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A review of optical concentrators for portable solar photovoltaic systems for developing countries

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ABSTRACT

Worldwide, over 1.1 billion people have no access to electricity. The consequences for the affected people include health hazards from fuels used for lighting, limits to learning when it gets dark, a short productive day and high expenditures on lighting alternatives. Since 85% of affected people live in rural areas in developing countries, increasing access to electricity through grid supply is logistically and financially challenging. As a potential solution to this issue off-grid solar chargers have been gaining popularity. This technology is under continuous development to achieve lower costs, faster battery charge and more electricity generation to prolong light hours. This review contains a comprehensive analysis of possible improvements to solar lights and the role solar PV concentrators can play in it. It aims to provide the reader with a critical comparison of existing solar PV concentrators and to consider the advantages and drawbacks if applied to portable solar systems used in developing countries. From this review, static nonimaging concentrators have been identified as best suited since they are easy to operate and maintain and have shown high reliability. A detailed comparison of existing static nonimaging concentrators is presented in this work and their suitability for being deployed in portable solar systems in developing countries is evaluated. It concludes that the existing designs need adjustment if to be used for this purpose. Thus, novel concentrator designs for portable solar systems for developing countries are needed to facilitate more off-grid solar power generation. It is the aim therefore of this review to stimulate more research in this field.

1. Introduction

Worldwide, over 1.1 billion people have no access to electricity and thus no access to clean lighting [1]. The poor quality of light from alternative sources such as kerosene lamps, candles or burning switchgrass limits the ability of the affected people to study or work after the sunset. Furthermore, these light sources have associated health risks such as poisoning from the inhaled fumes, chronical lung diseases, eye irritation as well as increasing the potential for burns from accidental fires. These hazards mostly affect women and children since they are predominantly involved in household chores like cooking [2].

Not having access to clean electricity has a negative impact on people and the environment. Kerosene (for lighting) is responsible for 3% of global black carbon emissions and the contribution of black carbon to global warming is stronger than CO_2. One kilogram of black carbon produces a "positive forcing"[1] during its atmospheric lifetime[2] equivalent to 700 kg of CO_2 over 100 years [3]. Burning local biomass on the other hand leads to erosion and reduces the fertility of the local land.

In Sub-Saharan Africa (SSA) the rural electrification ratio is only 14% [4] whilst in Malawi it is just 1% [5]. Despite progress in the electricity supply has been made in SSA, the population not connected to the grid is expected to increase in the future. This is due to electrification happening at a slower rate than population growth [4]. The gap between supply and demand has further increased with the introduction of mobile phones. In rural Zambia, 50% of homes own mobile phones [6] whilst the electrification ratio is only 3% [7]. Consequently people have to walk to the nearest town to charge their phones [8]. The resulting high electricity prices lock communities into energy poverty, as fuel-based lighting is up to 150 times more expensive than efficient lighting [4].

Approximately 85% of the affected people live in rural communities

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[1] Measure of atmospheric warming.
[2] Atmospheric lifetime of black carbon is estimated as 4 – 12 days [114].

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in developing countries [1]. The lack of infrastructure is one of the main obstacles to the electrification of rural areas. Low electricity demand, small population density and long distances to the nearest substation make the connection of remote areas extremely challenging. In Kenya for example, when a household is further in distance than 600 m to the nearest substation, the full cost of the grid extension has to be met by the household [9]. Additionally, in many Sub-Saharan countries the electricity supply is characterised by increasing prices and frequent blackouts. This is mostly due to insufficient generating capacity and a high reliance on fossil fuels [4].

It is however not the grid connection that people want, but the potential benefits the energy provides. This suggests the way towards electrification does not need to be a centralised solution. Whilst Baurzhan et al. [10] state there is little evidence that off-grid solar systems contribute to poverty alleviation, the World Bank identified that the benefits of off-grid renewable energy solutions in rural areas are low costs, environmental sustainability, a contribution to Millennium Development Goals[3] and a faster service provision than grid supply [11]. For instance, access to clean lighting has helped improve children's education, facilitated longer working hours (e.g. by illuminating a kiosk); and enabled households to make financial savings [12,13]. Since SSA has an abundance of solar radiation throughout the year [14], solar systems are seen as the way forward to decentralised electrification.

The options for local renewable energy generation include mini- and microgrids as well as solar home systems (SHS). Since microgrids involve larger capital costs and are more complex to operate [9], SHSs have been regarded as a more viable solution. Yet, investment costs remain high [10], and SHSs are primarily targeted at middle and high income families [15–17]. A further problem with SHSs and microgrids, as argued by Baurzhan et al. [10], is the underestimated operation and maintenance costs, which are not given sufficient consideration in financial schemes. Furthermore, the authors argue that repaying a solar installation over multiple years as fixed debt, does not offer the same flexibility as purchasing kerosene, which can be done according to the financial constraints.

As a smaller solution, solar lights have been introduced into the market. The main components are a solar panel, a rechargeable battery, a light-emitting diode (LED) lamp and more commonly a USB charger with phone adapters [4]. These have the advantage of smaller upfront costs, do not involve operational and maintenance costs [4] and are easier to stock and distribute by non-specialist shops. Solar lights retail at different prices according to the amount of electricity they generate, therefore more solar lights can be purchased when the demand or financial means increase. This makes them more scalable than SHSs and microgrids.

In this paper the performance, affordability and sustainability of solar lights is discussed and potential ways to improve the systems are highlighted. This work focuses on a new approach of using solar PV concentrators to improve the properties of solar lights. While other reviews of solar PV concentrators are available in literature [18–21], this article presents a comprehensive review of existing concentrator types and discusses their potential and suitability specifically for portable solar systems for rural areas in developing countries. Conclusions and recommendations are drawn and discussed.

2. Solar lights and solar chargers

While some people are highly satisfied with their solar lights, others feel the low quality of the light compared to grid power further reinforces their poverty and low social status.[5] A solar lantern at the lowest range provides a luminous flux of 20 lm [22,23], only twice as much as a kerosene lamp and just enough to illuminate a small area. However, compared to a kerosene lamp where light is emitted in all directions and only a half to a third of it is usable light [24], LED light is directional and therefore more efficient. Furthermore, current lamps take 5–10 h to charge to provide 4–6 h of light at high intensity. In addition, solar lights are still considered expensive to purchase. A low range study light providing 20 lm currently costs USD 5 (Table 1) [23,25–31], and whilst USD 5 might not seem a large investment, the financial possibilities of the poorest of a rural community need to be taken into account. In Malawi for example, only a quarter of a million people have an income above USD 5 per day and around 74% of the total population live below the poverty line of USD 1.25 per day (effective 2010) [32,33].

Table 1
Current price range of solar lamps, data from [23,25–31].

Light intensity	Price (USD)
Up to 25 lm	5–10
Up to 50 lm	20–25
Up to 100 lm	30–50

To be an efficient solution, a solar light needs to generate more electricity, store it more quickly while being low cost and highly portable. This can be achieved by improving different parts of the design: the LED light, the battery and the solar module.

2.1. Higher efficiency LED light

LED light sources have a longer life span and a higher luminaire efficacy than compact fluorescent lamps (CFL) and incandescent light sources. The main drawback is the price per lumen, which is currently considerably higher than other light sources. The relative cost however is predicted to fall by 70% between 2013 and 2020 while the luminaire efficacy is expected to increase by 36% by 2020 [34].

2.2. Quicker charging battery

Lithium-iron-phosphate ($LiFePO_4$) batteries are most commonly used for portable solar devices and have several advantages over the alternatives. These benefits include not requiring specific recycling facilities which is crucial for applications in rural areas; a long life time of up to 2000 cycles and a low self-discharge [4]. Furthermore, they are chemically more stable and are best suited for outdoor usage. The drawbacks are: higher costs than nickel-metal-hydride (NiMH) and nickel-cadmium (NiCd) batteries and a lower mass-energy density than lithium-cobalt-oxide ($LiCoO_2$) batteries [35]. A comparison of batteries most commonly used for portable solar systems is shown in Table 2 (not including sealed lead acid batteries).

The charging time of a $LiFePO_4$ battery depends on the charging current. An 800 mA h 3.2 V battery for example takes 6 h to charge at 160 mA and 3 h at a 400 mA [36]. Thus increasing the charging current would be an advantage. Additionally, overvoltage can be applied without damage to $LiFePO_4$ batteries to reduce charging time by 1/3 [35]. Further improvements in battery technology are expected in the near future; MIT researchers for instance fabricated a single cell which can be charged within $10-20$ s instead of 6 min [37,38].

[3] Eight targets set by the UN nations to reduce extreme poverty by 2015 and extended to 2030 as Sustainable Development Goals [115].

[4] The only operational cost is the battery replacement, which is due around every 5 years [23,25–31] The battery cost at the moment are around 25% of the overall cost.

[5] Joanna Gentili, Founder and CEO, Team Planet (http://www.goteamplanet.com/), pers. comm with Glasgow Caledonian University, Centre for Climate Justice (7May15).