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Innovative Approaches to Energy Provision in Off-Grid Rural Communities—A Case of Botswana

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Abstract

Although renewable energy technologies applications to rural communities to improve energy access have been embraced in numerous parts of the world, sustainability of these systems is increasingly becoming critical as far as realization of long term benefits is concerned. The current manuscript proposes approaches deemed to provide appropriate match between technology and users in a select of Botswana's rural communities. The methodology includes a participatory and inclusive approach in which the local community is engaged in the generation of their own energy. Available information indicates that available feedstock in selected communities is sufficient to generate and provide sustainable energy supply for the community.

Keywords

Energy Provision, Innovation, Off-Grid, Rural Communities, Sustainability

1. Introduction

Available evidence indicates that approximately 1.3 billion people world over do not have access to electricity. Several authors including Mandelli *et al.* (2016) [1] echoed that most of the affected population live in rural areas of developing countries, which are often isolated, haphazard scattered settlements characterised by poor infrastructure and service. The situation makes the extension of electricity grid to such communities uneconomical. Williams *et al.* (2015) [2] observed that regions such as Sub-Saharan Africa, South Asia and Southeast Asia are the most affected regions. Botswana as part of the Sub-Saharan community is equally affected. For example, the Southern African Development Community (SADC) Renewable Energy Strategy and Action Plan 2012-2030 technical report [3] indicates that about 25% of urban and 43% of rural households in Botswana have no access to electricity and its services despite the importance of grid power in human development activities. This is also supported by the work of Barkat *et al.* (2002) [4] who reported that access to electricity has significant impact on the reduction of both income-poverty and all dimensions of human poverty such as health, education and women empowerment. The authors further echoed that rural access to this commodity has deep-rooted impact on agricultural development, industrialisation and business and commercial activities. It is on this basis that several countries have developed programmes aimed at stimulating development of electrical infrastructures in residential sector. However, the challenge is in isolated communities where grid electricity is inaccessible.

In Botswana, like in many other developing countries in the SADC region, a state-owned electric utility (Botswana Power Corporation) is the primary agent for rural electrification. The utility receives subsidies from the government for extending national grid to rural areas. However, the utility engages private operators to build grid extension projects. Despite such arrangement between the government of Botswana and the power utility, there are still several isolated areas particularly in the region such as the Kgalagadi District where extension of national grid to such locations is uneconomical and likely to have limited social benefits in a number of dimensions of human poverty. The observation is consistent with those made by Mondal *et al.* (2010) [5] who echoed that it is not economical to extend grid access to lowly populated areas. The authors further stated that electricity supply to low-load rural and remote areas is characterized by relatively high transmission and distribution losses, and heavily subsidized electricity pricing. Such is the case with Botswana. For example, in April 2010 the government introduced the National Electrification levy of BPW 0.05 per kilowatt purchased by the consumer. This was introduced in order to generate revenue for the National Electrification Funds established to assist rural electrification programme [6]. However despite the introduction of the National Electricity levy, extension of electrical grid to isolated communities in the country is still a major challenge. The challenge appears to be influenced by the pattern of settlement among rural communities, which is also characterised by small population and scattered households and/or villages with relatively small electricity load requirements. The current study focuses on one such village called Inalegolo.

Figure 1 depicts actual geographical spread of Inalegolo village located in the Kgalagadi District in Botswana with a population of approximately 533, which is approximately 76 households, based on the average household size of seven (7) persons [7]. The village is located approximately 363 km South West of Gaborone City, which is the main administration of the country, at latitude of 23˚57'1.79"S and longitude of 22˚58'17.99"E. As demonstrated by **Figure 1**, the village is characterised by few and scattered households. It is pertinent to mention that the nearest national electricity grid from Inalegolo village is approximately 90 km away, making the extension of the grid to such a small community uneconomical for power generation and distribution company in the country. It should also be mentioned here that with the exception of the old age (65 and above) relief funds, the majority of the residents in isolated villages such as Inalegolo do not have regular income due to absence of economic activities in the majority of isolated villages in the country. This is one of the factors which affect rapid development of electricity infrastructure in isolated communities in Botswana.

The map of Inalegolo village shows scattered households and other features such as Inalegolo primary school and community church. Although access to electricity is expected to improve quality of life and promote growth on a range of socioeconomic activities among the rural communities, it is the view of the authors that the situation is likely to be different in Inalegolo. The observation is based on a study by Ketlogetswe and Mothudi (2009) [8] which revealed that the level of connectivity to the national electricity grid among the rural population was relatively low mainly due to relatively high connection fees. Considering the current rural electrification funding structure where household owners are expected to pay BPW 5000.00, which is an equivalent of US$ 714, to cover connection charges. This charge excludes installation cost which is likely to be three quarters of the connection charge. It is on this background that extension of grid electrical to majority of isolated areas in Botswana is still uneconomical. The situation is expected to have adverse impact in achieving the Millennium Development Goals.

Based on the above observations, the authors believe that the provision of energy to the community of Inalegolo should be approached differently from the norm. The community should participate in the provision of modern energy. The purpose of the current manuscript is therefore to highlight proposed sustainable ways of providing energy for education and health sectors in Inalegolo using B30 (30% biodiesel blend) to run a small diesel generator and also use pellets produced during the production of biodiesel for cooking as demonstrated by **Figure 2**. The authors believe that the proposal will be a more attractive option for the provision of modern energy for education and health sectors in isolated communities in Botswana. The authors also believe the approach has immense potential to improve pupil's academic performance and public health which are catalyst for poverty alleviation. The paper therefore provides a framework for the provision of energy for education and health sectors in Inalegolo village. The framework demonstrated by **Figure 2** can be replicated to other similar communities in the country. It is believed that the framework also provides huge opportunity for stimulating economic activities due to the participation of community groups in the collection of plant seeds for oil extraction and subsequent production of biodiesel. Such seeds include abundant indigenous species such as *Tylosema esculentum* and trichilia, and plantation of energy plants such as Jatropha.

Figure 1. A map of Inalegolo village.

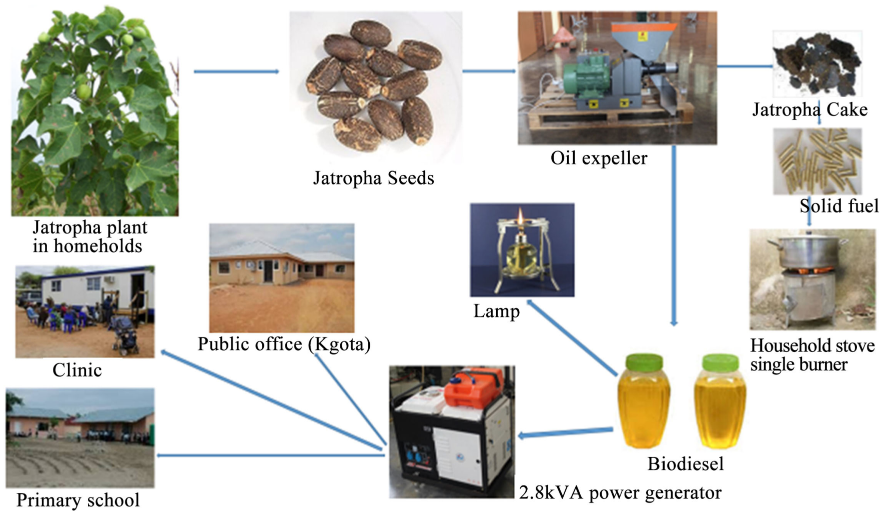

Figure 2. Proposed supply of electrical power to Inalegolo village.

2. Sustainable Energy for Inalegolo Village

Botswana is home to numerous indigenous high kernel oil plants such as *Sclerocarrya birrea*, *Tylosema esculentum*, *Schiziophyton rautanenii*, *Trichilia* and *Jatropha curcas* which have demonstrated to be good feed stock plants for production of biodiesel. Investigations by Gandure *et al.* (2014) [9], Khethiwe *et al.* (2017) [10] and Mbako *et al.* (2016) [11] have revealed that the chemical properties of biodiesel derived from the same species meet major international biodiesel standards such as American Standard Test Methods (ASTM D6751) and European Standards (EN14214). The authors reported that the indigenous species have sufficiently high oil yield levels desirable for potential biodiesel feedstock. Some of these indigenous species such as *Tylosema esculentum* are abundant in the region of Kgalagadi where the case study village Inalegolo is located. Figure 3(a) and Figure 3(b) present the plant as found while Figure 3(c) demonstrates the kernels which contain oil.

Other plant species such as Jatropha also provide complementary feedstock for the proposed community biofuel industry in Inalegolo village. Though exotic to Botswana, Jatropha plant has thrived in harsh climatic conditions in regions such as Rakops village which is located in Makgadikgadi Salt Pan (alkaline type of soil). Figure 4 shows two Jatropha species in Rakops village. It is on basis of its adaptation to harsh climatic conditions that in 2012, the government of Botswana, through an international strategic partnership with the Japanese International Corporation Agency (JICA), engaged in a five year scientific research project on development of Jatropha species adapted to Botswana's climatic conditions.

As earlier stated, the paper presents a framework for the provision of energy using B30 for selected sectors of economy (Education and Health) in Inalegolo village. The framework is demonstrated by experimental work for evaluating electrical power output from a single cylinder diesel electrical generator. Figure 2 presents the proposed framework for the provision of energy for the residents of Inalegolo. The framework begins with the plant (such as Jatropha) through plant seeds and oil pressing, to biodiesel used directly for lighting and for generating

(a) (b) (c)

Figure 3. Tylosema Esculentum [9]. (a) Plant; (b) Pods and seeds; (c) Kernels.

(a) (b)

Figure 4. Jatropha plant with green leaves and flowers (Rakops Village), Photo by: Ketlogetswe (9th December 2017). (a) Large Jatropha plant; (b) Small Jatropha plant.

electricity for use at primary school, clinic and public office. The seed cake from oil expeller will be used as a solid fuel for household cooking and water heating. It is believed that the proposed framework could be replicated to similar communities. Section 2.1 describes how the system works, while Section 3.0 presents the preliminary experimental procedures performed by the authors to evaluation the maximum electrical load power produced by the generator, as well as fuel consumption rate. Section 4.0 covers the results and discussion.

System Operation

It should be reported here that in a situation where grid electricity is connected to public facilities such as primary schools and clinics, electricity bills are paid by the local authority. It is the view of the authors that the proposed supply of electricity demonstrated by **Figure 2** should be a joint project between the community and the local authority as mentioned earlier in section 1. In this case the role of the community would be to collect oil seeds particularly *Tylosema esculetum* which is found at larger quantity in Kgalahari region as demonstrated by **Figure 3**. The community would also be expected to develop small Jatropha plantation for the supply of feedstock at an agreed fee between the community and the authority. Pressing and processing of biodiesel would be performed by trained personnel among the committee members. The biodiesel produced will then be blended with petro diesel and used to fuel 2.8 kVA power generator for providing lighting at public primary school and clinic as demonstrated by **Figure 2**. Seed cake will be used as solid fuel at household levels mainly for cooking and heating water. As a joint project between the community and the local authority it is envisaged that the approach is likely to stimulate economic activities and create rural employment among community members. The authors believed that isolated communities are likely to participate positively in the proposed sustainable energy system. The observation is based on the fact that currently, a number of individual family groups among the rural communities are collecting indigenous fruits found in different regions of the country for improving their household income. It is on basis of this observation and the huge potential for improving household income that the proposed scheme is likely to receive support from rural communities such as residents of Inalegolo.

Section 3.0 covers the experimental work performed to evaluate the technical part of the proposed sustainable energy scheme.

3. Experimental Investigations and Measurements

The biodiesel was prepared, by transesterification as described by Gandure and Ketlogetswe (2012) [12], Khethiwe *et al.* (2017) [10] and Mbako *et al.* (2016) [11]. For this reason, preparation stage for biodiesel production is not included in this paper. As such, this section focuses on the performance of different blends (B30 and B40) and diesel fuel for comparison purpose. The decision for proposing blend ratios is derived from the fact that biodiesel has relatively low energy content which may compromise the electrical load requirements for the proposed sustainable energy system.

The compression ignition engine used for the study was a single cylinder, four stroke, and direct injection air cooled engine with rated output of 2.8 kVA, rated voltage output of 230 V, 50 Hz and power factor of 1.0. The compression ignition engine was coupled to an electricity generator. The overall objective was to determine the maximum electrical power which the engine produced when fuelled with different biodiesel blends and diesel fuel in order to make comparisons. For each test run, the rate of fuel consumption was recorded. This enabled the amount of biodiesel fuel and corresponding quantity of Jatropha seeds required for feasibility of the project to be established. A schematic arrangement for the apparatus used for the determination of maximum electrical power is shown in Figure 5.

The electrical resistor bank with 3 kW by 12 elements was then connected to the output socket in order to apply engine load. Each electrical resistor was 210 Ω 250 W. Fuel samples were prepared and a quantity of 1litre of blended fuel was charged into the fuel tank. The engine was then started and allowed to reach operating conditions before applying electrical load. After the engine reached stabilised operating conditions, the electrical load was incrementally applied at a rate of 3 kW at a time till the engine started to stall indicating operating point above maximum electrical load. The electrical load was then reduced by 250 W in order to maintain a smooth running of the engine which suggested the optimum operating load. The time taken for the engine to consume the charged fuel under its optimum operating load was recorded and used for calculating fuel consumption rate. The same procedure was repeated for the rest of the blend ratios including diesel fuel.

Considering the proposed sustainable energy scheme demonstrated in Figure 2, which also indicates the use of blended fuel (biodiesel plus kerosene) for lighting at household level, a comparison between different blends and liquid paraffin purchased from local petrol station was performed in terms of rate of combustion and emission levels. These were performed in order to evaluate suitability of using blended fuels for lighting at household level. The apparatus for the test run is demonstrated by Figure 6.

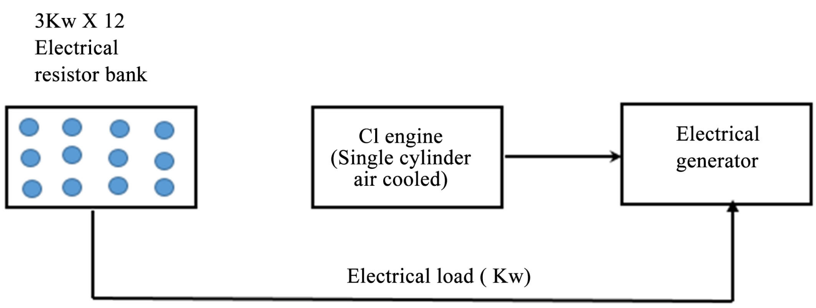

Figure 5. Schematic arrangement for the apparatus.

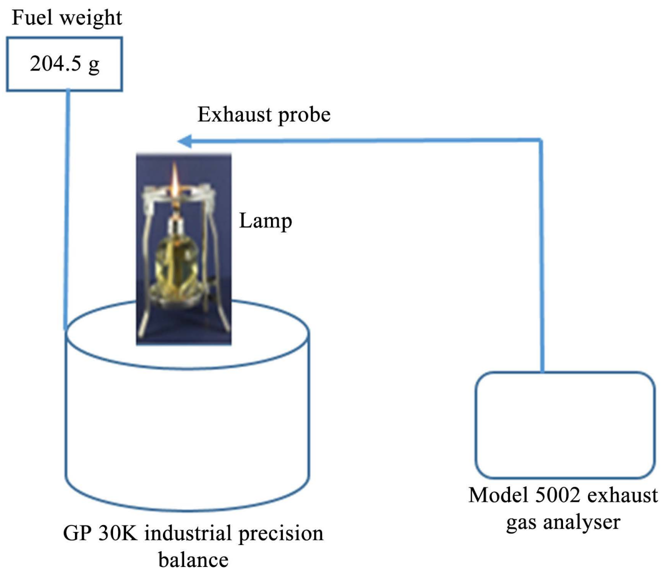

Figure 6. Apparatus of the tests.

Figure 6 shows GP 30 K industrial precision balance with super hybrid sensor which was used to perform comparison analysis between different blends and liquid paraffin. The weight of table lamp was recorded using the industrial precision balance as demonstrated by Figure 6. With the table lamp still on the precision balance, the balance was set to zero. The lamp was then charged with blend fuel and the weight of the fuel was then recorded. The charged lamp was then ignited manually by introducing a burning match. A model 5002 exhaust gas analyser was also used to record the concentrations of the pollutants (CO, CO_2, NOx and HC) during the test run. Immediately after the establishment of the ignition the exhaust probe was set in place to record the concentration of the pollutants. The recording of the reduction in fuel weight and levels of concentrations of the pollutants were recorded every 5 minutes for a period of one hour. Prior to the combustion processes the density of blend fuels and kerosene were recorded using a hydrometer.

In addition, temperature profile recorded during the combustion processes of Jatropha pellets (solid fuel) was performed using the same apparatus demonstrated by Figure 6. However, the lamp was replaced by a single burner household stove (combustor) and temperature recording device using K-type thermocouple formed part of the apparatus. The combustor was of internal diameter and a depth from the grate of approximately 300 mm and 100 mm respectively. The thermocouple was located approximately 350 mm from the grate.

4. Results and Discussions

The authors performed analysis on the performance of different blended fuels, combustion profiles of solid pellets produced during the biodiesel processes. In addition, analysis on different blends of liquid paraffin and biodiesel were performed as mentioned under Section 3.0. The results obtained are presented and discussed in this section. The overall objective of the investigation is to evaluate the proposed system demonstrated by Figure 2. It should be reported here that the results for B10 and B20 are not presented here because they were not different from the results recorded for petroleum diesel and those for B30in terms of electrical load. Consequently, only results for B30 and B40 are presented and discussed in this paper. Table 1 presents summary on performance for petroleum diesel and two selected blends namely B30 and B40. The data in Table 1 should be viewed in parallel with Table 2 which shows the total running time for 50 litres of blended fuel (B30). One of the most discernible trends connected to Table 1 is that there is a significant shift in electrical load and the number of 4 W bulbs which could be powered by the proposed scheme when the blend increase from B30 to B40. Similarly, electrical load dropped by 25.5% and the number of 4 W bulbs which could be powered by the proposed scheme also drop by 125 bulbs, thus 20% drop.

The data in Table 1 confirm that B30 would be the best optimum blending ratio based on the maximum electrical load when compared with petro diesel fuel. In a situation where 4 W energy saving bulbs are used, a total of 625 bulbs could be used which is believed to be enough electrical energy for lighting in public primary school and clinic as proposed by Figure 2. Available information indicate that light intensity in teaching and learning space (classrooms) particularly during rainy periods in isolated public schools is not conducive for teaching and learning. It is on this basis that authors believe that if the proposed energy scheme is implemented, it will have positive impact on academic performance for learners in the village under review. The proposed energy scheme as demonstrated by Figure 2 will offer opportunity for learners to participate in other modes of lesson delivery including radio lessons which currently does not form part of teaching and learning in majority of public schools located in isolated communities. It should be reported here that basic education in all public schools are provided with audio equipment including television and radio sets in order to support teaching and learning at basic education level. However, only limited public schools located in cities, towns and peri-urban areas enjoy such schemes because of access to grid power which makes teaching and learning space conducive for the purpose. The situation brings imbalance in the education system in the country. The proposed scheme seeks to reduce the imbalance between the two situations. The primary question here is sustainability/feasibility of the proposed energy system.

The current investigation has revealed that 50 kg of Jatropha seeds produced approximately 15 litres of biodiesel using mechanical oil expeller model GmbH (KK20F Universal) and that 35 litres of petroleum diesel will be required to produce 50 litres of B30. Based on the consumption rate of 0.723 l/hour to sustain electrical load of 2.5 kW, a total running time of 68.3 hours was attained. Table 3 depicts energy analysis for the proposed scheme. The analysis is based on 8 operating hours per day and 264 operating days per annum which exclude weekends and public holidays.

Table 1. Maximum electrical load under different blends ratios and diesel fuel.

Fuel type	Consumption rate (L/hr)	Electrical load (kW)	Number of 4 W energy saving bulbs
Diesel	0.723	2.5	625
B30	0.723	2.5	625
B40	0.723	2.0	500

Table 2. B30 (30% biodiesel +70% Petro diesel).

Quantity of seeds (kg)	Biodiesel produced (L)	Petro diesel fuel (L)	Total blended fuel (L)	Running hours @ rate of 0.723 L/hr. (hrs.)
50	15	35	50	68.3 hrs.

Table 3. Energy analysis for the proposed scheme.

Operating hrs./day	Fuel required for 8 hrs @ 0.723 l/hr.	Total operating days/year (days)	Annual fuel demand (litres)	Proportion of biodiesel (litres)	Proportion of Petro diesel (litres)
8	5.8	264	1531.2	459.36	1071.84

Based on the results presented in Table 3, production of 459.36 litres of biodiesel will require 1531.2 kg of Jatropha seeds which translate to approximately 31 bags of 50 kg of Jatropha seeds. The investigations also revealed that 3 Jatropha trees with relatively big canopy as demonstrated by Figure 7 produce approximately 50 kg of Jatropha seeds annually.

The analysis suggests that a small Jatropha plantation with a yield capacity of approximately 1.6 tonnes of seeds will be required to support the proposed energy scheme for Inalegolo village. It is the view of the authors that if implemented and replicated to other isolated communities, the proposed energy scheme will offer huge potential in stimulating rapid development of biofuels in the country and creating jobs at rural community level.

The combustion analysis of Jatropha seed cake produced during mechanical oil expeller was performed as described in section 3.0. The results on temperature, weight and emission profile are presented in Figure 8 and Figure 9.

Overall the results in Figure 8 and Figure 9 shows combustion rate, temperature and emission profiles recorded during the glowing stage. In the present investigation, the glowing stage was of interest due to the absence of polyaromatic hydrocarbons (PAH's), which are mostly released during flaming combustion processes. One of the most discernible trends connected to results in Figure 8 is that approximately 52 g of pellets from Jatropha seed cake maintained fuel bed temperature above 100˚C for over an hour. This is a result of relatively low rate of weight loss of approximately 0.85 g/minute. The results suggest that the proposed energy system once implemented could be more environmentally friendly because it offers huge potential to displace limited wood resource particularly in areas where such resource is becoming scarce.

Figure 7. Jatropha trees at Mmadinare village homestead (Pictures by Ketlogetswe: 11th November 2017).

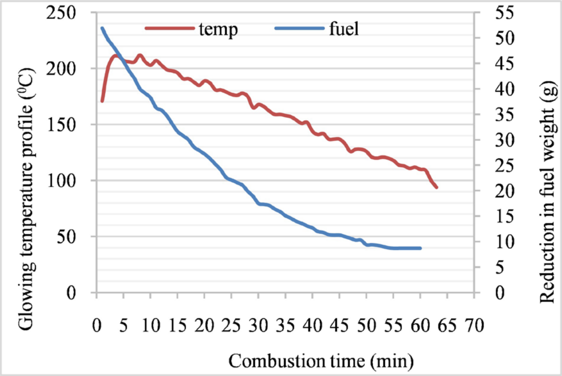

Figure 8. temperature and weight profiles.

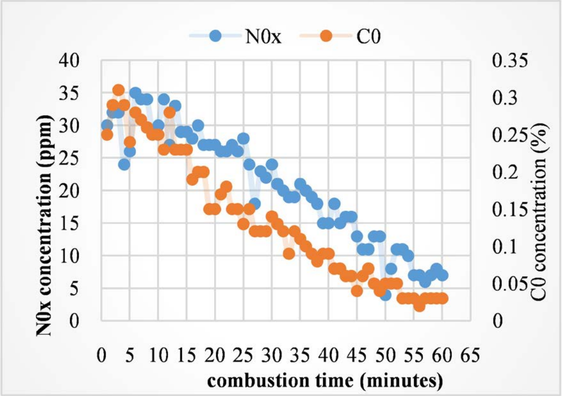

Figure 9. NOx and CO emission profiles.

The results in Figure 9 demonstrate emission profiles of CO and NOx recorded during the glowing combustion stage of 52 g of pellets from Jatropha seed cake. One of the most noticeable trends linked to results in Figure 10 is that the maximum CO emission level recorded during the combustion processes was approximately 3.5 ppm which is 61% below the maximum recommended indoor CO level (ASHRAE). The same results show emission levels of NOx which according to United States of America Occupational Safety and Health Administration are above permissible exposure limit of 5 ppm not to be exceeded at any

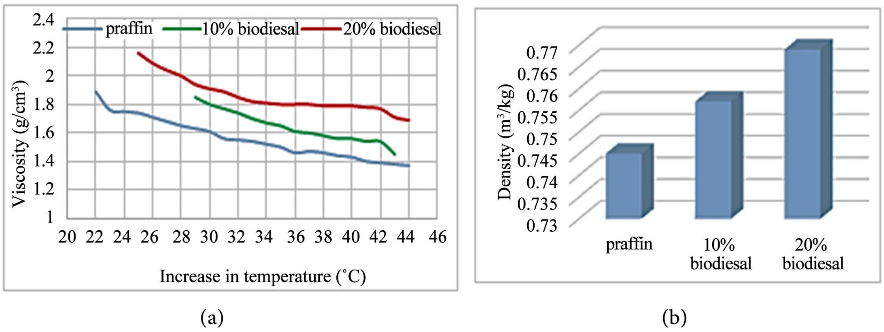

Figure 10. Fuel properties. (a) Viscosity profiles; (b) Density profiles.

time. It should be noted that the emission profile of solid fuel stove is influenced by its design features. However, issues related to eco-design of solid fuel stove do not form part of the present investigation. It is therefore appropriate to conclude that approach under review should be used where there is good ventilation and extraction of gaseous of combustion.

Figure 10(a) shows viscosity profiles of liquid paraffin and different mixtures of liquid paraffin and biodiesel, while Figure 10(b) depicts the density of the liquid paraffin and different mixtures.

The results in Figure 10 show that increasing proportion of biodiesel in liquid paraffin increases the viscosity and density of the mixtures. This made the mixture of liquid paraffin and biodiesel difficult to burn efficiently and effectively in a table lamp. The problem was assumed to stem from the mass weight of the mixtures, which made it difficult for the fuel mixture to be transported in the upwards direction along the wick cotton. This resulted in the burning of the wick cotton which produced relatively high levels of pollutants particularly hydrocarbons.

5. Conclusions

1) Based on the maximum recorded electrical load, B30 was the optimal blend, with electrical load comparable to those recorded for petroleum diesel. These findings are confirmed by the results in Table 1.
2) Thermal output of pellets from Jatropha seed cake confirms huge potential for the proposed sustainable energy system to displace wood resource at household level.
3) Energy analysis demonstrated increase in the economic case for the proposed sustainable energy system for isolated communities in Botswana.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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