Solarising tropical Africa's rural homes to sustainably overcome energy poverty

K E Kanyarusoke

Mechanical Engineering Department, Cape Peninsula University of Technology, Cape Town, South Africa

E-mail: kanyarusokek@cput.ac.za

Abstract. At less than 30% electrification, Tropical Africa is the most energy-poor electrified region of the world. At home level, the annual per-capita electric energy consumption ranges between 0 and 150 kWh in rural areas, where 83% of the population reside. This is well below the 250 kWh recommended by the International Energy Agency (IEA) as the threshold for exiting rural 'Energy Poverty'. Some governments have tried to extend the grid to such areas but these efforts have not yielded much. The approaches of rural electrification – as is being done now have therefore failed – and they may not be able to electrify every home in the countries concerned. An alternative approach promoting stand-alone photovoltaic (PV) and other solar powered heat and mass transfer systems at home level is proposed. An example of the approach in a village home in rural Uganda, East Africa is given. It is estimated that the combined unit energy cost over the systems' lifespan would be just about US 3 cents. Health, Education, and Sustainability in all its forms would be greatly improved. The main recommendation is for policy makers to adopt this approach for rural homes while sparing grid supply only for commercial and industrial activities.

1. Introduction

The energy poverty paradox in Africa is well documented. On one hand, here is a continent with 7.7, 7.6, 3.6, and 13 percentage points of the world's known oil, gas, coal and hydro electric energy reserves [1] on the other, is a 15.4% world population consuming 3.1% of the world's electric energy output [2]. If relatively 'developed' South Africa and semi tropical to Mediterranean North Africa are removed from the energy statistics, we get a 2017 Tropical Africa with 681 out of 951 Million people having no access to electricity at all [3]. The concerns in this paper are not that levels of industrialization and electrified transport in the region are low - which they are, anyway [4]. Rather, the absence of convenient, safe, clean, reliable and sustainable forms of energy in the homes of the 681 Million people above amidst a plentiful unharnessed solar energy resource [5]. This, at a time when literacy in the region is rising and when technology is diffusing faster, incentivizes a contribution in addressing the paradox in a way that could impact significantly on the lives of these people.

As of now, in non-electrified tropical African homes, non-muscle energy is mainly required for cooking food, boiling water, lighting and limited space heating at night. Excluding the latter, Williams estimated these activities to consume approximately 1 GJ or 277.8 kWh per month per household in rural South Africa [6]. In most of tropical Africa, this energy comes from incomplete combustion of bio fuels - mostly wood fuel and sometimes charcoal, in poorly ventilated kitchens and living spaces

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

[7]. Daily chores like water sourcing, all forms of washing, animal tending, cultivation, crop harvesting and processing, etc. are handled manually. Many of these activities are left to women and children [8]. This is unlike modern homes where running water, washing machines, electric stoves, water geysers, televisions, electric/electronic security systems etc. may be the norm [9]. Doesn't it matter that in spite of limitations facing women and children of the first group, they are largely responsible for primary manual production of food even for the second group? It does, principally because of reasons to do with health and sustainability. These are now briefly reviewed as a basis for the reported work in subsequent sections.

1.1. Some health and environmental concerns

The incomplete combustion of biofuels mentioned above produces large quantities of particulates and poisonous gases which affect both the environment and the health of fire attendants. Nussbaumer *et al* for example, report presence of wood tar in soot and of total particulate matter concentrations of 5000 mg per m^3 in flue products of poorly combusted wood fuel [10]. This is two orders of magnitude as high as emissions from a well-run combustion unit. The World Health Organization (WHO) gives emissions guidelines on two particle aerodynamic size limits: the 10 μm (PM10) threshold particles, which can be filtered by the upper respiratory tract, and the 2.5 μm (PM2.5) limit defining the observed smallest particle to exhibit a 95% chance of damaging lung and heart functions upon prolonged exposure [11]. The annual mean limits are given as 20 and 10 $\mu g/m^3$ respectively while the daily values are 50 and 25. Poor wood fuel combustion leads to exceeding these limits as reported in [7] and [12]. Figure 1 is a modified illustration on how the concentration of particles, and hence of mass, between the two limits increases with different combustion modes.

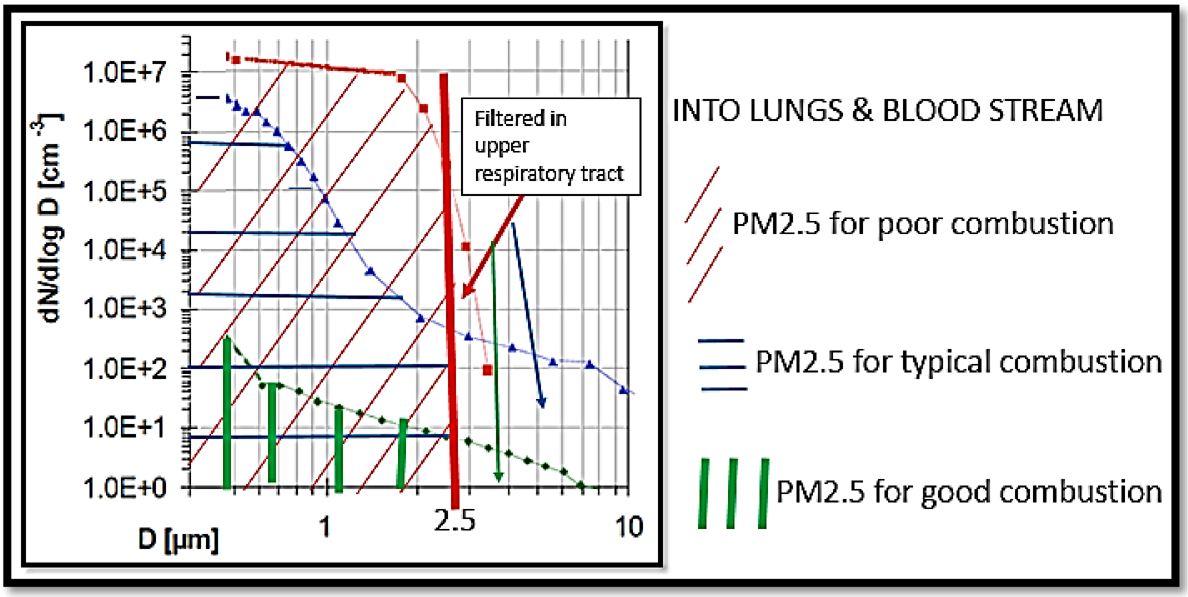


Figure 1. Illustrating effects of incomplete combustion on PM2.5 and PM10 values (modified from [10]).

The fact that most primary production of food and export agricultural products in tropical African countries is from efforts of people who are subjected to the above off limit exposures means food security and economic stability could be compromised if timely action is not made on addressing this situation. Moreover, the inefficient combustion additionally implies that more of the increasingly scarce fuel has to be burnt for a given task. This means more man hours have to be spent in the wild to fetch the wood or to produce charcoal. The latter is believed to lead to environmental degradation and adverse climate change. On the former, the United Nations Department of Economic and Social Affairs (UNDESA) reports that between 1990 and 2003, rural women were spending 2 to 4 hours a day, looking for firewood [13]. It adds that worldwide, 3.1 Million people die annually of indoor and outdoor pollution.

Following the above background information, the rest of the paper is organised as follows: Section 2 gives a commentary on current approaches to addressing the energy problem in the region. Section 3 reviews systems that were developed by the author to augment the above efforts. In section 4, previously unpublished results of the work are given and they are then discussed in the penultimate section. The paper concludes with an overall summary and makes one key recommendation.

2. Some approaches to alleviating the problems

In this section, a short commentary on efforts by different people, organizations and governments to address the energy problem for the 681 Million energy-poor tropical Africans. The efforts include those on: combustion improvements, rural electrification, and Concentrated solar power (CSP) systems developments. Some research on Solar Thermal Systems (STS) has been done especially in Nigeria and Kenya as exemplified by Arekete [14], Mwithiga and Kigo [15] and Ozuombo *et al* [16].

2.1. Actions on combustion

On combustion, methods used to tackle the problem include use of less polluting fuels and of improved stoves. Actions on fuels are however more expensive as some require capital expenditure in addition to running fuel costs. Thus, ethanol gels, plant oils, kerosene, natural and bio gas, - all require upfront investment in a suitable burner and/or a safe fuel storage system. More effort has been put in improved stoves partly due to a low investment cost (e.g. equivalent of US$ 2.00 in Ethiopia [17]) but mainly because of continuity in use of the familiar wood/charcoal fuel. Human behaviour is such that it is easier to accept one change at a time rather than several, simultaneously. Thus, different stove designs capable of reducing fuel consumption and consequent emissions by up to 50% on ‘typical’ combustion mode of figure 1 have been introduced in Ethiopia, Kenya, Rwanda, Uganda, Nigeria and many other tropical African countries [17-20]. Both the change of fuel and change of stove, however do not remove the other less talked about risk: that of fires in grass thatched houses that many of Africa’s rural populations reside in. The author for example recalls that between 1966 and 1977, his homestead in rural Uganda lost most household items on three occasions, two of which were due to in-house made fires for lighting, and a third was due to day cooking needs. Today, even in rural South African homes - where paraffin has been used to augment solid fuels – ref [21] reports of homes which have been burnt on annual basis.

2.2. Rural electrification

Out of social political considerations, many African governments are trying to address these problems by extending national electric grid systems to rural areas. For example, as early as 1989, Ghana started a series of 5 year rural electrification programs, intended to avail electricity to everyone by 2020 [22]. Starting at 28% access rate then, they had nearly doubled that percentage by 2005. As figure 2 below shows, they are now at 75%, well on course to achieving their 2020 target. Nigeria set up a rural electrification agency in 2006 but it had continuity problems and 1946 electrification projects were temporarily put on hold midway. They resumed in 2012 [20]. The first decade of this century saw other tropical countries setting up similar agencies or authorities. Thus, Zambia set up an authority in 2006, when rural electrification was at 3.1%. Because of challenges on tariffs, population distribution and incomes, staffing and funding they have since struggled to maintain the rural access rate at 3% [18]. Zimbabwe’s agency targeted rural income generating activities like Small to Medium scale Manufacturing Enterprises (SMMEs) for sustainability [24]. Kenya set up an authority in 2006 which started work in 2008. Unlike Zimbabwe, they targeted public facilities and rural trading centres. As a result, by May 2013, they had added 25873 schools, health and trading centres to the grid. This brought the national household electrification rate to 26% [17]. Between 2009 and 2012, Rwanda perhaps outperformed expectations in relative terms. Starting with a generating capacity of 69.5 MW and 110000 connections, they had 165 MW connected to 350000 users by 2012. All administration centres, health facilities and 50% of all primary and secondary schools were connected to the grid during the period [19]. This raised overall national access from 6 to 16%.

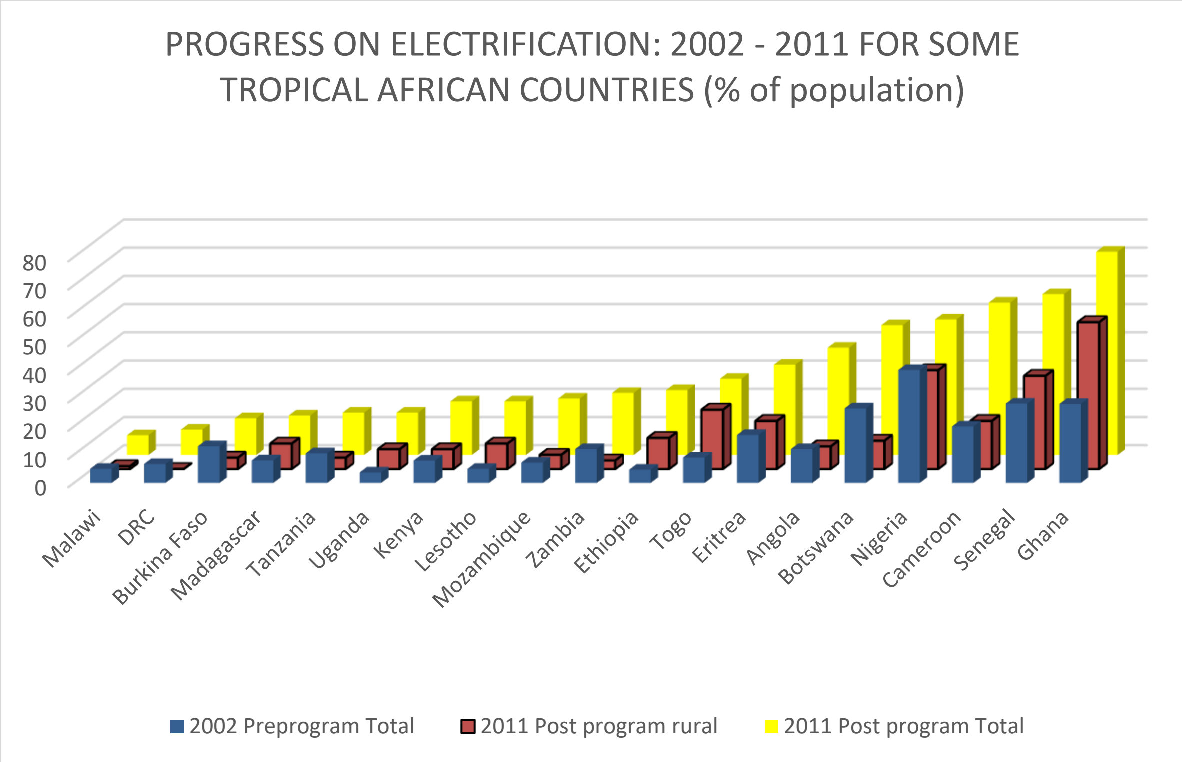


Figure 2. Changes in electrification for some countries between 2002 and 2011: Data compiled from national governments publications and the IEA [2].

The above relative achievements notwithstanding, there are problems with centralized efforts to rural electrify. In addition to those faced by Zambia mentioned above, Abeeku and Kemausuor mention lack of energy marketing strategies for small systems as a hindrance to full exploitation to narrow the supply-demand gap [24]. Mulugetta *et al* observe that more effort was being directed to a "Technology push" than to a Market pull [25]. Yet, if there were to be a shift in focus, the demand-supply gap could only get bigger as the population is growing rapidly. For example, it is estimated in [26] that tropical countries in the Nile basin alone will need to generate an additional 375 GW to attain present day South Africa's per capita energy consumption by 2050. It is shown that this is well beyond present day hydroelectric potential of the basin. It is perhaps because of such limitations that attention is being drawn to other renewables. In fact, some of the successes mentioned above would not have been possible were it not for inclusion of solar and geothermal forms of energy in the programs. Kenya in particular has had 200 MW added to the grid from geothermal sources [27]. Ghana, Zambia, Zimbabwe, Tanzania agencies/authorities have included photovoltaic (PV) power in their achievements. Kenya has gone a step further. The Naivasha based assembly plant is the only one from tropical Africa - of eleven reported by Enfsolar to be making PV panels in Africa [28]. To the extent that PV connections in Kenya are reported to be outpacing new normal grid connections now [29]. Rwanda's success is partly attributed to inclusion of 8.5 MW of PV electricity and the exploitation of Methane gas under Lake Kivu waters.

The above experiences illustrate the importance of using a mixed strategy on rural electrification. Central planning may be necessary for connecting public facilities and rural trading centres to the grid.

Dispersed individual homes, however, can be difficult and expensive to access. Kenya's example on PV panels shows that these are better left to private individuals and organizations. In Uganda, the rural electrification program has connected many trading and district administration centres [30]. But recent efforts to overstep this and freely connect homes in some areas involve a bureaucracy and create potential grounds for corruption as stated by Kanyarusoke *et al* [31]. In addition, they might be politically misunderstood or economically unsustainable – as the recipients will have to pay the high recurrent bills. That said, we now turn to efforts in non-electrical applications of solar energy.

2.3. Actions on CSP systems

Solar radiation reaches the earth as a composite mixture of beam and diffuse radiation. The beam part, coming directly from the sun, about 150 Million km away, arrives as parallel rays. CSP systems use refraction and/or reflection to concentrate these rays on a smaller area, thus increasing their intensity and effect either in terms of electricity generation or of heating ability. Here, we comment on efforts that use the latter.

Although concentration could be achieved using convex refractors, flat and concave reflectors, documented work shows that researchers and users in Tropical Africa have so far focused on reflectors. At domestic level, perhaps a most significant flat reflector application has been the CooKit cardboard cooker, designed in 1994 by Roger Bernard [32]. Figure 3 shows an illustration of the cooker. It is reported to be: effective in heating (70-90^{o}C); affordable by the poor (US$10); light (0.5 kg); easy to construct (about 2 hours with support of an instruction manual); and easy to store or transport (foldable). With these attributes, the cooker has been popularised in West African countries and in refugee camps of East and Central Africa.

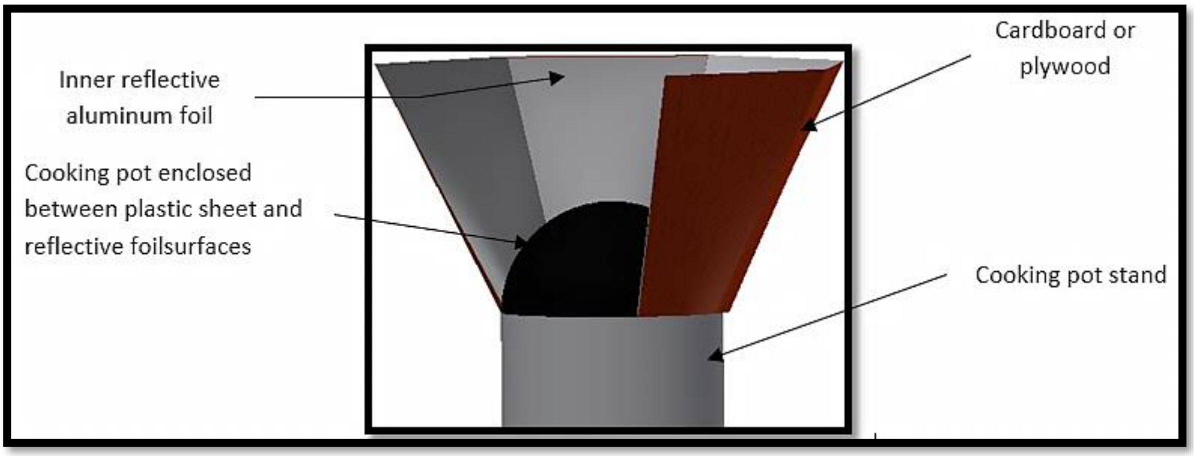


Figure 3. A 3-D illustration of the CooKit panel cooker.

Kimambo gives a summary of studies on solar cookers being used in Tanzania [33]. He classifies them as: Panel (e.g. CooKit and plane glass reflectors), Box (e.g. Sunstove) and Parabolic (polished and unpolished aluminium surfaces). Research results on six cookers in these categories are given and a recommendation that glass reflectors and polished aluminium cookers should be used in clear sky, high beam radiation areas is made. Unpolished aluminium types are discouraged. Panel types are recommended where there is medium sky cover. Box types are reported to be most advantageous in cloudy areas because of their ability to use diffuse radiation.

In Nigeria, much effort has gone into parabolic units. Notable is Dasin's solar tracking parabolic cooker [34] and Abdulrahim's bifocal solar tracking parabolic collector [35,36]. While most other solar cookers in the region require manual adjustment every 15 to 20 minutes to face the sun, these two have a mechanical clock – weight system to automatically keep the paraboloids' foci at the cooking pot position. Figure 4 shows Abdulrahim's cooker.

Figure 4. Abdulrahim's bifocal parabolic cooker [36].

Widespread acceptance of solar cookers faces problems mainly because of variability of solar radiation and other weather components, longer cooking time when compared to combustion assisted cooking and inability to perform from late afternoon onwards. The Tanzania research above [33] appears to suggest that most kitchens would require more than one solar cooker type if reliance on this resource is to be increased. Variability and cooking time problems could be mitigated by augmentation of the incident radiation using boosters. Elsewhere in the world, cooking temperatures are reported to have been raised by values of up to 17°C relative to those of ordinary cookers by augmentation with extra reflecting surfaces and/or finned pot surfaces [37]. Thus, cooking times can be reduced. Use of heat storage materials, including sand jackets and phase change materials like Magnesium nitrate hexahydrate ($Mg(NO_3)_2.6H_2O$), Stearic acid, Acetalmide among others have enabled cooking in the evenings. However, all these improvement methods do not seem to have been adopted in tropical Africa to any reported measure yet.

3. Developing sustainable energy systems for rural homes

In this section, examples of affordable and sustainable engineering actions that could be taken to overcome rural homes' energy poverty are given in areas of electricity, heat and mass transfer. These three areas form the bulk of energy requirements in a household and they have profound effect on the social-economic wellbeing of rural communities. Other needs such as transportation and land tilling in agriculture are also important in rural homes but no work has as yet been done by the author on these. They are, therefore, not discussed.

3.1. Photo electricity

The most basic requirement for electricity in a rural home is lighting at night – so that the useful work day can be extended. Also, communication and entertainment through respective use of radios and fully charged cell phones are enabled. Work done in this area is reported in refs. [31], [38] and [39]. In [31], a MATLAB® program is used along with ASHRAE weather data [40] to predict manufacturer photovoltaic (PV) panels' performances in Tropical Africa. Ref [38] uses validated TRNSYS modelling [41] to give optimal fixed panel tilts and optimised PV equipment selections for sub-Sahara Africa's rural homes in colour-coded maps. In [39], performance testing of a patented solar tracking device suitable for rural Africa's conditions of low technical skills and disposable incomes is described. Outcomes of most of this work have been put to use in a rural home in Kyegegwa, Uganda since June 2016. Figure 5 shows the installation. Costs and performance indications of the installation after about one year are given in sections 4 and 5 below.

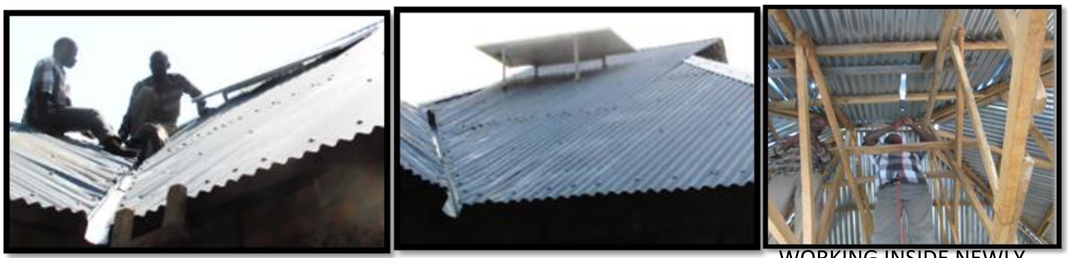


Figure 5. Typical rural village house trying to emerge from energy poverty.

3.2. Heating and cooling

Heating in a rural home is a major consumer of energy because of cooking. Prevalent usage of biomass [42] has also affected the environment through cutting of trees for firewood and/or charcoal [43]. Cooling in rural homes has not been a big energy consumer though the need for food preservation and air-conditioning is evident in hot and humid climatic regions - such as the coastal areas, and in warmer hinterlands [44]. Work done on heating has so far been on water heating using solar thermal units. That on cooling has been on use of PV- powered refrigeration systems.

3.2.1. Water heating. For rural home use, a series of low cost fixed slope solar syphon systems ranging from 1 to 2 m^2 and heating 50 to 150 litre of water have been developed. Figure 6 shows the construction and installation of one such unit in a household compound – as opposed to being on a roof since there is no pressurised water to fill the tanks in most rural areas. Suitable optimal slopes for 2 m^2 units have also been determined for the entire Tropical Africa region using TRNSYS modelling. They are different from those of PV panels because of added thermal necessity to generate a sufficient hydraulic head to circulate the water. Other developments on solar syphon systems have included azimuthal and inclined axes solar tracking. The full theoretical development of the latter tracking is given in [45]. Figure 7 shows the two tracking units.

Figure 6. Installing a fixed slope solar collector in a household compound.

Figure 7. Solar tracking collectors.

3.2.2. Refrigeration. An inverter-less PV run refrigeration system was developed for rural small scale farm daily fruit and vegetable harvests. The system was able to cool 20 kg of straw berry fruits from 30°C to 5°C in 5 hours on successive days as described and tested in [46].

3.3. Mass transfer: Water purification and crop drying

Rural homes have to use some of their heating energy resource for boiling water to make it relatively safe to drink. The alternative is to have high susceptibility to water borne diseases because most water sources are microbiologically contaminated [47]. In some cases, water as collected from the sources has dissolved salts which affect healthy development of the overall human body [48]. A low cost solar water purifier was therefore developed to address these problems. It is slightly different from ordinary solar stills in that the evaporated steam is condensed outside the still, thereby improving the effectiveness of the still. Figure 8 shows a unit that can be installed in a homestead compound for purifying at least 5 litre of water per day in most tropical African areas.

Another low-cost mass transfer device developed for rural homes is the crop dryer. Homesteads normally do not expend heating energy on drying of crops. However, they use both manual and mental energy to dry crops and protect them from not only weather elements but from birds, rodents and even human thieves as well. Mental effort, in this case, is deployed to plan when and where to place the crop for ease of covering/removing it in case of rain. Also, judgment as to the attainment of a desired final moisture content depends on a mental recollection and observation of crop physical features that mark the desired end point. The crop dryer such as in figure 9 was developed to address these problems.

Figure 8. A rural solar water purifier.

Figure 9. A rural solar crop dryer.

4. Results

In this section, key results of the above work which have not been discussed in other publications are given. These include costing of PV systems, energy yields of solar syphon systems and typical water yields from the water purifying system. Costing of heat and mass transfer systems is based on current developmental costs since there are at present no known players on the market.

4.1. Costing of PV electricity

Costs of the installation of figure 5 in Kyegegwa, Uganda (nearest TRNSYS weather station – Mbarara) are given in table 1. For comparison purposes, they have been worked out on a present net value basis after taking into consideration of different inflation rates on various products and services over a system life time of 25 years. A full development of these costs is available in the appendix.

Table 1. Approximate energy cost comparisons between fixed and tracking panel using different versions of the solar tracker.

	FIXED SLOPE	**MANUAL TRACK**	**SEMI AUTO**	**FULLY AUTO**
SOLAR PANEL REQUIRED (Wp)	200	150	150	150
TOTAL 'POSSIBLE' ELECTRICITY IN 25 YEARS (kWh)	6568	6600	6600	6600
CAPITAL COST (excluding non-material tracker costs) (US$)	**685.02**	**856.64**	**903.15**	**931.47**
PRESENT VALUE 25 YEAR OPERATING COST (US$)	527.58	527.58	527.58	527.58
PRESENT VALUE 25 YEAR MAINTENANCE COST (US$)	406.12	507.87	535.45	552.24
PRESENT VALUE RUNNING UNIT ENERGY COST (US$/kWh)	**0.14**	**0.16**	**0.16**	**0.16**
PRESENT VALUE TOTAL UNIT ENERGY COST (US$/kWh)	**0.25**	**0.29**	**0.30**	**0.30**

4.2. Energy yield from a 2 m^2 solar syphon system
A TRNSYS simulation for a 2 m^2 collector with slope fixed at 5° gives daily energy yields as shown in figure 10 when heating 50 litres of water for the Kyegegwa site. This gives an annual energy harvest of 2434 kWh. Peak water temperatures are at 57°C as shown in figure 11.

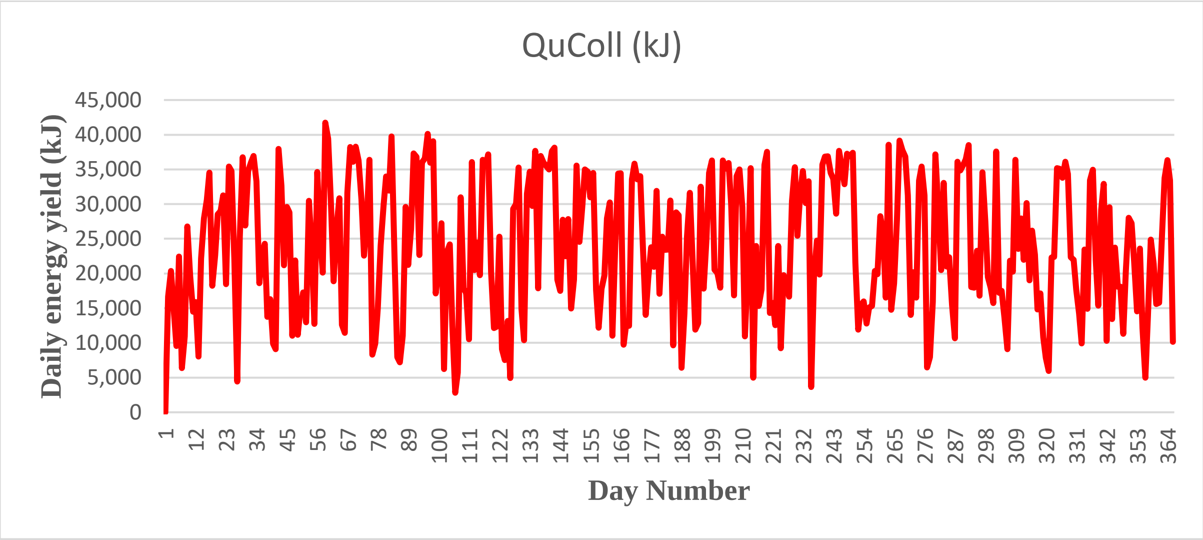


Figure 10. TRNSYS predicted Energy yield from a 2 m^2 solar syphon system heating 50 Litre water in Kyegegwa, Uganda.

4.3. Water yield from a solar water purifier
Typical performance on a sunny day of the newly developed water purifier of figure 8 is shown in figure 12. Along the distillation data are shown environmental conditions as well. On this particular day (22 Nov 2014), 2.8 Litre was produced from the prototype purifier. A larger unit producing about 5 Litre from an average 'dirty' water temperature of 20°C would save 3.6 kWh of direct heating energy per day.

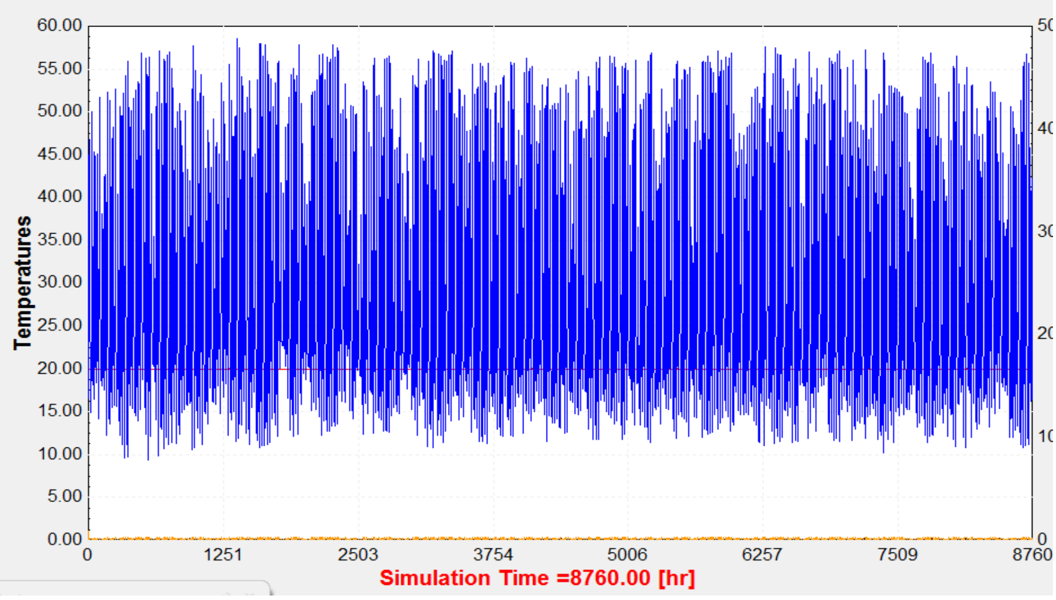
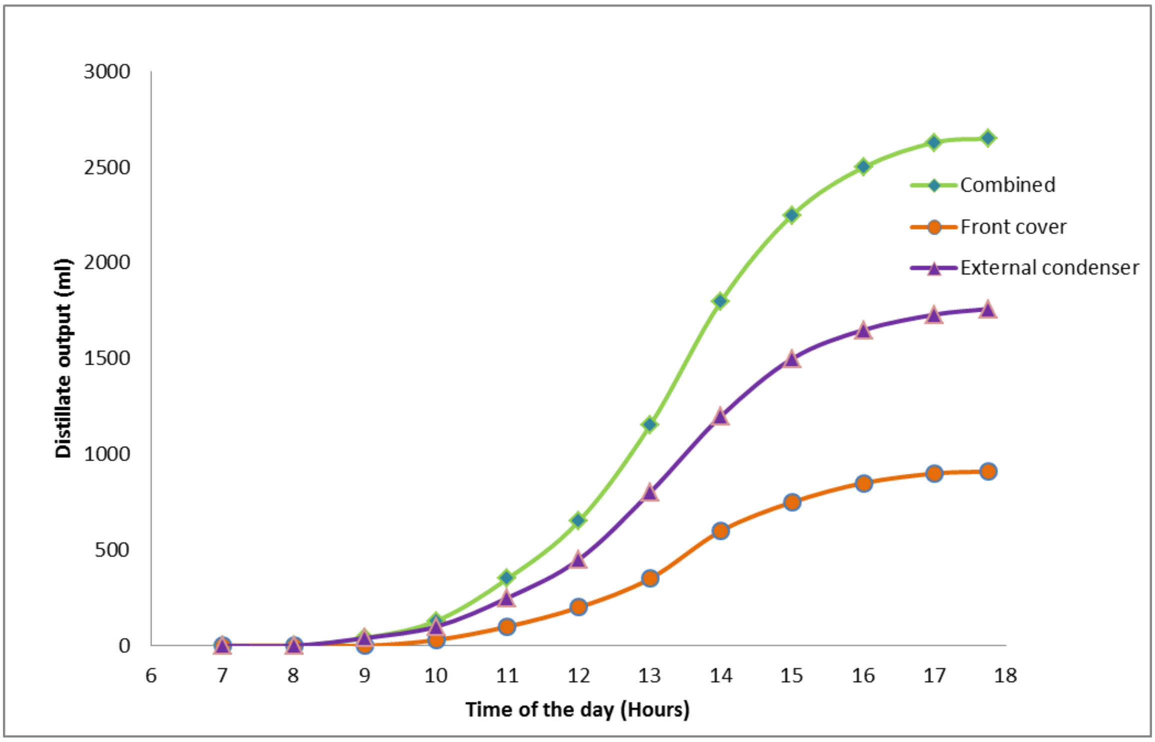


Figure 11. TRNSYS predicted water temperature variation from a 2 m^2 solar syphon system heating 50 Litre water in Kyegegwa, Uganda.



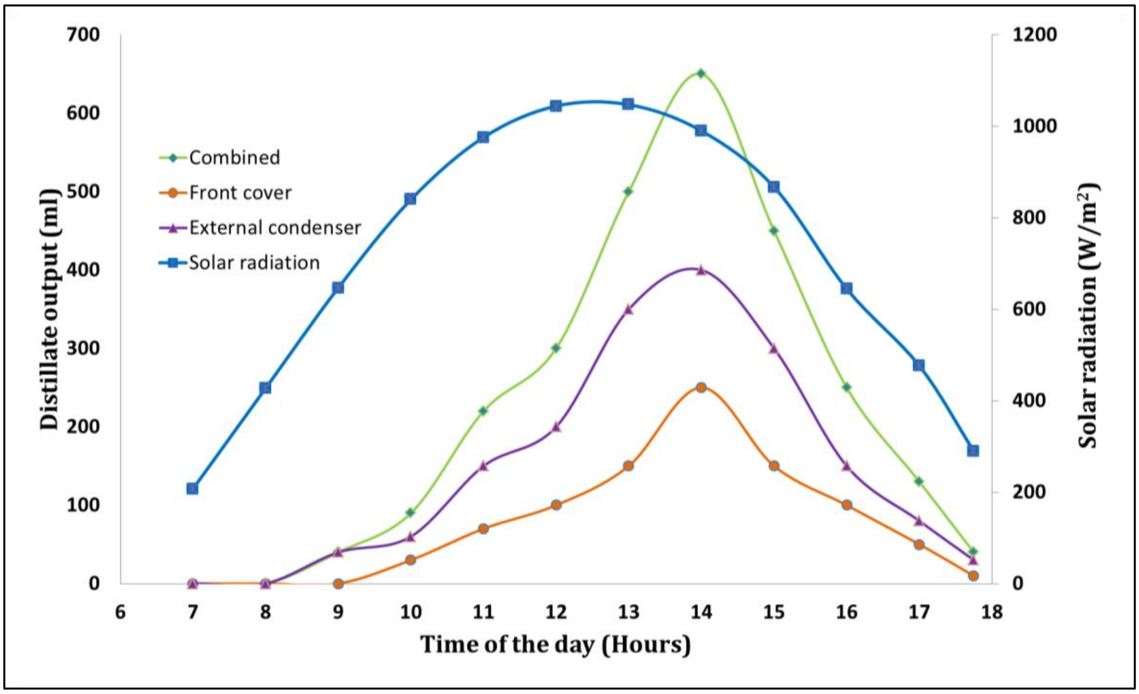


Figure 12. Measured typical performance and solar radiation data in the newly developed solar water purifier [49].

5. Discussion

The above results are discussed from perspectives of: energy utility, energy costs, social utility and sustainability. The discussion is concluded with a look at whether or not, centralising the provision of these energy services would be a worthy effort at accelerating reduction of energy poverty in Tropical Africa.

5.1. Energy utility

The most important benefit of the systems is the availability of useful energy in all places to people who would otherwise be constrained to live without it, and therefore miss opportunities availed by it. For a system life time of say 25 years in Kyegegwa, estimates of quantity of energy so availed by the systems are given in table 2.

Table 2. Useful energy availed by the solar resource in Kyegegwa, Uganda.

	Annual quantity (kWh)	Life time quantity (MWh)
Electricity (for 200 Wp panel)	263	6.6
Solar water heating (for 2 m^2 collector)	2434	60.9
Solar water distillation (at 5 L/day)	1314	32.9
Total energy	4011	100.3

The IEA defines energy poverty for rural areas at a per capita annual consumption of below 250 kWh electricity and below 500 kWh for urban dwellers [2]. Since electricity is used mostly for lighting and heating in homes, it could be said that the 4011 kWh in table 2 is more than adequate to change the status of homesteads of 8 to 16 people from energy poverty. Given that the household size in Uganda averages 4.7 with rural districts averaging between 2.5 and 7.6 persons [50], it seems clear that the systems would fundamentally alter the status. Quality of this energy may be judged from what it helps the homesteads achieve and how. These are discussed in section 5.3 below.

5.2. Energy costs

In table 1, the unit energy cost of US $0.25 from a fixed axis PV panel may seem high when compared with the April 2017 quoted value of US$ 0.19 for Uganda's grid electricity [51]. But the comparison is erroneous. The former cost includes both capital and running costs while the latter refers only to the bills paid to the grid supply company. This is part of the running costs which should include maintenance (e.g. bulbs and heaters replacements). In addition, the cost of acquisition should be amortised over the installation period. In 2012, the indicative acquisition cost for a home about 200 m from the nearest low voltage pole in Uganda's capital city, Kampala was US$ 800 [31]. This is greater than the capital cost of the PV system of figure 5. For a Kyegegwa rural home 5 km from the nearest pole, the cost can for practical purposes be taken as infinite. Hence, there cannot be a basis for comparison with grid supply cost. In like manner, there is no basis for comparing costs of the other two systems with grid supply. To estimate their energy cost however, actual costs of prototype construction materials were simply doubled to get an estimate of selling prices of commercial units. On treatment of these estimates like for PV, unit energy costs of table 3 were obtained.

Table 3. Estimated Solar energy cost of different systems in Kyegegwa, Uganda.

	Energy cost (US$/kWh)
Electricity (for 200 Wp panel)	0.25
Solar water heating (for 2 m^2 collector)	0.017
Solar water distillation (at 5 L/day)	0.013
Total solar energy	0.031

It is seen that the heating and mass transfer energy costs are very small, under 2 US cents. This arises from higher thermal efficiencies (40 to 60%) of conversion of solar energy to heat in the systems compared to the 15-17% of converting the same to electricity in crystalline silicon PV panels. Because of the large quantities of energy used in heating relative to lighting, the overall energy cost is very low, at about 3 US cents. The importance of this fact will become more apparent in section 5.5 below.

5.3. Social utility

From a health point of view, reduction in cardio pulmonary dysfunction in women is the most prominent possibility because of reduced exposure to smoke. Studies by Mills *et al* [52] and Hunter and Mills [53] among many others, explain how combustion derived pollutants lead to cardiovascular disease. But also among children, it is noted that poor lighting from paraffin lanterns and candles at night has two immediate implications. One – that for reading, the children would have to be closer to the lanterns to increase the intensity. This increases chances of airborne disease transmission between them, aggravating the effects of incomplete combustion of paraffin and wick. Secondly, the low intensity can lead to eyestrain and headaches. These problems are eliminated by the PV system of figure 5. Heating water either for hygiene purposes such as baths, laundry, dish washing helps reduce possibilities of water borne infections, since it is seen in figure 11 that temperatures achievable on many days are high enough to deactivate microbes as reported in [54]. Education can be enhanced by the systems in at least two ways. First, the children are able to read and do their homework at night in good light (and possibly health). Secondly, they would spend less time collecting firewood on weekends, perhaps devoting more time to private study. A real possibility is that all rural children would grow up knowing what 'electricity' and 'solar energy utility' are. This can stimulate study of Science among a bigger fraction of them than at present.

5.4. Sustainability

Replacing paraffin lanterns with PV lighting eliminates acid rains and millions of Tonnes of CO_2 from these sources. This addresses global warming and soil degradation issues. Solar water heaters lower the CO_2 load if adopted in urban centres. Action on either of the systems in rural areas could lead to growth in the latter. That way, the CO_2, acid rain gases and deforestation increases would be checked.

The other aspect of sustainability is the ability of users to continue affording to use the systems after initial trials. This problem does not arise for the water heating and mass transfer systems because the running costs are almost non-existent. For PV panels, occasional replacements of LED bulbs and replacements of batteries every after 5 or more years is the major expense. But because the periods are so long, there is enough time to prepare for them. For the Kyegegwa case of figure 5, approximately one year since installation, there has been no expense on the unit.

5.5. Why not centralise solar energy sourcing?

Centralising PV electricity for distribution as has been done by the Uganda government in some areas [55], and by Rwanda [56] is beset with problems. First, the dc power has to be inverted and then, the voltage stepped up before feeding into a long transmission line. Each of these steps has some of the generated electricity being converted to thermal energy in line with the second law of Thermodynamics. For initial efficiencies of 15-17%, the overall efficiency even before transmission drops towards 10 -12%. Transmission line and distribution network losses in many African countries are high (e.g. Nigeria, 12% in 2014 [57], Uganda 33% in 2011 [58], etc.). This means less than 10% of the original energy received by the panel eventually becomes ‘useful’ electricity. The second problem has to do with multiphase ac supply – which requires either multiple inverters or a single three phase inverter. The problem of line balancing in such cases become more critical [59]. The third problem on electricity is simply that most households in rural Africa are dispersed. This makes it difficult - if not impossible - to make electricity generated centrally to reach every homestead.

For heat and mass transfer systems, centralised systems need a lot of space, management and possibly conflict resolution practitioners to effect. These professionals are not available in most rural areas.

6. Conclusion

To conclude, this paper tried to show how a social economic problem of energy poverty in rural Tropical Africa could sustainably be addressed using solar energy technologies. There are some health and environment degradation issues attendant to this poverty which could be addressed by the technologies. Current alternative efforts by different countries to address the problem were explored and it was found that success was limited – mainly to electrification of rural public sectors. Reaching individual rural homesteads from centralised supply was fraught with capacity, cost and distribution problems because of the homesteads’ dispersal. Efforts to address health issues through improved combustion and stove designs were also not yet universal. Besides, they did not remove the danger of fires in rural homesteads.

The paper then proceeded to suggest and illustrate simpler ways to address these and other problems at the household level. On lighting, previous work on photo-lighting rural homes was cited and an example, implementing results of that work at one place in rural Uganda was given. A US$ 700 home installation was reported to have been running in line with performance expectation but with nil cash outflow for about one year. It was also shown that water heating for hygiene purposes could be achieved using simply constructed, low cost solar syphon systems. Most importantly, a system for converting both micro-bio and chemically contaminated water into safe potable water was illustrated. It was shown to save significant amounts of energy otherwise required to boil the water in attempt to destroy biological contaminants. A solar crop dryer employing similar principles of mass transfer as the water purifier was illustrated. So were references to work on inverter-less solar-assisted refrigeration.

Cost estimates based on actual PV commercial prices, doubled construction material costs of other systems and life time running costs were done and shown to give a very low unit energy utility cost of the order of US$ 0.03. Because of universal availability of solar energy, unlike other sources - especially grid electricity, there was no basis for comparing unit costs.

To summarise therefore, in presence of the illustrated devices, it could be said that solar energy usage by rural households in lighting, hygiene water heating and family drinking water should be strongly advocated to reduce energy poverty. When the three are taken together, possibilities of health improvement, focus on educational work by children, and positive national productivity changes are availed. Both household capital and recurrent expenses are much lower than with a grid supply. There is less demand for wood or other carbon-based fuel, and hence, less consequent environmental harm. Using solar energy for much larger projects such as centralised services may however be problematic. There is less certainty about its potential effectiveness, and therefore this paper presents no strong support for it. It is suggested that such services as would be required at a rural community or commercial centre might be better served with grid supply like is being done in some countries. Therefore, the main recommendation of this work in respect of rural areas is that governments, development partners and private sectors should be looking at a dual system where homes are served with solar energy systems while grid electricity is reserved for commercial and bigger institutions at commercial and industrial centres.

Acknowledgments
Most of this research and development work was funded by the Cape Peninsula University of Technology over a period of about 5 years through its URF mechanism. The author is most grateful especially to the University Research staff.

Appendix

A1: Computation of photo electric energy costs: an approximation

A1.1. Development of costing

The cost of electricity from the systems in this paper – namely the optimised fixed slope 200 Wp panel and its equivalent inclined axis solar tracking 150 Wp panel – is estimated for a rural home near the equator in Uganda. Actual June 2016 prices of components are used in the estimates. The other data on the economy used is as follows:

General inflation rate i_r = 6% (based on long term value over the past 20 years)

Bank interest rate over inflation, i_b = 10% (based on a savings interest rate of 16% from Bank of Uganda)

Special item inflation rates over and above general rate were assumed as follows (i_{pdct}):

Maintenance labour:	=	5%	Maint. cost rate	=	4% of initial capital
Batteries:	=	2.5%	Life	=	5 years
Charge controllers:	=	5%		=	15 years
LED bulbs:	=	-2.5%		=	15 years
System life expectancy	=	25 years;	Maintenance	=	1 year

For an item costing an amount ***C*** today, the present value cost after ***n*** years is given by the equation [60].

$$C_n = C\left[\frac{1+i_r+i_{pdct}}{1+i_r+i_b}\right]^n \tag{A1}$$

Also, the present value $\boldsymbol{E_n}$ of total annual expense ***E*** growing at a rate $\boldsymbol{r_p}$ over and above general inflation after ***n*** years is given as:

$$E_n = E\left[\frac{1+i_r+r_p}{r_p-i_b}\right]\left[\left[\frac{1+i_r+r_p}{1+i_r+i_b}\right]^n - 1\right] \tag{A2}$$

For the actual costs of items as purchased, equations (A1) and (A2) were laid out in an Excel spreadsheet and present day costs evaluated as given in A1.2.

Different data can be in-put into the grey-shaded cells to reflect given economic conditions and/or prices but all unshaded cells are automatically computed.

A1.2. Energy costing for fixed slope 200 Wp and 150 Wp solar tracking panels

Capital costs:					**Fixed slope**	**Manual Track**	**Semi auto**	**Auto track**
	SIZE	LOCAL PURCH. PRICE (US$)	QTY.	LOCAL TRANSPORT	DELIVERED COST	150 Wp panel	150 Wp panel	150 Wp panel
Solar Panel	200 Wp	141.6	1	0	141.60	106.20	106.20	106.20
Batteries	105 Ah	121.21	2	0	242.42	242.42	242.42	242.42
Charge Controller	15 A	120	1	0	120.00	120.00	120.00	120.00
Bulbs (LED)	11 W	7	12	0	84.00	84.00	84.00	84.00
Installation Materials	Lot	67	1	0	67.00	67.00	67.00	67.00
Sub Total basics					655.02	619.62	619.62	619.62
Installation labour					30.00	35.00	40.00	40.00
Solar Tracker (materials only)					0	202.02	243.53	271.85
Total capital costs					685.02	856.64	903.15	931.47
Running costs:								
System expected lifespan: years	25							
Expected charger lifespan: years	15							
Expected LED Bulbs Lifespan: years	15							
Expected Battery Lifespan: years	5							
Anticipated general annual inflation rate(%)	6							
Excess alternative investment return rate relative to inflation on general items: e.g. Bank saving interest rates over and above inflation (%)	10							
Annual Maintenance charge as % of initial capital	4		**Running costs**					
Anticipated excess price inflation over and above that of general items (%)		**Batteries**	**LED Bulbs**	**Charger**	**System Maintenance costs**			
		2.5	**-2.5**	**5**	**5**			
	Repl. No.							
Number of replacements expected over entire life time		4	1	1	25			
Present worth of Operational expenses for 1st replacement (US$)	1	173.55	15.2	61.97				
Present worth of Operational expenses for 2nd replacement (US$)	2	124.25	0.00	0.00				
Present worth of Operational expenses for 3rd replacement (US$)	3	88.95	0.00	0.00				
Present worth of Operational expenses for 4th replacement (US$)	4	63.68	0.00	0.00				
Present worth of Operational Expenses: US$		**450.43**	**15.2**	**61.97**	**406.12**	**507.87**	**535.45**	**552.24**
Total Present Worth Capital + Running costs (US$)					**1618.73**	**1892.1**	**1966.2**	**2011.3**
Total Present Worth Running costs (US$)					**933.71**	**1035..5**	**1063.0**	**1079.8**
Total useful energy produced over lifecycle: kWh					**6568.00**	**6600**	**6600**	**6600**
Present worth Running unit energy cost: US$/kWh					**0.14**	**0.16**	**0.16**	**0.16**
Present worth Capital unit energy cost: US$/kWh					**0.10**	**0.13**	**0.14**	**0.14**
Present worth Total unit energy cost: US$/kWh					**0.25**	**0.29**	**0.30**	**0.30**

References

[1] BP 2014 *BP Statistical Review of World Energy* https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-full-report.pdf
[2] IEA 2014 *Key World Energy Statistics* http://www.iea.org/publications/freepublications/publication/KeyWorld2014.pdf
[3] IEA 2016 *World Energy Outlook 2016* http://www.iea.org/publications/freepublications/publication/WorldEnergyOutlookSpecialReport2016EnergyandAirPollution.pdf
[4] African Development Bank, Organization for Economic Co-operation and Development, United Nations Development Programme 2014 *African Economic Outlook 2014*: Global value chains and Africa's industrialization
[5] European Commission and Heliochem-1 2008 Africa - Photovoltaic solar electricity potential http://www.soda-is.com/eng/map/maps_for_free.html
[6] Williams 1994 Energy supply options for low income urban households (University of Cape Town)
[7] Ayazika W 2002 Health related effects of traditional biomass fuels: the Ugandan case study (NEMA DfID KaR Project R8019)
[8] UN 2010 *The World's women 2010* http://unstats.un.org/unsd/demographic/products/Worldswomen/WW2010%20Report_by%20chapter(pdf)/Environment.pdf
[9] Statistics South Africa 2013 *GHS Series, volume V, Energy*, 2002 -2012. Report 03-18-04 18-9
[10] Nussbaumer T, Czasch C, Klippel N, Johansson L and Tullin C 2008 Particulate combustion in IEA countries Survey on measurements and emission factors *IEA Bioenergy Task 32* (Zurich, Swiss Federal Office of Energy (SFOE))
[11] WHO 2006 *Air quality Guidelines for particulate matter, ozone, nitrogen, dioxide and sulphur dioxide*, *Global Update* 2005
[12] Klippel N and Nussbaumer T 2007 Health relevance of particles from wood combustion in comparison to Diesel soot *15th Eur. Biomass Conf.* (International Conference Centre, Berlin) pp 7-11
[13] UNDESA 2014 A survey of international activities in rural energy access and electrification May 2014 "Global tracking framework," *Sustainable Energy for All* (2013), 262
[14] Arekete A S 2013 *Journal of Energy Technologies and Policy* **3** 1-8
[15] Mwithiga G and Kigo S N 2006 *J. Food Eng.* **74** 247-52
[16] Ozuomba J O, Edebeatu C C, Opara M F, Udoye M C and Okonkwo N A 2012 *Research Journal of Chemical Sciences* **2** 64-7
[17] Ayieko O Z 2011 Rural electrification programme in Kenya *AEI Practitioner workshop* Dakar Senegal, Nov 2011 http://siteresources.worldbank.org/EXTAFRREGTOPENERGY/Resources/717305-1327690230600/8397692-1327691237767/Rural_Electrification_in_Kenya_presentation_Final_11thNov2011.pdf
[18] Lyalabi S 2011 REA's experience in implementing rural electrification projects *AEI Practitioner workshop* Dakar Senegal Nov 2011 http://siteresources.worldbank.org/EXTAFRREGTOPENERGY/Resources/717305-1327690230600/8397692-1327691245128/Implementing_REAs_ZAMBIA.pdf
[19] Uwamahoro Y 2013 Rural electrification in Rwanda *PACEAA*
[20] Elusakin J E, Ajide O O and Diji J C 2014 A*frican Journal of Engineering Research* **2** 51-7
[21] Lloyd P 2014 *JESA* **25** 2-8
[22] Abavana C G 2011 *Electricity access progress in Ghana* (Noxie Consult, Ghana)
[23] Mapako M and Prasad G 2007 *Rural electrification in Zimbabwe reduces poverty by targeting income generating activities* CSIR ECR University of Cape Town http://hdl.handle.net/10204/871
[24] Abeeku B-H and Kemausuor F 2009 *Current Opinion in Environmental Sustainability* **1** 83-

8
[25] Mulugetta Y, Nhete T and Jackson T 2000 *Energy Policy* **28** 1069-80
[26] Kanyarusoke K 2013 Water and energy needs in a developing Nile Basin *The New Vision* (Kampala Uganda)
[27] Energy Information Administration 2014 Kenya country analysis note http://www.eia.gov/countries/country-data.cfm?fips=KE
[28] Enfsolar 2014 Solar panel Manufacturers in Africa www.enfsolar.com/directory/panel/africa
[29] Eveleens I 2011 EAfrica's first solar-panel plant supports Kenya's clean energy push *AlertNet*, 23rd Nov 2011
[30] Uganda Rural Electrification Agency 2012 *Annual Rural Electrification Report* 2010/2011 http://www.rea.or.ug/
[31] Kanyarusoke K E, Gryzagoridis J and Oliver G 2012 Predicting photovoltaic panel yields in sub-Sahara Africa *Proc. ICEAS* (Beijing China July 2012) pp 223-55
[32] Toonen H M 2009 *Phys Chem Earth* **34** 65-71
[33] Kimambo C Z M 2007 JESA **18** 41-51
[34] Dasin D Y, Asere A A and Habou D 2011 *Nigeria Journal of Solar Energy* **22** 7-13
[35] Abdulrahim A T, Diso I S and Abdulraheem A S 2012 *JMER* **4** 136-41
[36] Abdulrahim A T, Diso I S and Ngala G M 2011 *Nigeria Journal of Solar Energy* **22** 29-33
[37] Cuce E and Cuce P M 2013 *J. Ap Energy* **102** 1399-421
[38] Kanyarusoke K E, Gryzagoridis J and Oliver G 2016 *Turk J Elec Eng & Comp Sci* **24** 4763-72
[39] Kanyarusoke K E and Gryzagoridis J 2016 The new hydro-mechanical solar tracker: Performance testing with a PV panel *Proc. 24th DUE Conf.* (Cape Town Mar 29-31, 2016) pp 178-85
[40] ASHRAE 2009 *ASHRAE Handbook-Fundamentals* Atlanta: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc. Ch. 14
[41] Klein S A, *et al* 2012 TRNSYS 17: *A transient system simulation program* Madison, WI, USA: Solar Energy Laboratory, University of Wisconsin
[42] VENRO 2009 Rethinking Biomass Energy in Sub-Sahara Africa http://www.venro.org/fileadmin/redaktion_afrikas_perspektive/publikationen/Projekt-Publikationen/091124_Arfikas-Perspektive_Bioenergiestudie_Final.pdf
[43] Malhi Y, Adu-Bredu S, Asare R A, Lewis S L and Mayaux P 2013 African rainforests: past, present and future. *Phil Trans R Soc* B 368 20120312
[44] Kula N, Haines A and Fryatt R 2013 Reducing vulnerability to climate change in Sub-Saharan Africa: The need for better evidence *PLOS Medicine* 10 e1001374 https://doi.org/10.1371/journal.pmed.1001374
[45] Kanyarusoke K E, Gryzagoridis J and Oliver G 2013 Modelling Annual Yields of a solar-tracking Solar syphon Using ASHRAE's Weather Data for Tropical Africa. *Trans. 2013 ASHRAE* July 2013 Denver CO http://www.thefreelibrary.com/Modeling+annual+yields+of+a+solar-tracking+solar+syphon+using...-a0371285197
[46] Alkilani F & Kanyarusoke K E 2016 Inverter-less solar assisted farm level refrigeration system for fruits and vegetables *2016 Proc. of 24th ICUE Conf.* (Cape Town 15-17 August 2016. Cape Town) 178-84
[47] Pan Africa Chemistry Network 2010 *Africa's water quality* http://www.rsc.org/globalassets/04-campaigning-outreach/tackling-the-worlds-challenges/water/rsc-pacn-water-report.pdf
[48] World Health Organisation 1996 Health criteria and other supporting information *Guidelines for drinking-water quality* 2nd ed. Vol. 2. http://www.who.int/water_sanitation_health/dwq/chemicals/tds.pdf
[49] Mbadinga P J K 2015 A solar water purification system for rural areas *MTech dissertation* (Cape Peninsula University of Technology)

[50] Uganda Bureau of Statistics 2016 *National Population and Housing Census 2014 report* Kampala, p 12
[51] UMEME 2017 Electricity end user tariffs for the period April to June 2017 http://www.umeme.co.ug/assets/resources/Tariff%20Adjustments/Tariff_Adjustment.pdf
[52] Mills N L, Donaldson K, Hadoke P W, Boon N A, MacNee W, Cassee F R, Sandström T, Blomberg A and Newby D E 2009 *Nature Reviews Cardiology* **6** 36-44
[53] Hunter A, Mills N and Newby D 2012 *Br J Hosp Med (Lond).* **73** 492-7
[54] Kanyarusoke K E 2016 Seeding energy sustainability through transformative teaching: any way forward for sub-Sahara Africa? Delfino E & Vezzoli C Eds. *Proceeding of 2016 LeNSes Conference on Sustainable Energy for All* (28 – 30 September 2016, Cape Town) pp 167-76 Online e-book https://www.scribd.com/document/324775328/LeNSes-Conference-Proceedings
[55] ESI Africa 2016 Uganda: Soroti solar power plant comes online https://www.esi-africa.com/news/uganda-soroti-solar-power-plant-comes-online/
[56] GigaWatt Global 2016 *Rwanda gets a solar field* https://gigawattglobal.com/projects3/rwanda/
[57] Amadi, Hachimenum N, Ephraim N C, Okafor and Izuegbunam F I 2016 *AJEEE* **4** 123-30
[58] Parsons Brinckerhoff Africa 2011 *Study on distribution system losses and collection rates by UMEME Ltd* Kampala Uganda Electricity Regulatory Authority 32
[59] Peacock Media Group 2017 Phase Solar: What you need to know about connecting solar to your 3 phase supply https://www.solarquotes.com.au/blog/3-phase-solar-what-you-need-to-know-about-connecting-solar-to-your-3-phase-supply/
[60] Blank L P E and Tarquin A P E 2012 *Engineering Economy* 7th ed. (Singapore Mc Graw Hill) pp 367-74