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Energy requirement analysis for the design of solar photovoltaic micro-grids in Botswana

A study of Jamataka village

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Abstract

Substantial proportions of the world's poor live in remote areas that are geographically isolated and are often sparsely populated or have a comparably low electricity demand to justify the extension of the main electricity grid. Botswana with an average national electrification rate of 65.4% and 58.6% in rural areas as per December 2018 is no exception. Against this background, renewable energy is identified as a key enabler for increasing physical access to electricity to off-grid communities. The government of Botswana through its Sustainable Energy for All (SE4All) action and its Vision 2036 intends to increase the use of renewable energy sources for electrification purposes in Botswana with a mainstream to solar energy.

The core of a solar energy project for rural electrification is an energy requirement analysis which is critical for purposes of site selection, sizing and scaling of a solar-photovoltaic (PV) system. This paper conducts an energy requirement analysis of the un-electrified off-grid village called in the Central District of Botswana. The gained knowledge forms a basis to accommodate the load demands of the village I the course of the development of a PV micro-grid. The analysis at hand is based on the estimated daily load demand of government premises, commercial premises and residential buildings. Residential buildings were categorised into low-income, middle-income and high-income household as the amount of energy consumption is assumed to correlate with the disposable income. The user's basic energy need and their daily energy usage was obtained through a preliminary in-situ energy demand survey characterised by questionnaires, verbal interviews and on-site visits to the village. An aggregate load requirement profile for the community is derived from daily load profiles of the individual users. Hence, the total electricity demand of the community has been established to be 174kWh with a peak load and average demand of 16kW and 8kW respectively.

Keywords—Energy requirement analysis; rural electrification; solar-photovoltaic micro-grid; end-use model; energy load profile

I. INTRODUCTION

Substantial proportions of the world's poor live in remote areas that are geographically isolated and are often too sparsely populated or have a very low electricity demand to justify the extension of the main grid [1]. Botswana as a developing country is no exception with an average national electrification rate of 65.4% and 58.6% in rural areas in December 2018 [2]. Renewable energy is identified as a key enabler for increasing physical access to off-grid communities. Aside from physical access, the availability, reliability and affordability of supply are also central policy objectives for enabling energy access. A lack of domestic generation capacity and reliance on non-firm imports until recently resulted in substantial load shedding [3]. The government of Botswana through its Sustainable Energy for All (SE4All) action and the vision 2036 intends to increase the use of renewable energy sources for electrification purposes in Botswana with a mainstream to solar energy [4] [5].

This paper reviews existing literature on energy requirement analysis and reflects on the general principles of power requirement analyses including guidelines, recommendations and experiences regarding energy requirement planning for the design of solar PV micro-grids for electrification. Based on this thorough review, the paper gives an overview on the Solarfin2Go project by which the partners-Ulster University (UK) and Botswana International University of Science and Technology (BIUST) are aiming at the electrification of Jamataka village, Botswana. The core of this paper presents the energy requirement analysis carried out for Jamataka and the employed methodological approach. The results of the energy requirements analysis are discussed, and the electricity consumption profiles derived. The significance of the generated knowledge for the effective planning of the solar-PV micro-grid, systematically taking into consideration the demands of the village in the early planning stages, is shown. The paper concludes with an outlook on the current project funded by InnovateUK.

The SolarFin2Go project is a formed by a collaboration of international companies spearheaded by Ulster University in partnership with BIUST. The project conducts a pilot project of an innovative stand-alone PV-system developed by Ulster University's Centre for Sustainable Technology. SolaFin2Go stand-alone solar-storage systems designed are designed to provide affordable access to both electricity and hot water for off-grid households, businesses and community facilities through improved pay-as-you-go business models enabled by an innovative FinTech platform delivered through mobile, cloud and blockchain [6]. The smart connection of the individual

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stand-alone PV-systems to provide a PV-micro-grid is an objective of the follow-up SolaNetwork project. The study at hand was carried out to professionally consider the village energy requirement in the planning process.

II. LITERATURE REVIEW

An essential component of the engineering planning and design of a solar energy system is to determine the net energy production required off the plant and hence its required net power supply [7], which matches the expected energy demand and load. This type of studies are forecasting the eventual energy requirement based on a load assessment. Energy demand refers to the required energy over whereby load relates to the instantaneous power. Demand analysis is a disaggregated, end-use based approach for modelling the requirements for final energy consumption in an area [8]. This process improves the quality and accuracy of the anticipated energy requirement since the diverse data required to conduct an energy requirement analysis is clustered into manageable divisions. The energy can be estimated at different levels depending on the intended application and its magnitude. Generally, grid-tied systems are flexible to solar intermittence compared to stand-alone PV-systems or micro-grids where energy is supplied instantaneously to the loads without grid backup. For this study, a candid energy consumption is of paramount importance since the nature of the energy service provided is a solution off the national electricity grid.

Energy requirement analysis is data intensive and based on the evaluation of diverse parameters [9]. Projecting energy requirements that reflects reality is rather complex, especially for prospective consumers with no record of prior energy and power use [10] as is the case for Jamataka village. In an ideal situation where a record of energy consumption such as electricity bills is available for a considerable timeframe (usually 1 year), a planner is able to compute average monthly consumption and total annual energy consumption. In the absence of such data, it is requisite for the designer to deduce an estimation of the total annual energy consumption based on the energy loads of the target group. This is referred to as a load analysis [9]. There are various guidelines and principles available on conducting power requirement analysis. In general, the procedure for carrying out an energy load analysis for a renewable energy project is dependent on numerous factors such as seasonal data, climate parameters, demographics, topology and economical boundary conditions [11]. Furthermore, seasonal factors, vacation and holidays have a significant impact and influence on the energy consumption. Last but not least the heat and power demand is influenced by the operational parameters of enterprises with large energy demand and by the consumer's behavior. Additionally the power and heat demand follow a daily cycle with low periods during the night hours and with peaks at different hours of the day.

Numerous codes and standards governing solar energy projects from a pool of different internationally recognised bodies are documented in literature. Akinyele extensively employs the Institute of Electrical Engineering and Electronics (IEEE) and International Electrotechnical Commiss ion (IEC) guidelines and standards in his research. The IEC standards are proposed for this research since they explicitly reflect on energy requirement analysis.

IEC standards

IEC/TS 62257-9-1: mainly provides technical specifications and recommendations for micro-power systems for isolated communities and gives insights with regard to selection an appropriate system for a particular area and discusses possible scenarios [12].

IEC/TS 62257-9-2: gives recommendations for small renewable energy systems for rural electrification with regard to developing electrical systems from energy demand requirements [13]. In this context, the standard presents methodologies for evaluating the socio-economic aspect of decentralised energy projects [14].

IEC/TS 62257-4: presents technical specifications and recommendations on the assessment of user needs and addresses different electrical power topologies for the specified needs [15].

In addition to the IEC standards, numerous methods exist for energy estimation and forecasting. These methods are classified into three groups; short, medium and long term and implore analytical concepts based on statistics, artificial intelligence (AI), knowledge based expert systems and hybrid techniques [16]. A wide variety of tools are available for computational analysis of energy needs based on available data requisite. Tools for energy demand forecasting specifically for Africa arguing that existing modelling tools are biased since they are developed for developed countries and extrapolated to low-income countries are discussed by Ouedraogo, [17]. Ouedraogo uses the Long-range Energy Alternatives Planning (LEAP) modelling system which is also used by Randall et al. [18] in the bottom-up demand analysis of long term electricity supply in the Southern African power pool. This modelling type is suitable for modelling energy forcast at a large scale however not suitalbe for small scale application due to its reliance on empirical data. In their study on energy supply, consumption and access dynamics in Botswana, Essah and Ofetotse [19], use questionnaire surveys combined with empirical study. They implore the end-use model as described by Alkhathami, [20] on their target group. The end use model fundamentally sources raw data from end user's by exploring data collection methods such as questionnaire surveys. The data collated is then aggregated to deduce energy demand profiles reflective of the end-users needs. End-use modelling is now a well-accepted energy forecasting approach of electricity usage and peak demands at national and utility level [21]. End-use modelling is adopted for this study based on the lack of empirical data for off-grid communities in Botswana and to ascertain accuracy in energy demand estimations. In-situ site surveys are conducted to collect first-hand data and access the behavioural patterns of end users.

III. METHODOLOGY

As described above, the load forecasting method employed in this power assessment analysis is referred to as the end-use model which is categorized as a bottom-up approach model. It estimates the energy consumed by utilizing information obtained directly from end users. This information might be in terms of consumers' use, size of houses, age of consumers, and

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applications, among many others. The technique relies on statistical information from consumers accompanied by changes, which form the basis of the forecast [20]. This implies that end-use models focus mainly on the various uses of electricity in commercial, government and residential sectors. Thus, this method is based on the concept that electricity demand will always depend on the end user demand for refrigeration, cooling, lighting, etc. [22].

Mathematically the end-use model is a set of equations designed to disaggregate end-user household's prospective total annual energy consumption generally through residential energy consumption survey (RECS) [20]. RECS's were conducted during in-situ site visits and the disaggregated data sets in combination with population estimates were taken into consideration to determine the total energy consumption of end users. A questionnaire survey with a sample size of 60 was administered in Jamataka covering the various sectors within the village. Given a return rate of 83%, 50 questionnaires formed the basis for empirical study. The accuracy of this model is based on its ability to express electricity demand as a function of its various applications. However, the effectiveness of the model is extremely dependent on the quality and quantity of information sourced from end users. This method permits for integration of econometric methods such as client behavior and thus provides a realistic representation of the energy consumption. Supplementary to data gathered from prospective users, an in-situ survey characterized by interviews of strategically end users was conducted. This supplementary survey targeted the government officials, business owners and residents of different economic statuses according to the categorization made. Households were categorized into three groups; low, medium and high-income houses based on the average disposable income, size and price of a house in an area [19].

The following assumptions were considered regarding the analysis of energy demand data of Jamataka community:

- constant loads for cold appliances. Fridges are assumed to run for 5hrs per day at nominal power.
- electric water heaters (geysers) are not considered as part of the loads as the SolarFin2Go technology under investigation is equipped with a solar catcher (innovative solar-thermal collector).
- based on the dependence of residents on wood fuel for hot water supply and space heating, the lack of electric water heaters and air conditioners, electricity demand is assumed to be constant for all seasons and therefore only holidays considered for variation in electricity demand.
- the daily load demand is considered to be a worst case scenario.

A systematic set of basic mathematical functions relating various parameters to energy are used to generate and power demand requirements of clients. MS-Excel based peak load calculator was utilized to compute and reconcile all gathered electricity demand data into final load profiles. Equation (1) illustrates the formula used to compute the load estimation in this study;

$$E = \frac{I P H_d N_w}{7} \qquad (1)$$

where;

E: total energy in Watt-hr

I: quantity of appliances

P: rated power of an appliance

H_d*: number of operating hours per day*

N_w*: number of operating days per week*

Thereby, the total energy consumption for all end use electricity consuming institution in Jamataka village was calculated. The procedure was applied to both AC and DC appliances and aggregated to derive the final energy consumption estimate for the community sampling only 50 residential households. The power ratings were gathered from available appliances during the conducted in-situ site surveys and from empirical data sets for estimation of appliances without power ratings and variant energy usage patterns over a day such as fridges, printers and desktop computers.

A. Site selection

Jamakata village is located in the Central District of Botswana 40 km west of Francistown. The coordinates of the village are -21.08 °N and 27.14 °E. The location of Jamataka is shown on the map below.

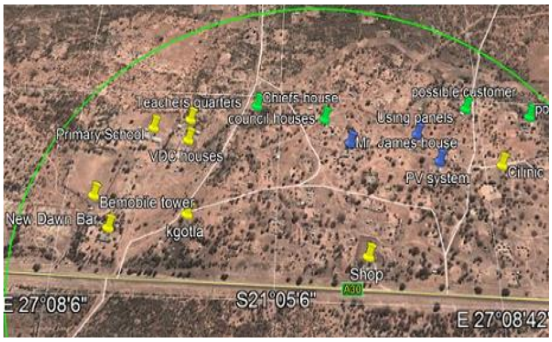

Fig. 1. Picture of Jamataka village with energy consuming institutions located [23]

According to the national statistics census conducted in 2011, the population of Jamataka was enumerated 650 inhabitants at an estimated annual expected growth rate of 1.9%

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[24]. This trend in population growth has to be considered in designing the micro-grid flexible for expansion to accommodate the increasing population.

The current energy mix in the village was determined from literature and questionnaires distributed during an in-situ site survey of the village. The main source of energy is firewood which is extensively used for cooking and heating water. This has raised concern with the village leadership as it is reported that the harvesting of firewood has vastly grown as a means of gaining profit from selling it and thus has a negative environmental impact. The primary school also depends firewood purchase for the school kitchen. This is a direct result of the in-situ survey and verified by the findings of Statistics Botswana [24] which indicate that the use of wood for cooking and heating in the Central District is estimated at 71.9%

Other sources of energy include diesel for the operation generators to provide electrical energy for AC loads mainly at the school, the shopping facilities and a few high-income households. Otherwise candles are widely used for illumination whilst paraffin is the least used fuel in the entire village.

B. Solar Potential Assessment

The annual sum of direct normal irradiation (DNI) and GHI ranges around 2,000 kWhm^{-2}a^{-1} (~5, 5 kWhm^{-2}d^{-1}). The annual daily sums of the global horizontal irradiation (GHI) in Botswana for the years 1996-2009 are within average ~ 5.6 – 6.5 kWhm^{-2}d^{-1} (~2,050 – 2,400 kWhm^{-2}a^{-1}). The country-wide average is 6.17 kWhm^{-2}d^{-1} which is (2,254 kWhm^{-2}a^{-1} [3]. The solar resource map in Figure 2. shows that the geographical location of Jamataka village has the potential to yield 1889kWh of electricity per installed 1kW annually which results in an average 5.19kWhkWp^{-1}. The average GHI of Jamataka village over 10 year is shown on Figure 3.

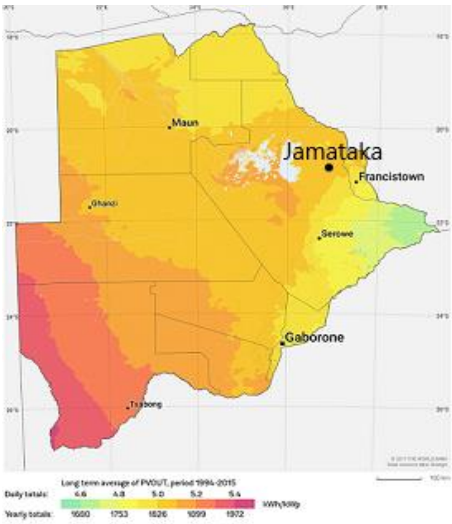

Fig. 2. Solar resource potenetial of Botswaha [25]

Fig. 3. The GHI of Jamataka village from 1995-2005 [26]

C. Energy Requirement Analysis

The load profile is a client's electric energy consumption pattern as a function of time. It is typically the energy demand over a period of 24hrs and regarded as the daily load curve [27]. The curve represents a composite of energy demands by the category of users in the community. The operation of loads varies with time (e.g. hourly, daily, weekly, seasonal, etc.), also depending on the users' lifestyles [28]. This data is used to determine the critical parameters in the design of the renewable energy system for both thermal and electric requirements: These include peak load and annual energy demand. In addition, six daily cycles are determined for workday, Saturday and Sunday, each for at least two typical seasons (summer and winter) including hourly averages and an annual load curve [7].

IV. RESULTS AND DISCUSSION

The result of power requirement analysis of the primary consumers in Jamataka village is shown in Table 1. The community's load profile as aggregate energy demand by the individual entities is illustrated in Figure 5. The residential sector is constituted by 50 households ranging from low, middle and high-income families and are split into a 15:10:5 ratio. The total daily residential energy demands according to the aforementioned categorization is 21kWh, 29kWh and 25kWh respectively. Altogether, residential consumers form 43% of the total daily consumption of the community which amounts to 174kWh with a peak load of 16kW and average demand of 7kW respectively. The estimates of daily energy consumption of the various groups of consumers' in village are shown in Figure 3. They were used to project the annual estimated energy consumption represented in Figure 4. The load profile depicts that energy consumption increases in the morning between 5am and 6am due to users preparing for work which reveals the significant number of government employees being analyzed. The curve further illustrates a reduction in consumption during day hours with hikes at 10am and 1pm. These hikes can be interpreted as tea and lunch breaks where e.g. teachers use electric appliances at their households. The peak load is projected for 8pm when the majority of users is predicted to be

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home utilizing electricity consuming appliances such as television, lights, radio, cell phone chargers, etc. Furthermore, the ordinary residents are mainly farmers and spend their daytime in farms and communal grazing sites whilst some go to work in the city only to return in the evening. The shape depicted by the demand profile therefore reflects on the lifestyle of the residents of Jamataka.

TABLE I. TABLE OF AGGREGATE ENERGY DEMAND PER DAY, WEEK, MONTH AND YEAR FOR JAMATAKA

Facility	***Estimated Energy Demand in kWh***			
	Day	***Week***	***Month***	***Year***
School	25.90	181.33	725.32	9455.12
Staff housing	43.79	306.54	1226.18	15984.08
Clinic	9.15	64.07	256.29	3340.95
Kgotla	1.40	9.83	39.31	512.46
Bar	13.52	94.64	378.56	4934.80
High income	25.25	176.75	707.00	9216.25
Middle income	29.22	204.54	818.16	10665.30
Low income	20.70	144.90	579.60	7555.50
Kitsong centre	4.73	33.14	132.56	1728.01
Total in kWh	**174**	**1216**	**4863**	**63393**

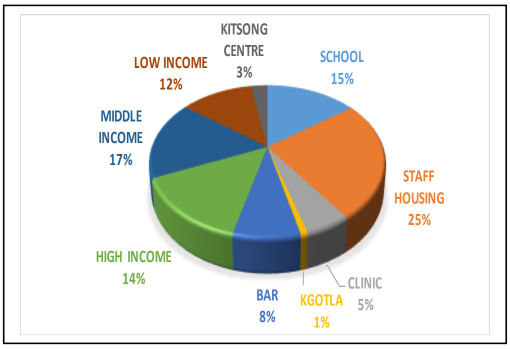

Fig. 4. Estimated relative proportion of the users and institutions to the energy demand in Jamataka village

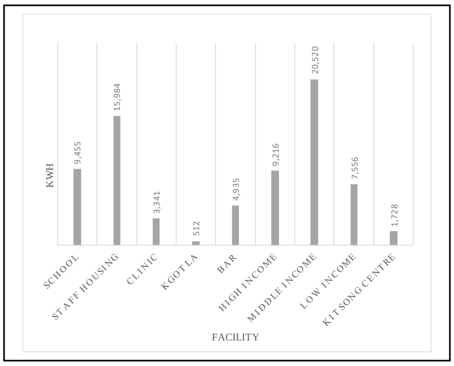

Fig. 5. Estimated annual energy demand of primary institutions in Jamataka

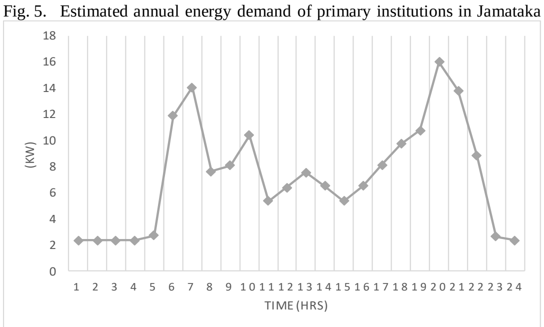

Fig. 6. Estimated daily energy demand profile of Jamataka village

V. CONLUSION

The analysis of energy requirement is essentially a critical aspect to the planning and development of renewable energy projects and associate technologies. This paper utilizes a systematic approach of analyzing disaggregated data following power requirement principles, guidelines, codes and standards. The end-use model is employed and a peak calculator used to generate a daily community load profile which is constitute of aggregated energy consumption profiles of institutions in Jamataka village. Non-numerical factors affecting energy consumption such as consumer preferences and behavior have been integrated into the model hence the load profiles generated are realistic representations of scenario of the community. The total energy demand of the community has been established to be 174kWh with a peak load, and average demand of 16kW and 7kW respectively. This energy demand accounts for all institutions together with a residential sector of a sample of 50 households which constitutes 43% of the total demand of the village. The commercial institutions represented by two shopping facilities constitute 8% of the total village consumption. The pattern expressed by the demand curve correlates with the lifestyle of the residents of Jamataka since most are day workers in government institutions who work regular 8 hours and constitute 46% of the electricity consumption.

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The applicable codes and standards considered in this analysis are the International Electrotechnical Commission (IEC) relating to estimation of energy demand and consumption forecasting. Furtherance to that, they are other codes to be considered though they are not solar specific. Such codes are related to buildings and fire and are described by international bodies such as the ICC, IRC, IBC and IGCC. Local standards relating to solar are BOS 68-1:2005, BOS 13-1:2000 and BOS 13-2:2000 documented in the Botswana Bureau of Standards (BOBS).

The findings of this analysis are to be used in the expansion of the SolarFin2Go which is stand-alone technology catering for electrical and hot water supply.

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