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# Development and assessment of a solar home system to cover cooking and lighting needs in developing regions as a better alternative for existing practices

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ABSTRACT

An estimated 1.2 billion people around the world don't have access to electricity, while many more suffer from supply that is of poor quality. Domestic energy poverty is most severe in the rural areas of South Asia, South East Asia and Sub-Saharan Africa. Basic energy needs, such as cooking and lighting, are covered using traditional biomass and fossil fuels. These are consumed inefficiently in fire stoves and flame lamps. This situation hampers economic growth and social development and implies severe stress on resources and the environment. Photovoltaics could play a major role in overcoming domestic energy poverty, especially as most of the affected regions are within the Earth's Sunbelt. This paper provides such a solution in the form of a solar home system with lithium-ion battery in combination with an energy efficient multicooker and LED lamps to cover the needs for cooking and lighting for one family. A solar home system layout is provided and assessed in terms of its cost and benefits in contrast with the existing practices for cooking and lighting in developing regions. Thereby, evolutionary aspects are taken into account to capture the incremental cost advantage of the solar home system technology over time, and with that support the idea of projecting large-scale implementation in developing regions.

## 1. Introduction

Around 16% of the world's population don't have access to electricity, most of them living in rural areas in South Asia, Southeast Asia and Subsaharan Africa. Many more suffer from supply that is of poor quality. As a consequence, 38% of the world's population lack clean cooking facilities. This results in high reliance in the developing world on traditional biomass and fossil fuels to cover basic domestic energy needs, such as cooking and lighting. This situation implies a poverty trap and development barrier, and goes together with severe stress on resources and the environment (UNDP, 2011, 2013, 2014). Safety is a concern when it comes to the domestic storage and use of fuels, such as kerosene (Lam et al., 2012). Furthermore, indoor fires have severe negative health effects (WHO, 2011). There is also a striking relation between domestic energy poverty and gender inequality, as well as a major effect on the life of children, as they often have limited resources and limiting conditions to perform their educational tasks. Overcoming energy poverty in developing regions is a global challenge, and should be perceived as an integral part of our common duty to promote human development and equality while conserving our plant.

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*Abbreviations:* AC, Alternating Current; BaU, Business as Usual; BMS, Battery Management System; CRI, Color Rendering Index; C-Si, Crystalline Silicon; DC, Direct Current; EV, Electric Vehicle; iHOGA, improved Hybrid Optimization by Genetic Algorithms; LCO, Lithium Cobalt Oxide ($LiCoO_2$); LCoE, Levelized Cost of Electricity; LED, Light Emitting Diode; LFP, lithium iron phosphate ($LiFePO_4$); Li-ion, Lithium-ion; LMO, Lithium Manganese Oxide; LPG, Liquified Petroleum Gas; LTO, Lithium Titanate ($Li_4Ti_5O_{12}$); NCA, Lithium Nickel Cobalt Aluminium Oxide; NMC, Lithium Nickel Manganese Cobalt Oxide; NPC, Net Present Cost; PV, Photovoltaics; SHS, Solar Home System; SOC, State of Charge.

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Several solutions have been followed so far to tackle domestic energy poverty in developing regions. Among others, solar-thermal cooking systems, such as the solar-box and parabolic cooker, have been developed and implemented. These systems are simple, affordable and don't have practically any environmental impact. Nevertheless, they have found little success until today, basically as they provide limited added value. The solar-box, for instance, is very easy to build and is made of cheap materials, but cooking is very slow and the maximum reachable temperature is relatively low, which limits the cooking options. More details on the solar-box are available in the references (Raji Reddy and Narasimha Rao, 2007; Kumar et al., 2010). On the other hand, concentrating solar cookers, like the parabolic cooker, are more powerful, but the cooking rate cannot be controlled and it's potentially hazardous due to the focusing of the sun beam. The cooking time is also limited to clear sky periods. More details on parabolic cookers are available in the references (Bardan et al., 2010; Abu-Malouh et al., 2011). In another approach, a hybrid solar cooking system has been suggested (Prasanna and Umanand, 2011). In this case a solar thermal collector heats a fluid, which is transferred to the kitchen and supplements a conventional LPG (Liquified Petroleum Gas) source. This system has a relatively low solar fraction, basically due to the temperature requirements of fast cooking, and is therefore not much cleaner than a pure LPG stove, while bringing substantial system complexity. Altogether, solar-thermal cooking systems can alleviate energy poverty, but they have limited potential to revolutionize development in affected regions. In the broader context, research should gravitate towards access to electricity with focus on a rapid transformation that gives priority to sustainable growth under minimal environmental impact. PV (Photovoltaics) is especially an interesting solution here as most of the global population that live under energy poverty are in the Sunbelt Countries. Accordingly, the focus of this paper is on SHS (Solar Home Systems).

A key factor in the successful implementation of SHS in developing regions, i.e. under severe economic constrains, is to limit their application to very high added value appliances and to properly exploit innovations, especially in energy efficiency and cost reductions. High added value is achieved with moderate cost high efficiency electric appliances that make a difference in time spent for domestic tasks, in the preservation of a healthy living environment and provide the required conditions for children to perform their educational tasks. The two basic appliances within this context are a multicooker and LED (Light Emitting Diode) lamps. Furthermore, a SHS allows for the recharge of portable electronics such as a mobile phone. The battery is a critical component in the SHS; the choice of battery in this paper is Li-ion (Lithium-ion). This differentiates this work from many others on SHS, where it is opted for lead-acid batteries, basically due to their low cost advantage. Nevertheless, lead-acid batteries are less reliable, have higher maintenance requirement and a shorter lifetime; all these are critical factors when it comes to a SHS application in remote developing regions where technical support is not easily available. Li-ion batteries have also a substantial energy density advantage over the lead-acid chemistry, which makes them relatively light and compact and storable indoors, with all the advantages this implies in terms of lifetime and its predictability. The key components of the SHS of this paper are: the PV generator, Li-ion battery, multicooker, LED lamps and a U-socket for the recharge of portable electronics.

There is a big number of scientific publications on stand-alone PV systems, both pure solar and hybrid systems (mostly PV with diesel generator and/or wind turbines), that tackle electrification in developing regions. These focus on the application, simulation, engineering, monitoring and performance in different countries and locations. For instance, Ranaboldo et al. present and analyse a design for a community electrification project in Nicaragua based on a PV-Wind system (Ranaboldo et al., 2015). Ibrahim et al. detail a demonstration project of a PV-based micro-grid in a rural area in Bangladesh (Ibrahim et al., 2002). 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. (2013). 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 (Adaramola et al., 2014). 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 (Ahlborg and Hammar, 2014). Suresh Kumar & Manoharan analyse the economic feasibility of hybrid off-grid renewable energy for remote areas in the state of Tamil Nadu in India (Suresh Kumar and Manoharan, 2014). Bekele & Palm provide a feasibility study for hybrid solar-wind power supply systems for off-grid applications in Ethiopia (Bekele and Palm, 2010). Dufo-López et al. present a techno-economic assessment of an off-grid PV-powered community kitchen for developing regions (Dufo-López et al., 2012). Zubi et al. perform a techno-economic assessment of an off-grid PV system to provide electricity for basic domestic needs (Zubi et al., 2016a). The same authors present in another article a detailed comparison between kerosene lamps and a SHS powering LED lamps (Zubi et al., 2016b). They concluded that, on a lumens-based comparison, a SHS-LED solution is roughly 15 times cheaper than Kerosene. 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, 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 (Dufo-López et al., 2016). Al-Karaghouli & Kazmerski provide a PV solution for a health clinic in a rural area in southern Iraq supported with system optimisation and cost assessment performed with HOMER software (Al-Karaghouli and Kazmerski, 2010). There are also several review articles on off-grid PV. For instance Akikur et al. present a comparative study for hybrid PV systems for powering single houses and small communities for various locations throughout the world (Akikur et al., 2013). 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 (Mohammed et al., 2014). Bernal-Agustín & Dufo-López review the current simulation and optimization techniques for stand-alone hybrid systems (Bernal-Agustín and Dufo-López, 2009). A similar, but more recent work is available by Sinha and Chandel (2014).

Based on the energy ladder hypothesis, the most common practice to alleviate domestic energy poverty in developing regions is currently the subsidy of kerosene and LPG to encourage the switching from traditional biomass to these fossil fuels. This measure is easy to implement for governments, but it's also very costly; India alone spends more than 5 billion US$ per annum in such subsidies. Thereby, the achievements through such budgets are far from satisfactory. Fossil fuel subsidies have often led to fuel stacking rather than complete fuel switching; it's often so that the consumer opts for the alternative fuel as long as it's cheap, i.e. subsidized. This implies in real terms a subsidy addiction that can only aggravate over time with the general upwards tendency of crude oil prices. This current path has definitely a grim long-term perspective, both environmentally as economically. On the other hand, this paper defends that a SHS in combination with state of the art batteries and electric appliances is a better solution, both in terms of achievable results in overcoming energy poverty and the budget this