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TABLE OF CONTENTS

Papers

Distributed Generation as an Alternative Paradigm for Electric Power Planning in Southern Africa: A Modelling-based Study

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ABSTRACT

The objective of this paper is to present a quantitative assessment of some of the technological, economic and environmental implications of extending electricity to households in Southern Africa through the distributed generation approach as an alternative and complementary approach to the dominant centralised generation strategies. The first part of the paper presents an overview of the status of demand, supply, and access to electricity in the region. Second, based on meteorological data, the paper uses a 'component sizing' procedure to demonstrate how solar photovoltaics, and wind turbines (and their associated components such as batteries, charge controllers and inverters) can meet the basic electricity requirements of individual households in non-electrified areas. Third, the paper presents the results of a set of simulations using the Hybrid Optimization Model for Electric Renewables (HOMER) software package to compare the costs of renewable electricity in a setting with little or no grid access, when compared to the more widely available diesel generator sets, and more generally, to the estimated costs for mass electrification through grid-based electricity. The results strongly suggest that a bottom-up, distributed generation approach to electrification is a viable and complementary policy paradigm for energy planning in Southern Africa.

INTRODUCTION

The objective of this paper is to present a quantitative analysis of some of the key environmental and economic implications of extending distributed renewable electrification to residents of the Southern African region not currently connected to the existing grid. The Southern African region, as used in this paper, refers to the 15 countries that are part of the Southern African Development Community (SADC), which includes the 12 member countries of the Southern African Power Pool (SAPP) and three island nations that are not currently part of the regional power pool. Although the accuracy of international energy data varies by source, according to the SAPP, the average electrification rate of its member states is about 36 per cent (SAPP, 2014), with the International Energy Agency (IEA) reporting rates ranging from about nine per cent in Malawi and the DRC to 85 per cent in South Africa, and 97 per cent and 100 per cent in the island countries of Seychelles and Mauritius, respectively (IEA, 2014). Among other objectives, some of the key goals of the SAPP are to implement a competitive electricity market in the region, promote regional expertise through training and research, and increase access to electric power in rural communities (SAPP, 2015).

While the goals of the SAPP highlighted above are commendable, there is no explicit linkage between its planned energy generation and transmission projects and increasing energy access. It should also be noted that the eight generation projects highlighted in its 2014 annual report that received approval of their Environmental and Social Impact Assessments (ESIA) are based on large coal, natural gas and hydroelectric plants (SAPP, 2014). Since such large projects necessarily incur immense costs, which are typically funded by international financing institutions (IFIs), a prior study done on a sister institution, the West African Power Pool (WAPP), by Pineau (2008) suggested that the return on such investments is typically seen as being unlikely to come from rural and peri-urban residents, whose generally low income and minimal consumption of electricity are unlikely to justify such expenditures. Similarly, a more recent comparative assessment of the Grand Inga Dam project in the Democratic Republic of Congo (DRC), which is expected to generate about 39,000MW at a cost of about $US80 billion, suggests that, with respect to affordability, the national debt burden, social and environmental sustainability and innovation, the outcomes of the project are likely to be negative for the country, though they might be beneficial for large players in the extractive industry (Green, Sovacool, & Hancock, 2015). Lastly, a compelling study by Levin and Thomas (2011) employs spatial modelling based on a network algorithm to determine the conditions under which centralised or decentralised electrification can be provided at least cost across the globe, and demonstrates that, for most of the world's population, especially in Africa, large regions can be served by decentralised electrification at low cost. Levin and Thomas (2011) emphasise that the advantages of distributed electricity include an installation time of days instead of years or even decades for grid-based electricity, accessibility and reliability, which could make it attractive even in countries that have high population densities such as Bangladesh or Nigeria.

The three examples cited above are reflective of a wider literature that argues that large, centralised projects in many less industrialised countries (this is typical for sub-Saharan Africa), tend to guarantee the reliability of supply for large industrial, commercial and urban consumers, thereby leaving the problem of sustainable access generally unresolved. Consequently, the critical premises of this paper situate it within that body of work. However, there are a few exceptions to this pattern of centrally-planned power generation only serving a minority of residents across sub-Saharan Africa, the most notable of which was South Africa's post-1994 electrification programme which, although primarily reliant on coal-based power, nevertheless increased the country's electrification rate from about 30 per cent in 1990 to over 80 per cent in 2007 (Bekker, Eberhard, Gaunt, & Marquard, 2008). While the small island nations of Seychelles and Mauritius have also achieved high electrification rates, the general situation in other SADC countries (except Botswana and South Africa) is that they all have electricity access rates of less than 50 per cent. As shown in Table 1 below, 10 of the 15 SADC states have electrification rates of 30 per cent or less.

Table 1: Electricity Access and Consumption (KWh) (IEA, 2014)

Country	**Electricity Access Rate (%)**	**Electricity Consumption Per Capita (kWh)**
Angola	30	248
Botswana	66	1,603
D.R.Congo	9	105
Lesotho	28	-
Madagascar	15	-
Malawi	9	
Mauritius	100	-
Mozambique	39	447
Namibia	30	1,549
Seychelles	97	-
South Africa	85	4606
Swaziland	27	-
Tanzania	24	92
Zambia	26	559
Zimbabwe	40	757

Following the brief description of the electricity access situation above, the focus of the paper is to demonstrate the feasibility of an alternative planning approach for increasing the rate of sustainable electricity in Southern Africa, namely through the distributed generation of renewable energy, with off-grid or microgrid electrification as its basic building block, and subsequently, a distributed utility. Distributed generation (DG) or decentralised generation typically refers to small-scale technologies that generate power on the order of 10kW up to 50MW in the vicinity of a consumer, and which may include both renewable systems such as solar panels, biomass generators or wind turbines, and non-renewable systems such diesel generators or combined heat and power systems (CHP) (Sovacool, 2008). DG can also be defined as a class of small-scale electrical power generation technologies that provide electric power at a load site, or adjacent to one, and that can either be directly connected to a consumer's facility, to a distribution system, or both (Borbely & Kreider, 2001). A distributed utility then refers to a future utility architecture or network that is based on distributed generation, distributed resources (demand and supply side) and distributed capacity (generation, resources, reserve capacity and transmission/distribution system (Ackermann, Andersson, & Söde, 2001). The paper therefore sets out to illustrate how this planning approach might work in Southern Africa from the point of view of increased access, sustainability of supply, costs, and environmental benefits. Although the planning concept may apply to various renewable sources, the paper focuses on solar and wind energy, either in combination with diesel engines or as stand-alone sources of power, and that can be organised to form a distributed utility.

The paper begins the assessment with a quantitative representation of the current demand and supply of power in Southern Africa as provided by the authorities of the Southern African Power Pool (SAPP). Secondly, it provides an estimate of both the theoretical potential and a more operational or practical potential for distributed renewable solar and wind energy, based on the available meteorological data and explicit assumptions applied to a spreadsheet model. Using a 'component sizing' procedure that allows consumers to tailor their energy generation capacity to their needs and financial means, the paper further demonstrates how solar photovoltaics, wind turbines, biomass gasification generators, and their associated components such as batteries, charge controllers, inverters, or gasifiers, could meet the basic electricity requirements of individual households in non-electrified areas. The basis for modelling these minimum requirements is drawn from the electrification experience of South Africa, which implemented a Free Basic Electricity (FBE) Policy that required that every indigent or poor household be provided with 50kWh a month free of charge in order to stimulate residential electricity consumption (Bekker et al., 2008). While some provinces such as KwaZulu-Natal have raised this figure to 100kWh, certain environmental groups have lobbied for the FBE to be raised to 200kWh, either through grid-based electricity or through distributed resources such as solar home systems (SHSs) for remote areas (Earthlife Africa, 2010). In the case of indigent households, Free Basic Alternative Energy (FBAE) subsidies are in existence, which include SHSs as well as non-electricity sources such as paraffin, bio-ethanol gel, liquefied petroleum gas and coal (DME, 2007). Finally, the paper presents an analysis of the comparative costs of renewable electricity in a setting with no grid access, when compared both to the more widely available diesel generator sets and grid-based electricity, through simulations with the Hybrid Optimization Model for Electric Renewables (HOMER) software package.

STATUS OF POWER DEMAND AND SUPPLY IN SADC

The most recent data for electricity generation in Southern Africa by the SAPP was made publicly available in 2014, but was released in terms of installed generation capacity in MW, which does not tell us how much was actually generated as a result of maintenance or related issues. Thus, the data on the actual electricity generated, though dating to 2012, was acquired from the International Energy Agency (IEA), which tracks this data globally, and was deemed to be more appropriate for the analysis. The figures are primarily from centralised generation (both renewable and non-renewable sources), since electricity from distributed generation in SADC is considered to be negligible and the corresponding energy data is not yet tracked in most of its member states. Figure 1 below shows the relative share of various energy sources across the region by installed capacity and reveals that coal is dominant, followed by large hydroelectric power, distillate (oil and diesel), nuclear power, and finally, energy from combined cycle gas turbine (CCGT) technology.

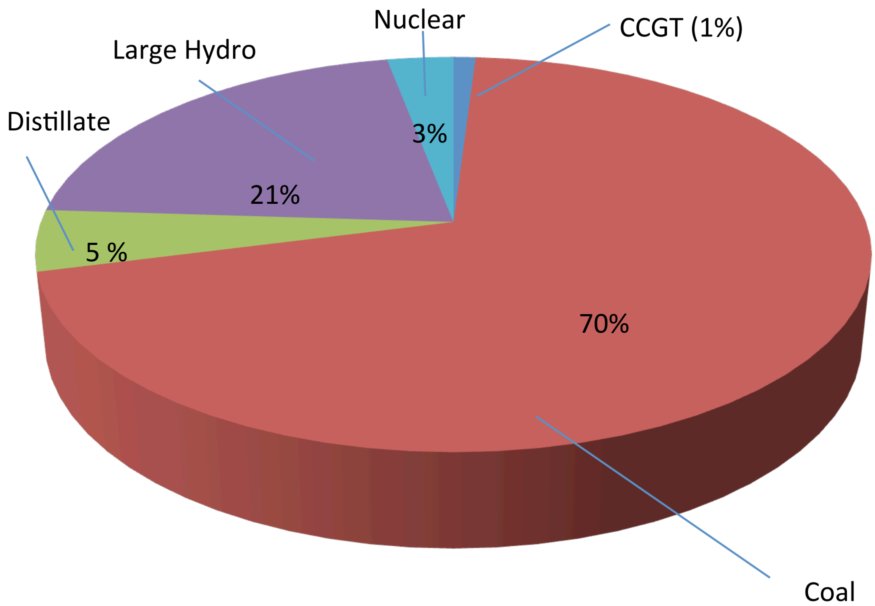

Figure 1: Installed Capacity by Technology (SAPP, 2014)[1]

Table 2 below shows the net energy generated per country and by source, and highlights the fact that only South Africa, as of 2012, generated utility-scale solar and/or wind power, while Mauritius, Zimbabwe, Tanzania and South Africa all generated minimal to modest amounts of electricity from biomass. It should be noted that in this paper, only solar, wind, biomass power from waste, and pico, micro and mini-hydroelectric technologies are considered to be renewable. Large hydroelectric dams are not considered renewable energy technologies (RETs) because they tend to radically alter the flow of the river that has been dammed, flooding large areas of land that include farm land, buildings and other property, or wildlife habitats, as well as routinely displacing people who live downstream from the dam. On the other hand, small dams, also known as run-of-the-river schemes, only divert a small part of the river to produce electricity due to the gravity upstream, but the water later flows back into the river, thereby significantly reducing land use impacts. Furthermore, the water requirements of large dams, which create artificial lakes with stagnant water, are highly competitive with other critical needs such as drinking, fishing, sanitation and recreation, among others. This typically implies the diminished use of the river for these purposes, unless power production itself is reduced and balanced with other needs. Finally, a

[1] CCGT – Combined Cycle Gas Technology; Distillate – Distillate Fuel Oil.

review of hydrological studies between 1950 and 1989 has shown a disruption in rainfall patterns since 1970 in the case of West Africa (Gauthier et al., 1998), which currently manifests itself as a reduction in water levels in rivers and dams in the region that adversely affect electric power generation. Thus, the combination of factors highlighted above seriously undermines the notion of large hydroelectric dams being based on an inexhaustible or renewable resource.

Table 2: Net Electricity Generated in SADC (GWh) (IEA, 2012)

Country	Thermal	Nuclear	Hydro	Biofuels	Renewables (Solar + wind)	Total (GWh)
Angola	1,633	--	3,980	--	--	5,613
Botswana	250	--	--	--	--	250
D.R.Congo (DRC)	35	--	7,931	--	--	7,966
*Lesotho	--	--	--	--	--	486
*Madagascar	--	--	--	--	--	2,025
*Malawi	--	--	--	--	--	2,180
Mauritius	2,218	--	74	500	--	2,792
Mozambique	21	--	15,145	--	--	15,166
Namibia	36	--	1,607	--	--	1,643
*Seychelles	--	--	--	--	--	320
South Africa	239,538	13,075	4,860	293	153	257,919
*Swaziland	--	--	--	--	--	425
Tanzania	4,106	--	1,657	19	--	5,795
Zambia	36	--	11,814	--	--	11,850
Zimbabwe	3,638	--	5,387	63	--	9,088
Total (GWh)						323,518

***Note:** No specific or general data for Lesotho, Madagascar, Malawi, Seychelles and Swaziland was provided by the International Energy Agency (IEA) and, therefore, the numbers for 'Total Electricity Generated' were based on the electricity generation data reported in 2012 by the US Energy Information Administration (EIA).

ESTIMATION OF RENEWABLE RESOURCES

Following the case made in the preceding section, this section then seeks to address another popularly expressed scepticism about the practical availability of renewable energy sources. It thereby illustrates the abundance of these resources, specifically with respect to meeting the electricity requirements of the region. The renewable resources chosen in this section are based on a cursory view of meteorological maps that suggest their availability, and the assessment of these resources is deemed sufficient to support the argument that is being advanced in this paper.

Solar Energy

Solar energy technologies can exist as either solar thermal systems or solar photovoltaics (PV). The first set of technologies focus sunlight on a fluid to produce steam that can then be used in a turbine to generate electricity, while the latter convert sunlight directly into electricity. I focus here on the energy potential from solar home systems (SHSs), as these are more suitable for residential use. SHSs typically include the PV modules, batteries, a charge controller and an inverter. However, it should be noted that while an inverter is primarily needed only if one intends to use appliances that operate with Alternating Current (AC), it is also a useful device to have in order to provide the flexibility to connect with an existing or future centralised grid.

The approach employed to obtain the meteorological data for assessing the solar potential was obtained in the following manner. In order to find geographical coordinates for the countries in the region, the Google Earth software was used to select two diagonally located cities or towns on a given country's map so as to increase the chances of capturing any significant climatic contrasts in that particular country and consequently, in the region overall. The average insolation incident on a horizontal surface was then acquired by entering each coordinate into a database on surface meteorology and solar energy that is maintained by the Atmospheric Science Data Center of the US government's National Aeronautics and Space Administration (NASA) database. The software associated with the database then derives the average solar radiation resolved over the area between the two locations for the user. The latitude, longitude, elevation and corresponding resolved average solar insolation data (collected over a 22-year period from July 1983 to June 2005) of the selected locations for analysis are displayed in Table 3 below.

Estimation of Electricity Potential from Solar Photovoltaics

The goal of the first part of the calculations in this sub-section is to illustrate that solar energy can meet the electricity requirements of the region, as well as show how various sizes of solar PV modules could meet the minimum electricity requirements of a non-electrified household. Based on the characteristics of current solar technologies, the solar resource in Southern Africa is shown to be sufficient to meet all its electricity needs many times over. This kind of expansive assessment is frequently done to demonstrate the technical feasibility of using a given resource. For example, Sobin (2007) relies on several seminal studies that show that the amount of solar energy that the US receives is comparable to 500 times its energy demands, and that about 0.4 per cent of its area (or 10 million acres) could provide all the electricity consumed in the country using current PV technologies, in order to refute the myth that renewable energy can never meet the electricity demand in the US. For the case of Southern Africa, the number of PV modules is calculated that would be needed to meet minimum household electricity requirements of 50kWh, 100kWh and 200kWh in each country, given its average solar radiation resolved over a large area of the country. The calculation used to estimate the amount of electricity from solar energy that can be generated from the land area available in each Southern African country is shown below for the case of Botswana.

The solar power that can be produced from a particular land area is given by:

$Power = Area * S_{avg} * \eta$ (Hafemeister, 2007)

Where;

$$S_{avg} = Average\ solar\ flux\ \left(\frac{kW}{m^2}\right) = Avg.solar\ radiation\left(\frac{kWh}{m^2 day}\right) * \left(\frac{1\ day}{24\ h}\right)$$

$\eta = Efficiency\ of\ Solar\ PV\ cells$

$Area = Land\ area\ in\ a\ given\ country\ (m^2)$

The solar energy produced in one year can then be calculated as:

$$Energy\ Generated = Solar\ Power * 8{,}760\ hours = \left(Area * S_{avg} * \eta\right) * 8{,}760\ hours$$

Thus, in one year in Botswana:

$$Energy\ Generated = [5.82 * 10^{11} m^2 * (6.362 \frac{kWh}{m^2 day} * \frac{1\ day}{24\ hrs}) * 0.15] * 8{,}760\ hrs$$
$$= 1.29 * 10^{15} kWh = 3.16 * 10^7 GWh$$

This amount is about 5.2 million times the total amount generated (250GWh) in Botswana in 2012 (see Table 3). More specifically, if that amount of 250GWh were to be generated from solar energy, it would represent only 0.00002 per cent (or 0.12km^2) of the total land mass of the country. Depending on the country's size and its electricity demand, there is a wide variation in this hypothetical measure, wherein South Africa would need to dedicate the equivalent of 0.01 per cent (or 122.1km^2) of its land to solar energy, whereas Seychelles would need 0.14 per cent (or 0.64 km^2).

The calculations that follow below are then used to estimate a more practical policy, that is, the amount of solar energy that can be generated to meet the minimum monthly requirements of the Free Basic Electricity policy in South Africa, which is applied to the entire region and hereby referred to as 'Basic Electricity' (BE). As explained in the introduction, it is important to recall that this minimum requirement is not adequate for a typical household but, as in the centralised case, it does ensure that households have access to electricity, after which they can increase their consumption to the extent that they can afford to. Indigent households that are connected in this way will have to use non-electric sources for heating and cooking, such as paraffin or LPG – the latter already widely used for cooking and heating even in wealthier households.

Four sizes of polycrystalline PV modules are considered (50W$_p$, 100W$_p$, 150W$_p$, 250W$_p$), which are available on the market and are suitable for use in Solar Home Systems (SHSs). The number of panels of each type that would be needed to meet the three possible minimum levels of electrification is then calculated. As Swaziland's annual solar insolation is very close to the regional average for SADC countries, that country's data for the purpose of demonstration is used. The results are shown in Table 7 below. The method used for the estimation of the number of PV panels that would be needed to meet monthly basic electricity (BE) requirements of 50kWh, 100kWh and 200kWh, is shown as follows:

The capacity factor (CF) of a solar PV panel, which is determined from the power rating on the panel at a peak solar flux (S_{peak}) of 1 kW/m^2, is given by:

$CF_{PV} = S_{avg}/S_{peak}$ (Hafemeister, 2007)

The solar energy generated by one panel is calculated as:

$$\begin{aligned} Energy\ Generated &= Average\ Solar\ Power * 30\ days * 24\ hours \\ &= Average\ Solar\ Power * 720\ hours \\ &= (Power\ rating * CF * Panel\ loss\ factor) * 720\ hours \end{aligned}$$

In this calculation, the panel loss factor includes a multiplier to account for operating temperature (0.9), a multiplier to account for losses through the cables (0.98), the efficiency factor of an inverter (0.85), and an installation factor, which accounts for the incline, orientation and coatings on a PV panel (1.04) (Coley, 2008).
Thus, for an average insolation of 5.29 kWh/m^2day in Swaziland,

$$CF_{PV} = \frac{S_{avg}}{S_{peak}} = \frac{(5.29\frac{kWh}{m^2 day} * \frac{1\ day}{24\ hrs})}{1\ kW/m^2} = 0.22$$

The energy generated from one $50W_p$ (or $0.05kW_p$) in one month is calculated as:

$$\begin{aligned} Energy\ Generated &= (Power\ rating * CF * Panel\ loss\ factor) * 720\ hours \\ &= (0.05kW * 0.22 * 0.98 * 0.9 * 0.85 * 1.04) * 720\ hours \\ &= 6.19kWh \end{aligned}$$

Finally the number of $50W_p$ panels required to meet a BE of 50kWh is:

$$No.of\ panels = \frac{Total\ energy\ generated}{Energy\ generated\ by\ one\ panel} = \frac{50kWh}{6.19kWh} = 8.08 = \sim 8\ panels$$

This demonstration can then easily be extended to the other power ratings and BE requirements in the case of Swaziland as shown in Table 5 below.

Table 3: Number of PV Modules Needed to Meet Monthly Basic Electricity Requirements

Panel Size	**50kWh/mo.**	**100kWh/mo.**	**200kWh/mo.**
$50W_p$ panel	8	16	32
$100W_p$ panel	4	8	16
$150W_p$ panel	3	5	10
$250W_p$ panel	2	3	6

In steps 1 to 11 in Table 4 below, the number of batteries that would be needed to store the energy required to meet each of the monthly electricity requirements is calculated. The total number of batteries is shown in step 11, which indicates that two, four and six batteries would be needed to meet monthly requirements of 50kWh, 100kWh and 200kWh respectively.

Table 4: Number of Batteries Needed to Meet Basic Electricity Requirements

	Measure*	**50kWh/mo**	**100kWh/mo**	**200kWh/mo**
1	Daily Amp-hr Requirement ($I*hr=P*hr/V_{system}$); V_{system}=12 V	34.7	69.4	139
2	# of days of autonomy (# of consecutive days of cloudy weather)	1	1	1
3	# of Amp-hrs battery needs to store (1 * 2)	34.7	69.4	139
4	Depth of discharge	0.5	0.5	0.5
5	Effective Amp-hr requirement (3 ÷ 4)	69.4	139	278
6	Ambient temperature multiplier (at 80 F)	1	1	1
7	Total battery capacity needed (5 * 6)	69.4	139	278
8	Amp-hr rating of battery (12V SONX RT12260D Deep Cycle Battery)	26	26	26
9	# of batteries wired in parallel (7 ÷ 8)	2.67 (~3)	5.34 (~6)	10.68 (~11)
10	# of batteries wired in series (Nominal V ÷ Battery V)=12V ÷ 12 V	1	1	1
11	**Total # of batteries required (9 * 10)**	**3**	**6**	**11**

Note: The specifications for the selected battery type above were obtained from the websites of the vendors, as well as the heuristic for calculating the number of required batteries. The calculation also assumes six hours of battery power needed per day, that is, in the evenings/early morning.

Wind Energy

In this section, the potential of wind energy to meet the electricity access requirements of the region is assessed. Wind turbines convert the kinetic energy of the flowing wind into electricity. The wind speed varies by height, and the wind speeds at 10m and at 50m for selected locations in Southern Africa are shown in Table 5 below.

Table 5: Wind Energy: Geographical Coordinates and Average Wind Speeds (NASA, 2015)

Country	City	Latitude	Longitude	Elevation (m)	Resolved average wind speed at 10m (m/s)	Resolved average wind speed at 50m (m/s)
Angola	Luanda	13.26	8.83	59	--	--
	Cuando Cubango	18.8	16.33	1,221	4.43	5.60
Botswana	Gaborone	25.89	24.65	1,159.26	--	--
	Maun	23.42	19.98	942	4.51	5.70
D.R. Congo	Lubumbashi	27.5	11.67	1,303	--	--
	Kinsasha	15.32	4.33	351	4.47	5.66
Lesotho	Maseru	29.31	31.98	1,642	--	--
	Mokhothong	29.07	29.29	2,209	3.78	4.79
Madagascar	Antananarivo	47.53	18.93	1,352	--	--
	Itampolo	43.95	24.68	51	3.39	4.29
Malawi	Lilongwe	33.77	13.98	1,135	--	--
	Kaphiika	34.09	10.45	692	4.77	5.79
Mauritius	Port Louis	57.52	20.17	85	--	--
	Mahebourg	57.7	20.4	44	6.33	7.40
Mozambique	Maputo	32.56	26.01	22	--	--
	Tete	33.6	16.17	270	4.90	5.83
Namibia	Windhoek	17.11	22.6	1,723	--	--
	Okahandja	16.92	21.94	1,578	4.73	5.99
Seychelles	Victoria	55.45	4.62	72	--	--
	La Digue	55.83	4.36	206	9.67	11.31
South Africa	Cape Town	18.42	33.9	-1	--	--
	Thohoyandou	30.48	22.95	576	4.32	5.47
Swaziland	Mbabane	31.13	26.32	1,335	--	--
	Hluti	31.59	27.22	519	4.73	5.53
Tanzania	Dar es Salaam	39.28	6.78	23	--	--
	Mwanza	32.9	2.51	1,187	4.28	5.24
Zambia	Lusaka	28.28	15.43	1,185	--	--
	Kasama	31.2	10.23	1,365	4.10	5.19
Zimbabwe	Bulawayo	28.62	20.12	1,211	--	--
	Harare	31.03	17.85	1,351	4.29	5.32

Estimation of Electricity Potential from Wind Turbines

According to Wood (2011), the primary factors that should be taken into consideration in order to estimate the electricity generation potential from wind at a particular location include the following: site assessment, which consists of mapping the wind resource and choosing ideal locations for the turbines, and optimal height of wind towers and installation loads during the raising and lowering of the turbines. The electrical power that can be generated by a wind turbine is given by the equation below:

$$P_{wind} = 0.5\eta\rho v^3 A_{wind}$$ (Hafemeister, 2007)

Where:

η = efficiency of the windmill = ~25%

ρ = density of air = 1.293kg/m^3

v = average velocity of wind

A_{wind} = Swept area of turbine with rotor diameter (d) = π(d/2)^2

The energy generated by such a wind turbine then, is given by:

$$Energy_{wind} = P_{wind} * hours\ of\ operation$$

From the equation for wind power above, we can observe that other than the wind speed, the rotor diameter is the most important determinant of the power that can be produced by a wind turbine. The rotor diameters that are typically used for wind turbines are 1.5m (micro) turbines used on yachts, for instance, 2.5m (mid-range) normally used for single-user remote or grid-connected households, and 5m (mini) used for mini grids or remote communities (Wood, 2011).

Even though the estimation of wind potential is very model dependent, it can roughly be calculated by assuming the use of small wind turbines placed at an average height of 10m or they can be mounted higher at 50m and calculated over a given area. However, if wind speeds are too low, that is, below the *cut-in speed*, the turbine will not produce any power even though it may appear to be spinning. Wood (2011) discusses site assessment for wind turbines and states that as a rule of thumb, a wind speed of 5m/s is considered to be a good value at an average height. For a small 0.4KW generic wind turbine (rotor diameter = 4m), the *cut-in speed* is 3m/s. Given that all SADC countries have average wind speeds that are at least 3.39 m/s or more at a hub height of 10m, for the selected sites the corresponding potential power generation is justifiable in this calculation. If we consider the country of Mozambique, for instance, with a land area of 799,380 km^2 or 4.03 $*$ 10^9 m^2, then the wind volume is:

$$V_{wind} = A_{wind} * height = 7.99 * 10^{11} m^2 * 10m = 7.99 * 10^{11} m^3$$

Thus, if we assume the use of windmills that operate at an efficiency of 25 per cent (note that the Betz limit or theoretical maximum is 59 per cent), the wind power that can be produced in Mozambique, with an average wind velocity of 4.9 m/s at a 10 m height is:

$$P_{wind} = 0.5\eta\rho v^3 V_{wind} = 0.5 * 0.25 * \frac{1.293kg}{m^3} * \left(\frac{4.9m}{s}\right)^3 * 7.99 * 10^{12} m^3$$
$$= 1.517 * 10^{14} W_e = 151{,}723GW$$

The onshore wind energy potential from Mozambique in one year at 10m can then be calculated as:

$$Energy_{wind} = P_{wind} * hours\ of\ operation = 151{,}723GW * 8{,}760\ hours$$
$$= 1.33 * 10^{9} GWh$$

At 50m, where the wind speed is 5.83m/s, the wind energy potential from Mozambique would be equal to 1.12 * 10^{10} GWh, which is higher by an order of magnitude. At 10m, the wind energy potential is about 87,636 times the met demand of 15,166GWh in Mozambique, while at 50m, it is about 739,765 times the demand. As with the solar energy resource in the previous section, the analysis above shows that there is also a sufficient wind energy resource to meet the electricity needs of the region in principle. More specifically, the amount of land that is needed to produce Mozambique's current electricity generated is 0.001% (or 7.99km^2) at a height of 10m and 0.0001% (0.8km^2) at a height of 50m.

In order to demonstrate the consumption of this energy resource in practice, the three Basic Electricity (BE) scenarios of 50kWh/month, 100kWh/month and 200kWh/month as in the previous section are used, and how the small wind turbine rotor dimensions of 1.5m, 2.5m, and 5m could meet this demand is estimated. For a wind turbine with a rotor diameter of 2.5m, for example, the electricity produced in Mozambique with an average annual wind speed of 4.9m/s at 10m is:

$$P_{wind} = 0.5\eta\rho v^3 A_{wind} = 0.5\eta\rho v^3 \pi(\frac{d}{2})^2 = 0.5 * .25 * \frac{1.293kg}{m^3} * \left(\frac{4.9m}{s}\right)^3 * \pi\left(\frac{2.5m}{2}\right)^2$$
$$= 93.168W_e$$

The energy that can be generated in one month is then calculated as:

$$Energy_{wind} = P_{wind} * hours\ of\ operation = 93.168\ We * 30\ days * 24\ hours$$
$$= 67081Wh = 67.081kWh$$

Thus, the number of turbines needed to meet a BE of 50 kWh per month is:

$$No. of\ turbines = \frac{Total\ energy\ generated}{Energy\ generated\ by\ one\ turbine} = \frac{50kWh}{67.081kWh} = 0.54$$
$$= \sim 1\ turbine$$

This calculation is extended to the other rotor diameters and for all the BE requirements for Southern Africa as a whole and the results are shown in Table 6 below. The number of batteries needed to meet the BE requirements is approximately the same as that shown in Table 4. Thus, two, four and six batteries are needed in combination with the turbines to produce BE requirements of 50kWh, 100kWh and 200kWh respectively.

Table 6: Number of Wind Turbines per Household Needed to Produce Minimum Electricity Requirements.

	BE = 50kWh/mo.	**BE = 100kWh/mo.**	**BE = 200kWh/mo.**
1.5m turbine	2	3	6
2.5m turbine	1	1	2
5m turbine	1	1	1

The analyses above have revealed some of the technology and resource combinations by which solar and wind energy could increase energy access and meet minimum basic electricity requirements in Southern Africa. The amount of energy that would need to be generated for each country to meet the minimum monthly basic electricity requirements per household of its non-electrified population is then estimated. The comparison between this energy needed to meet the minimum B.E. requirements and the actual energy generated is shown in Table 7 below. It is evident from the table that, for the countries with low electricity access rates, more energy is required to meet the minimum B.E. of 50kWh a month than the current energy generated by those countries. Ideally, this should be done through renewable energy to reduce the level of pollution associated with fossil-based generation, as discussed in Section 3.

Table 7: Estimated Annual Generation (GWh) needed to meet BE Requirements

	Total Population (UNData, 2013)	**Fraction W/out Electricity Access**	**Existing Energy Generated (GWh)**	**BE=50 kWh/mo (GWh/yr)**	**BE=100 kWh/mo (GWh/yr)**	**BE=200 kWh/mo (GWh/yr)**
Angola	21,471,618	0.7	5,613	9,018	18,036	36,072
Botswana	2,021,144	0.34	250	412	825	1,649
D.R. Congo (DRC)	67,513,677	0.91	7,966	36,862	73,725	147,450
Lesotho	2,074,465	0.72	486	896	1,792	3,585
Madagascar	22,924,851	0.85	2,025	11,692	23,383	46,767
Malawi	16,362,567	0.91	2,180	8,934	17,868	35,736
Mauritius	1,258,653	0	2,792	0	0	0
Mozambique	25,833,752	0.61	15,166	9,455	18,910	37,821
Namibia	2,303,315	0.7	1,643	967	1,935	3,870
Seychelles	89,173	0.03	320	2	3	6
South Africa	53,157,490	0.15	257,919	4,784	9,568	19,137
Swaziland	1,249,514	0.73	425	547	1,095	2,189
Tanzania	49,253,126	0.76	5,795	22,459	44,919	89,838
Zambia	14,538,640	0.74	11,850	6,455	12,910	25,821
Zimbabwe	14,149,648	0.6	9,088	5,094	10,188	20,375
Total	**294,201,633**		**323,518**	**117,579**	**235,157**	**470,315**

COST ANALYSIS: HOMER MODELLING

The general purpose of this section is to identify the most cost-effective technology options for distributed electrification, namely wind and solar power, in Southern Africa when compared to both diesel generator and grid-based electricity. A previous study by

Szabó, Bódis, Huld, and Moner-Girona (2011) used different optimisation tools than the one used here to map and estimate the least-cost off-grid electrification from solar power or diesel in all of Africa when compared to grid-based electricity. However, the present study not only includes wind power, it focuses on the meteorological conditions in Southern Africa, and uses the most recent generation and cost data available for the region. It also reveals which alternatives to the grid are environmentally preferable with respect to their level of emission of pollutants even though no prices are placed on these in this study.

The main tool that was used for the analysis of the costs of the distributed renewable energy options described in this paper is the Hybrid Optimization Model for Electric Renewables (HOMER), which was developed by the US National Renewable Energy Laboratory (NREL). HOMER is a micro-power optimisation model that simplifies the evaluation of off-grid, microgrid and grid-connected power system designs for various applications (NREL, 2005). It works by performing three main tasks: simulation, optimisation and sensitivity analyses.

The software first simulates the operation of a given system configuration by making energy balance calculations for each of the 8,760 hours in the year, and then determines whether the configuration is possible. It does this by verifying whether it can meet the electric demand under specified conditions and by estimating the installation and operating costs over the lifetime of the project, which include capital costs, replacement costs, operation and maintenance costs, fuel and interest. HOMER optimises the system by simulating all its possible configurations and displays them as a list of the lowest to the highest net present cost, which it also defined as the life cycle cost, in order to compare different design alternatives. The software also performs a sensitivity analysis by repeating the optimisation process for each sensitivity variable that is specified, such as a range of wind speeds or a range of diesel prices.

The cost analysis in this section evaluates four scenarios as follows: 1. Diesel only 2. Solar power versus diesel 3. Wind power versus diesel 4. Hybrid solar-wind power versus diesel. The analyses that are presented in this section include a description of all the technology and cost assumptions that are made, a display of the net present cost (life cycle cost) of the optimised technology options, the levelised cost of electricity for each energy resource, and a display of the emissions released by each of the resource options. The rand costs of components and fuels in South Africa are relied on since these are available online (Sustainable.co.za, 2015) and because that is the currency that the SAPP uses in its analyses. Thus, it is assumed that the results presented can be generalised for the SADC region in terms of purchasing power parity (PPP).

Table 8: Technical Specifications and Costs of Selected Components of Energy Systems

	Capacity	Capital Costs	Fuel Costs	Lifetime
Solar PV	250W	R3,009	R0	20 years
Wind turbine	400kW	R16,006	R0	15 years
Diesel Generator	4kW	R25,400	R11.318/L	15,000 hrs
Deep Cycle Battery	12V, 26 Amp-hr	R743	N/A	5 years
Inverter	12V, 150W	R389	N/A	

Simulation

A sample schematic of the solar-wind-diesel hybrid scenario that was conducted in HOMER is shown in Figure 2 below where Generator 1 represents the diesel generator, and the primary load represents a basic electricity load of 200kWh/month (or 6.7kWh/d). The icon with 'S6CS25P' label represents a deep-cycle battery, while the icons under 'Resources' allow the modeller to import characteristics such as average daily wind speed for every month of the year, the average daily solar radiation per month, modify the average daily amount of biomass used per month (tonnes/day) and the average price of the biomass used ($/tonne), and enter the average fuel price ($/L) in the case of diesel.

For the icons under 'Other', the user can modify parameters such as the annual real interest rate (for which 6 per cent is used here), the project lifetime, and/or the system capital and O&M costs. A converter icon is also shown because the diesel generator runs on electricity in an Alternating Current (AC) form, while the wind and solar generators run on a Direct Current (DC), which requires a converter in the form of an inverter (to convert DC to AC) or what is generically called a 'converter' to convert AC to DC. However, if household devices use a type of current that is the same as that of the generator being used, a converter is not needed.

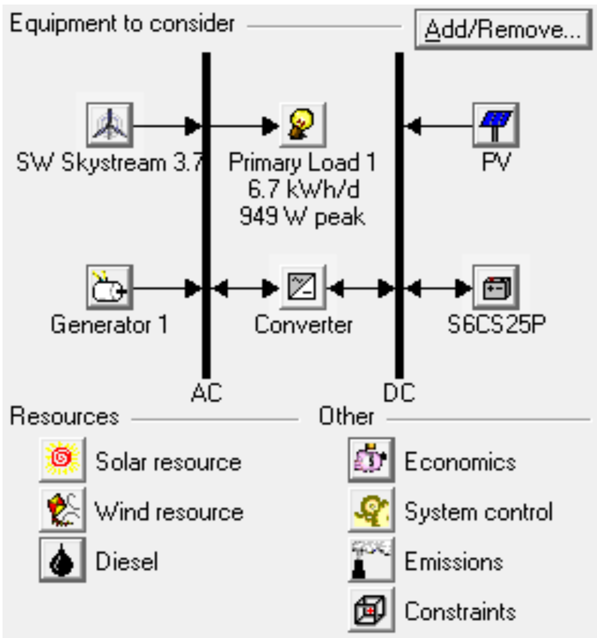

Figure 2: Solar-Wind Hybrid versus Diesel

Optimisation and Sensitivity Analysis

The optimisation procedure that HOMER performs, which consists of simulating all the possible configurations of a system and ranking the most optimal configuration from the least expensive one to the most expensive, does not provide the 'solution' to the problem per se, but only allows the user to compare various alternative designs. However, it should be noted that optimisation itself, understood as the result of a formal objective function, helps to clarify given objectives under specific conditions such that learning can then occur over multiple iterations, as is typical of ecosystem management, for instance (Walters, 1986).

Therefore, the modelling results presented in this section show the costs associated with the various alternatives prior to the social, technological and policy learning that will take place.

The total net present cost in the HOMER model is defined by Lambert, Gilman, and Lilienthal (2006) as given by:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\ (i, R_{proj})}$$

where $C_{ann,tot}$ is the total annulised cost, i is the discount rate, R_{proj} is the project lifetime, and CRF(.) is the capital recovery factor, which is given by:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}$$

where i is the annual real interest rate and N is the number of years.

The levelised cost of energy of energy (LCOE) is then given by:

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}}$$

where $C_{ann,tot}$ is the total annualised cost, E_{prim} are the total amounts of primary load, E_{def} represents the deferrable load that the system can generate per year, while $E_{grid,sales}$ is the amount of energy sold to the grid per year (Lambert et al., 2006). In this case, $E_{grid,sales}$ is zero since no sales either to or from the grid were included in the model.

The results of the optimisation for each set of loads, for example, 50kWh/month basic electricity requirement (1.67kWh/day), while the sensitivity analysis runs the optimisation procedure again for 100kWh/month, 200kWh/month, 400kWh/month and 800kWh/month as shown in Tables 9 to 12 below for all four scenarios. The sensitivity analysis feature in HOMER most closely models the concept of component sizing, which has been used in this paper to capture the possibility of gradually and adaptively building up electricity generation infrastructure. Thus, the main purpose of the sensitivity analysis was to determine what combination of the components could produce the daily equivalent of the monthly primary loads of 50kWh, 100kWh, 200kWh, 400kWh and 800kWh, and to subsequently observe the evolution of the levelised cost of electricity (LCOE) with an increase in consumption.

In Table 9 below, for the diesel-only scenario, the labels in order are as follows: The Diesel (kW) tab represents the installed capacity of the diesel generator, followed by the initial capital required to install it, the operating costs per year, the total Net Present Cost (NPC) or life cycle cost, the levelised cost of electricity (LCOE), and the fraction of renewable energy in the resource used.

Tables 10, 11 and 12 also show the components of the PV and wind turbine systems, and display the net present costs of all the feasible configurations.

Table 9: Diesel only

Pri. Load (kWh/d)	Diesel (kW)	Initial capital	Operating cost (R/yr)	Total NPC	LCOE (R/kWh)	Renewable fraction
1.667	0.65	R4,128	12,154	R159,492	20.51	0
3.333	0.65	R4,128	12,154	R159,492	10.26	0
6.667	0.65	R4,128	14,181	R185,409	5.96	0
13.333	0.65	R4,128	20,981	R272,337	4.38	0
20	1.3	R8,255	35,160	R457,723	4.91	0
26.667	1.3	R8,255	41,966	R544,721	4.38	0

Table 10: Solar power versus diesel

Pri. Load (kWh/mo)	PV (kW)	Diesel (kW)	Initial capital	Total NPC	LCOE (R/kWh)	Renewable fraction
50	0.5	0.65	R14,993	R20,707	2.66	0.93
100	1	0.65	R21,011	R31,421	2.02	0.92
200	2	0.65	R33,047	R53,952	1.73	0.92
400	5	0.65	R73,613	R100,134	1.61	0.97
600	5	1.3	R77,740	R157,816	1.69	0.87
800	10	1.3	R146,836	R199,749	1.61	0.97

Table 11: Wind power versus diesel

Pri. Load 1 (kWh/d)	Wind turbine	Diesel (kW)	Initial capital	Total NPC	LCOE (R/kWh)	Renewable fraction
50	1	0.65	R24,981	R70,352	9.05	0.14
100	1	0.65	R24,981	R113,904	7.32	0.07
200	1	0.65	R24,981	R187,547	6.03	0.04
400	1	0.65	R24,981	R297,474	4.78	0.02
600	1	1.3	R29,108	R472,259	5.06	0.01
800	1	1.3	R29,108	R569,826	4.58	0.01

Table 12: Solar-Wind hybrid power versus diesel

Pri. Load (kWh/d)	PV (kW)	Diesel (kW)	Initial capital	Total NPC	LCOE (R/kWh)	Renewable fraction
50	0.5	0	R26,871	R35,628	4.58	1
100	1	0.65	R37,017	R50,314	3.24	0.95
200	2	0.65	R49,053	R71,628	2.30	0.94
400	5	0.65	R89,619	R120,528	1.94	0.97
600	5	1.3	R93,746	R177,852	1.91	0.87
800	10	1.3	R162,842	R220,011	1.77	0.97

The tables above show that the levelised cost of electricity (LCOE) is reduced as consumption increases. This demonstrates that the economies of scale are clearly beneficial over the life cycle of the respective energy generation technologies. However, only the solar-diesel scenario shows a significant uptake of the renewable energy component (minimum 87 per cent, maximum 97 per cent). The wind-diesel scenario still relies on diesel to keep the cost at a minimum, while the solar-wind-diesel scenario also primarily relies on solar power to keep the cost at a minimum. Thus, over the average area of the various countries modelled, solar power is the most cost-effective resource across the region. What this suggests is that, outside of specifically well-resourced areas with respect to wind energy, household residents are not likely to benefit from this resource as much as solar, which is virtually ubiquitous in the region. Table 13 and Figure 3 below show the evolution of the cost of electricity for the four hybrid scenarios with increased consumption.

Table 13: Levelised Cost of Electricity (LCOE) across Four Hybrid Scenarios

Primary Load (kWh)	Diesel (R/kWh)	Solar-diesel (R/kWh)	Wind-diesel (R/kWh)	Solar-wind-diesel (R/kWh)
50	20.5 (0.00)	2.66 (0.93)	9.05 (0.14)	4.58 (1.00)
100	10.27 (0.00)	2.02 (0.92)	7.32 (0.07)	3.24 (0. 95)
200	5.96 (0.00)	1.73 (0.92)	6.03 (0.04)	2.30 (0. 94)
400	4.39 (0.00)	1.61 (0.97)	4.78 (0.02)	1.94 (0. 97)
600	4.91 (0.00)	1.69 (0.87)	5.06 (0.01)	1.91 (0.87)
800	4.38 (0.00)	1.61 (0.97)	4.58 (0.01)	1.77 (0.97)

Note: The numbers in brackets reflect the fraction of renewable energy in each scenario.

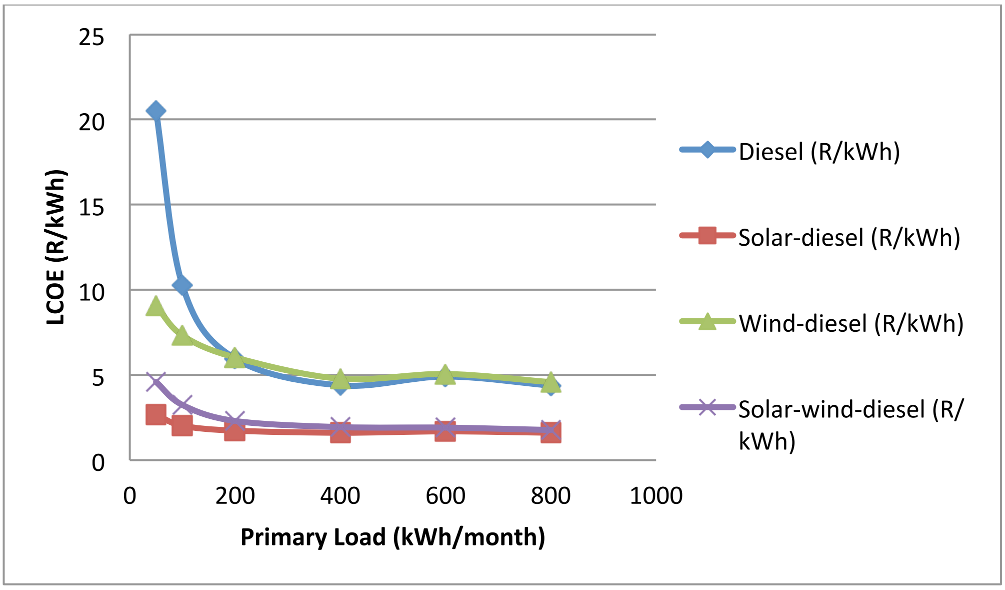

Figure 3: Evolution of Levelised Costs of Electricity (LCOE) across Four Hybrid

Scenarios

Two important points can be gleaned from the analyses presented above. In the first instance, the costs of the various scenarios are still higher than the average costs for grid-connected consumers in SADC, with the average consumer in Swaziland paying 1.37 R/kWh, those in the DRC paying 0.57 R/kWh and those in South Africa paying 1.03 R/kWh (SAPP, 2014). It should be noted, however, that this average for residential, commercial and industrial consumers conceals the fact that the industrial consumers often pay 'bulk rates' that are on the order of 50 per cent of the cost that other consumers pay, as in South Africa, for instance, although lower level consumers (less than 200 kWh/month) in that country are also given preferential rates (ESKOM, 2014). Secondly, the increased consumption of the distributed, renewable technologies (solar, in this case) beyond what was modelled could very well benefit from economies of scale if larger neighbourhoods or communities were considered. Nevertheless, Table 16 below proceeds to estimate the capital costs that non-electrified households in Southern Africa would need to invest to gain access to 50kWh per month of solar power. The assumption that was made was for five persons per household, and a capital cost of R10,865 (the difference between the initial capital cost of the solar-diesel scenario in Table 12 and that of the diesel-only scenario in Table 11, which leaves us with the capital cost of solar-only) was used.

Table 14: Estimated Costs of Extending Electrification through Renewable Energy

	Total Population (UNData, 2013)	Fraction without electricityaccess	Households without electricity access	Capital cost (BE=50kWh)
Angola	21,471,618	0.7	3,006,027	32,660,478,140
Botswana	2,021,144	0.34	137,438	1,493,261,610
D.R. Congo (DRC)	67,513,677	0.91	12,287,489	133,503,570,310
Lesotho	2,074,465	0.72	298,723	3,245,624,960
Madagascar	22,924,851	0.85	3,897,225	42,343,346,040
Malawi	16,362,567	0.91	2,977,987	32,355,830,863
Mauritius	1,258,653	0	0	0
Mozambique	25,833,752	0.61	3,151,718	34,243,413,289
Namibia	2,303,315	0.7	322,464	3,503,572,447
Seychelles	89,173	0.03	535	5,813,188
South Africa	53,157,490	0.15	1,594,725	17,326,683,866
Swaziland	1,249,514	0.73	182,429	1,982,091,563
Tanzania	49,253,126	0.76	7,486,475	81,340,552,526
Zambia	14,538,640	0.74	2,151,719	23,378,423,893
Zimbabwe	14,149,648	0.6	1,697,958	18,448,311,062
Total	294,201,633		39,192,911	425,830,973,756

Table 14 above estimates the total cost of providing at least 50kWh/month to each household in Southern Africa to be about R426 billion. For a sense of proportion, it is necessary to compare this figure to the $80 billion dollars (R1140 billion) estimated for the construction of the Grand Inga project (Green et al., 2015) and the estimated $17.8 billion (R250 billion) required for the 4,800 MW Medupi Coal Power Station in South Africa, with its attendant controversies around the environment, labour and delayed completion (Rafey & Sovacool, 2011). Thus, this analysis suggests that the cost of electrifying the whole of Southern Africa based on household systems could be less than 40 per cent of the cost of completing the Grand Inga Dam project, about 1.7 times the cost of building the Medupi Power Station, and about 30% of their combined cost. Given that such large infrastructure projects have a poor record of providing services to energy-poor consumers, and even when they do, this usually occurs a decade or more after their construction, the argument made for an investment in off-grid or microgrid electrification as the basis for a distributed utility is both technically practical, and economically feasible.

EMISSIONS

HOMER automatically calculates the amount of the various emissions that are released from the use of various resources as part of the optimisation procedure. Table 15 below shows the emissions result for all four hybrid scenarios for a household that consumes 200kWh/month, and a similar result can also be retrieved for the other loads. It should be noted that these results represent emissions that are proportional to the fractions of renewable versus diesel in all the hybrid scenarios that were run as shown in the optimisation results in Tables 9 to 12. The diesel generator emits the largest amount of CO_2 as well as all the other pollutants, followed closely by the wind-diesel scenario because only very little wind uptake was recorded due to the cost of wind technology and the relatively low wind resource in the areas surveyed. The solar-diesel scenario and the solar-wind-diesel scenario (mainly due to the solar component) demonstrate the significant emissions reductions that can be derived from the adoption of renewable energy.

Table 15: **Estimated Emissions of Hybrid Scenarios at BE of 200kWh/month**

	Diesel	**Solar-diesel**	**Wind-diesel**	**Solar-wind-diesel**
% Renewable Resource	0%	92%	4%	94%
Carbon dioxide (kg/yr)	3,539	283	3,397	212
Carbon monoxide (kg/yr)	8.73	0.70	8.38	0.52
Unburned hydrocarbons (kg/yr)	0.97	0.08	0.93	0.06
Particulate matter (kg/yr)	0.66	0.05	0.63	0.04
Sulphur dioxide (kg/yr)	7.11	0.57	6.83	0.43
Nitrogen oxides (kg/yr)	77.9	6.23	74.78	4.67

SUMMARY OF ANALYSES

In conclusion, this paper has sought to demonstrate the technological and economic feasibility of power planning in Southern Africa through distributed electrification using suitable renewable energy resources, as a viable alternative to the centralised generation approaches that are dominant in the region. The study began with a presentation of the energy access situation in the region, the currently used resources for electricity generation and the energy demand and supply in the SADC region. The second part of the analysis estimated the electricity generation potential from both the solar and wind energy resources available in the various countries, and showed that they are sufficient to meet the energy demand of each of the countries many times over. Furthermore, the analysis showed how the various technological components needed for solar and wind power could meet the electricity of households needing to consume 50kWh/month, 100kWh/month or 200kWh/month.

Once the practical potential of both the renewable resources and the possibility of currently available technologies to exploit them were demonstrated, an analysis of the cost of these sources of electricity for distributed electrification was undertaken. The analysis showed that on a life cycle basis, the levelised costs of electricity (LCOE) for all the scenarios evaluated were higher than the average cost of grid-based electrification. In the case of the diesel-only scenario, which is the traditional alternative to grid-based electricity, it was shown that the recurring cost of the diesel fuel made this option many times more expensive than grid-based electricity even at higher consumption levels.

On the other hand, the solar-diesel scenario, which demonstrated a high uptake (> 90%) of the solar resource, showed that its LCOE was consistently declining and was not much more expensive than grid-based electricity at consumption levels greater than 200kWh/month. However, the cost of the wind-diesel scenario was expensive due to the relatively high cost of the wind generation technology and the modest energy resource over the areas surveyed. The solar-wind-diesel scenario was also favourable, due to the cost-effective solar resource and a slight contribution from wind. Thus, this part of the analysis showed that of the two renewable resources, solar power is the preferred option from both a resource and a cost perspective.

It should be noted that the bulk of the costs of the renewable energy scenarios was in the capital costs, since the fuel costs are non-existent. Thus, the costs of supplying the initial equipment for generating 50kWh/month per household in Southern Africa were estimated, which is consistent with the Free Basic Electricity (FBE) policy in South Africa that was responsible (in conjunction with institutional and technical innovations) for its rapid electrification programme. The results suggest that the total costs needed to provide every non-electrified household in the region with a minimum of 50 kWh/month of solar power would represent less than 50 per cent of the estimated cost of completing the Grand Inga Dam and about twice the cost of one power station, the Medupi Coal Power Station. Given that the residential consumers in South Africa represented approximately 94 per cent of ESKOM's customers and used about 20 per cent of the total electricity generated in 2006 (National Treasury, 2011), then the following proposition can be considered. In the event of an ambitious regional electrification programme, the prospect that only two times the allocated costs for new generation at one South African power plant could supply power to all the non-electrified residents in the wider region (or half of them, if a quarter of the generating capacity of each of the two plants were dedicated to residential consumers) and within a much shorter period of time, remains compelling. This strongly suggests that the generalised neglect or deficiency of state-based initiatives for widespread electrification in sub-Saharan Africa in general, and in Southern Africa more specifically (with few exceptions such as South Africa with respect to grid expansion, and some of the island nations), cannot continue to be justified on the basis of cost, while simultaneously championing the development of mega projects and restructuring efforts that, since the early 1980s, have only made marginal contributions to either electricity access or reliability of supply (Turkson, 2000) – a situation that appears to continue to deteriorate. More fundamentally, the overwhelming support for rural electrification in countries that have achieved near-universal access such as China, Tunisia or Mexico (Barnes, 2007), and empirical support for the link between off-grid electrification and human development in Brazil's Luz para Todos (Light for All) programme (Gómez & Silveira, 2010), for instance, all point to the soundness of such an approach.

In addition, it should be pointed out that the scenarios investigated in this study by no means exhaust the opportunities for distributed electrification, with biomass power from waste crops being one option that would be especially suited to farming communities in rural areas. For instance, a modelling-based assessment of hybrid PV-fuel cell systems coupled with batteries by Lagorse, Paire, and Miraoui (2009) demonstrates its potential for an off-grid application related to stand-alone street lighting systems, but the study's findings underscore the fact that such an option is particularly attractive for locations that are distant from the equator and where PV-battery systems cannot work all year round. Thus, while South Africa, in particular, with its rich platinum reserves, has the potential to develop proton exchange membrane fuel cells for off-grid applications (Ferreira & Perrot, 2013), the reality of the region's generally exceptional solar radiation suggests that this technology is not likely to be a cost-competitive solution in the short to medium term. Lastly, the scenario analysis in this paper has shown that the renewable energy scenarios (particularly the two that included solar power) would result in less pollution at the point of use than in the diesel-based scenario. Thus, if one considers the extended delays that are typically associated with large power generation infrastructure as well as the environmental ramifications of both fossil-fuelled generators and large hydroelectric dams, along with the cost and debt implications of constructing those, the combined analyses presented in this paper show convincingly that power planning based on distributed electrification deserves serious contemplation in the near future.

RECOMMENDATIONS

While the analyses offered in this study may be revised and some of its assumptions may be subjected to critique, the objective was to make a credible case for an alternative planning paradigm based on the magnitude of the demand, resources and costs of the available technologies. A few additional recommendations for implementing such a paradigm are offered as follows:

Financing

The current study has pointed out that sub-Saharan African countries and regions have been able to generate the capital needed for large energy infrastructure projects with highly skewed distributional consequences and that the approach suggested here would only represent a very small percentage of those costs even if the capital costs of the small scale DG technologies were entirely paid for. Other approaches to financing distributed electrification would be other forms of subsidies (partial), remittances, rotating credit and savings associations, village and cooperative savings and credit institutions, or investment funds for manufacturing and research, as discussed in more detail in a study by O. C. Soumonni and Soumonni (2011). With specific reference to Southern Africa, the Integrated National Electrification Plan (INEP) of the Department of Energy (DoE) of South Africa supports a rural concessions programme for solar home systems by providing 80 per cent of the capital costs, with the one run by the Nuon-RAPS (NuRA) private utility since 1999 having achieved notable success in KwaZulu-Natal (Lemaire, 2007).

Technological Capability Building

The technical capability needed to install and maintain the energy generation technology is minimal at the moment, but this represents an opportunity for training young people at all post-secondary levels including technical and artisan training institutes, as well as traditional polytechnics and universities. Adopting this paradigm of electrification would provide an opportunity to foster an approach to education that is more directly linked to pressing developmental issues, while simultaneously creating opportunities for entrepreneurship and work opportunities.

Industrial Consumers

It has been suggested in this study that large infrastructure projects tend to favour large industrial consumers that are predominantly linked to the extractive sectors of the economy. Yet, such consumers have the financial means and the opportunity to also explore opportunities for distributed electrification through co-generation or Combined Heat and Power (CHP). If the preferential electricity supply arrangements for such consumers were more equitably revised with respect to other societal groups, they may find that the possibilities of generating a large proportion of their own power may be cost-effective and competitive with the current prices they pay. In addition, for the various countries, promoting such an approach through policy instruments could both stimulate manufacturing (i.e. non-extractive industry), promote associated job growth and negate the need for building expensive and ecologically compromised large power stations, as suggested in a number of recent studies (Baer, Brown, & Kim, 2015; Brown, Cox, & Baer, 2013).

Grid-connected Residential and Commercial Consumers

In many countries in Southern Africa, many grid-connected consumers are experiencing power cuts or load shedding, including in countries that have historically had access to an abundant energy supply, such as South Africa. This recent development has tended to relegate issues of electricity access to the background, in favour of the reliability of supply for grid-connected consumers. Given the indications that this situation may continue for at least a few years, it is possible for such consumers to adopt distributed renewable electricity to supplement their current supply, thereby mitigating the need for additional centralised generation capacity, as well as ensuring the reliability of their own power supply. These consumers could ultimately be connected with those who started out as off-grid or microgrid users in order to develop, in the future, what has been proposed in the US as a distributed utility (Ackermann et al., 2001; Feinstein, Orans, & Chapel, 1997). This may be much more applicable to the socio-technical conditions of communities in Southern Africa in the form of a modified microgrid having as its basic unit, a single ring local node surrounded by distributed generators, which could be upgraded to a double ring node, and subsequently, a more complex distributed utility architecture (Bai K Blyden & Lee, 2005; Bai K. Blyden & Lee, 2006).

Innovation

Ultimately, the goal of moving from resource-dependent economies to knowledge-driven economies must revolve around solving the problems that affect the majority of African people. In the case of electricity access, adopting a distributed generation paradigm based on renewable energy could provide opportunities to integrate the technological learning and capability that would be gained through adoption, with the ongoing research and development efforts at university and governmental research centres. This would enable the countries in Southern Africa as well as other sub-Saharan African countries to develop a range of innovation capabilities in the area of renewable energies that are tailored to their own environments, and that can subsequently serve as a basis for a future export industry to other parts of the world. Such considerations for the continent from an innovation systems perspective have been further developed in a study by (O. Soumonni, 2013).

Appendix 1: Solar Energy: Geographical Coordinates and Average Radiation Data (NASA, 2015)

	City	Latitude	Longitude	Elevation	Average
Angola	Luanda	13.26	8.83	59	--
	Cuando	18.8	16.33	1,221	6.54
Botswana	Gaborone	25.89	24.65	1,159.26	--
	Maun	23.42	19.98	942	6.36
D.R. Congo	Lubumbashi	27.5	11.67	1,303	--
	Kinsasha	15.32	4.33	351	6.19
Lesotho	Maseru	29.31	31.98	1,642	--
	Mokhothong	29.07	29.29	2,209	5.81
Madagascar	Antananarivo	47.53	18.93	1,352	--
	Itampolo	43.95	24.68	51	3.49
Malawi	Lilongwe	33.77	13.98	1,135	--
	Kaphiika	34.09	10.45	692	5.33
Mauritius	Port Louis	57.52	20.17	85	--
	Mahebourg	57.7	20.4	44	3.17
Mozambique	Maputo	32.56	26.01	22	--
	Tete	33.6	16.17	270	5.54
Namibia	Windhoek	17.11	22.6	1,723	--
	Okahandja	16.92	21.94	1,578	6.38
Seychelles	Victoria	55.45	4.62	72	--
	La Digue	55.83	4.36	206	3.02
South Africa	Capetown	18.42	33.9	-1	--
	Thohoyandou	30.48	22.95	576	6.19
Swaziland	Mbabane	31.13	26.32	1,335	--
	Hluti	31.59	27.22	519	5.29
Tanzania	Dar Es Salam	39.28	6.78	23	--
	Mwanza	32.9	2.51	1,187	4.95
Zambia	Lusaka	28.28	15.43	1,185	--
	Kasama	31.2	10.23	1,365	5.57
Zimbabwe	Bulawayo	28.62	20.12	1,211	--
	Harare	31.03	17.85	1,351	6.54

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Development of container based community factories

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Abstract

The main obstacle to electrification in Africa is not constructing power stations and building overhead power lines. It is working out how to help the region's households acquire sustainable energy with limited and irregular cash flows, little collateral and no access to credit. They cannot afford to pay for the huge investment needed to bring electricity to them. Even if the electricity was brought to them, most can barely afford to pay for usage. This problem can only be addressed by providing tools that bring wealth to the communities. After water, food and shelter comes the need of lighting to extend the productive hours of the day. The Department of Mechanical Engineering at the University of Johannesburg, in collaboration with Ecovest, a South African upcoming small scale enterprise, developed an innovative solar home lighting solution that can be manufactured off the grid in a community based container factory. Solar lighting is significant for many without electricity and the developed solution allows the Sun to pay to eradicate expensive unsustainable on-grid energy. The container based solution empowers the community to create jobs and generate wealth while producing affordable durable products due to reduced distribution and marketing costs. In existing and emerging markets, the gross product cost includes the costs of distribution which is well developed in existing markets but poorly developed in the emerging African market. Additionally, existing markets innovate incrementally (features of products) whilst emerging markets innovate radically (sustainable technology). Moving users from hazardous and expensive open flame solutions like candles to solar home systems, provides a more sustainable standard of living for off grid living.

Keywords: Community factories, Container factories, Home lighting system, Open community manufacturing, Solar Energy

Introduction and motivation

The current global economic conditions are worsening poverty levels, especially in developing countries. This is more pronounced in Sub-Saharan Africa. The economic conditions of most of these countries is directly linked to low levels of manufacturing. Most of the goods and services consumed are imported. This is despite the large resource base most African countries sit on. The main exported commodities of African nations include unprocessed gold and diamonds, oil, cocoa, timber and palm oil (Economy Watch 2010). The main imported commodities include finished machinery and equipment, scientific equipment and food. Imports from the USA have been reported to increase more than 100 % between 2009 and 2013 (International Trade Adnimistration, US Department of Commerce 2014). Some of the imported products can be manufactured or partly manufactured locally. This provides significant hope and possibility to create employment and mitigate poverty levels.

The lack of production capacity in most Sub-Saharan countries is a major concern as GDP growth and poverty alleviation hinges on manufacturing as an engine for economic growth and development. The modern society depends on manufacturing capability and capacity. The state of society depends on the state of manufacturing as it promotes economic activities in all the other sectors. Having a strong manufacturing base is a prerequisite to eradicating poverty. The economic boom that has been observed in the countries Brazil, Russia, India, China and South Africa (BRICS), is testimony that this comes at the back of widespread manufacturing growth in both consumer products (toys and clothing from China) and machinery such as the automotive sector. Therefore, there is need to implement programs to stimulate and broaden manufacturing with special focus on the local manufacture of products.

One program that has potential to achieve this is the concept of open community manufacturing (OCM) (Oosthuizen, et al. 2014). OCM is proposed as an innovative sustainable system that can be used to transfer knowledge and skills to the bottom of the pyramid (BoP) (Prahalad and Hart 2002) section of the population, those who are disconnected from the means of production and economic activity. It is based on the principles of value co-creation, open design and internet based networking. Harnessing the power of open source software and hardware, it proposes provision of open source design to allow communities to have access to knowledge and skills that promote ubiquitous manufacturing. Solutions for problems identified through community participation are developed by volunteer specialists such as mechanical and industrial design engineers. Blue prints of such solutions are made available for free access to communities and entrepreneurs through electronic and social media. The open design approach can be extended beyond products to actual manufacturing equipment (Vallance, Kiani and Nayfeh 2001). In the absence of intellectual property (IP) protection, open design of manufacturing equipment can empower communities to participate in product manufacturing in a way that broadens their economic activities and hence help grow the formal economy.

The model for the complex interactions that are required to make this successful have been articulated by Rebensdorf et al (Rebensdorf, et al. 2015). There is need to connect the community to designers, manufacturers, venture capital and the formal market. The target community exists largely in an informal economic space which remains largely isolated from the formal economy. Formal funding in such space is dominated by donors. However, the success rate of such a model is limited. The donor approach does not provide conditions for recipient commitment to solutions developed outside the community. The other sources of funding include government support, social corporate investment (CSI) and social corporate responsibility (CSR). Government support is limited and CSI/CSR has been largely committed to social good activities such as providing food to orphanages, old people’s homes etc. This approach has largely lacked sustainability. A few years after such donations, nothing much exists to show evidence of such interventions. This is the major drawback of such an approach. However, if viable solutions with potential for significant impact on the community are available, a business model can be developed to channel such funding sustainably into community empowerment through OCM. This inevitably requires synergistic collaboration between CSI/CSR and financial services sector to provide a mechanism for revolving funding models to be developed in a way that nurtures entrepreneurial initiatives while promoting community commitment.

The biggest challenge in OCM is to identify products that can be manufactured successfully and sustainably in the community. Furthermore, there is need for manufacturing tools to be developed that are easily accessible to the community. This work presents the development of OCM products and manufacturing tools to empower communities to participate in the manufacturing space in an effective and sustainable way.

Methodology

The approach that was applied to address this problem has three main stages i.e. Product Identification, Product Development, Factory Development. The product that is developed has to be relevant to the target community. This requires community participation. Once the product has been identified, there is need to harness technical expertise to develop the product. This is where the OCM concepts such as Open Source Hardware become effective. Manufacturing tools and processes can then be developed to enable product manufacture in the community. These steps are detailed next.

Product identification

The first challenge was addressed by identifying the key community needs in informal settlements of Gauteng, the economic hub of South Africa. A 2007 survey reported that Gauteng has 453 000 households living in shacks in 625 informal settlements spread around the province (The Housing Developement Agency, 2012). This represents 14% of households in the province. This does not include the segment that lives in backyard dwellings. The major challenges identified through community consultation (through target groups) and expert observation can be identified as; 1.) Food, 2.) Water and sanitation, 3.) Energy and 4.) Clothing.

The energy component was found to be significant. Most households depend on paraffin for cooking and heating and candles for lighting. Given the large number of annual shack fires that are reported annually (Fire Protection Association of South Africa 2016), some of which take human lives, a decision was jointly taken to develop solutions that may address the energy needs with special focus on lighting and cooking. The identified lighting challenges are not unique to Gauteng but have been reported throughout Africa (Lighting Africa 2010). The International Energy Agency (IEA) estimates that only 290 million out of a population of 915 million people in sub-Saharan Africa have access to electricity (International Energy Agency (IEA) 2014). This is despite the fact that the region is rich in energy resources, especially freely available solar energy, but is poor in energy infrastructure delivery and energy supply.

Product design requirements

A product was required to address the lighting challenges in informal settlements. The key requirements identified for the product were:

1. Low cost (not more that R500 for a payback period of three to six months)
2. Solar powered
3. Provide lighting for a single shack
4. 2.1 Watt bulb
5. 240 luminens
6. Providing lighting for at least 8 hours on a single charge (2400 mAh)
7. Easy to partly manufacture and assemble in a community based factory

Product development

Product design entails functional analysis (FA) and product embodiments taking into account the concepts of design for manufacture (DfM), design for assembly (DfA) and design for the environment (DfE) (Dieter and Schmidt 2009). The FA framework developed for this home lighting system is shown in Figure 1. Several concepts were then developed to meet this functional need. The major design constraint was to arrive at a solution that can be manufactured in a container based community factory.

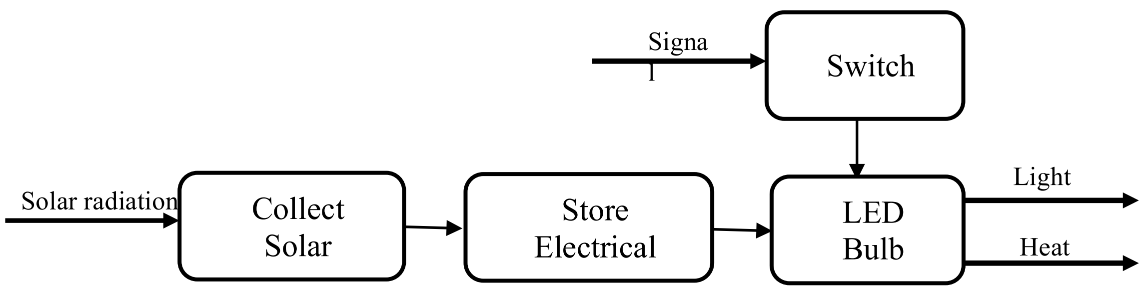

Figure 1: Home lighting system functional analysis

Key embodiment components included the solar PV panel, battery storage pack, LED light and switching and control system. Components that can be obtained off the shelf include the solar PV panel, storage batteries, LED light and control system. The product housing and mounting system can manufactured using simple tools. A Pretoria based company was tasked with development of the LED control system while the PV panel was procured off the shelf. The housing of the battery storage and control system housing and the LED housing and mounting were developed for manufacture in a community factory. This required most of the components to be made with straight lines and holes. The sample parts are shown in Figure 2. A deliberate decision was taken to make most of the housings out of 3CR12 stainless steel for durability and low cost manufacture. The full embodiment of the product is shown in Figure 3.

Figure 2: Laser blanked and drilled components designed for community factory manufacture

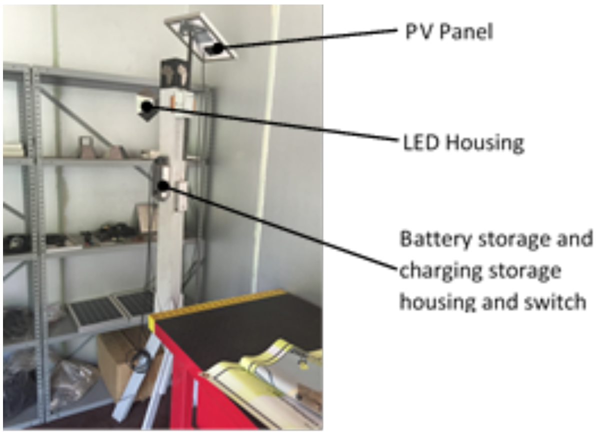

Figure 3: Home lighting system embodiment

Factory development

The identified product was design for community manufacture. A decision was made to develop an off grid factory given the large percentage of people in sub-Saharan Africa living off the grid. However, factory design and development is a complex process requiring special attention to sustainability issues (Terkaj, et al. 2014), (Chen, et al. 2012). For distributed OCM to succeed, the factory must meet certain criteria including:

1. Off grid capability
2. Mobile
3. Sustainable
4. Affordable
5. Easy to use
6. None polluting

Fox discusses most of these concepts in great detail (Fox 2015). It is critical to note also the importance of the type of product that has to be manufactured in the factory. In this work, a manually operated 10 ton press was designed as the tool for the main factory operations. This allows off grid manufacturing that is none polluting. The press also offers manufacturing flexibility as more products can be produced from the same press with a simple change of tooling. The press would be applied mainly to bending and punching operations. This therefore, requires that the components to be processed in the factory are supplied in a form suitable for the required processes. An entrepreneur and business incubation facility in Mpumalanga (Mpumalanga Stainless Steel Initiative (MSSI)) provided the pre-processing operations required to implement this part of the value chain. The full steps required for product realisation are presented in Figure 4.

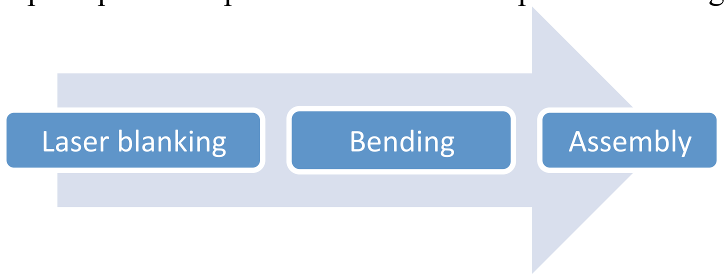

Figure 4: Product realization chain

A total of four tool sets were developed for the LED and battery storage housings. The components would be assembled using standard rivets and machine screws. The developed 10 ton bending press is shown in Figure 5. The figure also shows the layout of the interior of the workshop including working benches and storage shelves. This is also depicted in Figure 3.

Figure 5: Off grid manually operated 10 ton bending press

The factory was housed in a composite panel structure. The light weight structure ensures full mobility. It can be easily towed to any location for use and is not dependent on access to grid power. The factory can also be made from a shipping container at the risk of reduced mobility. The simple tooling applied also meant low training is required for skill transfer reducing turnaround time from procurement to full production. Furthermore, a supply chain was established for easy access to raw materials.

Figure 6: Trailer mounted community factory

Products produced in the factory had 30 % community value add. The raw materials were supplied at a price of R250 pack and could be sold at R450 with a minimum profit of R150. Therefore, the model has real potential of creating employment. In addition, other products can also be produced in the same factory. Trial runs were made to make cooking stoves and curios in the same factory and potential for this was demonstrated. The developed factory opens up new opportunities for distributed manufacturing while encouraging the Bottom of the Pyramid (BoP) segment of the population to participate in economic development, reducing poverty and saving lives.

Conclusions

This paper has presented the development of a product that can make a contribution to the support of open community manufacturing. The product was identified from the needs of local households living in informal settlements. A value adding chain for the product realisation was developed which included local incubation centre. A container based factory was developed which used a 10 ton manually operated press to add 30% value to the product by performing mainly bending and punching operations. In addition, all the components are assembled in the factory with reduced labour costs.

The proposed community manufacturing solution was successfully developed and tested. It has real potential to create jobs, add BoP sector into economic activity, reduce poverty and minimise loss of human life by providing safer, renewable and sustainable home lighting system to low income housing in informal settlements. The solution is easy to use, needs no grid power and can be moved from one place to the next. A supply chain was developed in the process to ensure sustainability.

The major challenge to widespread implementation is cost. Each factory can be procured from a local SME at a cost of R200 000 (two hundred thousand rands) with one month supply of raw materials. This is not affordable for low income households living in an informal settlement. However, this is a solution that can attract government funding and even corporate funding through CSR/CSI if the business model is well developed.

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Feasibility Study Of Microgrids in North Kurdufan State.

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(DISPLAYED IN POSTER SESSION)

Abstract

North kurdufan recorded as one of the states below energy poverty line of electricity. Its rural population has no access to electricity service. Essential efforts needed to provide energy for these rural areas ' via available renewable energy resources. The local government, International non-governmental organizations (INGOs) and non-governmental organizations (NGOS) had established many solar projects to supply energy, nevertheless, all implemented solar projects faces a sustainability challenges. In order to meet power demand for rural communities' Microgrids system is needed, it can be viewed as a promising option for remote village's electrification. A comprehensive review of socioeconomic enablers and inhibitors was conducted beside the identification of successful optimized potential energy sources mix, collected data of rural electrification needs is used for system optimization utilizing Homer energy software. As the results show, the high initial capital cost and sustainability of the optimized system pose real challenges. Our focus is on how to build an effective financing strategies and how to engage local communities to enhance the deployment and the expansion of rural Microgrids.

Keywords: Microgrids; rural electrification; system optimization; sustainability.

Introduction:

Currently around 1.5 billion people worldwide live without electricity in their homes. An estimated 80% of those people live in rural areas (Simon and Guido 2011); according to International Energy Agency projections, the number of people without electricity is not likely to drop due to population growth, the electrification rate in Africa is 40%. In Sudan 71% of population do not have access to electricity, large projects will be implemented by Ministry of Energy and Water Resource to reduce the rate to 51% by 2030 (Simon and Guido 2011).

North kurdufan state lies in semi-arid zone with 2,474,427 person of which 25% in urban areas and 75% in rural areas. Inhabitant mainly engage in agricultural activities, their basic energy consumption is based on traditional fuel, 93% wood (zero cost) and 7% charcoal for cooking, kerosene lamps, Handy torch for lighting, and batteries for their radios.

The village's remoteness, transmission cost and low demand for power made grid extension not feasible to electrify rural areas. Only 24% of state populations are grid connected. 7.3% are supplied by diesel generators (for 6 hour per day), 3.2% are families' generator and 0.8% solar home systems. (Remond 2015).

The focus of solar energy projects implemented by local government, International non-governmental organizations (INGOs) and non-governmental organizations (NGOs) was on the installation of small solar system to provide basic services (water- education – health care) rather than electrification of households sector.

Many countries around the word implemented microgrids systems in remote areas with different specifications, such as Senegal, Uganda and India (J.A. azola et al 2014, Raymond et al 2014, Debajit Palit and Gopal K Sarangi 2014, T.E. Del et al 2010), to supply electricity in public institutions, household and business sector to enhance socio- economic growth within local communities.

Cold storage for low cost air conditioning

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(full paper will appear in AJSTID)

Abstract

Building heating, ventilation and air conditioning (HVAC) is estimated to consume approximately 50% of the energy consumed by a building. Such high costs are based on the conventional vapour compression refrigeration cycle for air cooling and are benchmarked for on grid buildings. However, there are alternative passive and active phase change based cold storage systems that can be used to reduce building HVAC costs for on grid systems and provide a viable solution for off grid HVAC. This paper reports on tests conducted at a site in Johannesburg that demonstrate the potential of such technology under sub-tropical conditions. Tests were conducted for a phase change material (PCM) with a melting point of 25^{o}C with varying air flow rates for air supplied at ambient summer conditions. The PCM was encapsulated in aluminium casing (in plate form), which provided good thermal contact between the PCM and the conditioning air. Although the tests were conducted on a specially designed and constructed test rig, the results demonstrated the potential to reduce the conditioning air temperature by about 3^{o}C before supplying the air into the conditioned space.

Keywords: Cold storage, Displacement ventilation, Phase change material

Motivation

The current day levels of population growth imply that power supply (especially electricity) cannot keep up with demand. Increased technological development and urbanisation can only increase demand further. Furthermore, buildings consume a significant portion of energy. In South Africa, heating, ventilation and air-conditioning systems are reported to consume about 50% of the building energy demand (ESKOM - Generation Communication, 2014). This translates to 15% of South Africa's current peak demand consumption in summer. Various strategies have been implemented to try and reduce this demand with limited success. ESKOM encourages consumers to increase the target temperatures in conditioned spaces to reduce energy consumption. Moreover, off grid communities living in hot areas such as the Limpopo Province of South Africa have no means of cooling down buildings in summer. One possible solution is to use free cooling to provide comfortable conditions in occupied spaces. The purpose of this paper is to investigate the viability of using a combination of displacement ventilation (DV) and phase change materials (PCM) cold storage for low cost air conditioning. If successful, this will lead to a reduction of energy consumption in building HVAC systems and provide a low energy solution to HVAC in off grid communities.

Methodology

Materials

Various materials are available for cold storage. For this work, a phase change material with commercial name RT25HC supplied by Rubitherm (Rubitherm® Technologies GmbH, 2016), a Germany company was used. It was supplied enclosed in aluminium plates for good thermal contact with the conditioning air. The materials were supplied encapsulated in aluminium plates. The dimensions of the plates were 300 × 450 × 10 mm.

Equipment

A special rig was design with capacity to take 15 PCM plates. The main housing was built with Perspex glass which is easy to machine and is a good thermal insulator. The inlet and exit ducts were made of galvanised plates and were then insulated for the required thermal performance. The conditioning air was drawn through the plates using a variable speed fan. Temperatures were measured at various points along the air flow path using K-type thermocouples. Air flow velocity was measured using a hotwire anemometer while humidity and ambient pressure were measured using a barometer.

Experimental Procedure

The fan use in the tests was calibrated for three speed settings. For each measurement cycle (over a 24 hour period), a single fan speed was selected and data logging was made every ten minutes including humidity measurements. The system was left to run for 24 hours in order to capture the charging and discharging behaviours. The same procedure was repeated for each of the selected fan speeds.

Conclusions

This paper has presented the experimental work conducted to determine the effectiveness of using PCM based cold storage to transfer the night time cold to cold air for air-conditioning purposes during the day. Experimental tests were successfully conducted using a specially designed rig with packaged PCM encapsulated in aluminium plates. The results obtained clearly demonstrate the viability of this approach. Based on the results obtained, the following conclusions can be made:

1. A packaged bank of PCM plates can be successfully used to transfer night time cold to cool air during the day
2. The lower the air mass flow rate, the more effective is the heat transfer
3. Average temperature drops of 3, 2 and 1.5 decrees were achieved for air flow rates of 0.02552, 0.06434 and 0.07313 kg/s respectively
4. Total energy transferred averaged 2.3, 1.1 and 0.9 kJ for air flow rates of 0.02552, 0.06434 and 0.07313 kg/s respectively
5. This technique is a viable approach to reducing air conditioning energy consumption and affords opportunities for off-grid air-conditioning

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Why are Households Adopting Small-Scale Solar in Northern Tanzania? Survey results from the Arusha and Kilimanjaro regions.

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Abstract
The proliferation of modern energy services is a key component to advancing development in the Global South. Grid expansion to serve this population is slow and costly, but a technology exists which can serve as a stop-gap to grid electricity, and even has the potential to leapfrog grid technology: solar energy. We carried out surveys in Northern Tanzania to gain an understanding of the factors – such as knowledge, opinions, social networks, and product quality – which are associated with a person's decision to invest in a small-scale solar product. While overall opinions of solar are high and knowledge is relatively low, we found that solar users have higher opinions, more knowledge, and more solar users in their social network. We also found that 47% of our sample uses a solar product as their primary source of light. This number likely has some bias due to our sampling methods, but the actual number is almost certainly higher than the approximately 4% value published in the most recent census. This growth may be attributable to increased availability due to international solar retailers active in the area.

1 Introduction

Modern energy services and other infrastructure technologies are a critical component of improving quality of life and enhancing human development in the Global South. There is a positive relationship between a country's access to electricity and selected Millennium Development indices related to gender, education, poverty, and maternal mortality. If used efficiently, even the first few watts of electricity have high marginal benefits for household health, education, and poverty reduction (Alstone, Gershenson, & Kammen 2015). However, in mainland Tanzania the electrification rate is 18.4%, with only 3.8% of people in rural areas having access to grid electricity (National Bureau of Statistics 2014). A significant amount of work needs to be done in order to provide modern energy services to Tanzania, which will contribute to the nation's development.

Despite the importance of electricity, there is little hope for nationwide expansion of grid electricity in the near future. The estimated cost to extend the grid to rural areas ranges from 550 to 4300 USD per customer, with an average of 1547 USD, in 19 different regions examined in Tanzania (Rosnes & Vennemo 2012). When comparing these values with Tanzania's per capita GDP of 865 USD (2015) it is clear that the costs of extending the grid cannot be supported by Tanzanians themselves; thus, the situation is unlikely to improve without significant financial assistance (World Bank 2016).

In the absence of electricity, the majority of Tanzanians turn to kerosene as their primary source of light, with 61% of people in mainland Tanzania and 70% in rural areas using kerosene, as of the most recent census. Other light sources include battery powered torches and lamps, candles, and wood (National Bureau of Statistics 2014). Despite its widespread use, there are many disadvantages to kerosene lamps, including: indoor air pollution that may impair lung function and increase the risk of tuberculosis, asthma, and cancer (Lam, Smith, Gauthier, & Bates 2012; Mills 2012); safety risks due to poisonings, fire, and explosions (Lam, Smith, et al. 2012; Mills 2012); inefficient, dim flickering light (Mills 2005); substantial kerosene expenses, with approximately one fourth of income in rural areas being spent on lighting (Greenmax Capital Advisors 2013; SolarAid 2014); and greenhouse gas and black carbon emissions that have a significant contribution to climate change (Lam, Chen, et al. 2012). The recent WHO Guidelines for Indoor Air Quality discourage the use of kerosene (World Health Organization 2014). Despite these evident disadvantages, the vast majority of Tanzanians continue to use kerosene and other rudimentary sources, possibly due to a lack of perceived alternatives.

Solar photovoltaic (PV) lighting products (henceforth referred to as solar lights/lamps/lanterns, solar home systems, or simply as solar) may be a viable alternative to kerosene lamps and other sources of light for off-grid populations in Tanzania. There are many benefits to using solar over kerosene lamps since they have zero emissions, do not have the safety concerns of kerosene, are significantly brighter than kerosene lamps, and pay for themselves in kerosene savings. A random-control trial in Rwanda quantitatively demonstrated the benefits of solar lamps, showing users consumed 128% more light per day (lumen hours) while their kerosene expenditures were 70% lower, 45% reported improved indoor air quality, and 71% more children study after dark (Grimm, Munyehirwe, Peters, & Sievert 2014). SolarAid also found a significant increase in students' studying time among users of solar lamps (SolarAid 2014).

Despite the benefits of solar lights compared to kerosene lamps, the most recent national surveys conducted in Tanzania showed that very few people had adopted solar power as their primary light source. According to the 2011/12 Household Budget Survey only 1.6% of people in mainland Tanzania and 1.8% of people in rural areas used solar energy as their primary source of electricity or light (National Bureau of Statistics 2014). The census numbers are slightly higher in the Arusha and Kilimanjaro regions of Tanzania at 3.9% and 3.5%, respectively (National Bureau of Statistics 2015).

We began this research under the assumption that the number of solar users had not significantly increased since 2012. As such, our primary objective was to gain a better understanding of why solar adoption is so low by gaining insight on the underlying factors that affect a person's choice to purchase and use solar lighting products. A better comprehension of these factors might enable practitioners to increase market demand for solar products, thereby reducing the use of harmful kerosene lamps. Although the results of our sample indicate that solar use in the Arusha and Kilimanjaro regions has increased significantly since 2012, our primary objective is still relevant: an understanding of solar adoption factors could be used to further increase solar uptake in these regions, and this knowledge may be applicable in other parts of Tanzania and Sub-Saharan Africa.

The factors of primary interest in this research are those relating to the adopter's (purchaser/end-user) perspective. Through a thorough literature review, we have found availability, affordability, awareness/knowledge, and attractiveness/opinions to be the four main factors influencing the adopter. While some of our survey results are directly related to availability and affordability, to gain a better understanding of these factors we need to undertake additional geospatial and economic analyses, which are beyond the scope of this paper. As such, this paper focuses on people's knowledge and opinions of solar, and how this knowledge and these opinions can be impacted by the adopter's social network and their perceived product quality.

2 Literature Review

The literature shows that having information about a technology is an important prerequisite to adoption. Using the literature, focus groups, and interviews of experts who have experience with small scale solar PV, Hirmer and Cruickshank (2014) find one of the key elements of sustainable product development for rural electrification is ensuring the end-users are aware of a product's existence and its benefits. They find a large disconnect between how critical awareness is and the extent to which it is being addressed by practitioners. Further, they express the importance of raising awareness and understanding of a product's benefits in transitioning to a technology 'pull' by rural customers for small scale solar products (Hirmer & Cruickshank 2014).

Other researchers have noted the deficit of awareness or knowledge of solar light and power products in Sub-Saharan Africa (e.g. Grimm et al. 2014), and other research has noted that this lack of awareness and knowledge negatively affect uptake (e.g. Eder, Mutsaerts and Sriwannawit 2015; Amankwah-Amoah 2015). Thus, the literature expresses the importance for potential adopters to have knowledge about a technology, yet there is a significant lack of knowledge about solar PV products, and a lack of action being taken to address this problem.

While it is important for potential users to have knowledge about solar technology, there are many possible means by which this information can be disseminated. There is some evidence in the literature of solar clustering, which may imply that information exchange occurs via social networks. In Kenya, Lay et al. (2013) found that a potential solar home system (SHS) user has a greater probability of adopting if they live in an area with greater SHS predominance. The authors reason that local knowledge of SHS is very important when a user is deciding to adopt. Similarly, in Nicaragua, Rebane and Barham (2011) found that the presence of SHS in an area is the strongest and most consistent predictor of people's level of knowledge related to different aspects of solar technology. Therefore, solar clustering and the resultant exposure to nearby systems has a significant impact on knowledge of this technology, and likely shapes people's opinions as well.

There is some evidence of solar clusters affecting not only knowledge (i.e. Awareness) and opinions (i.e. Attractiveness) of solar technology, but also the speed and overall rate of uptake. In Sri Lanka, McEachern and Hanson (2008) found that being proximate to installed SHSs is correlated with less time to adoption after becoming aware of the technology. Also, in the study of SHS adoption in Nicaragua, 100% of adopters surveyed (40) had "other SHSs present" in their immediate vicinity, whereas only 37% of non-adopters had other SHSs present near them (Rebane & Barham 2011). Thus, there is some indication that proximity to installed solar PV systems increases adoption in the nearby area, perhaps via the effects of these networks on product knowledge and opinions.

There is additional evidence that solar clusters may be a result of information diffusion through social network. A survey of SHS adopters in Kenya showed that they first learned about these systems from friends, relatives, and neighbors, often by observing an installed system (Acker & Kammen 1996). Through a survey of the literature on solar PV in various developing countries, Nieuwenhout et al. (2001) find that word of mouth and observations of installed systems appear to be the most effective ways of spreading awareness. Therefore, it appears that social networks have an important role to play in diffusion of information related to solar PV technology.

While social networks have the ability to increase awareness and attractiveness, and may increase adoption of these products, these networks also have the ability to negatively affect adoption rates. If shared opinions are negative due to poor quality products, or other reasons, it is possible that this could "spoil the market" for these products. For example, LED flashlights are becoming ubiquitous in East Africa, and a 2009 surveys of consumers in Kenya showed 87% of those surveyed had quality issues with their flashlights in the last 6 months, and the average lifetime reported was approximately three and a half weeks (Tracy, Jacobson, & Mills 2009).

A 2010 Lighting Africa report confirms the poor quality of these LED flashlights through lab tests of samples collected in the Kenyan market. Most of the products tested had severe lighting performance degradation or total failure within 2 months. Additionally, even when new, the performance specifications, such as brightness and battery life, were not as advertised (Mink, Alstone, Tracy, & Jacobson 2010). As such, Lighting Global created a product testing program to help ensure quality. However, 65 of 110 products tested as of 2014 did not pass the minimum quality standards, with only 31 of 65 products being revised to meet the standards (Mills, Tracy, Alstone, Jacobson, & Avato 2014). These products were voluntarily submitted by manufacturers, so there is likely to be many other low-quality lighting products on the market in Tanzania.

These low-quality off-grid lighting products have the ability to spoil the market for other off-grid lighting products including small scale solar PV products, which also use LED lights. In Kenya, Mills et al. (2014) demonstrated this market spoiling effect; their experiment revealed that prior experience with low-quality LED lighting products led to skepticism and significantly less uptake of a different – high-quality – LED product offered for sale, even though it was offered with a one year money back guarantee. This market spoiling effect is especially problematic because consumers are aware of the availability of low-quality products but are not able to distinguish high-quality products from low-quality products before purchase. Mills et al. (2014) refer to this as a case of information market failure. Thus, low quality products have the potential to hinder the market for solar lighting products.

3 Methods

3.1 Sampling

The location of our study was approximately within a 60 km radius of both Arusha and Moshi, as seen in the map in Figure 1, excluding Arusha city and Moshi municipal districts. This area was of particular interest, as two major solar retailers are active in this area, Mobisol and Mpower (Off-Grid Electric). This enabled us to understand how awareness and attractiveness might be affected in relation to these retailers' activities and their reach. The selection of a limited geographic area for the study was also necessary given time and resource constraints. Ideally we would have included a control region where international solar enterprises are not active, in order to better assess the impact of these businesses.

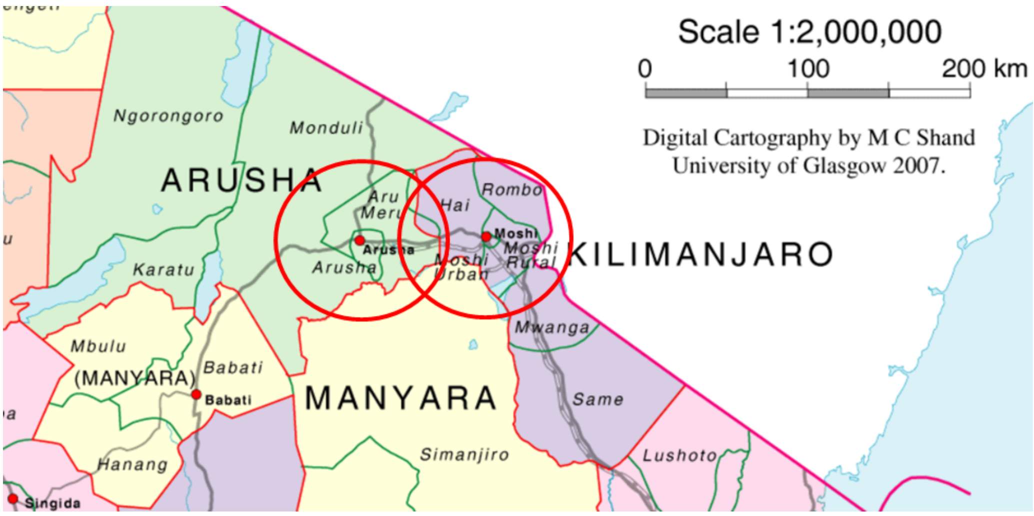

Figure 1: Map of study area within 60 km of Arusha and Moshi

In order to maximize the representativeness of our sample population, while maintaining a feasible study design, a random cluster sample was used. Random selection occurred at the ward level, since that was the highest resolution data publicly available.

There were 45 wards within the study area in the Arusha Region, and there were 101 wards within the study area in the Kilimanjaro Region. We randomly selected 9 wards from each region, but were only able to carry out surveys in 8 wards per region. Two villages were randomly selected within each ward, and 10 surveys were carried out in each village.

Since census data was not available, the village chair was asked to generate a list of households from memory. This proved to be a somewhat difficult task, so we generally deemed a list 30 households to be sufficient, from which 12 were selected (2 extra in the event that someone from a listed household could not be reached). Upon our arrival, the village chair was informed about the study, therefore he had knowledge of our interest in solar. To minimize the bias this might have induced, we specifically instructed the village chair to write household names without thinking about their energy/light source. Still, it is likely that this sampling method introduced some bias, which must be taken into account when considering the number of solar users present in our sample; however, this bias should not affect the validity of the survey results which explore the relationship between various factors and solar use. In fact, having surveys from a large number of solar users increases our statistical power to examine similarities and differences among different users.

3.2 Surveying

Participants were asked questions verbally in Swahili, the national language of Tanzania. The survey consisted of questions regarding socioeconomics and demographics, current light sources, knowledge and opinions of solar, social network as it relates to solar, and perceived product quality.

3.3 Analysis

For this paper a set of bivariate analyses were carried out, in order to get a broader understanding of how awareness, attractiveness, and other factors may be related to a person's decision to adopt solar technology. We explored the relationship between the outcome variable of solar use (yes or no), and responses to other survey questions in the categories mentioned above (independent variables). To put this another way, we tested if there is a meaningful difference in how users and non-users responded to these questions. Questions with disparate answers between the two groups can illuminate potentially interesting patterns that could be explored through further data analysis or additional data collection, since the relationships cannot be taken as causal.

We tested for relationships using a chi-square test for discrete independent variables, and a point biserial (Pearson's product-moment) correlation for continuous independent variables. A higher chi-square statistic indicates that there is a stronger relationship between the independent and outcome variables. The r value associated with the point biserial ranges from 1 to -1, with 1 indicating a perfect correlation, -1 being a perfect inverse correlation, and 0 indicating no correlation. Significance is determined at the 0.05 level. Blank responses or multiple responses for any given question were not included in the statistical analysis.

4 Results

4.1 General

Preliminary analysis showed that 46.6% of respondents use some form of solar for their primary source of light. By region, this translates to 59.9% of respondents in Arusha and 33.3% of respondents in Kilimanjaro, which was surprising, given that 3.9% of people in Arusha and 3.5% of people in Kilimanjaro used solar for their "main source of energy for lighting" as of the 2012 census (National Bureau of Statistics 2015). When accounting for solar used as a backup source of light, a total of 56.5% of respondents use this technology. Furthermore, 30.4% of the sample use solar home systems (SHS) as their primary source of light, and 16.2% of the sample use self-contained solar lanterns, meaning 65% of solar users are using a larger solar system capable of delivering more than light. Among SHS users, 92% report using the system for cell phone charging, 55% are powering a radio, and 29% are powering a TV.

The sample may be subject to some bias introduced by having a limited list of households to choose from, which was generated from memory by a village leader who had knowledge of the purpose of our research, rather than a complete list of households. However, the mean income of our sample ($18.82/week) is not significantly different from the 2014 or 2015 World Bank figure for GDP/capita ($18.36/week, $16.63/week respectively), so there isn't evidence of an income bias (World Bank 2016). Additionally, we do not purport that our sample is representative of Tanzania as a whole, since there are two international solar enterprises based, and actively operating in this part of the country. This may have played a role in the high adoption rate in this area.

4.2 Socioeconomic and Demographic

In order to better understand the adopter perspective, we will start by examining how their demographics and socioeconomic indicators are related to the decision to use solar. The only discrete socioeconomic data which has a significant relationship ($p \leq 0.05$) with the choice to use solar is the ease with which respondents are able to save money. Those who do not use a solar product were 64% more likely to disagree or strongly disagree that it is easy to save money.

The data which are not correlated with the choice to use solar are just as interesting as the data which are correlated. For example, the decision to use solar does not appear to be significantly correlated with one's level of education. Additionally, the respondents' cooking source (e.g. an improved cookstove) and their home construction do not seem to be related to solar use. The chi-square statistics and p-values for discrete socioeconomic and demographic data can be seen in Table 1.

Table 1: Chi-square test for relationships between solar use and discrete socioeconomic and demographic data, ordered by strength of relationship.

Survey Question	*chi-square*	*p*
'it is easy to save money'	9.31	0.05
'source of income'	8.59	0.13
'it is easy to borrow money'	7.39	0.12
'level of education'	4.10	0.53
'primary cooking source'	3.83	0.57
'type of wall construction'	3.47	0.32
'wage or variable income'	1.81	0.18
'type of roof construction'	1.07	0.30
'marital status'	0.58	0.45

In addition to the results in Table 1, the continuous socioeconomic and demographic variables can be found in Table 2. Interestingly, number of children living at home is a significant independent variable, but the total number of children is not. Solar users have a higher number of children at home than non-users, with an average of 3.6 and 2.8 respectively.

As with the discrete data in Table 1, continuous socioeconomic and demographic data that is not significantly correlated with solar use is quite interesting. Foremost, income does not appear to be correlated with the decision to adopt solar, though income measurements aren't always reliable. Similarly, questions about the amount to be saved or borrowed in a week, or the amount of time needed to save enough to buy a solar lamp are not significantly correlated with solar use. Additionally, it appears that the ownership of cows and land is correlated with solar use, while other measured assets are not correlated.

Table 2: Correlations coefficients for continuous socioeconomic and demographic data and solar use, ordered by correlation coefficient.

Survey Question	***User mean***	***Non-user mean***	***r***	***p***
'number of cows'	11.10	3.20	0.20	0.00
'acres of land'	3.38	1.75	0.17	0.00
'number of children living at home'	3.62	2.75	0.16	0.00
'number of children'	5.13	4.43	0.09	0.10
'number of houses'	1.31	1.17	0.09	0.11
usual/average weekly income' (USD)	21.91	16.12	0.07	0.3
'number of goats'	3.37	2.63	0.05	0.43
'number of motorcycles'	0.21	0.19	0.02	0.71
'number of cellphones'	1.12	1.11	0.01	0.88
'number of other people living with you'	0.86	0.95	-0.03	0.63
'number of chickens'	9.81	14.12	-0.07	0.25
amount able to be saved in one week' (USD)	7.19	8.56	-0.08	0.31
amount able to be borrowed in one week' (USD)	11.00	14.25	-0.09	0.54
'number of days to save 15,000 Tsh'	14.19	19.71	-0.09	0.12
'number of cars'	0.02	0.06	-0.09	0.13
'age'	41.84	44.85	-0.10	0.13

4.3 Social Network

As seen in the literature review, understanding the influence of one's social network may provide insight into their decision to adopt solar. There is a significant relationship between solar use and the majority of questions asked relating to participants' social networks. Solar users were 68% more likely to report knowing more than 20 family members or friends and neighbors who use solar products. Non-users were 87% more likely to know zero family members or friends and neighbors who use solar products.

While having heard convincing reasons to use solar is significantly correlated with solar use, there is not a significant difference between users and non-users having heard convincing reasons *not* to use solar from people they know. Additionally, the number of people known who have had a solar product break is not significantly different for users and non-users. The social network chi-square and p-values can be seen in Table 3.

Table 3: Chi-square test for relationships between solar use and discrete social network data, ordered by strength of relationship.

Survey Question	***chi-square***	***p***
'number of family members using solar '	21.62	0.00
'number of friends and neighbors using solar '	19.1	0.00
'family member's opinions of solar'	14	0.00
'friends and neighbor's opinions of solar'	9.09	0.01
'have heard convincing reasons to use solar from people they know'	7.75	0.05

4.4 Product Quality

Poor product quality has the potential to spoil the market for solar lighting products, so it is important to gain understanding of adopters' perspectives on quality. Non-users were more likely to agree or strongly agree that flashlights are of good quality, even though there are documented quality issues with flashlights in Sub-Saharan Africa. Solar users are more likely to agree or significantly agree that there are high quality *and* low quality solar lamps available for purchase. Solar users were 78% more likely to agree or strongly agree that they can tell the difference between high and low quality solar lamps available at the market. The chi-square and p-values for these question topics can be seen in Table 4.

Although solar users believed that solar home systems lasted significantly longer than non-users, there is no difference in the expected life of a flashlight between the two groups, nor the expected life of a solar lamp. Interestingly, flashlights are expected to only last 10.5 weeks on average, and solar lamps are expected to last 26.5 months on average. These statistics can be seen in table 4.

Table 4: Chi-square test for relationships between solar use and discrete product quality data, ordered by strength of relationship.

Survey Question	*chi-square*	*p*
'can identify between high quality and low quality solar lamps'	27.99	0.00
'there are low quality solar lamps available at the market'	27.63	0.00
'there are high quality solar lamps available at the market'	24.68	0.00
'most flashlights are of good quality'	8.05	0.09
'have had problems with flashlights in the past'	2.48	0.65

Solar users believed that solar systems would last longer than non-users, with an average expected life of 8.9 years and 5.4 years respectively. While there is not a significant difference in the number of people having experienced problems with flashlights between the two groups, it is worth noting that 80% of respondents strongly agreed that they have had problems with flashlights. The chi-square and p-value for this question can be seen in Table 5.

Table 5: Correlations coefficients for continuous product quality data and solar use, ordered by correlation coefficient.

Survey Question	*User mean*	*Non-user mean*	*r*	*p*
'expected life of a solar system' (years)	8.90	5.40	0.22	0.01
'expected life of a solar lamp' (months)	27.34	25.62	0.04	0.57
'expected life of a flashlight' (weeks)	10.05	10.88	-0.02	0.76

4.5 Opinions of Solar

In order to better understand the relationship between attractiveness and the decision to purchase solar, we must understand how opinions differ between users and non-users. Nearly all of the questions relating to people's opinions of solar were significantly different between users and non-users. In these instances, users had more strong favorable opinions than non-users. Despite this difference between groups, the majority of non-users also have strong favorable opinions of solar, except on questions about availability and proximity to purchase.

The only opinion question about solar that was not significant between the two groups is the likelihood of purchasing a solar product in the future. Among solar users and non-users 72% said they agree or strongly agree that they will buy a solar product in the future. The statistics for all solar opinion questions can be seen in Table 6.

Table 6: Chi-square test for relationships between solar use and discrete solar opinion data, ordered by strength of relationship.

Survey Question	*% Users 'Strongly Agree'*	*% Non-Users 'Strongly Agree'*	*chi-square*	*p*
'solar products have bright light'	88	68	42.78	0.00
'solar products are available'	77	48	41.25	0.00
'solar products increase income'	89	70	40.41	0.00
'solar products increase security'	93	74	38.35	0.00
'solar products (would) save me money'	93	71	36.60	0.00
'solar products increase time available to do work'	89	71	34.31	0.00
'solar products increase quality of life'	95	71	32.24	0.00
'solar products are reliable'	82	70	28.39	0.00
'solar products are sold nearby'	48	32	25.66	0.00
'solar products increase leisure time'	80	66	23.96	0.00
'solar products are good for the environment'	97	81	21.78	0.00
'solar products increase study time'	97	83	21.31	0.00
'solar products are good for health'	91	83	10.74	0.03
'I will purchase a solar product in the future'	58	65	4.82	0.31
'solar products have bright light'	88	68	42.78	0.00

4.6 Current Level of Knowledge about Solar

Knowledge, or awareness, is seen as an important prerequisite for solar use, so it is useful to examine peoples' current level of knowledge related to solar, and how that knowledge differs between users and non-users. All of the questions pertaining to people's self-reported knowledge related to solar had significantly different responses among solar users and non-users. In general, self-reported knowledge is low for both groups. Solar users had higher levels of knowledge in areas that would come as a result of owning a solar product, but their knowledge is comparatively low in other areas. These results can be seen in Table 7.

Table 7: significant correlations for discrete solar knowledge data and solar use.

Survey Question	*% Users 'Agree'*	*% Non-Users 'Agree'*	*chi-square*	*p*
'know how solar energy works'	69	15	118.06	0.00
'know how to match panel size to battery size'	21	5	31.53	0.00
'have general knowledge about solar products'	22	5	43.88	0.00
'know about the different types of solar products'	34	10	51.76	0.00
'know how to identify high quality products'	20	6	31.05	0.00
'know how to use solar products'	61	15	116.68	0.00
'have knowledge about the solar market'	9	2	20.11	0.00
'know where to buy solar products'	60	28	43.18	0.00
'know the price of a single solar lamp'	71	28	72.49	0.00

'know about the benefits of solar products'	82	30	90.47	0.00

The reported price of a solar lamp is significantly different between solar users and non-users, with an average of 16,197 Tsh (7.53 USD) and 10,285 Tsh (4.78 USD), respectively. The approximate actual price of a single standalone solar lamp is 15,000 Tsh (6.97 USD). The r value and p-value for this question are 0.17 and 0.02, respectively.

4.7 Desire for Knowledge about Solar

Knowledge was relatively low among the respondents, so it is important to understand if this is the result of a lack of desire for knowledge, or a lack of availability of knowledge. For those who have received any information about solar, the source of this information is significantly different between users and non-users, with a chi-square of 27.77 and a p-value of 0.00. The actual sources of information can be seen in Table 8. The majority of information comes from people known to the respondent, for both users and non-users. Solar users tend to get more of their information from NGOs and retailers, compared to non-users. Non-users are more likely to have gotten information from the radio, compared to users.

Table 8: source of information about solar for solar users and non-users

	NGO	*Government*	*Radio*	*Television*	*Sellers*	*People I know*	*Other*
Users	14	0	9	5	45	67	5
Non-users	1	3	22	8	23	75	5

The difference between the two groups was not significant for the desire for additional information about solar, or the type of information, with p-values of 0.09 and 0.47, respectively. However, there is a clear desire for more information from both groups, with 91% of respondents strongly agreeing with the statement that they want more information about solar. The type of information desired is primarily about the benefits of solar, and how to identify the quality of solar products.

5 Discussion

Firstly, the multiple comparisons issue should be taken under consideration when looking at the results as a whole; when considering a larger set of statistical inferences, the likelihood of finding a false positive by chance increases (Hsu 1996). The large number of variables included in this analysis increase the chances of one or more of the results being a false positive. Since this is an exploratory analysis, we do not explicitly correct for multiple comparisons, but note that results should not be overinterpreted as definitive relationships. Rather, this analysis highlights relationships that may warrant further exploration.

5.1 Demographics

There is some evidence that the ability to save is related to the ability to purchase a solar product. Both the self-reported 'ability to save money,' and the number of cows and acres of land are significantly correlated with the decision to use solar. Cows and land represent significant investments; thus, these metrics may also support the position that the ability to save is an important factor when a person is deciding whether or not to adopt solar energy. However, these results may be due to the Masaai culture that is associated with cows and land, and is more dominant in the Arusha region where solar use is also higher compared to Kilimanjaro. Additionally, the self-reported amount a person is able to save in a week is not correlated with use. This may be because solar products, especially solar home systems, represent long term investments. The fact that other pieces of property are not correlated with solar use is not seen as strong evidence against the importance of the ability to save money: chickens do not represent a significant investment, nearly everyone in the sample owns a house and a cellphone, car and motorcycle ownership is infrequent.

Although one might expect income to be a factor in the decision to use solar, there is not evidence of this based on a direct question about income. Besides number of cattle and acres of land, other proxies for income are not correlated with the decision to use solar, such as house wall and roof type (e.g. mud and brick walls, or grass or metal roofs). Other questions about income, such as the amount able to be saved in a week, or the number of days to save 15,000 Tsh (6.97 USD), are not correlated with solar use. Furthermore, the source of income or the variability of income does not appear to be related to the decision to use solar. Income variability is likely not a factor because 96% of our sample reported having a variable income. The evidence in this analysis appears to suggest that income is not an important factor. This could be due to the difficulties encountered when measuring income in this context, such as accounting for the temporally variable nature of income or the unreliability of self-reported income. A principal component analysis (PCA) should be used to distill all of the wealth and asset related variables into a single wealth indicator to be used for further analysis.

It is unclear why the number of children living at home would be significantly correlated with solar use, but total number of children is not. In long form interview questions, respondents often expressed the importance of solar light for their children's studies, and many also said that their children were most influential in their decision to adopt solar. Thus, if children have grown and left the house, or have finished their studies, there may be less imperative to get solar powered light.

Level of education is a factor which is seemingly relevant to one's decision to use solar; however, our survey does not find evidence of this. It is possible that education level does not matter as much as technology specific knowledge. Similarly, one might assume that younger people have more knowledge of this newer technology, but age is not found to be correlated with solar use. Cookstoves are another newer technology with many benefits, and may have similar factors that influence adoption, yet cooking fuel is also not found to be correlated with solar use.

5.2 Social Network

There appears to be a relationship between a person's social network as it relates to solar, and their decision to use a solar product, as predicted by the literature review. Solar users are much more likely to know a large number of friends, neighbors, and family members who use solar, while non-users are more likely to not know of any solar users. This may be a result of the solar clustering effect seen in the literature review. However, in this analysis we are unable to differentiate actual social effects from geographic effects and other influences, due in part to the complex nature of social networks.

There is a relationship between solar use and 'having heard convincing reasons to use solar', but 'having heard convincing reasons *not* to use solar' is not significantly associated with solar non-use. This may be a result of confirmation bias, a phenomenon where people are more likely to accept information that is consistent with their preexisting beliefs, and give less credit to information that does not conform to their beliefs (Nickerson 1998). Since opinions of solar are generally high, even among non-users, confirmation bias may cause people to disregard negative opinions of solar that are provided by a peer.

5.3 Product Quality

The results of this survey add to the body of literature documenting quality problems with lighting products in Sub-Saharan Africa – especially flashlights. Respondents expect a flashlight to only last 10.5 weeks. More than half of respondents believe there are low quality solar lanterns available at the market. At the same time, our results do not provide clear evidence of a market spoiling effect. The results seem to suggest that solar users are more aware that there are high *and* low quality solar products available at the market, and are better able to differentiate high quality and low quality solar products. This is an example of information market failure, which Mills (2014) has previously expressed concerns about with regard to solar product quality in Sub-Saharan Africa.

Non-users were more likely to indicate that flashlights are of good quality, even though 80% of respondents strongly agreed to having had problems with flashlights in the past, and that they have a short expected life. This may be attributable to non-users' lack of experience with alternative light sources, such as solar lanterns; thus, frequent issues and short lifetimes seem normal for flashlights. This lack of experience may underlie the significant difference in the expected life of a solar system, as reported by users (8.9 years) and non-users (5.4 years). This question also had the highest absolute r value, meaning it showed the strongest correlation with solar use.

The reported lifetime of a solar lantern was not significantly different between users and non-users. Both groups expect solar lamps to last more than 2 years, which is much longer than the expected life of a flashlight. This suggests non-users do have some familiarity with solar products, especially smaller ones. While solar users are more aware that there are high *and* low quality solar products available at the market, non-users may be less certain about solar product availability in general.

5.4 Opinions of Solar

Nearly all of the questions relating to people's opinions of solar were significantly different between users and non-users. In all instances users were more likely to have strong positive opinions, but non-users also largely have positive opinions of solar. We cannot determine if solar users' opinions are higher because they have firsthand experience, or if they had a high opinion beforehand, which led them to purchase a solar product. However, both users and non-users have the same amount of desire to purchase a solar product, which seems to indicate that higher opinions may not lead to a higher desire or likelihood of purchase above a certain opinion threshold.

5.5 Current Level of Knowledge about Solar

All of the questions pertaining to people's self-reported knowledge related to solar had significantly different responses among solar users and non-users. Solar users had higher levels of knowledge in areas that would come as a result of owning a solar product, but their knowledge is comparatively low in other areas. Knowing how solar energy works, how to use a solar product, and the benefits of solar had the highest chi-squared values, in that order. Also, the average reported price for a solar lamp is much closer to the actual value. These types of knowledge most likely come as a result of actually buying and using the products, so we are not able to conclude that having more knowledge about solar leads to an increased likelihood of solar adoption. We also cannot rule out the possibility that increasing knowledge, especially about benefits, location, and price, would have a positive effect on adoption.

5.6 Desire for Knowledge about Solar

It is clear that both groups want more information about solar, with 91% of respondents strongly agreeing to this assertion, especially with regard to benefits and how to discern product quality. The fact that more users have gotten information about solar from an NGO suggests that NGOs may have a positive effect on uptake. The fact that more non-users have gotten information about solar from the radio may indicate that this is not an effective medium for increasing the purchase of solar products. It is unsurprising that more users have gotten information from businesses, since this likely occurred during the purchase process.

6 Conclusions

The most striking finding of this study is the high number of solar users in the Arusha and Kilimanjaro regions of Tanzania, with 46.6% of our sample using solar as their primary source of light. While our sample is not statistically representative of the region due to bias in the sampling method, it seems clear that solar usage in this area is significantly higher than it was as of the 2011/2012 census. It is unclear if other parts of Tanzania and Sub-Saharan Africa are experiencing similar growth in solar adoption, or if this is the result of the international solar corporations that are active in these regions. These solar retailers are undoubtedly making solar more available in the area, and are likely affecting awareness (knowledge) and attractiveness (opinions) of solar, as well.

We set out to research the importance of availability, affordability, awareness, and attractiveness on the adoption of solar products, and how these factors might be influenced by social networks and product quality. With this analysis we are unable to draw conclusions about how availability affects solar uptake, but it is evident that users believe solar is more available than non-users. Furthermore, it is unquestionable that the availability of a product is a prerequisite to its purchase.

With regard to affordability, the results seem to indicate that income is not important, but due to the unreliable nature of self-reported income we should explore this relationship further by generating a composite wealth indicator using PCA. Additionally, we find some evidence that one's ability to save and invest is an important indicator related to affordability.

Although everyone surveyed knew of solar technology, specific knowledge about the technology is low. It is likely that users have a higher level of knowledge about solar as a result of using the technology. Users are also more likely to have more solar users in their social network, but the causes and effects of this relationship are too complex to draw meaningful conclusions with the information at hand. Both groups conveyed strong interest in learning more about solar. We have limited evidence that NGOs may be an effective means for disseminating this information, while the radio may not be an effective means of communicating solar knowledge.

The presence or perception of low quality products does not appear to be negatively affecting solar uptake or the attractiveness of solar, so we do not find clear evidence of market spoiling. However, given that non-users are less certain about solar product availability and its benefits, and strongly desire additional information on these topics, there is evidence of information market failure. Still, both users and non-users expressed a strong desire to make a future solar purchase.

While we found a clear relationship between solar use, and opinions and knowledge, we do not have enough information to conclude that increasing opinions and knowledge of solar will increase the rate of adoption. Nevertheless, providing knowledge should be considered as a possible method for increasing adoption, and this relationship should be tested for causality using an experimental or quasi-experimental method rather than an observational study. Similarly, the evident relationship between solar use and the number of solar users in one's social network cannot be used to draw causal conclusions. However, since most people have received information about solar from people they know, and the size and opinions of the solar social network are larger/higher for users, the importance of the social network on knowledge and adoption of solar should also be examined with an experimental or quasi-experimental method.

Before undertaking the above proposed research, we will attempt to gain additional insights using this dataset. We will undertake a multivariate logistic regression analysis to better understand the interactions between variables, which might change our interpretations of the data or provide additional insight. We will also perform a similar analysis using village average data, in an effort to see how the variables – especially those related to availability – vary spatially, and how these spatial variations are related to the adoption of solar products.

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Sustainable Energy for Africa and the African Diaspora.

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Abstract

Several initiatives are going on to develop a sustainable energy program throughout Africa and the African Diaspora. Regional bodies have developed plans in this efforts. One of these is SE4ALL (Sustainable Energy for All) by the United Nations. Worldwide it is divided into three regions called hubs, one of those is Africa. The other two are the Asia-Pacific hub , and the Latin America hub. Sustainable Energy has many dimensions. A program using the Acronym WEALTH captures the full range of these dimensions which are Water, Energy, Agriculture, Learning, Training and Health. This program is an example of appropriate technology developing sustainable energy programs. Technology is also tied to well-being, community based approaches, and entrepreneurism including the role of women enterprises. The African Union, as an engine for the African hub of SE4ALL, is actively engaged in Sustainable Energy. It also has established the sixth region which includes the African Diaspora; those of African descent scattered around the world. It was developed to help in developing the African Continent. CARICOM (Caribbean Community and Common Market) is also working with SE4ALL and as part of the African Diaspora can be helpful because of its relationship to Africa. Best practice models will be gleaned from the Caribbean, Latin America, Asia and other regional African groups as part of the overall strategy of sustainable energy development. It is the purpose of this paper to connect these models to development goals by linking them to objectives that positively impact Africa and the African Diaspora.

Keywords: Sustainable Energy, Entrepreneurship, Africa, African Diaspora, Community Development

OBJECTIVES

1. Identify the need to develop sustainable energy resources that impact the people of Africa and the African Diaspora
2. Describe the economic and entrepreneurial possibilities and results of Sustainable Energy development in African and the African Diaspora
3. Analyze the impact of community development and technology on developing sustainable energy resources.

SE4ALL

From a global perspective, The United Nations is the body that looks at issues involving all nations. In the area of Sustainable Energy, they have formed the Sustainable Energy for All (SE4ALL) program that will assist national and regional efforts. Worldwide it is divided into three hubs, one of those Africa. The other two are Asia-Pacific and Latin America and the Caribbean.

Launched in 2011, the Sustainable Energy for All (SE4All) Initiative aims to ensure universal access to modern energy services, double the global rate of improvement in energy efficiency and double the share of renewable energy in the global mix by 2030. The SE4All Action Agenda is a country-level umbrella framework for energy sector development with a long-term vision, ensuring overall sector-wide coherence and synergy of the accumulated efforts towards the three goals.

In Africa there is an African HUB and it links with the African Union. The African Union has also created a region to bring in the resources of the African Diaspora; those Africans scattered around the world through migration, slavery, immigration, and as refugees. The African Hub was launched on May 19, 2014 in Kigali, Rwanda. See "The Africa Launch of the Sustainable Energy for All (SE4ALL)" (https://www.youtube.com/watch?v=qaSU45XqM2U)

THE AFRICAN EXPERIENCE IN SUSTAINABLE ENERGY DEVELOPMENT

A perfect example of African Agency is developing sustainable energy system is the work of Akon, a Senegalese singer and performer who is using his resources to bring from his estimation 600 million Africans, electricity It is an impressive undertaking impressively building solar panels across Africa starting in Senegal with the idea to provide over 600 million Africans with electricity and most notable providing entrepreneurial opportunities. This follows on the heel of a Project call "YES in Africa" in Benin where basketball, learning about computers and solar technology, and building solar grids links with health and cultural issues. In Niger it has had enormous success owing to the support of the Ministry of Youth in Niger, Coca Cola and the United Federation of Basketball in Niger.

Both of these projects speak to the issue of entrepreneurism and the collaboration of those in the African Diaspora and has what we may call Pan African Agency. Akon has recently developed a Solar Academy taking advantage of the sun in Africa to train graduates in technology and will be dispatched to other parts of Africa. See "Akon's Lighting Company to Provide Electricity to 600 Million People in African Countries" (https://www.youtube.com/watch?v=R_0qSK1fjYU).

Energy continues to be the pivot of economic and social development of all nations around the world. Although it has brought great economic prosperity, the way it is produced and used is inefficient and has adversely affected local, regional, and global environments. This brings in the idea of appropriate technology. "Appropriate Technology (AT) implementation should result in community empowerment, independence and sustainability. AT success depends on engagement and support of impacted community through entire technology conceptualization, development and implementation process. Sensitivity to socio-cultural context and respect for local knowledge is critical.

An example is WEALTH. WEALTH is a community based approach and enjoys support from the government, community based NGO's, engineers, economists, academia and looks at a coordinated effort to address these issues using technology and is designed for the Sudan and India.

The WEALTH initiative as

"a pilot project to build a platform that utilizes Appropriate Technology (AT), Service Learning (SL) and Product Development to develop, design and deploy an integrated basic rural infrastructure around (Water, Energy, Agriculture, Learning, Training and Health. The framework challenges the integration and collaboration of academia, rural communities, engineering practitioners, economist, development agencies and NGOs to design a robust knowledge and capacity platform that develops community based participation model to capture the rural community needs and requirements about infrastructures problems, and to build capacity through service learning that is capable to design and deploy the sustainable and appropriate technology's solution which maximizes the community participation".

OTHER INITIATIVES

Another example is the use of the cell phone in rural Uganda which addresses health and education efforts. This follows the introduction of mobile learning in South Africa in educational institutions where students and teachers get connected through smart phones by telephony, messaging, multi-media and computing. See "Using the mobile phone as learning tool for rural farming communities in Uganda" (https://www.youtube.com/watch?v=OCo2zIfVMG0) and "Mobile phones in rural Uganda (Kumi)" (https://www.youtube.com/watch?v=sCMo-4H4QM8"

The Women in Entrepreneurship, Infrastructure and Sustainable Energy Development (WEISED) International Conference has been designed to actively seek progress in recognition of the growing importance of procurement in energy for economic development and climate change mitigation following the designated 2012 year as the International Year of Sustainable Energy by the UN General Assembly resolution 65/151.

In addition, WEISED has been developed as a follow on from the GWIIN event held in Accra, Ghana on the 24 April 2012 and the recent report by the newly launched Women Investment Programme (WIP), a part of the Leading Women of Africa, which emphasizes the significant and positive role women play in various sectors such as Oil And Gas, Construction & Housing, Solutions For Water And Sanitation Crisis In Africa, Women's Entrepreneurship, Investing In People To Improve Organizational Performance: and Women In Investment. See "Women in Entrepreneurship, Infrastructure and Sustainable Energy Development" (http://www.weised2020.org/about-us/)

THE AFRICAN DIASPORA, CARICOM AND SUSTAINABLE DEVELOPMENT

AFRICAN DIASPORA

THE African Union in order to utilize the resources of the African Diaspora has established the sixth region of the African union. African American and those of African Descent have established the World African Diaspora Union (WADU). Spearheaded in the United States, it has established chapters devoted to assisting African in many areas including technology. It's mission is to:

"take concrete measures that would promote and sustain linkages between AU and the Diaspora in the following priority areas: trade and investment, science and technology, travel and tourism, communication and transportation infrastructure, energy, information and communication technology and cultural industries; and to encourage the civil society in the Diaspora and in Africa to support, advocate and mobilize resources for the development of Africa and its Diaspora;".

WADU has a ten point plan and is strongly involved in promoting reparations; payment for the institution of slavery and Jim Crow in the Americas as well as those issues impacting the African Continent such as the impact of colonialism and apartheid.

It is important to list those points:

"THE WADU MANIFESTO

The World African Diaspora Union (WADU) having been created for the unification and solidifying the various associations, groups and individuals of the Black Diaspora and having accepted the Pan African centric philosophy as the means of establishing a new global order of justice and equality for all by African empowerment for the accomplishment of the African Renaissance; Resolved:

1. To work towards the unification of Africa with one central Government under an African Union continental government body;

2. To work towards the official acceptance of the Diaspora as the 6th Region of the United Africa;

3. To oppose and eradicate racism, imperialism and neo-colonialism and its vestiges in all forms, everywhere;

4. To dedicate itself to the promulgation and recognition of the full dignity and equality of women in all aspects of life, globally;

5. To recognize and emulate the philosophy and teachings of our history, culture and the sciences and to perpetuate it in the education of our children;

6. To promote economic sustainable development of businesses, trade and commerce amongst African people and the world;

7. To promote humanitarian support, peace, reconciliation and security for the African people and its most vulnerable, our children;

8. To acknowledge and support the Abuja Declaration to support its mandate in pursuance of the claim to Reparations;

9. To accept the findings of the Durban Conference on Racism, Xenophobia and other related matters and to pursue the plan of action arising thereof;

10. To assist and cooperate with all individuals, groups and associations which adopt these tenants and principles."

Support for the Diaspora can be found in the following videos: "Africa Today - Why is the African Diaspora important for the motherland? (27.8.2014)" , **and** "AU Diaspora African Forum Mission" (https://www.youtube.com/watch?v=MUpPYaqW8Oc **and** https://www.youtube.com/watch?v=EF0svui4qLM)

SE4ALL – LATIN AMERICA AND THE CARIBBEAN

The nations in the Caribbean are moving briskly toward sustainable energy for all. They are developing toward the following three areas:

Energy Access: Ensuring universal access to modern energy services has far reaching social and economic benefits for society. The Latin America and Caribbean region is very close to achieving universal access. In electricity this means advancing from 95% to 100% access and this requires an even larger investment and a new set of solutions.

Energy Efficiency: Doubling the global rate of improvement in energy efficiency – getting more from our existing resources – is an achievable goal that will improve living conditions, create sustainable patterns of consumption, and promote practices that ensure our long-term energy future. In the global context, Latin America and the Caribbean present great opportunities to improve energy efficiency, and this means that both individual citizens and industries can save money and become more sustainable.

Renewable Energy: Investing in renewable energy creates jobs, fosters economic growth, and improves energy security for countries. Increasing the share of energy from renewable sources can:

a. Reduce greenhouse emissions and local pollution
b. Insulate countries from fuel price volatility
c. Help improve national balance of payments

THE CARIBBEAN EFFORT

In this area, twenty countries together with seven regional and international organizations have released a joint statement in support of the transformation of the energy systems of Caribbean countries "toward clean sustainable energy for all". This was sponsored by the Council of the Americas, the Atlantic Council and the US Department of State showcasing the Initiatives under the Caribbean Energy Security Initiative and the US has offered technical support through the Energy and Climate partnership. This includes a 34 million dollar wind energy project sponsored by the US.

The OAS said that the last five years had seen an unprecedented push toward the regions renewable energy sources, noting that this was "doubly impressive" in a time of low oil prices. CARICOM (Caribbean Community) with it 15 nations is a signatory. CARICOM has recently in 2014 prepared a 10 point plan for reparations which includes technology transfer (http://www.finalcall.com/artman/publish/World_News_3/article_101422.shtml).

A summary of sustainable energy initiatives are covered in two videos and captures models of sustainable development. See "CARICOM Towards Sustainable Energy- Part 2 - https://www.youtube.com/watch?v=Ldwv73UInAc and CARICOM Towards Sustainable Energy- Part 1 https://www.youtube.com/watch?v=-e_8DUo_8f0.

A model similar to WEALTH which has been proposed is the main result of the work presented is a conceptual model encapsulating the dynamic processes involved in community perceptions and decision making, in order to better understand the impacts of the adopted technology on wellbeing along with the behavioral dynamics and pathways that prompt those impacts. The focus is on rural electrification in remote farming communities using renewable energy based mini-grids, with Duchity, Haiti as a case-study.

RESULTS

The Sustainable Energy for All (SE4All) Africa Hub launched on Tuesday, October 13 in Abidjan its Annual Report for 2014-2015, which outlines the progress made to date in helping the 44 partner countries create strategic frameworks necessary to mobilize investment for realizing their long-term energy goals aligned with the SE4All initiative objectives: ensure universal access to modern energy services, double the global rate of improvement in energy efficiency and double the share of renewable energy in the global mix by 2030, enshrined in the Sustainable Development Goal (SDG) 7 adopted at the end of September in New York.

The Hub provides guidance to African Governments and energy stakeholders, delivers technical assistance, fosters networking and communication, and contributes towards finance mobilization. A model of African leadership, the Hub has been at the forefront of SE4All's implementation, contributed to the shaping of the initiative globally, and set a standard for others to follow. AfDB President Akinwumi Adesina in the foreword to the report highlights that "the SE4All Africa Hub plays an important role in forging the transformative partnerships needed to make access to energy for all a reality." The Hub has also been tasked to play a lead role in the coordination of the implementation of the G20 Action Plan on Energy Access in Sub-Saharan Africa adopted by G20 Energy Ministers on October 2, 2015 in Istanbul in collaboration with the SE4All partnership.

Speaking about the report, SE4All Africa Hub Coordinator Daniel-Alexander Schroth said,

"The last year was a successful year with the Hub being able to assist many African countries in laying the fundamental ground for mobilizing investments, yet this is only a first step, as the focus now has to shift decisively towards implementation."

Over the past year, the Hub has been providing direct technical assistance in response to Government requests, to more than 10 African countries supported in most cases through the Pilot African Climate Technology and Finance Centre and Network. In addition, the Hub has supported the establishment of the West African Energy Leaders Group, which was launched successfully at the end of June 2015 in Abidjan. It also started the implementation of the Green Mini-Grid Market Development Program in cooperation with the Sustainable Energy Fund for Africa (SEFA) to scale-up the adoption of mini-grids as an important part of the solution to enhancing energy access in rural areas.

Moving ahead, the SE4All Africa Hub will focus on mobilizing support towards the implementation of the action agendas and investment prospectuses and the strengthening of SE4All focal points, communication and networking.

LISTING OF AUDIOVISUALS

a. https://www.youtube.com/watch?v=8pCRs8e__0g 3 - 4
b. http://www.weised2020.org/about-us/ 3
c. https://www.youtube.com/watch?v=R_0qSK1fjYU
d. https://search.yahoo.com/yhs/search?p=aFRICAN+PROVIDING+ELECTRICITY+TO+AFRICA&ei=UTF-8&hspart=mozilla&hsimp=yhs-001 1akon
e. https://www.youtube.com/watch?v=Ldwv73UInAc
f. https://www.youtube.com/watch?v=-e_8DUo_8f0
g. https://www.youtube.com/watch?v=MUpPYaqW8Oc
h. Yes with Africa Video 1 – 4 - Education
i. https://www.youtube.com/watch?v=EF0svui4qLM
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SECTION III

Development of the loose biomass briquetting value chain

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Abstract

Biomass (roundwood, agricultural residues, forestry residues, organic municipal waste) has the largest carbon reserve with potential to replace unsustainable fossil energy sources. Furthermore, off grid communities produce significant amounts of loose biomass through agricultural and forestry activities. These include maize stalks, tobacco stalks, ground nut leaves and stalks, tree leaves, elephant grass etc. These are traditionally burnt in fields after harvesting. In addition, annually, forestry residues such as elephant grass, yellow thatching grass, dry tree leaves etc. are destroyed in perennial veld fires. Such loose biomass can be harnessed for cooking and heating energy and thus minimise the use of round wood, which results in deforestation that cause desertification if not done sustainably. The major challenge in harnessing energy from loose biomass is their low energy density. This can be overcome by developing loose biomass briquetting technologies. This paper reports on the development of loose biomass briquetting technologies at the University of Johannesburg over the past five years. These include shredding, pre-treatment, compaction, off grid solar drying, and combustion. Briquetting required the selection of good feed stock and binders. Cow dung and cactus were found to be good binders producing briquettes with good combustion behaviour. The developed loose biomass briquettes were tested for moisture content, energy content and combustion behaviour and were found to be adequate for domestic cooking and heating requirements.

Keywords: Agricultural residue, Biomass, Biomass briquettes, Forestry residue, Loose biomass

Introduction

Biomass is the only source of energy with sufficient carbon to sustainably and reliably replace fossil based fuels as a source of energy. It has been a traditional source of energy for billions of people around the world for centuries (Wilke, et al. 2011). The International Energy Agency reports that 47.6 % of Africa relies on biomass as a source of energy (International Energy Agency (IEA) 2009). The proportion is higher at 61.2 % for sub-Saharan Africa while it's even more substantial at 81.2 % for sub-Saharan Africa excluding South Africa. Most of this consumption is round wood. This rate of consumption is unsustainable in this current age of global warming and climate change. Sub-Saharan Africa has notable potential to develop biomass based energy through loose biomass (agricultural and forestry residues), energy crops (jatropha, sugar cane etc.), solid wastes (municipal wastes) and round wood forests (Stecher, Brosowski and Thrän 2013). These segments are estimated to contribute a total of 13900 PJ/yr by 2020. Of this, loose biomass would contribute 5254 PJ/yr. This is a significant amount if properly harnessed. Already, large amounts of loose biomass are produced annually through agricultural activities. In sub-Saharan countries, Savannah grasslands are awash with elephant and yellow thatching grasses. These residues are destroyed annually after harvest by burning in the case of agricultural residues, and by wild veld fires in the case of forestry residues. There is currently no practice of harvesting such loose biomass residues for energy.

Loose biomass is not attractive as a source of energy (either for cooking or heating) due to its low energy density. Steam coal (1% water) has a calorific value of 36 MJ/kg compared to 16 MJ/kg for wood with 15% moisture content (National Physical Laboratory

2015). This poses serious challenges in terms of transportation and storage. Furthermore, large volumes (in their natural state) would be required to cook a normal meal. In addition, the type and quality of loose biomass available for potential energy use is site dependant. A number of studies have been conducted to quantify the energy content of various loose biomass available in various sites. A detailed study conducted on loose biomass samples collected from a village in the Limpopo Province of South Africa revealed that eucalyptus saw dust, peanut shells and Mopani leaves had the highest energy content and hence are suitable candidates for further development as an energy source for that region (Shuma, et al. 2015). However, energy content is not the only metric of interest. Taking into consideration material density, burn rate during combustion, moisture content and availability in the vicinity of the site of study, cow dung, ground nut leaves & stalks, yellow thatching grass and maize stalks and cobs were identified as good loose biomass energy feed stocks. Although cow dung has low energy content, it is widely available in most off grid communities in sub-Saharan Africa and has also been used as a binder for briquetting projects (Emerhi 2011).

To encourage use of loose biomass as an energy source, a number of interventions are required. One approach is the beneficiation of the energy value of the material by techniques such as loose biomass briquetting (Chen, Xing and Han 2009). Alternatively, the loose biomass can be converted into a higher energy content form by gasification methods (Yaman 2004). Loose biomass in green state can also be used for biogas production through anaerobic digestion (Ward, et al. 2008). Irrespective of the chosen technique, loose biomass requires pre-treatment (preparation and densification) to make it suitable for use. Densification has been the widely used approach.

This paper reports on biomass value chain that has been developed at the University of Johannesburg over the last five years. The aim is to improve the uptake of loose biomass as a source of sustainable, freely available renewable energy. This is done in a way that acknowledges the commercial value of the technology. This also opens up the potential for employment creation if implemented in support of the open community manufacturing (OCM) concept (Oosthuizen, et al. 2014), (Rebensdorf, et al. 2015). The developed technologies within the loose biomass value chain can be implemented in container based community factories in modular fashion that allows for progressive organic growth of the loose biomass processing centres. Commercially viable innovative and entrepreneurial solutions can be developed while at the same time mitigating deforestation and global warming challenges.

Loose biomass briquetting value chain

Background

Beneficiation of loose biomass as a source of energy has been achieved mainly by briquetting. However, traditional approaches have failed to attract widespread adoption due to high capital costs creating a commercialisation barrier. Simpler tools (appropriate technology) can be developed that are more affordable and attractive for widespread use. These tools can be developed for each of the identified steps in the loose biomass briquetting process enabling poor communities to access energy available in the loose biomass. These steps include:

1. Shredding
2. Preparation
3. Compaction
4. Drying
5. Briquettes packing
6. Briquette combustor

The aim is therefore to develop low cost technologies that can be used to process loose biomass into usable form. This has to be done in a sustainable manner. Technologies being developed include biomass shredding machines (manual or solar powered), biomass briquetting machines (manual), biomass briquette drying tools (solar powered), and biomass briquette packing machines (solar powered).

Shredding

In most cases, loose biomass exists naturally in a form that cannot be effectively used for briquetting. Loose biomass such as maize stalks, yellow thatching grass and ground nut stalks need to be reduced in size prior to briquetting. Studies conducted on mixtures of grass and dry eucalyptus leaves revealed that the loose biomass should be reduced to 20 mm size particles for optimum compaction. This can be achieved using various technologies. The technology of choice in this work was the disc cutter as shown in Figure 1.

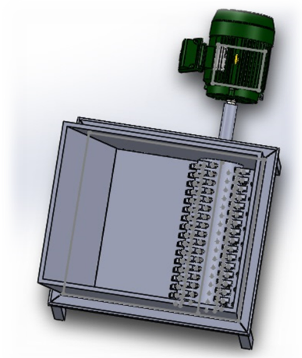


Figure 1: Biomass shredding machine

The machine has production capacity sufficient to produce 8000 briquettes per day. The machine is powered by a dc motor that can be powered by solar energy.

Preparation

Trying to compact raw dry lignin results in spring back and poor binding. Common approaches to resolve this include soaking the loose biomass in water to soften the lignin. Hot water has been reported to yield good results. Other researchers have also reported good performance when the loose biomass is preheated in the absence of moisture. It was also found to be more effective and less expensive to compost the loose biomass for 7 to 14 days to assist in breaking the lignin. In addition, various types of the loose biomass can be mixed to improve energy content and binding. Common binders include cow dung and cactus and these were employed in this work.

Compaction

The briquetting process involves the compaction of loose biomass under pressure. The compaction increases density and hence the energy content per unit volume. Various technologies have been applied which include piston and screw compaction. For off grid production, piston compaction is the preferred approach. Successful compaction depends on a number of factors such as the type of material being compacted, particle size, temperature and moisture content. Proportion of loose biomass to binder also determines the compaction performance. A study conducted on a mixture of leaves and grass in the absence of any binder revealed an optimum moisture content between 15 and 25% and compaction pressure of 35-40 MPa (Madyira and Kaymacki 2015). The variation of pressure with density is shown in Figure 2.

(a)

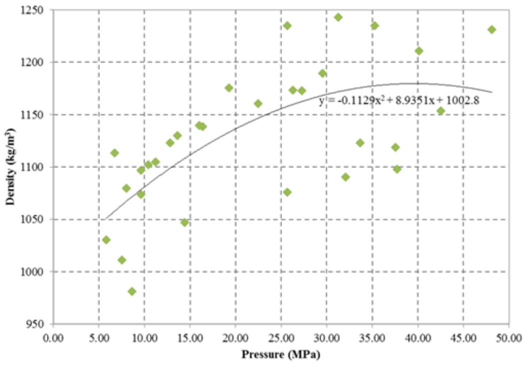
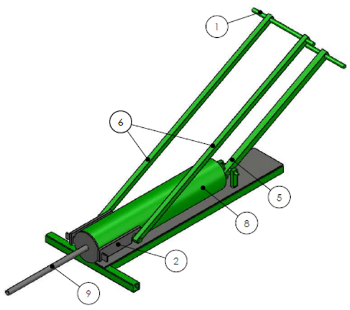


Figure 2: Effect of pressure on loose biomass briquette density

The briquetting was conducted using a piston/cylinder configuration. Figure 2 also shows that the density of the briquettes increases with increase in compaction pressure and stabilise after 30 MPa. In this work both screw type and piston type machines were developed. The two machines are shown in Figure 3. The piston machine (Figure 3(a)) is manually operated for full off grid capability whilst the screw type machine (Figure 3(b)) is powered by a dc motor that can be powered by electricity derived from a PV solar plant. The piston machine can produce 2000 briquettes per day while the screw ca produce an equivalent of 8000 briquettes per day.



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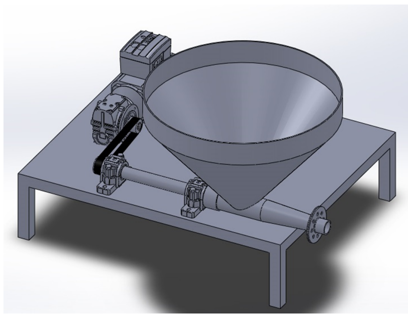


(b)

Figure 3: Biomass briquetting machines (a) Piston manually operated (b) Screw type powered

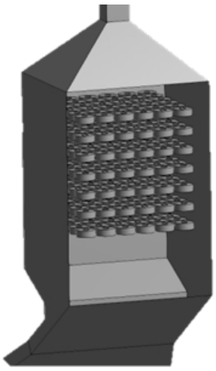
The biomass briquettes produced are shown in Figure 4. Figure 4(a) shows briquettes produced from various stock materials but with cow dung binder while the same is shown in Figure 4(b) with cactus binder. In general, both binders produced good quality briquettes.

(b)

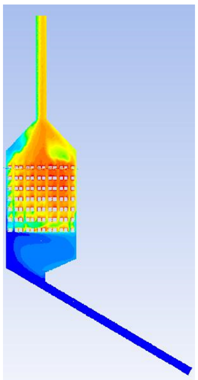
Figure 4: Loose biomass briquettes produced (a) with cow dung binder (b) with cactus binder

Drying

For maximum energy extraction during combustion of the briquettes, the briquettes must be dried to a moisture content below 10 %. Solar drying was found to be the most sustainable way of drying the briquettes. A cabinet type indirect solar dryer was developed using a combination of numerical analysis tools (computational fluid dynamics (CFD)) and experimentation. The developed solar dryer is shown in Figure 5.



(a)



(b)

(c)

Figure 5: Cabinet solar dryer (a) Model of cabinet interior (b) Numerical model showing moisture distributions (c) Actual prototype tested

Figure 5(a) shows the geometrical model developed to represent the briquettes inside the cabinet, Figure 5(b) shows the distribution of moisture in the cabinet during drying and Figure 5(c) shows the actual prototype that was built and tested prior to optimisation of the dryer. The cabinet had the capacity to dry 250 briquettes over 16 hours of sunshine in summer and 24 hours in winter. This is equivalent to removal of 13 kg of moisture. Solar collector temperatures of about 80^{o}C were recorded leading to average cabinet temperatures of 45^{o}C in summer. This corresponded to solar collector efficiencies averaging 68%.

Briquette Packing

Once dried the briquettes must be packed either for storage, transportation or sale. To achieve this, a packing machine was developed. The objective was to design a machine that could measure a certain mass of briquettes that can then be delivered into a packaging container. The solution that was developed is shown in Figure 6. The machine is driven by a dc motor powered by electricity from a PV plant with capacity to pack 10000 briquettes per day.

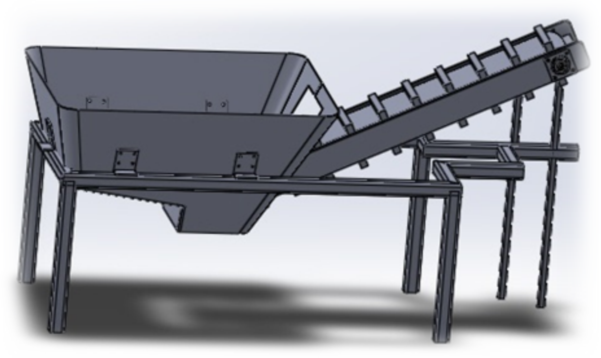


Figure 6: Biomass briquette packing machine

Combustion

A wide range of stoves have been developed which are able to combust biomass briquettes. However, some technologies have not been fully exploited. A good example is the down draft stove which has the main advantage of affording cleaner combustion. Work is therefore in progress to optimise the performance of this technology for biomass combustion. The main challenge with downdraft stoves is the extraction of heat especially for domestic cooking applications. Figure 7 shows solutions that are being optimised using CFD models to both improve the combustion and to develop heat extraction solutions.

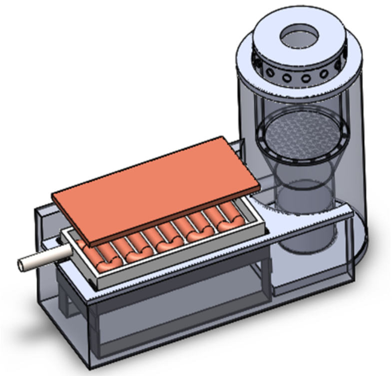


Figure 7: Model of down draft stove.

Summary

This paper has presented the work being done to develop an integrated production system for harnessing loose biomass as a source of energy. Key processes identified include shredding, preparation, compaction, drying, packing and combustion. Potentially effective solutions for each of these stages have been developed and described. The solutions that were implemented and tested produced good results. Work is still on going to optimise and finalise the system. Harnessing of loose biomass for energy, especially for off grid communities has significant potential socio-economic benefits that must be pursued and implemented.

Acknowledgements

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Design of a self-sustaining biogas and bio-fertilizer producing plant that uses rumen injesta and manure as raw materials for Zimbabwean abattoirs.

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Abstract

The objective of this new biogas plant design is to effectively manage waste from abattoirs in Zimbabwe by recycling cow dung and injesta to generate biogas and bio-fertilizer at an optimum rate. The biogas plant designed caters for an amount of 30 cattle slaughtered per day at an abattoir. The amount of manure (combining both the injesta and dung) expected to be added daily into the mixing tank of the plant will be at least 20kg of manure per cow. The manure is mixed with water in a volume ratio of 1:1 in the mixing tank, before being channeled into the digester chamber. The design incorporates 8 flat plate solar thermal collectors spanning an area of 3.72m^2 *and a solar hot water tank designed to keep a temperature of above 30℃ of the stored water using direct radiation. The use of both injesta (paunch manure) and cow dung in the volume ratio of 1:1 results in an increase in biogas production by at least 65% due to the synergistic effect mainly attributed to more balanced nutrients. Again, the gas production efficiency, which is the gas produced per unit kilogram of feedstock, generally increases with temperature, roughly doubling for every 10℃ rise between 15℃ and 35℃. The design uses an arduino controller and temperature sensors to regulate the heating system and solar power to run the plant.*

Keywords: abattoirs, biogas, renewable energy, anaerobic digestion, digester, rumen injesta, hybrid system

Biochemical Characterization, Morphological and Ultrastructural Configuration of *Chlorella vulgaris* Cultivated in Wastewater Supplemented with Varying Dosages of Free Chlorine

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Abstract

The biorefinery concept proposes the integration of biofuel production with extraction of co-product(s) and other high-value compounds. The sustainable utilization of wastewater for biomass propagation and nutrient removal is desirable and cost-effective. In this study, a strain of Chlorella vulgaris was obtained from a wastewater maturation pond in Durban, South Africa. The effect of chlorine on algal growth kinetics and biomolecule production was studied by adjusting the BG-11 growth medium with various chlorine concentrations (0 to 1.0 mg/L). Growth rates of 0.016 h^{-1} and 0.008 h^{-1} were achieved at 0.2 mg/L and 1.0 mg/L of chlorine respectively. Chlorophyll-a was used as proxy for microalgal growth showing a positive correlation with the growth rates determined spectrophotometrically. Microalgal dry cell weight increased gradually at low chlorine dosages, with the highest biomass of 89 mg/L at 0.4 mg/L chlorine. Carbohydrate and protein production was determined using the Anthrone and Bradford methods respectively. Intracellular total carbohydrate concentration was estimated to be 0.52 mg/mL and 0.45 mg/mL at 0.2 mg/L and 1 mg/L of chlorine respectively. Highest intracellular protein concentration (0.1 mg/mL) was estimated at 0.4 mg/L of chlorine. Various lipids were produced at all chlorine dosages. Highest lipid content per dry biomass (17.86% [w/w]), was obtained in the control which had no chlorine and the lowest was 1.37% (w/w) at 1.0 mg/L chlorine dosage. Chlorine was found to cause cell disfigurement at the highest free chlorine (1.0 mg/L). Wastewater was found to support robust microalgae growth from day 4 to 12, with the highest growth observed in 100% wastewater.

Key words: Biomass; Carbohydrate; Chlorophyll-*a*; Chlorine; Lipid; Microalgae.

Introduction

The world depends largely on fossil fuels for energy for transport systems, domestic and industrial use. Fossil fuels are associated with many limitations such as high demand on energy and fuels, depleting natural sources, skyrocketing prices and environmental concerns associated with their processing and noxious emissions (Rawat *et al.,* 2013). Therefore, researchers are currently looking into alternative renewable and sustainable methods for fuel production for energy security. There are many attractive alternatives that are currently being investigated for fuel production, such as biofuels, wind, solar and nuclear fuels. Nuclear and solar energy are associated with environmental and sustainability concerns, therefore, most research is focusing on biofuel production from renewable sources (Turney and Thnefakis, 2011; Christodouleas *et al.,* 2011). Several environmental issues are associated with the use of fossil fuels, especially the emission of carbon dioxide to the environment, the main culprit responsible for the current global warming crisis. This has necessitated the utilization of biomass for biofuel production. Currently, a plethora of biomass sources are being investigated for bioenergy production, including soybean, sugar cane, palm oil *etc*. (Li *et al.,* 2008). The major problem with these sources is that they are edible and therefore not sustainable as they are also a human and animal food source. This calls for new sources of biofuels which are sustainable, renewable, and environmentally friendly. The focus is on using robust microorganisms as potential sources of biomass for biofuels (Li *et al.*, 2008). Microbial oils from fungi, bacteria, yeast and microalgae are currently being explored for potential commercialization (Ma *et al.,* 1999). Microalgae are gaining a lot of interest as potential sources of biomass for biofuel production. This is mainly because microalgae utilize cheap and readily available water, CO_2 and sunlight for growth and biomass accumulation. This eliminates the problem of high energy, nutrient consumption and suitable agricultural land required by other potential sources such as crops. Studies have shown that various autotrophic microalgal species have the ability to accumulate various oils suitable for biodiesel production. These microalgal species include *Dunaliella primolecta, Monallanthus salina, Neochloris oleoabundans, Chlorella vulgaris etc*. The type, quality and the amount of oil produced by these microalgae vary with species and growth conditions. There are also other factors that affect biomass production, such as temperature, light intensity, nutrient availability etc. (Li *et al*., 2008). There are several constraints for cost-effective production of biofuels from microalgae such as lack of suitable technologies for scaling up operations for commercialization.

Microalgal biomass is made up of various biochemicals and metabolites such as functional and structural proteins, complex carbohydrates, storage lipids, amino acids *etc*. These metabolites are commonly used for human nutrition as nutraceuticals (Spolaore *et al.,* 2006). The biochemical composition of microalgae varies with species and growth conditions such as light intensity, light quality, photoperiod, pH and temperature (Gatenby *et al.,* 2003). As microalgae enter stationary phase, there is nutrient depletion in the media with subsequent increase in intracellular carbohydrate and storage lipids, with a concomitant decline in protein content (Ogbonna and Tanaka, 1996). Various types of carbohydrates are found in microalgae, which can either be monomers or complex polymers (Williams and Laurens, 2010). The types of carbohydrates in the biomass vary due to microalgal diversity with different metabolic pathways. Carbohydrates have various biochemical functions which they facilitate in microalgae. Microalgal carbohydrates can be saccharified into fermentable sugars for potential bioethanol production (Indira and Biswajit, 2012). Photoautotrophic microalgae use starch as an energy source and this starch is structurally similar to that found in plants (Williams and Laurens, 2010). Red algae produce a carbohydrate polymer which is mainly composed of amylose (McCracken and Cain, 1981). Chrysolaminarin located in the pyrenoids in the chloroplast, is a polysaccharide which is commonly found in most algae. This polysaccharide is used by microalgae for storage (Williams and Laurens, 2010). Starch is the major carbohydrate in *C. vulgaris*, (Safi *et al*., 2014).

Cellulose is a structural polysaccharide found in the cell walls of *C. vulgaris* that acts as a protective barrier against antimicrobial agents (Safi *et al.,* 2014). Another polysaccharide found in *C. vulgaris* is β (1→3) glucan which can act as an active immunostimulator, a free radical scavenger and a reducing agent of blood lipids (Lordan *et al*., 2011). Proteins have both metabolic and structural functions e.g. growth and maintaining cell regulation. Since most proteins are enzymes, they can act as key catalysts in cell metabolism (Williams and Lauren, 2010). Scaffold proteins help bind the chlorophyll molecules in the chloroplast's light harvesting complex and are found inside lipid membranes where they have both structural and metabolic functions (Williams and Lauren, 2010). Proteins also act as a food source; their amino acids are usually part of the mammalian diets (Williams and Lauren, 2010). In *C. vulgaris,* proteins make up 42-58% of the total biomass (Seyfabadi *et al*., 2011). The amount of proteins is dependent on growth conditions (Safi *et al*., 2014). About 20% of the proteins are found on the outside of the cell wall, 50% inside the cell and 30% move between the inside and outside of the cell (Becker, 1994). The aim of this study was to investigate the effect of free chlorine on microalgal biochemical composition, physiology and ultrastructural configuration. The study also investigated the efficacy of utilizing nutrient rich wastewater streams for microalgal biomass propagation.

Materials and Methods

Microalgal Strain and Media Composition

The water sample for microalgal isolation was obtained from Kingsburgh wastewater treatment plant maturation pond in Durban, South Africa. *Chlorella vulgaris* was isolated and purified to axenic conditions by following conventional microbiological techniques. The BG-11 media was prepared by adding the following reagents to 1 000 mL of distilled water: 1.5 g of $NaNO_3$, 0.04 g of $K_2HPO_4.3H_2O$, 0.075 g of $MgSO_4.7H_2O$, 0.036 g of $CaCl_2.H_2O$, 0.006 g of citric acid, 0.006 g of ferric ammonium citrate, 0.001 g of EDTA and 0.02 g of Na_2CO_3. The media was autoclaved at 121°C for 20 min and allowed to cool. The pH of the medium was adjusted to 7.4 after cooling. A one millilitre aliquot of the filter sterilized trace metal mix (A5 + Co (2.86 g of H_3BO_3, 1.81 g of $MnCl_2.4H_2O$, 0.390 g of $Na_2MoO_4.2H_2O$, 0.079 g of $CuSO_4.5H_2O$ and $Co(NO_3)_2.6H_2O$ in 1 000 mL of deionized water) was added to 1 000 mL of BG-11 medium after autoclaving.

Cultivation and Growth Kinetics of C. vulgaris

A working volume of 400 mL of BG-11 medium was aseptically transferred to three sterile one litre flat bottomed Erlenmeyer flasks. The chlorine concentration of the medium was adjusted to 0.2, 0.4, 0.6, 0.8 and 1 mg/L using sodium hypochlorite solution. A control flask was prepared without chlorine in the media. Chlorine measurements were done using a Pocket Colorimeter II (Hach, China) using powder pillows (DPD method) as instructed by the manufacturer. A 40 mL (10% v/v) of 1.18×10^7 CFU/mL of *C. vulgaris* at the log phase of growth was inoculated into each flask at each chlorine concentration and this was done in triplicate for each concentration. The algae were grown for 9 days at 28 °C under optimal cool white illumination of 120 µmol $m^{-2}s^{-1}$ without shaking with a light regime of 12 h dark and 12 h light with utilization of ambient CO_2. The cultures were routinely checked for contamination using a light microscope. An aliquot of three millilitre of microalgal culture was aseptically retrieved from each flask at the different chlorine concentrations. The biomass was measured by reading absorbance at 600 nm using a spectrophotometer (Varian CARY 50 Conc, Agilent Technologies) at 3-day interval. Growth rates, division per day and generation time were calculated using the following equations (1 to 3) respectively.

$$\text{Growth rate } (h^{-1}) = \ln (N_2/N_1) / (t_2-t_1) \quad (1)$$

$$\text{Division per day} = \text{Growth rate} / \ln 2 \quad (2)$$

$$\text{Generation time} = 1 / \text{division per day} \quad (3)$$

(where N_2 and N_1 are the highest and lowest absorbance values in the log phase, t_2 and t_1 in hours are final and initial period of growth in the log phase respectively). A 10 mL portion of algal culture from each flask was harvested at 3 day intervals. The culture was centrifuged (Avanti J-26S, Beckman Coulter) at 9 605 × *g* for 20 min. The pellet was treated with 3 mL of 90% ethanol and kept in a water bath (Scientific, Model 130) for 30 min at 50 °C. After incubation, the tube was removed and allowed to cool and centrifuged at 9 605 × *g* for 10 min. The supernatant was transferred to a cuvette and absorbance was measured at 652 nm and 665 nm using 90% ethanol as a blank. The chlorophyll-*a* content was calculated using the following equation (4):

$$[\text{Chlorophyll-a}]\ \mu g/mL = (16.5169 \times A_{665}) - (8.0962 \times A_{652}) \quad (4)$$

Harvesting of Microalgal Biomass and Determination of Dry Cell Weight

After nine days of uninterrupted growth the cells were harvested from each flask by centrifugation at 5 000 × *g* for 20 min at 4 °C. The supernatants were kept at 4 °C for extracellular metabolite analysis and 5 mg of the biomass pellets were kept at 4 °C for intracellular protein analysis. Watch glasses were weighed on a digital analytical balance (PS 4500/C/2, Radwag) for each chlorine dosage. The microalgal pellets were placed in the pre-weighed watch glasses and dried in an oven at 60 °C overnight. The combined mass of the dried cells and the previously weighed watch glasses were determined. The net mass of the dried cells was obtained by subtracting the mass of the watch glass from the combined mass of cells and watch glass. The pellets were homogenized using a mortar and pestle to break open the cells for the extraction of intracellular proteins, lipids and carbohydrates. A 3 mL volume of distilled water was added to the pellet and the biomass was ground to a homogenous suspension and stored at 4 °C until required for analysis.

Determination of Protein Content

For each chlorine concentration, the microalgal supernatant and fresh cell crude extracts were used for extra- and intracellular protein determination respectively. Protein concentration was measured using the Bradford method (Bradford, 1976). A standard curve for protein concentration was prepared from a BSA stock solution of 2 mg/mL. The calibration curve was determined from 0 to 2 mg/mL of BSA at 0.4 mg/mL interval. A 100 µL aliquot of each protein sample was mixed with 3 mL of the Bradford's reagent in a test tube. After adding the protein sample, the tubes were swirled gently for thorough mixing without foaming. The tubes were allowed to react for 5 min at room temperature. The samples were transferred into cuvettes and the absorbance measured at 595 nm using a spectrophotometer. A 100 µL aliquot of distilled water was mixed with 3 mL of Bradford reagent and used as the blank. A standard curve was constructed using the authentic BSA standard protein for the estimation of protein concentration in the microalgal extracts.

Determination of Carbohydrate Profiles

Anthrone Method

The supernatant and 5 mg of the dried biomass cell extracts were used to determine total extra- and intracellular carbohydrates using the Anthrone method (Trevelyan *et al.*, 1952). Proteins were precipitated by the addition of 0.4 mL of 1.39 M trichloroacetic acid (TCA) and 0.05 mL of 9 mM sodium deoxycholate (DOC). The mixture was left to react for 10 min and soluble carbohydrates were recovered from the supernatant after centrifugation at 7 000 rpm for 15 min at 4°C. The carbohydrate sample solution (1 mL) was added to 5 mL of Anthrone reagent (0.02 g of Anthrone dissolved in 10 mL of 95% sulphuric acid in 25 mm diameter test tube). This preparation was swirled and allowed to stand for 10 min and measured in a spectrophotometer at 620 nm. Parallel blanks were run containing standards of 0 to 0.6 mg glucose per 1 mL of solution. A standard curve was used to determine the concentration of the carbohydrates in the extra and intracellular microalgal preparations using authentic glucose standards.

Determination of Reducing Sugars and TLC

Reducing sugars were measured using the dinitrosalicylic (DNS) method (Miller, 1959). The DNS reagent was prepared as follows: (2 g of 3,5-dinitrosalicylic acid, 36.4 g of sodium potassium tartrate, 0.4 g of phenol, 0.1 g of sodium sulfite and 2 g of NaOH) dissolved in 150 mL distilled water in a glass beaker. The solution was brought up to 200 mL in a volumetric flask. The reagent was stored in the fridge in a dark bottle until needed for use. A 5 mg/mL stock solution of fructose was prepared. The calibration curve was determined from 0 to 2 mg/mL of fructose at 0.4 mg/mL interval using the DNS method. A 500 µL aliquot of fructose standard solution was transferred to 3 mL of DNS in a test tube and the mixture was boiled for 10 min. The test tubes were cooled under running tap water.

The tubes were diluted by adding 20 mL of distilled water and absorbance was read at 540 nm. The 0 mg/ml tube was used as the blank. The mean absorbance was calculated and a standard curve constructed for the estimation of reducing sugars. An aliquot of 500 µL of the extra and intracellular sample extracts were transferred to 3 ml of the DNS reagent and boiled for 10 min. The tubes were diluted by adding 20 mL of distilled water and absorbance was read at 540 nm. The fructose calibration curve was used to estimate the amount of reducing sugars in the algal extracts. Thin layer chromatography (TLC) was used to detect and qualitatively analyze carbohydrates. Thin layer chromatography plates were spotted with 5 µL of extra and intracellular carbohydrate samples, and developed with a solvent system of n-butanol/acetic acid/water (5:4:1, v/v/v). The sugars were detected by heating the plates after spraying the dried plates with a reagent solution containing *p*-anisaldehyde in acid alcohol. A 5% solution of fructose, glucose, sucrose and starch were used as standard sugars.

Determination of Lipid Profiles

Lipids were extracted gravimetrically using the solvent n-hexane. A 5 mg portion of dried biomass was mixed with 50 mL of n-hexane and left to stir gently overnight on a magnetic stirrer. The mixture was filtered to remove debris and the filtrate was evaporated at 60 °C in a rotor vapor to remove n-hexane from the lipid solution. The lipids were transferred into a pre-weighed Eppendorf tube and the net weight of the lipid fraction determined. The lipids were detected and qualitatively analyzed using the TLC technique. Thin layer chromatography plate was spotted with lipid samples, and developed with a solvent system of ether/diethyl ether/acetic acid (80:20:1, v/v/v) as an irrigating solvent. The lipids were detected by heating the plate after spraying the dried plates with a reagent solution containing *p*-anisaldehyde in acid alcohol. After spraying, the plate was heated at 110 °C in an oven for 10 min to visualize the spots. Oleic acid and linoleic acid were used as neutral lipid standards.

Optimization of Post-Chlorinated Wastewater for Microalgal Growth

Wastewater was obtained from Northern wastewater treatment plant in Durban. In order to determine the optimal post-chlorinated wastewater media formulation for microalgal growth, the post-chlorinated wastewater was diluted with BG-11 medium in various ratios (0:100, 20:80, 40:60, 60:40, 80:20 and 100:0). A 40 mL of *Chlorella vulgaris* was cultured in 400 mL of these media formulations at 28 °C, 12 h:12 h light: dark cycles for 14 days. Growth was measured daily by taking 3 ml of biomass suspension for absorbance reading at 600 nm. The growth rate was measured for each media formulation for 14 days to establish the optimal media formulation for microalgal growth (Mutanda *et al*., 2011(a)).

Transmission Electron Microscopy

A one millilitre sample of microalgal cells was used for analysis of ultrastructural changes at each chlorine dosage using transmission electron microscope (Jeol JEM-1010) equipped with a CCD camera for digital image acquisition. The samples were centrifuged at 10 000 rpm and the pellet was fixed for 4 h using 2.5% glutaraldehyde solution. The cells were left for 20 min at room temperature. The cells were then rinsed 2 times with phosphate buffered saline (PBS). After rinsing, the cells were stained with osmium tetroxide solution and incubated for 30 min at room temperature. The cells were rinsed again once with PBS. The samples were then dehydrated in alcohol. The samples were then infiltrated and embedded in resins that were cured either with heat or UV. The cells were sectioned at a thickness of between 50 and 200 nm using microtomes. The samples were then contrasted with heavy metals and observed in a TEM and images captured.

Results and Discussion

The *Chlorella vulgaris* strain used in this study was obtained from Kingsburgh wastewater treatment plant in a previous study (Mutanda *et al.*, 2011). A pure culture of *Chlorella vulgaris* (10% v/v) was inoculated into BG-11 media with different chlorine concentrations (0, 0.2, 0.4, 0.6, 0.8, and 1.0 mg/L). Suitable inoculum cell density was prepared by performing a 10-fold serial dilution of the inoculum and plating onto BG-11 medium supplemented with bacterial agar for 14 days. Small, green colonies were observed on the plates after 14 days of growth. Plates with colonies between 30 and 300 were counted and the highest dilution with colonies falling within this range was used for the estimation of inoculum density. The 10^{-5} dilution plates had 114, 120 and 121 colonies with an average of 118 colonies. The number of viable cells in the inoculum was recorded as colony forming units (CFU). The viable inoculum concentration was estimated to be 1.18 x 10^{7} CFU/mL.

Determination of Growth Kinetics and Dry Cell Weight

Microalgal growth was determined by measuring absorbance of the biomass suspension at 600 nm at 3-day interval. Figure 1 shows the growth curve after 9 days of cultivation. Bioreactors with low chlorine concentrations achieved highest growth rates in the exponential phase (Figure 1). After the 6th day of growth, most of the cultures with the exception of the control, had reached stationary phase. Growth kinetics of microalgae at various chlorine concentrations was determined during the log phase from the 3rd to the 6th day (Figure 1). Growth rate was 0.016 h^{-1} and 0.008 h^{-1} for the 0.2 mg/mL and 1.0 mg/mL chlorine respectively (Table 3.1). All concentrations of chlorine investigated supported microalgal growth. Maximum growth was achieved during the exponential phase with growth rate. Since the cultivation conditions of the microalgae and the initial concentration of the cells inoculated in each flask were uniform, the differences in growth rates can be attributed to the effect of chlorine. In a previous study, Sommerfeld and Adamson, (1982), demonstrated the effectiveness of chlorine as an algicide with higher concentrations of residual chlorine inhibiting or killing microalgal cells. After 9 days of continuous growth, the biomass was harvested, dried and weighed. The low dry cell biomass achieved ranged from 60 to 90 mg/L and this is attributed to the small working volume, high inoculum density and subsequent rapid depletion of nutrients. Highest biomass production (89 mg/L) was achieved at 0.4 mg/L of chlorine while 69 mg/L was achieved at 0.8 mg/L of chlorine (Figure 2).

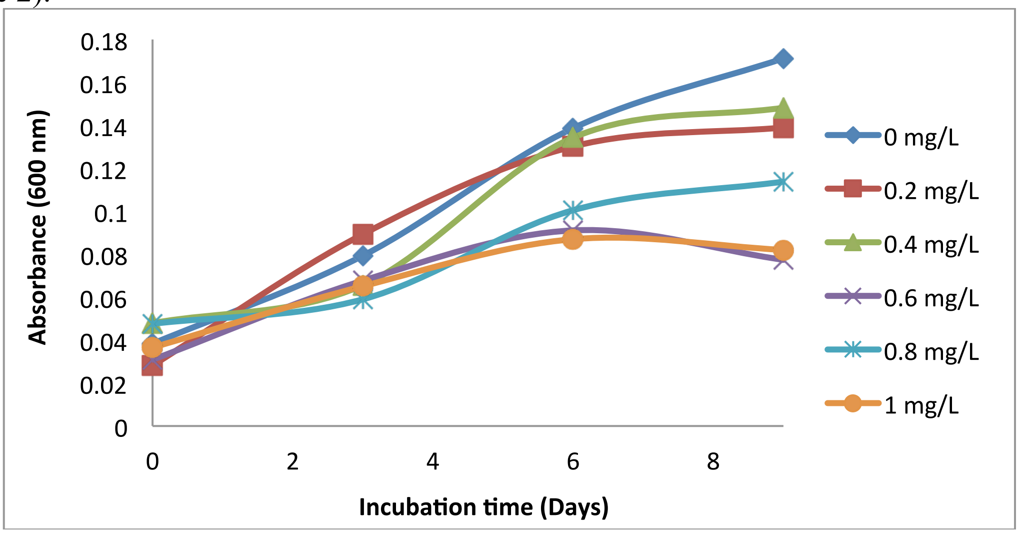


Figure 1. Spectrophotometric growth measurements of *C. vulgaris* cultivated in BG-11 media with varying concentrations of chlorine.

Table 1. Growth kinetics of *Chlorella vulgaris* in BG-11 media with varying dosages of free chlorine.

Free chlorine dosage (mg/L)	Growth rate (h^{-1})	Division per day	Generation time (h)
0	0.010	0.015	68.49
0.2	0.016	0.023	43.10
0.4	0.010	0.014	69.44
0.6	0.011	0.016	63.69
0.8	0.007	0.011	93.46
1.0	0.008	0.012	86.96

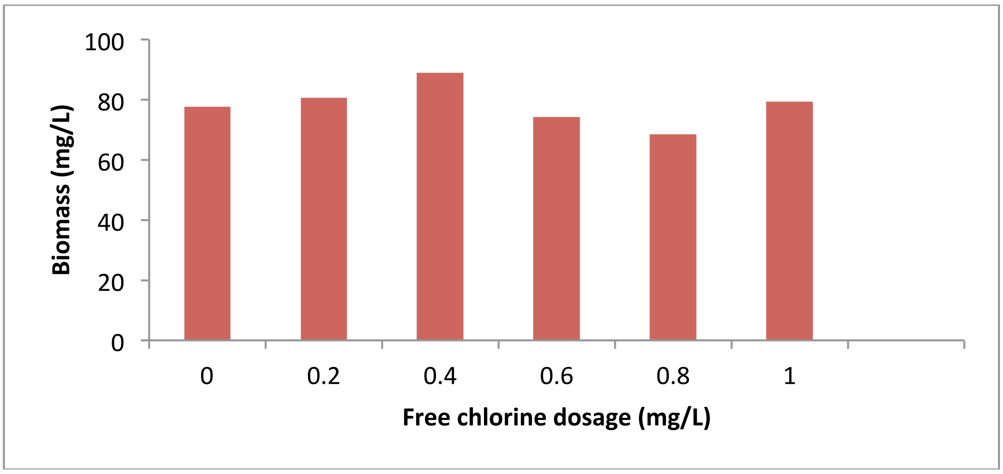


Figure 2. Dry biomass of *Chlorella vulgaris* after 9 days of cultivation at various free chlorine dosages.

Determination of Chlorophyll-a and Proteins

Chlorophyll-*a* content was used as a proxy for growth at varying chlorine dosages. There was a gradual increase in chlorophyll-*a* content in response to varying chlorine concentrations from the day of inoculation to the last day of growth (Figure 3). The highest chlorophyll-*a* content (16.61 µg/mL) was observed at 0.6 mg/L of chlorine. This could possibly be the threshold chlorine dosage at which there is maximum production of chlorophyll-*a*. In another study (Fukushima and Kanada, 1999), the effect of chlorine from a wastewater treatment plant on periphytic algae was investigated and chlorophyll-*a* concentration was used to estimate biomass accumulation. These co-workers observed a decrease in chlorophyll-*a* concentration with an increase in chlorine dosage after 24 h of cultivation. In the current study, growth curves obtained by spectrophotometry and chlorophyll-*a* content (Figure 1 and Figure 3) respectively, show similar growth trends. A previous study (Ramaraj *et al.,* 2013) showed that chlorophyll-*a* content is not an accurate measure of biomass. All statistical analysis in that study revealed no relationship between chlorophyll-*a* content and dry cell weight. Chlorophyll-*a* content can be affected by different physiological parameters, so it cannot be used as an accurate measure of biomass accumulation but rather a reflection of the photosynthetic rates. Wet biomass suspension was disrupted to break open the cells for protein extraction. Wet biomass was used since drying the biomass could potentially denature the proteins. Protein concentration in the biomass crude extract was determined by the Bradford method. Figure 4 depicts the production of proteins at various chlorine concentrations. Maximum protein production (2.032 mg/mL) was achieved at 0.2 mg/L of chlorine while 0.153 mg/ml of protein was produced at 1 mg/L of chlorine. No extracellular proteins were detected in the extracellular supernatant by *Chlorella vulgaris* at all the varying chlorine dosages investigated.

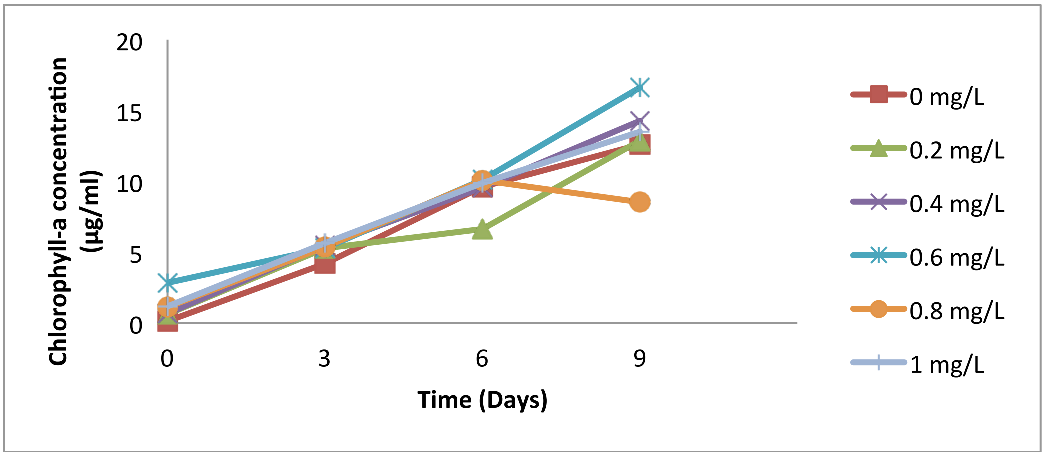


Figure 3. Growth measurement of *Chlorella vulgaris* by chlorophyll-*a* content at various free chlorine dosages.

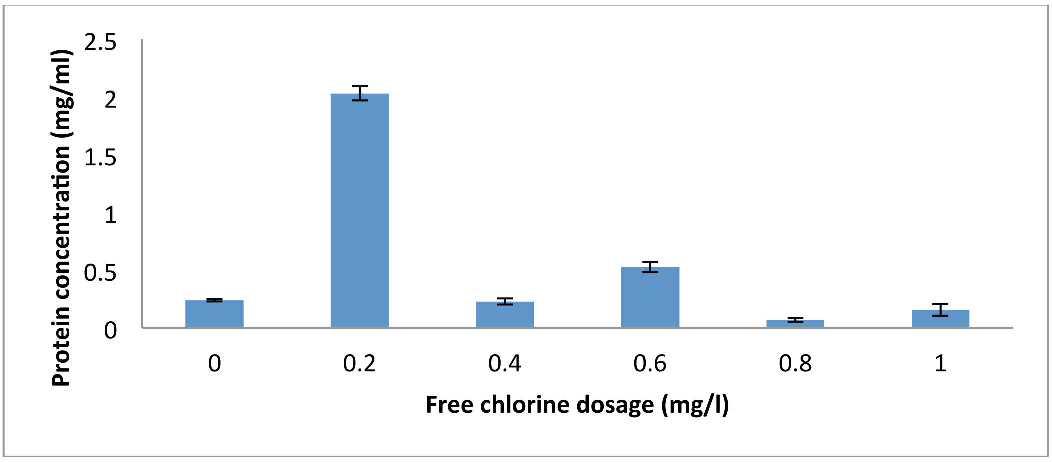


Figure 4. Determination of protein concentration by the Bradford method produced by *Chlorella vulgaris* at various chlorine dosages.

Determination of Carbohydrate and Lipid Content

Dried biomass was used for carbohydrates analysis. Firstly, the DNS method was used to determine if any reducing sugars were present in the biomass prior to hydrolysis by the Anthrone method. No reducing sugars were obtained by the DNS method. This was confirmed by qualitative TLC using reducing sugars, sucrose and starch as standards. In Figure 5, TLC confirmed that no reducing sugars were present in the biomass. The Anthrone method was performed to determine the total concentration of carbohydrates in the sample. Unlike the DNS, the Anthrone method detects reducing sugars liberated from the hydrolysis of complex carbohydrates. In Figure 6, total carbohydrates were obtained at all chlorine dosages. Approximately 0.524 mg/ml of carbohydrates were produced at the lowest chlorine dosage, (0.2 mg/L). There was a gradual decrease in carbohydrate production from 0 mg/L up to 1.0 mg/L of chlorine dosage. At the highest chlorine dosage (1.0 mg/L) approximately 0.444 mg/mL of carbohydrates were produced. No extracellular carbohydrates were detected at all chlorine dosages by using both the Anthrone and the DNS analytical procedures. Lipids were extracted from the biomass and lipid content was determined gravimetrically. The percentage of lipids produced from the biomass was calculated for each chlorine dosage. Low percentages of lipid per dry biomass (1.37% to 17.86%) were obtained due to low yields of biomass that were obtained. As the dosage of chlorine increased, lipid production decreased as shown in Figure 7. The control which had no chlorine showed maximum lipid production (17.86 %) while the highest chlorine dosage, 1.0 mg/L showed the lowest lipid production (1.37%). Thin layer chromatography was performed for qualitative analysis of total lipids. This was done to determine if *Chlorella vulgaris* was able to produce lipids that are suitable for biodiesel production at varying free chlorine dosages. Thin layer chromatography showed production of various neutral lipids at various free chlorine dosages. Figure 8 shows a gradual decrease in lipid production with increase in free chlorine dosage. This is evident by the decrease in lipid intensity at higher chlorine dosage.

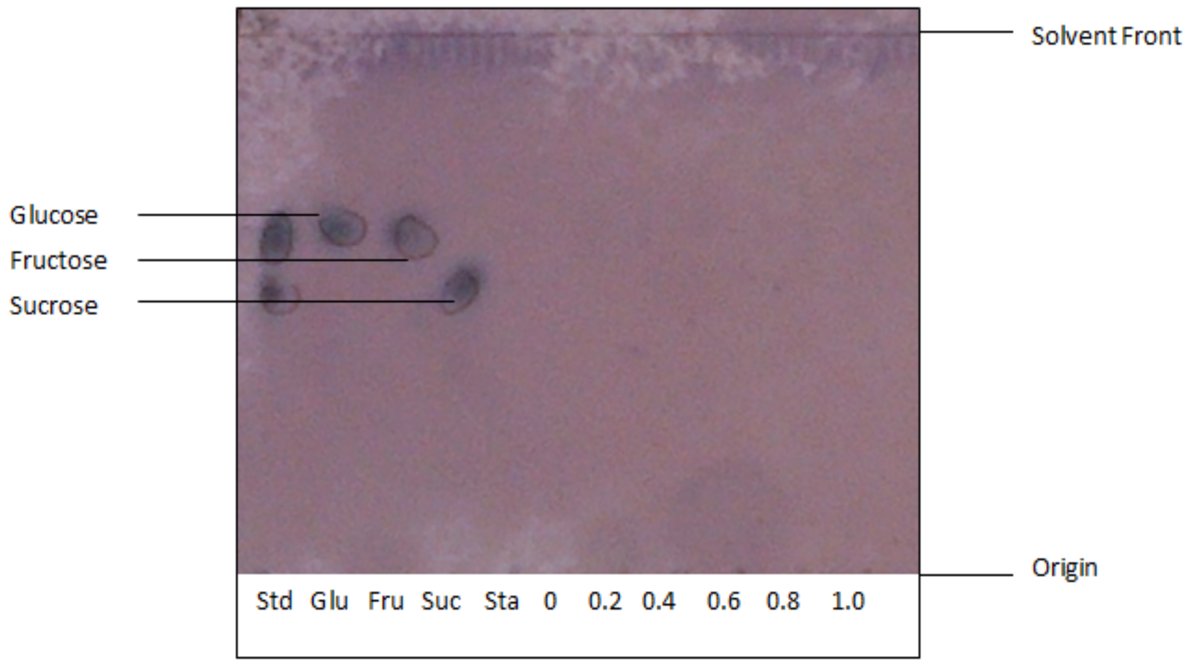


Figure 5. TLC chromatogram depicting absence of intracellular reducing sugars prior to hydrolysis. (Std: Standard mix, Glu: Glucose, Fru: Fructose, Suc: Sucrose, Sta: Starch, 0 - 1.0 Carbohydrate samples at various chlorine dosages).

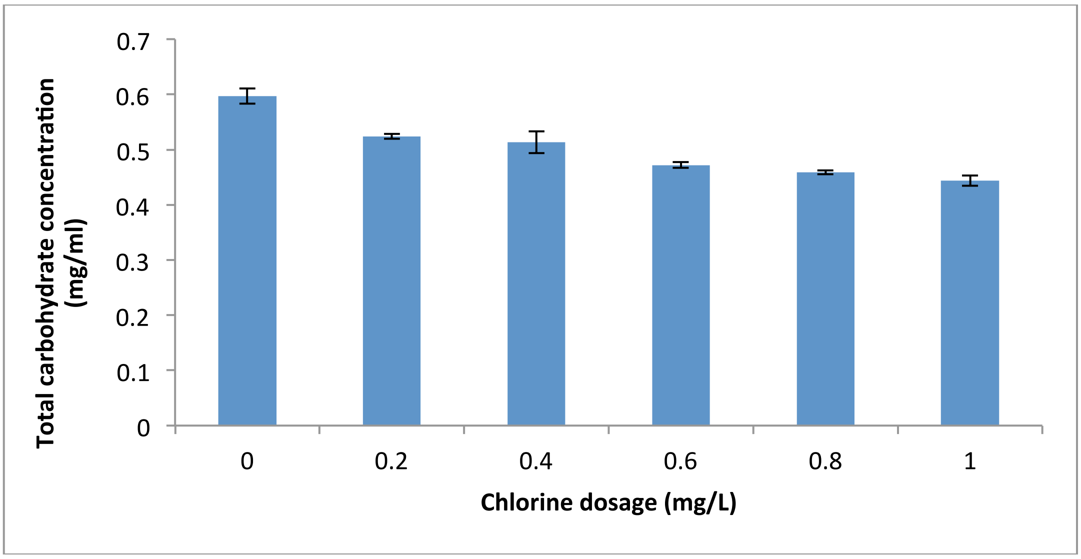


Figure 6. Determination of total intracellular carbohydrates by the Anthrone method produced by *C. vulgaris* at various chlorine dosages.

Some algal species have been shown to contain extracellular polymeric substances that can be proteins, lipids, carbohydrates, amino acids etc. These are usually produced as a form of protection from toxic compounds (Hu *et al.,* 2003). No extracellular metabolites were obtained in this study; this could explain the ability of chlorine toxicity towards algal cells. Lipid production in *Chlorella vulgaris* has gained major interest for use in biodiesel production. Microalgae produce various lipids in the form of neutral lipids such as storage lipids e.g. triacylglycerols. These lipids are readily converted into biodiesel (Kim *et al.,* 2015). Low lipid percentages were obtained per biomass; this is due to low yields of biomass used (Figure 7). Lipids have been reported to increase under stressful conditions such as nutrient deprivation. Even though no triacylglycerols were obtained in this study, other neutral lipids such as diacylglycerols and monoglycerols were obtained (Figure 8). These could also be converted into biodiesel. Other lipids including polar lipids were also produced. Other pigmented products were also produced; these could be carotenoids. Lipid production decreased with an increase in free chlorine dosage. This is accounted for by the absence of some lipids and the decrease in concentration at higher chlorine dosages. This could also be attributed to high free chlorine dosages interfering with metabolite production.

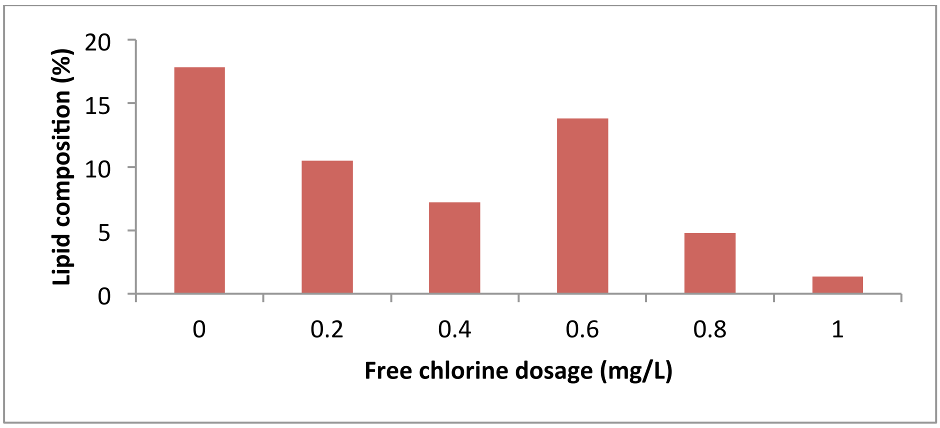


Figure 7. Lipid yield produced by *Chlorella vulgaris* at various dosages of chlorine.

Optimization of Post-Chlorinated Wastewater for Microalgal Growth

The ability of *Chlorella vulgaris* to grow in wastewater by utilizing macronutrients present in wastewater was investigated by cultivating *Chlorella vulgaris* at different BG-11: wastewater media ratios. Figure 9 shows that all media formulations supported algal growth from day 4 to day 12, after which there was cell death probably due to nutrient limitation. After 12 days, the highest biomass accumulation was observed for 100% wastewater medium while 100% BG-11 showed the lowest growth (Figure 9). Growth kinetics in Table 2 show that 100% wastewater had approximately double the growth rate (0.016 h^{-1}) of pure BG-11 medium (0.008 h^{-1}). Microalgae have gained major interest in wastewater remediation. Previous studies on *Chlorella* sp. have shown its ability to grow in raw wastewaters as well as removal of nutrients in wastewater during tertiary treatment (Krishna and Thankamani, 2012). In this study, *C. vulgaris* could grow in all BG-11: wastewater media formulations. However, best growth was observed in pure wastewater (Figure 9). This could be attributed to high nutrient levels present in the wastewater as compared to the artificial medium. Therefore, microalgae can potentially be used to remediate wastewater with concomitant biomass production. The microalgal biomass can subsequently be converted into bioenergy and other co-products and biomolecules.

Table 2. Growth kinetics of *Chlorella vulgaris* cultivated in BG-11 medium supplemented with wastewater.

BG-11 Medium %	Growth rate (h^{-1})	Division/day	Generation time (h)
100	0.009	0.013	78.13
80	0.016	0.023	43.67
60	0.018	0.026	38.76
40	0.021	0.030	33.44
20	0.020	0.028	35.59
0	0.016	0.024	42.55

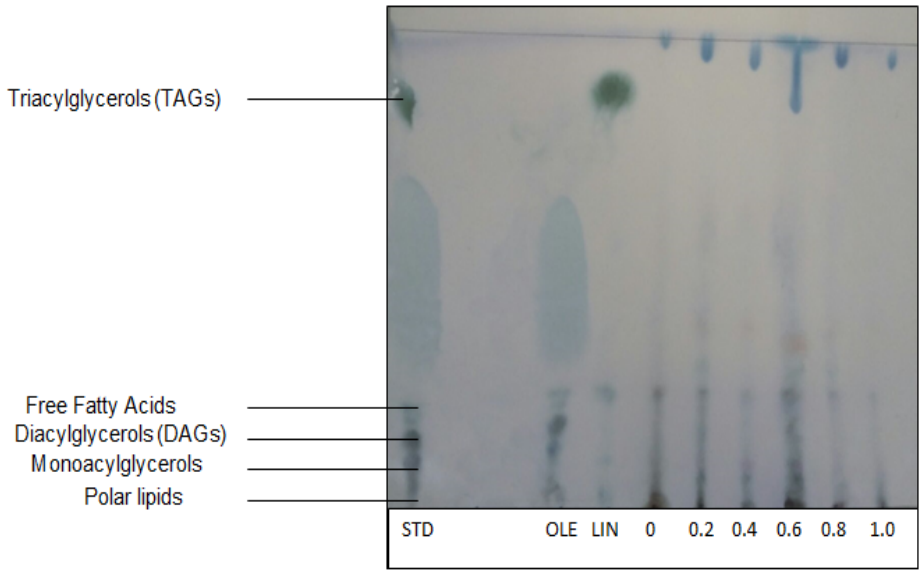


Figure 8. Qualitative analysis of lipids produced by *Chlorella vulgaris* at varying dosages of chlorine. (STD: Standard mix, OLE: Oleic acid, LIN: linoleic acid, 0 – 1.0: Lipid samples at varying chlorine dosages).

Transmission Electron Microscopy

Transmission electron microscopy was performed on microalgal samples cultivated at 0, 0.6 and 1.0 mg/L free chlorine dosages to investigate the effect of free chlorine on the ultrastructure and morphology of the microalgal cells (Figure 10). The control (a), which had no chlorine showed intact cell components as compared to the other cells exposed to free chlorine (b) and (c). In (b), the effect of free chlorine can be observed by some cell wall degradation. The cell wall is also pulling away from the cell membrane, but the cell is still intact. In (c), there is almost complete cell wall degradation which can be attributed to the oxidative effect of the high chlorine dosage. Free chlorine was found to have a detrimental effect on the morphology and ultrastructure of the microalgal cells at high dosages (Figure 10). There was a significant change in the cell wall architecture after chlorine exposure. Previous studies have indicated that chlorine at different dosages has distinct effect on microalgal cell surface architecture which might lead to release of cell organic compounds to the medium (Chen and Yeh, 2005).

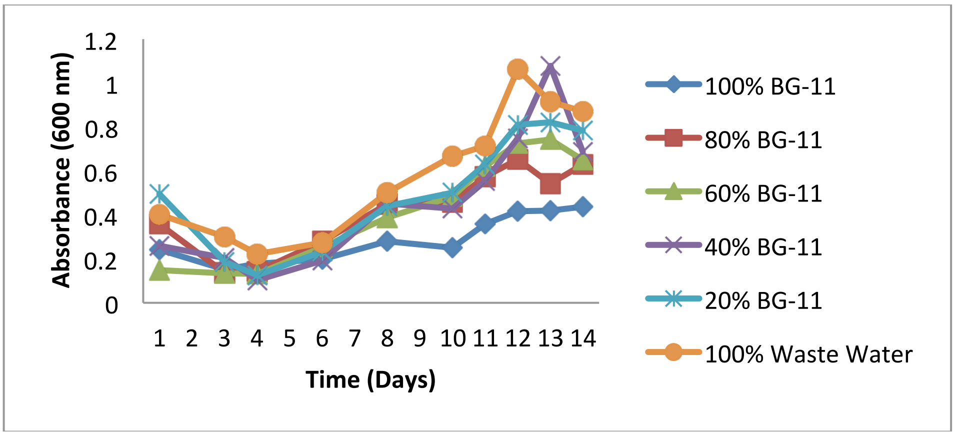
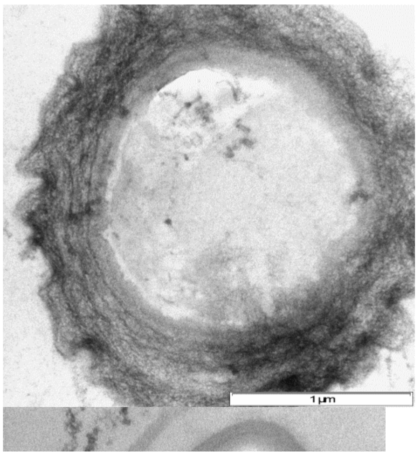


Figure 9. Growth of *Chlorella vulgaris* in BG-11 medium supplemented with wastewater, from 100% BG-11 to pure wastewater.



(a) (b) (c)

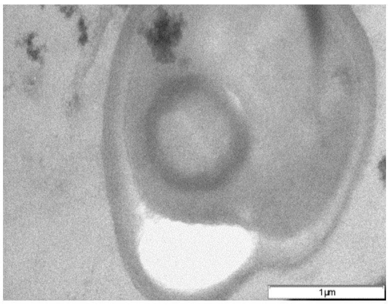


Figure 10. Transmission electron microscopy of *Chlorella vulgaris* cells exposed to various dosages of chlorine (a) 0 mg/L, (b) 0.6 mg/L and (c) 1.0 mg/L

Conclusion

In conclusion, results obtained from cultivation of *Chlorella vulgaris* in BG-11 with varying dosages of chlorine showed the effect of chlorine on microalgal growth and metabolite accumulation. High chlorine dosages had some detrimental effects while low chlorine dosages were had negligible effect and stimulated microalgal growth and metabolite accumulation. Wastewater was found to support microalgal growth, which could be an economically feasible method of wastewater treatment and microalgal cultivation. Future work could include quantitative analysis of the metabolites, analysis of metabolites produced from algal biomass cultivated in wastewater and conversion of these metabolites into biofuels.

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