Modeling of a Cost-Effective Implementation and Utilization Scheme for Micro-Hybrid Plants in Rural Areas: A Case of Mayukwayukwa, Zambia

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***Abstract*—Energy plays a very important role in people's lives, at the same time it contributes to economic development and growth. A sustainable energy system, supplying clean, affordable and reliable energy, is required in line with almost 70% of Sustainable Development Goals (SDG) - SDG7 in rural areas where energy poverty is prominent due to no energy access. A model and simulation of various energy source combinations were conducted using HOMER Pro Software with data collected from a survey done in Mayukwayukwa, Kaoma district in Zambia. A review of current energy scenario and electrification plans for Mayukwayukwa is discussed and evaluated and the aim is to demonstrate the economic viability of hybrid micro power plants using local resources and provide alternative energy solutions that would meet the end-users energy demand. Biomass-solar PV combination is found to be an affordable, reliable, sustainable and continuous clean energy for a micro hybrid power plant.**

Keywords: affordable energy, biomass-solar PV plant; hybrid power plant, reliable clean energy, sustainable energy

I. INTRODUCTION

Energy is a key factor in the economic development of every country. More than 1.3 billion people are living without access to electricity of which many are in developing countries with very high level of poverty [1]. The energy consumption patterns of poor people are mostly from traditional biomass and fossil fuels with an estimate of 2.6 billion people using it for cooking and lighting. Sub- Saharan African (SSA) is the most electrically disadvantaged region in the world with 621 million people lacking access to electricity [1]. This has resulted in 400, 000 deaths in SSA and an annual 1.6 million deaths globally [2]. More than 12 million Zambians (translating to over 2.3 million households) have no access to modern form of energy [3]. The country depends on hydro power generation, which is not sufficient and has resulted in 80% of its population, that is 17, 351, 822 as of 2019 estimates depending on wood and fossil fuels. Fig. 1 shows the grid power distribution in Zambia.

Fig. 1. Power distribution network in Zambia.

A proactive approach was undertaken by conducting a survey in Mayukwayukwa, one of the densely populated rural areas in Kaoma District, Western Province of Zambia. Mayukwayukwa is one of the oldest UN sponsored camps opened in 1966 by the Zambian Government for those escaping the conflict in Angola. The settlement has more than 15,000 people of which more than 12,000 are Zambians and over 3000 are refuges. Majority of refugees went back to Angola in 2010. At the moment, there is no commitment on electricity supply to Mayukwayukwa from the Zambian electricity grid. The camp has had a 24 kW water turbine located on the Luena River and operated well below its rating from 1999 - 2012 while been out of service till date. Currently, the area has two diesel generators, a 32 kVA diesel generator for the UN offices and household, and 45 kVA diesel generators for a boarding secondary school. The total power supplies is less than 10% of the total Mayukwayukwa population requirement for four hours a day when fuel is available.

The result obtained using HOMER Pro software from the survey is used to determine the economic value of providing

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hybrid micro biomass-solar PV as alternative energy to fossil fuel and diesel generators in rural areas. The focus of this paper is on Mayukwayukwa's current load profile, energy utilization and review for biomass-solar PV as an alternative energy solution.

II. GLOBE OVERVIEW

Access to clean, safe, affordable and sustainable renewable energy supply is one of the greatest challenges facing humanity [2], [4]. Most developing countries are short of modern energy supply due to poverty [5], [6]. The energy consumption patterns of poor people mostly from traditional energy (i.e. biomass) and fossil fuels tend to add to their misery and worsen their poverty. Improvement of energy services will allow the poor people to have a better life [7], [8], [9]. An estimate of 3 billion people worldwide of which 2.6 billion of these people live in developing countries rely on traditional biomass [2], [10] and fossil fuel for cooking and lighting. The traditional biomass supplies over 90% of household energy need in many developing countries [11], [12], [13]. The burning of biomass releases pollutants that are currently estimated to cause more than 1.6 million annual deaths globally from which 400,000 deaths are in Sub-Sahara Africa (SSA) [12]. These deaths are always children and women, which clearly shows the link of biomass directly or indirectly to sustainable development goals (SDGs) including environmental sustainability, clean and affordable energy, good health and wellbeing and gender equality. It is expected that one-third of the world's population will still rely on these fuels until 2030 [12], [14], [15]. Most women and children's valuable time and efforts are devoted to collecting fuel-wood instead of education, income generation, or leisure. For example, in SSA, women spend 3 to 5 hours collection time per head-load due to long distances of where the fuel-wood must be collected from. This will require 6 to 15 hours per week [16]. Deforestation also arises from cutting down of trees for charcoal production and firewood consumption, in the end causing environmental damage.

TABLE I. Electrification Rates across Major Regions [17]

Region	**Region Without Electricity (Million Persons)**	**Electrification Rate**	**Urban Electrification Rate**	**Rural Electrification Rate**
Developing countries	1283	76%	91%	64%
Africa	622	43%	68%	26%
North Africa	1	99%	00%	99%
Sub-Saharan Africa	621	32%	59%	16%
Developing Asia	620	83%	95%	74%
China	3	100%	100%	100%
Latin America	304	75%	94%	67%
Middle East	23	95%	99%	82%
Middle East	18	92%	98%	78%
Transition Economies & OECD	1	100%	100%	100%
WORLD	1285	82%	94%	68%

The lack of access to electricity in rural areas is shown in table 1 above with Sub Sahara Africa having the lowest electrification rate of 32%. The statistics presented in table 1 above shows differences in per capita household across energy utilization and electrification globally and gives a summary of the electrification rate in rural and urban areas.

A. *General Profile of Zambia*

Zambia is a landlocked Sub-Sahara Africa country, with an area of 752, 614 square kilometers [18] located in Central Southern Africa. It shares borders with Democratic Republic of Congo (DR Congo) and Tanzania to the North; Zimbabwe and Botswana to the South; Malawi and Mozambique to the East; Namibia to the South-West and Angola to the West with a population of 17, 351, 822 of which 56.48% [3] are in rural area. Zambia has more or less the same favorable climate throughout the country with average temperatures ranging from 15°C to 27°C (degrees Celsius).

III. ASSESSMENT OF DATA

The research questionnaires were distributed to 125 households and only 88 of these questionnaires were returned. Mayukwayukwa refugee camp is 7km from Kaoma- Lukulu gravel road as shown in Fig. 2. The community has two diesel

Fig. 2. Mayukwayukwa location from HOMER

generators; one for United Nation (UN) office's usage and the other for a Secondary Boarding School mainly for water pumping and for lighting during the night for pupils prep time. This power is not reliable because it is only available for 5 hours a day when there is fuel. In a month 122,000liters of diesel is required translating into 610 drums for a secondary boarding school. Similarly, for the UN generator they use 50 liters of diesel daily and in a month 1,500 liters for the offices. However, about 30 houses contribute a monthly amount of $11 each (taking the current exchange rate of Zambian Kwacha - ZMK18.53 to a United State Dollar - US$1 for power supply from 6 PM to 10 PM daily. The main reason for this erratic power supply is because of the distance from where the fuel is purchased, the high cost of fuel, and the poor road network in Western Province. In rain season vehicles find it difficult to transport material. Many of Mayukwayukwa residents depend on hurricane lamps, candles, firewood and dry cell batteries for lighting, almost all of the respondents to the questionnaires indicated they use firewood for cooking. Only 10% of total respondents use both firewood and charcoal for cooking. From the survey results, the average household family is 6 with the maximum number of persons per household of 12. The maximum total income spent on lighting and fossil fuel is $11.11 per month for those not connected to the diesel generator. The maximum willingness to pay for electricity is

$28, with an average willingness to purchase at $12 per month. Mayukwayukwa residents cover a maximum distance of 2km to charge their phones at a cost of $0.167 per phone charge.

A. Diesel Generator

There are two diesel generator systems, one at UN offices and the other at a secondary boarding school. They use them for water pumping, lighting, office appliances and clinic refrigerator in Mayukwayukwa. The school has over 300 pupils in boarding and 20 staff homes and 10 workers homes. The power from the diesel generators is unreliable because of its dependence on the availability of fuel, even when fuel is available, the teachers, workers and other residents cannot access or utilize it due to water pumping requirements.

B. Solar PV

Solar PV solution remains minimal in Mayukwayukwa. During the time of the survey, it was observed that solar home systems were in use in some households for lighting and phone charging. After interviewing some traders, many expressed need to have solar PV for refrigeration in order to sell fresh foods and cold drinks. When asked if they know of any other form of renewable energy apart from Solar systems, their response was NO.

IV. MODELING AND SIMULATION

A. Hybrid Power Plant Selection

Homer Pro Software was used to determine reliable, cost-effective and optimum micro hybrid power plant for Mayukwayukwa taking into consideration of Mayukwayukwa load profile, solar radiation, and local resource availability. Mayukwayukwa refuge camp is used as a case study, noting the accessibility to modern form of energy is low in Sub Sahara Africa and other developing countries. As a result, there is a need to develop a cost-effective implementation hybrid power plant to contribute to the energy mix utilization in rural areas where the electrification is very low.

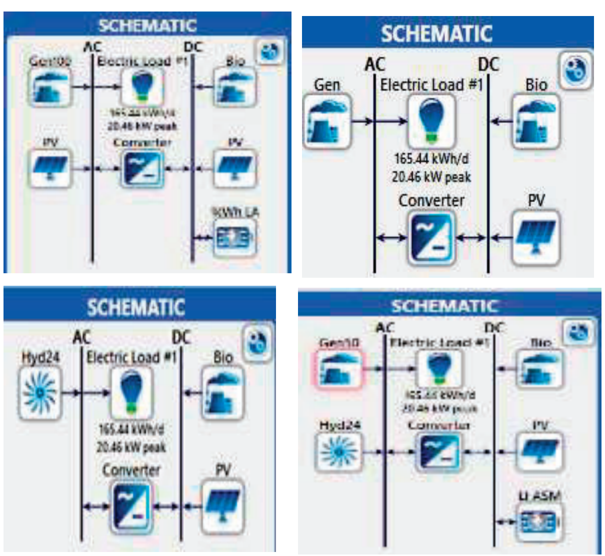

Fig. 3. Simulated hybrid renewable energy systems

Different schematic hybrid renewable energy system combinations were developed as shown in fig. 3.

B. Load profile

The load profile for Mayukwayukwa community is given in fig. 4. The load profile is a pattern of energy usage for a consumer or end-user over a given period. As observed from fig. 4 the load demand is more from noon to 9 PM daily. From the survey, it was discovered that utilization of energy is more in the evening due to activities such as cooking, lighting usage, entertainment/social (radios and TVs), etc. after a long hard day work.

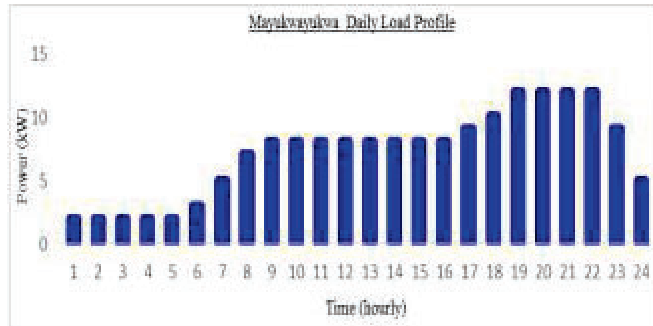

Fig. 4. Community load profile of Mayukwayukwa

C. Solar radiation

Global horizontal solar radiation of Mayukwayukwa refugee camp is average 5.62 kwhr/m2/day situated at 14°48.7,S latitude value and 14° 47.8'E longitude value is shown in fig. 5 below.

Fig. 5. Solar radiation from HOMER

D. Diesel Energy

A liter of diesel produces 5 kWh, this makes diesel generators to be the mostly employed form of power generation in remote areas and as standalone power plants all around the world. However, it is an expensive and unclean energy as it is seen from the result of this paper. Currently the cost of diesel is at $0.85/liter using Zambian kwacha (ZMK 18.52) to United States Dollar (US$1). Diesel generators are widely used despite their environmental unfriendliness.

E. Biomass

Biomass is the renewable energy that is found everywhere on earth in the form of solid and liquid from plants, animals and humans. It is the most used source of energy especially in rural areas for cooking. In urban areas biomass becomes unwanted waste and the way it is disposed off exposes health risks to people and the environment. Researchers have come up with methods of transforming biomass into modern forms of energy such as biogas, biofuels and electricity [5], [14], [16]. It is the most cheapest form of renewable energy technology, biomass into biogas and biofuel. The resources are locally available and people may find jobs - supply waste to the plant.

F. Mini Hydro Power

Mini hydro power plants are renewable energy that may be a substitute to large hydro power plants and can be installed in communities provided there is a river near/within the community. It is one of the reliable power supply with minimal operating costs.

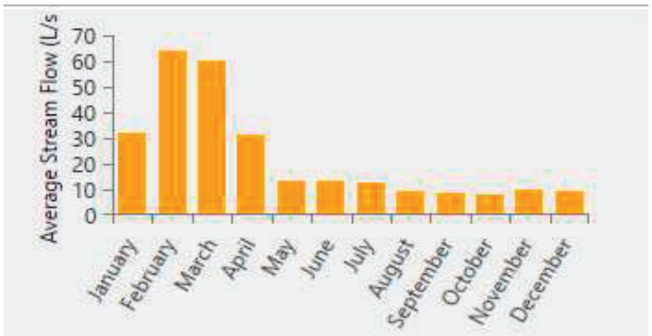

Fig. 6. Luena River flow rate in Mayukwayukwa

The only disadvantage is that it requires huge capital to be implemented. Mayukwayukwa is one of the areas surrounded by rivers and has a 24 kW mini hydro power station that is not in operation after a turbine became faulty. Fig. 6 shows the flow rate as of year 2017 from Luena River that used to supply discharge to Mayukwayukwa power plant at a head of 3.5 m.

V. RESULTS AND DISCUSSION

The evaluation and results obtained were based on 88 questionnaires responses received from the investigation survey captured number of 528 households. Just as other rural areas in developing countries, Mayukwayukwa population has no access to clean energy. The only energy is biomass that is used in a traditional way in the form of firewood for cooking and hurricane lamps, candles, dry battery cells and solar for lighting. 10 out of 88 households knew that there are alternatives to provide energy solutions in Mayukwayukwa. All the responses indicated there is a mobile network in the area and 54 of them had mobile phones. 19 out of 54 have nowhere to charge their phones in that they travel more than 1500m to charge their phones at a fee of $0.11/charge. They all were willing to pay an average of $11 per month, with over 76% of the respondent having the need of electricity (energy) for loads namely refrigeration, radio, computer, lighting, phone charging, television and fan, 8% of the respondent need energy for business such as welding, saloon/barber, internet café and chicken business, while 5% need electric power for heating and cooking.

From the developed model using HOMER Pro Software, it is observed that one source of energy would not meet the community energy requirement unless a hybrid system is employed. Table 2 was used as a guide to determine the cheaper, clean and reliable alternative hybrid renewable energy system i.e. micro-hybrid to be installed.

TABLE II. Process to follow before hybrid selection

1.	2.	3.	4.
Site survey for baseline planning	Load demand assessment	Technical design	Financial analysis

Mayukwayukwa has 15,000 people estimate from CSO 2016. To provide them with electricity with a solar radiation of 5.62kWh/m^2/day would need about 84MWh meaning close to 3.5MW average for 24hrs or peak of 17.6MW solar plant for 5 hours of insolation. A combination of biomass, solar PV, mini hydro, diesel generator and batteries technologies were considered as shown in Fig. 3. The results obtained are shown in Table 3.

TABLE III. Results from simulated hybrid renewable energies

Technology	Operation cost ZMK	Simple Playback Year's	Feedstock & Fuel Tons & ltrs	Capacity Shortage kwhr/year	Net Present Cost ZMK	Emissions CO_2 kg/year
DG/SPV1/2	37,606.98	8.76	25,056 L	0	508,297.70	65,586
SPV1/DG	37,552.41	8.97	24,998 L	0	508,312.90	65,436
DG/SP1/2/3	37,562.19	9.04	25,007 L	0	508,451.90	65,458
BIO/BLA/DG/SPV	17,691.38	1.79	114T	0	445,484.60	92.4
BIO/SPV/BLA	14,764.04	2.17	42.6T	22.6	448,960.00	7.5
BIO/SPV/SAFEP	10,625.67	2,87	47.1T	58.5	345,885.40	8.49
BIO/DG/SPV/SAFEP	12,853.67	2.64	1,949L	0	324,219.80	14,834
BIO/SPV/HYD/BLI	20,955.01	3.62	80	57	917,278.90	14.6
BIO/SPV/DG/HYD/BLI	20,980.72	3.64	81.7T & 11.8L	37.3	918,201.60	45.6
DG/SPV/BLI / HYD	21,540.06	7.34	6.58L	59.9	1,072,041.00	17.2
BIO/BLI/HYD	29,434.29	3.72	208T	47.7	1,008,812.00	37.2
SPV/BLI/HYD	22,012.02	7.8	0	59.4	1,077,120.00	0
BIO/DG/HYD/BLI	28,844.89	3.81	206T	53.3	1,009,432.00	79.7
BIO/SPV/BLA	15,773.71	2.11	60.5T	36.0	423,259.7	10.9

Where DG is diesel generator, BIO is biogas, SPV is solar PV, HYD is hydro, BLI is li-Ion batteries, SAFEP is power safe SBS 190 and BLA is lead acid batteries.

From the combinations done it was found that biomass-solar PV technology gives optimum energy with a simple payback of 2.17 years, less feedstock required, with NPC value of ZMK448, 960.00 and emissions of 7.5kg/year of carbon dioxide as shown in Table 3.

It was observed that a solution with diesel generator combination, emissions of carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, Sulphur oxides and nitrogen oxide are common. Table 4 shows the emissions obtained from various alternative energy source combinations, high emission is deduced from technology having diesel generator.

TABLE IV. Emissions from Biogas/DG/Solar PVenergy sources combination

Energy source combination	Emissions values kg/year					
	Carbon dioxide	Carbon Monoxide	Unburned Hydrocarbons	Particular Matter	Sulfur Dioxide	Nitrogen Oxide
Biogas-Solar PV	7.5	0.0833	0	0	0	0.0521
Diesel Generator-Solar PV	66,035	416	18.2	2.52	162	391
Biogas-Solar PV-Diesel Generator	1,483	12.7	0.217	0.0301	1.93	9.49

VI. CONCLUSION

This paper presented an investigative approach / simulation of different micro-hybrid technologies focusing on solar PV, hydro, biomass, diesel generators and batteries (lead-acid and Li-ion and power safe SBS) in order to determine a cost-effective solution for Mayukwayukwa refuge cape that has no access to clean, reliable and affordable energy.

The study found that not all renewable technologies are economically viable whether combined or not. Understanding the load profile and local resource availability of the community is important to getting the right energy solution combination. Solar PV and biomass have proved to be most reliable, cheap and clean to any community because these resources are available in most developing countries.

The following are recommendation to be considered:-

1. Finding a system that will not depend on batteries knowing that solar PV power can be used during the day when it is at peak and during the night biogas power to meet the night load requirements.
2. End user's behavior application towards energy utilization and how it can positively be influenced.
3. Qualitative interview approach to be engaged.

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