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Concept development and techno-economic assessment for a solar home system using lithium-ion battery for developing regions to provide electricity for lighting and electronic devices

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ABSTRACT

Around 18% of the world's population still don't have access to electricity, most of them living in rural areas in South Asia, Southeast Asia, and Sub-Saharan Africa. Kerosene lamps are widely used for lighting in these regions, but imply a big number of disadvantages including low light quality, reduced indoor air quality and safety concerns. Furthermore, the consumption of kerosene for lighting is very energy inefficient and implies a relatively high cost for the added value it provides, while its price volatility is a major concern for dependant developing regions. Global carbon dioxide emissions from kerosene lamps exceed 200 mega tons annually. A solar home system using light emitting diode lamps provides an effective solution for this problem. This paper elaborates such a solar home system while focusing on overcoming implementation barriers including lack of technical support and affordability. An evolutionary techno-economic assessment, considering the time period 2015–2030, is provided for the proposed system. This emphasizes not only the existing but also the increasing advantage of solar home systems over kerosene lamps.

1. Introduction

Close to 1.3 billion people around the world do not have access to electricity, most of them living in rural areas in South Asia, Southeast Asia, and Sub-Saharan Africa. Many families in these regions rely on kerosene lamps to have light during the night hours. These lamps are very energy inefficient, provide low quality light, reduce indoor air quality causing negative health effects, are not very safe and have a relatively high cost for the added value they provide. Furthermore, kerosene lamps emit annually more than 200 MT of CO_2 worldwide.

Kerosene prices are volatile and differ very much from one region to the other. Some countries subsidy kerosene to limit its price effects on the life of many families in developing areas. This implies substantial costs for the state which otherwise could be invested in infrastructure.

Solar Home Systems (SHS) combined with LED lamps provide an effective solution for this problem. Especially the use of solar energy makes much sense in this context as the most affected regions have favorable solar conditions, i.e. relatively high irradiation values along the year [1]. Unlocking the PV potential in the Sunbelt countries would tackle their major energy concerns by covering their accelerated demand growth with low-carbon, domestic energy sources [2]. On the other hand, LED lamps are very energy efficient; roughly an installed total of 60 W is sufficient to provide high quality light for a family house in a developing region. The SHS can also provide electricity for the recharge of electronic devices such as mobile phones. These consume very little electricity, while having a very high added value. A total energy demand of 250 W h per day would suffice to cover the needs highlighted here for a family. Such small SHS have the potential to bring huge socio-economic and environmental advantages to developing regions around the globe. Thereby, its evolutionary aspects are very favorable thanks to ongoing

Abbreviations: AC, Alternating Current; CdTe, Cadmium-Telluride; CIGS, Copper Indium Gallium Selenide; CRI, Color Rending Index; c-Si, crystalline silicon; DC, Direct Current; DoD, Depth of Discharge; GHG, greenhouse gas; iHOGA, improved Hybrid Optimization by Genetic Algorithms; LCoE, Levelized Cost of Electricity; LED, Light Emitting Diode; Li-ion, Lithium-ion; MPPT, Maximum Power Point Tracking; NPC, Net Present Cost; SHS, Solar Home System; TF PV, Thin Film Photovoltaic.

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improvements in all components, i.e. PV panels, batteries and LED lamps, in terms of cost reductions, performance and energy efficiency.

Within this context, it's highly relevant to tackle the implementation barriers for SHS. Technical support is a major issue; either there is a lack of technical support, which hampers feasibility, or it is available at a high cost. This affects especially system engineering and installation, as well as battery maintenance and replacement. Thereby, uncertainty about the battery lifetime causes concerns about potential costs. These aspects, however, could be tackled in the early stages of the SHS layout, especially through the elaboration of standard solutions that can be used within a wide geographic area and with similar performance. Most specifically, opting for Lithium-ion (Li-ion) batteries that could be installed indoors and the oversizing of components provide a more effective solution than tailored systems. Although this implies higher initial costs for the PV generator and battery, it reduces drastically the needed technical support and the associated costs for the engineering, installation, maintenance and battery replacement.

Many previous works tackle the application of renewable energy for rural electrification in different countries around the world. For instance, a study on the potential of applying renewable energy sources for rural electrification in Malaysia with focus on the poorest states is presented by Borhanazad et al. [3]. A system design and techno-economic analysis of a hybrid PV system comprising a battery and a microturbine for a remote community in Palestine has been carried out by Ismail et al. [4]. The same authors have also performed a techno-economic assessment of a hybrid PV system using diesel generator to supply power for off-grid houses in tropical areas [5]. Adaramola et al. focus on remote communities in Ghana and provide an economic analysis for a power supply system consisting of a PV generator and wind turbine with diesel backup [6]. Ahlborg & Hammer present a study on the drivers and barriers for the implementation of off-grid renewable energy for rural electrification in Tanzania and Mozambique [7]. Suresh Kumar & Manoharan analyse the economic feasibility of hybrid off-grid renewable energy for remote areas in the state of Tamil Nadu in India [8]. While stand-alone PV systems supply typically households and water pumping systems for irrigations, other applications, as for example the power supply of off-grid hospitals, are also important. For instance, the performance of a 7.2 kWp stand-alone PV plant located in Morocco to supply 16 households is shown in [9]. On the other hand, Campana et al. focus on PV water pumping systems for irrigation and propose thereby an economic optimization procedure based on an hourly simulation model [10]. Dufo-López et al. present a study on the PV power supply of off-grid healthcare facilities, providing a system optimization method using Monte Carlo simulation [11]. In many cases stand-alone systems are hybrid (PV plus diesel and/or wind turbines). Several reviews of this kind of systems can be found. For instance Bernal-Agustín & Dufo-López revise the simulation and optimization techniques, as well as the tools existing that are needed to simulate and design stand-alone hybrid systems [12]. A similar, but more recent work is available by Sinha & Chandel [13]. Akikur et al. present a comparative study for hybrid PV systems for powering single houses and small communities for various locations throughout the world [14]. Mohammed et al. review several substantial issues of hybrid renewable energy systems for off-grid power supply, including drivers and benefits, design and implementation, as well as the simulation and optimization tools [15].

This paper focuses in a first stage on providing a SHS solution to replace kerosene lamps in developing regions. Much importance thereby is given to elaborating one standard solution that can be widely used in the geographic areas or relevance (South Asia, Southeast Asia and Subsaharan Africa), with minimum or no need for technical support along the installation's lifetime of 10 years. This approach reduces drastically the implementation barriers. Furthermore, an evolutionary techno-economic assessment is provided for the proposed SHS. Thereby, as reference installation years the authors opt for 2015, 2020, 2025 and 2030.

2. Method

The purpose of this paper is to provide one SHS solution using Li-ion batteries for South Asia, Southeast Asia and Sub-Saharan Africa to cover the power needs for LED lamps and the recharge of electronic appliances. Thereby a clear understanding of the evolutionary techno-economic aspects of this solution within the time scope 2015–2030 should be provided. The following method is followed to achieve the mentioned objectives:

1. With focus on the purpose of this paper, the state of the Art of PV panels, Li-ion batteries and LED lamps is summarized with a special emphasis on the technological transitions and potentials.
2. Based on the above, justified modeling inputs for all the SHS components until 2030 are provided.
3. The modeling and optimization of the SHS is performed for different reference locations and the installation years 2015, 2020, 2025 and 2030 using the software iHOGA (improved Hybrid Optimization by Genetic Algorithms).
4. Through comparison of the results for the different locations, one SHS solution that could be used extensively within the wide geographic areas of South Asia, Southeast Asia and Subsaharan Africa is developed.
5. The results are analyzed to useful conclusions about the proposed SHS solution.

Points 1 and 2 are performed within Sections 3–5 of the paper which provide a brief techno-economic assessment for the PV generator, the battery and LED lamps respectively, highlighting thereby their transitions and potentials and providing their modeling inputs. Points 3 and 4 are performed with Section 7, where the modeling results are presented and structured to one SHS solution. Point 5 is covered in Sections 8 and 9, where the discussion is provided and the conclusions are summarized.

Nine reference locations are used in this paper: North India (32°N, 77°E), Central India (24°N, 79°E), South India (12°N, 77°E), North Pakistan (32°N, 72°E), South Pakistan (22°N, 66°E), Kalimantan (1°S, 114°E), Java (8°S, 111°E), Tanzania (2°S, 34°E) and Spanish Pyrenees (42.5°N, 0.3°W). This last location is out of the geographic area of interest and is added here for the purpose of providing contrast.

The modeling and optimization of the SHS is done using the software iHOGA, a tool developed by one of the authors [16]. This tool has been used in several scientific publications. For instance it has been implemented to perform a multi-objective optimization for minimizing cost and life cycle emissions of a hybrid stand-alone system that combines a PV generator, wind turbine, battery bank and diesel generator [17]. In another study it was used for the sizing of off-grid renewable energy systems for drip irrigation of Mediterranean crops with focus on the economic optimization by using genetic algorithms [18]. iHOGA uses the following inputs to model and optimize the installation:

- Latitude and longitude of the installation's site.
- Monthly average of daily solar radiation [19]; from that iHOGA generates hourly solar radiation values for an entire year applying the method of Graham and Hollands [20] and uses them in the system simulation.