in the project. Without its participation early on in the design process, the project risks failure. For example, as in the solar mini-grid in Mpanta in northeast Zambia, expectations of the residents did not match the final result, leaving consumers dissatisfied and disconnected.

The predicted capital costs of the project are summarised in Table 34.

Table 34. Capital Costs of Project

HOMER	**€**
PV	213,600
Gasifier	48,060
Batteries	67,640
Inverter	52,866
Total System	382,166
Other	
Battery inverter	15,000
Wood chipper	1,770
Power Cables	28,416
Land (850 m^2)	7,500
Facilities (100 m^2)	34,500

Total Others	87,186
Total	469,352
Total (€/Wp)	4.47

The approach of the cost data and calculations has been to "be on the safe side" and for cost variations the higher values have always been applied, meaning that the system costs can seem quite high. However, comparing to similar projects, the costs vary so much from project to project that the system cost for this project cannot be disregarded as either too expensive or underestimated (besides, this project includes the full electricity distribution system). Furthermore, there were not many similar projects to compare with, only one similar was found in Zambia and neither cost data nor consumption data was found for this. The projects used as comparison, are spread out in the Sub-Saharan Africa, and since costs are so site-specific (and depend on size of community/system, energy use behaviour, climatic data etc.) they are, in fact, not very comparable.

The LCOE of 0.485 USD/kWh, is not at all competitive to the grid prices in Zambia, that in turn, are not cost-reflective. Funding on investment cost would instead imply an LCOE of 0.104 USD/kWh, being more competitive and relatively similar to the electricity prices in Mpanta solar mini-grid. Having said that, 45% of originally connected households in Mpanta are now disconnected, because they have not been able to pay the electricity bills. A big risk with this project is therefore its economic feasibility and in addition to investment funding, there's most probably also need for subsidised tariffs. Furthermore, the inflation rate in Zambia is fluctuating and hard to predict, adding higher risks to financial investments. Finally, it has to be taken into consideration that farmers usually don't have a steady monthly income flow during the year, but get their incomes in relation to the farming season. Hence, without properly budgeting and allocation of money, there's a risk of people not being able to pay their electricity bills every month.

To summarise, the economic viability is found to be the most critical aspect of this system – to some extent, based on previous experiences, where consumers can't afford the electricity bill, but mainly based on unfeasible investment costs and high levelized costs of electricity. Funding and subsidies would therefore be necessary for this project to be feasible. In addition, Zambia's non-cost-reflective electricity tariffs don't trigger investments in the electricity sector.

Moreover, the design of the off-grid hybrid renewable energy system for the community of Mumbeji is based on several estimations due to lack of site-specific data. Hence, unreliable input data result in unreliable outcomes and before a possible implementation, a profound on-site data collection is needed.

7 References

[1] “Africa :: Zambia — The World Factbook - Central Intelligence Agency.” [Online]. Available: https://www.cia.gov/llibrary/publications/the-world-factbook/geos/za.html. [Accessed: 15-Apr-2019].

[2] Ministry of Energy, “Renewable Energy Feed In Tariff Strategy,” pp. 1–16, 2017.

[3] Resilience and Economic Inclusion Team, “Zambia Climate Action Report 2016,” 2016.

[4] “HOMER - Hybrid Renewable and Distributed Generation System Design Software.” [Online]. Available: https://www.homerenergy.com/index.html. [Accessed: 07-Jul-2019].

[5] “Zambia Data Portal, Central Statistical Office.” [Online]. Available: https://data.worldbank.org/indicator/EN.POP.DNST?locations=ZM. [Accessed: 15-Apr-2019].

[6] Government of the Republic of Zambia, “Rural Electrification Master Plan,” 2009.

[7] The Commonwealth Local Government Forum, “The Local Government of Zambia,” pp. 279–283, 2018.

[8] Government of Zambia, “Zambia’s Second National Biodiversity Strategy and Action Plan (NBSAP-2),” vol. 1, no. 1, p. 80, 2015.

[9] Ministry of National Development Planning, “Seventh National Development Plan 2017-2021,” 2017.

[10] “USD to ZMW Exchange Rate - Bloomberg Markets.” [Online]. Available: https://www.bloomberg.com/quote/USDZMW:CUR. [Accessed: 02-Jul-2019].

[11] Ministry of Finance, “Annual Economic Report 2017,” pp. 1–9, 2017.

[12] CSO, “Central Statistical Office Labour Force Survey-Republic of Zambia.,” 2015.

[13] C. S. O. Rebublic of Zambia, “Zambia in Figures 2018.”

[14] “Statistics | Zambia - Total Primary Energy Supply (TPES) by source (chart).” [Online]. Available: https://www.iea.org/statistics/?country=ZAMBIA&year=2016&category=Energy supply&indicator=TPESbySource&mode=chart&dataTable=BALANCES. [Accessed: 02-Jul-2019].

[15] Republic of Zambia, “Ministry of Energy Zambia.” [Online]. Available: http://www.moe.gov.zm/. [Accessed: 02-Jul-2019].

[16] “Electricity Access in Zambia | Energy Access - Africa.” [Online]. Available: https://energyaccess-africa.com/2017/08/11/electricity-access-in-zambia/. [Accessed: 05-Jul-2019].

[17] Energy Regulation Board, “Regulation Statistical Bulletin,” 2018.

[18] Energy Regulation Board, “Energy Sector Report 2016,” 2016.

[19] “Electricity production from hydroelectric sources (% of total) | Data.” [Online]. Available: https://data.worldbank.org/indicator/EG.ELC.HYRO.ZS?end=2015&locations=ZM&start=2005&view=chart. [Accessed: 06-Jul-2019].

[20] IRENA, "Zambia Renewables Readiness Assessment 2013," *Int. Renew. Energy Agency*, p. 84, 2013.

[21] ZESCO, "Transmission." [Online]. Available: http://www.zesco.co.zm/ourBusiness/transmission. [Accessed: 02-Jul-2019].

[22] Republic of Zambia, "ZAMBIA V I S I O N 2 0 3 0 ''A prosperous Middle-income Nation By 2030"," no. December, 2006.

[23] M. O. F. Energy and W. Development, "Power System Development Master Plan for Zambia 2010-2030," no. February, 2016.

[24] Republic of Zambia, "Scaling up Renewable Energy Programmes (SREP)," *Int. Demogr.*, vol. 5, no. 5, pp. 1–9, 2018.

[25] "Nationally Determined Contributions (NDCs) | UNFCCC." [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs. [Accessed: 06-Jul-2019].

[26] Republic of Zambia, "Zambia's INDC to the 2015 Agreement on Climate Change," no. 4291, p. 12, 2015.

[27] "Entiba Energy - Entiba Rural Improvement Project (Zambia) | The Alliance for Rural Electrification (ARE)." [Online]. Available: https://www.ruralelec.org/project-case-studies/entiba-energy-entiba-rural-improvement-project-zambia. [Accessed: 06-Jul-2019].

[28] A. Shane, S. H. Gheewala, B. Fungtammasan, T. Silalertruksa, S. Bonnet, and S. Phiri, "Bioenergy resource assessment for Zambia," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 93–104, 2016.

[29] "2015 LIVING CONDITIONS MONITORING SURVEY REPORT REPUBLIC OF ZAMBIA CENTRAL STATISTICAL OFFICE CSO-Serving Your Data Needs."

[30] "JRC Photovoltaic Geographical Information System (PVGIS) - European Commission." [Online]. Available: http://re.jrc.ec.europa.eu/pvgis.html. [Accessed: 21-Apr-2019].

[31] J. P. S. Veiga, T. L. Valle, J. C. Feltran, and W. A. Bizzo, "Characterization and productivity of cassava waste and its use as an energy source," *Renew. Energy*, vol. 93, pp. 691–699, 2016.

[32] V. Okudoh, C. Trois, T. Workneh, and S. Schmidt, "The potential of cassava biomass and applicable technologies for sustainable biogas production in South Africa: A review," *Renew. Sustain. Energy Rev.*, vol. 39, pp. 1035–1052, Nov. 2014.

[33] The International Renewable Energy Agency(IRENA), *Solar PV in Africa: Costs and Markets*, vol. 411, no. September. 2016.

[34] "HIGH PERFORMANCE SOLAR MODULES rec Peak energy SERIES."

[35] "REC Peak Energy Series REC260PE 260 Watt Solar Panel Module." [Online]. Available: https://www.renugen.co.uk/rec-peak-energy-series-rec260pe-260-watt-solar-panel-module-discontinued/. [Accessed: 01-Jul-2019].

[36] "REC Peak Energy REC310PE72 310w Poly Solar Panel - Solaris." [Online]. Available: https://www.solaris-shop.com/rec-peak-energy-rec310pe72-310w-poly-solar-panel/. [Accessed: 01-Jul-2019].

[37] N. E. Mbaka, N. J. Mucho, and K. Godpromesse, "Economic evaluation of small-scale photovoltaic hybrid systems for mini-grid applications in far north Cameroon," *Renew. Energy*, vol. 35, no. 10, pp. 2391–2398, Oct. 2010.

[38] M. Moner-Girona *et al.*, “Adaptation of Feed-in Tariff for remote mini-grids: Tanzania as an illustrative case,” *Renew. Sustain. Energy Rev.*, vol. 53, pp. 306–318, Jan. 2016.

[39] “6 Hoppecke Battery 12 OPzS 1500 - Merkasol Renewable Energy.” [Online]. Available: https://www.merkasol.com/6-Hoppecke-Battery-12-OPzS-1500. [Accessed: 02-Jul-2019].

[40] “Batería estacionaria OPzS de 2232Ah C100, 6 baterías de 2V HOPPECKE 12 OPZS 1500 o Power VL 2-1610 - Ecofener.” [Online]. Available: https://ecofener.com/baterias-opzs-o-gel-estacionarias/644-bateria-estacionaria-2232ah-c100-6-vasos-x-2v-hoppecke-12-opzs-1500.html?gclid=CjwKCAjw0N3nBRBvEiwAHMwvNn6uvT9sG0XIFk5xpI3lngi1YVMbYIhAdb_aqaf2bRB6tgYTYG0zthoCvlsQAvD_BwE. [Accessed: 05-Jun-2019].

[41] S. A. Solar Technology, “Sunny Tripower 60.”

[42] “Inversor a red trifásico 20.000W modelo Sunny Tripower 20000TL-30 de la marca SMA - Ecofener.” [Online]. Available: https://ecofener.com/inversores-a-red-trifasicos/1490-inversor-a-red-trifasico-20000w-modelo-sunny-tripower-20000tl-30-de-la-marca-sma.html?gclid=Cj0KCQjw3uboBRDCARIsAO2XcYCN63g2-wQYu_kIR_jDm-GmWJ6QA1JanfJolU7kQe20BuCYexiNk4kaAps6EALw_wcB. [Accessed: 01-Jul-2019].

[43] “Inversor Solar 25kW Sunny Tripower 25000TL Trifásico Sin Transformador.” [Online]. Available: https://www.puntoenergiashop.it/es/inversor-sma/5105-inversor-solar-25kw-sunny-tripower-25000tl-trifásico-sin-transformador-8380000026609.html?utm_campaign=merchantcenter&utm_source=google&utm_medium=ads&gclid=Cj0KCQjw3uboBRDCARIsAO2XcYDAwmsdlscOiWYl. [Accessed: 01-Jul-2019].

[44] A. Molino, S. Chianese, and D. Musmarra, “Biomass gasification technology: The state of the art overview,” *J. Energy Chem.*, vol. 25, no. 1, pp. 10–25, Jan. 2016.

[45] “Product Overview - ALL Power Labs.” [Online]. Available: http://www.allpowerlabs.com/products/product-overview. [Accessed: 05-Jun-2019].

[46] E. Hurtado *et al.*, “Optimization of a hybrid renewable system for high feasibility application in non-connected zones.”

[47] J. D. Martínez, K. Mahkamov, R. V. Andrade, and E. E. Silva Lora, “Syngas production in downdraft biomass gasifiers and its application using internal combustion engines,” *Renew. Energy*, vol. 38, no. 1, pp. 1–9, 2012.

[48] G. P. M. Fracaro, S. N. M. Souza, M. Medeiros, D. F. Formentini, and C. A. Marques, “Economic feasibility of biomass gasification for small-scale electricity generation in Brazil,” 2011.

[49] A. Pattiya, “Thermochemical characterization of agricultural wastes from thai cassava plantations,” *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 33, no. 8, pp. 691–701, 2011.

[50] M. K. Commeh, F. Kemausuor, E. N. Badger, and I. Osei, “Experimental study of ferrocement downdraft gasifier engine system using different biomass feedstocks in Ghana,” *Sustain. Energy Technol. Assessments*, vol. 31, no. October 2018, pp. 124–131, 2019.

[51] “Power Pallet PP30 Cogen-CS 2018 Price List Standard Package Optionals & Accessories Commissioning & Training Services,” vol. 30, p. 2018, 2018.

[52] “PP30 — Basic Considerations.”

[53] N. Kaewwinud, P. Khokhajaikiat, and A. Boonma, “Effect of moisture and region of cut on cassava stalk properties in biomass applications,” *Res. Agric. Eng.*, vol. 63, no. 1, pp. 23–28, 2017.

[54] Lusaka Voice, “Cassava commercialisation good for agro sector | Lusaka Voice.” [Online]. Available: http://www.lusakavoice.com/2013/08/13/cassava-commercialisation-good-for-agro-sector/. [Accessed: 05-Jul-2019].

[55] “Wood Chipper MHC-500.” [Online]. Available: https://www.alibaba.com/product-detail/chipper-machine-for-woods-log-wood_1743610457.html. [Accessed: 05-Jul-2019].

[56] D. P. Blechinger, E. Papadis, M. Baart, P. Telep, and F. Simonsen, “What size shall it be ?,” p. 65, 2016.

[57] L. Makashini, A. Ng’ombe, H. Abanda, A. Malama, and P. Mudenda, “Household lifestyle, energy related practices and perceptions of energy efficiency: Evidence from Kitwe, Zambia.”

[58] C. Muhoza and O. W. Johnson, “Exploring household energy transitions in rural Zambia from the user perspective,” *Energy Policy*, vol. 121, no. January, pp. 25–34, 2018.

[59] G. J. Prinsloo, “Scoping exercise to determine load profile archetype reference shapes for solar co-generation models in isolated off-grid rural African villages,” *J. Energy South. Africa*, vol. 27, no. 3, p. 11, 2016.

[60] “Anayochukwu and Nnene Simulation and Optimization of Hybrid Diesel Power Generation System for GSM.”

[61] “Energy for Rural Health Centers - energypedia.info.” [Online]. Available: https://energypedia.info/wiki/Energy_for_Rural_Health_Centers. [Accessed: 14-May-2019].

[62] “Wood Energy - List and values of wood fuel parameters - Part 1.” [Online]. Available: http://www.woodenergy.ie/woodasafuel/listandvaluesofwoodfuelparameters-part1/. [Accessed: 26-Jun-2019].

[63] “SMA Sunny Island Off Grid Inverters | Wind & Sun.” [Online]. Available: http://www.windandsun.co.uk/products/Inverters/SMA-Inverters/SMA-Sunny-Island-Off-Grid-Inverters#.XRsfNOjHyUk. [Accessed: 02-Jul-2019].

[64] “LAND AND BUILDINGS COSTS | Zambia Investment and Business.” [Online]. Available: http://www.zda.org.zm/cost/en/Cost of Doing Business/Land and Buildings Costs. [Accessed: 02-Jul-2019].

[65] “Precio en España de m de Cable con aislamiento. Generador de precios de la construcción. CYPE Ingenieros, S.A.” [Online]. Available: http://www.generadordeprecios.info/obra_nueva/Instalaciones/Electricas/Cables/Cable_con_aislamiento.html. [Accessed: 28-Jun-2019].

[66] “Low Voltage Power Cables.” [Online]. Available: https://www.zamefa.com/low-voltage-power-cables/. [Accessed: 02-Jul-2019].

[67] M. Moner-Girona, M. Solano-Peralta, M. Lazopoulou, E. K. Ackom, X. Vallve, and S. Szabó, “Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience,” *Renew. Sustain. Energy Rev.*, vol. 91, no. July 2017, pp. 1148–1161, 2018.

[68] “Mpanta Solar Mini Grid Project.” [Online]. Available: https://www.wame2015.org/case-study/1076/mpanta-solar-mini-grid-project-winner-of-the-wame-call. [Accessed: 05-Jul-

2019].

[69] “Zambia: Solar PV and Hydro Mini-Grids Case Study: Solar PV Mini-Grid in Sinda District.”

[70] Intergovernmental Panel on Climate Change (IPCC), “Emission Factor database - Main Page.” [Online]. Available: https://www.ipcc-nggip.iges.or.jp/EFDB/main.php. [Accessed: 06-Jul-2019].

[71] M. Brander, A. Sood, C. Wylie, A. Haughton, and J. Lovell, “Electricity-specific emission factors for grid electricity.”

[72] V. Raisch, “Financial Assessment of Mini-grids Based on Renewable Energies in the Context of the Ugandan Energy Market,” 2016.

[73] J. Hazelton, A. Bruce, and I. MacGill, “A review of the potential benefits and risks of photovoltaic hybrid mini-grid systems,” *Renew. Energy*, 2014.

[74] “Convert Zambian Kwachas (ZMW) to US Dollars (USD) - Exchange Rates.” [Online]. Available: https://www.exchange-rates.org/Rate/ZMW/USD. [Accessed: 05-Jul-2019].