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An open-source optimization tool for solar home systems: A case study in Namibia

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ABSTRACT

Solar home systems (SHSs) represent a viable technical solution for providing electricity to households and improving standard of living conditions in areas not reached by the national grid or local grids. For this reason, several rural electrification programmes in developing countries, including Namibia, have been relying on SHSs to electrify rural off-grid communities. However, the limited technical know-how of service providers, often resulting in over- or under-sized SHSs, is an issue that has to be solved to avoid dissatisfaction of SHSs' users. The solution presented here is to develop an open-source software that service providers can use to optimally design SHSs components based on the specific electricity requirements of the end-user.

The aim of this study is to develop and validate an optimization model written in MS Excel-VBA which calculates the optimal SHSs components capacities guaranteeing the minimum costs and the maximum system reliability. The results obtained with the developed tool showed good agreement with a commercial software and a computational code used in research activities. When applying the developed optimization tool to existing systems, the results identified that several components were incorrectly sized. The tool has thus the potentials of improving future SHSs installations, contributing to increasing satisfaction of end-users.

1. Introduction

About 1.2 billion people, mainly distributed in Sub-Saharan Africa (SSA), Central, South and East Asia, and Latin America, have no access to the electric grid [1]. Electricity allows people to light their homes, start up businesses, pump water for drinking and irrigation purposes, and preserve food and medicines. Access to electricity is essential for improving living standards, facilitating the economic development, and, in few words, meeting the Millennium Development Goals set by the United Nations in 2000, in particular, eradicating poverty and hunger, and ensuring a sustainable development [2]. In 2006, the World Bank estimated that an investment of 860 billion US$ was needed to achieve universal electricity access by 2030, highlighting the difficulty of meeting this target [3]. In 2015, about 620 million people were still lacking access to electricity in SSA [4]. In 2013, only 32% of the population in Namibia (about 0.7 millions), the case study for this work, had access to electricity [5]. Most of the Namibian population with access to electricity lives in urban areas (78%), whereas only 17% of the population living in rural areas has access to electricity [6]. Furthermore, it has been estimated that 74,000 households in peri-urban areas of Namibia have not yet been connected to the electricity grid, while 231,000 rural homes are without access to electricity [6]. Another issue is about the informal settlements since the government has the policy to not connect these areas to the electricity grid to prevent further urbanization. On the basis of the "Off-grid Energisation Master Plan", those settlements are considered grey areas, which means that the master plans are unclear whether or how the access to electricity will be provided [7]. In Windhoek, the capital of Namibia, almost one third of the population (105,000 residents) was living in informal settlements in 2011 [8].

Many rural electrification programmes in developing countries have faced social, economic and political problems [9]. At the same time, the connection to the electricity grid requires high

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investment costs related to the infrastructure system and is typically very slow. The basic lighting needs in non-electrified rural areas are typically satisfied by using kerosene lamps, candles, flashlights and car batteries [1]. Power generation in off-grid areas relies often on diesel generators with several disadvantages, e.g. limited fuel supply, high maintenance and operation costs, and greenhouse gas emissions [10]. The use of fossil fuels, such as kerosene and liquid petroleum gas (LPG), and firewood constitutes the main energy source in rural areas. Therefore replacing fossil fuels with renewable energies can contribute to the sustainable development leading to improved health and living conditions and reaching climate change targets. To meet these targets, in 2004, the Namibian Ministry of Mines and Energy established the Namibian Renewable Energy Program (NAMREP) with funding from UN Development Program (UNDP) and the Global Environment Facility to enhance electricity access and at the same time support the renewable energy sector [11]. The program aimed at spreading off-grid solar energy systems to fulfil the electricity requirements such as lighting, radio and television, water pumping for drinking and irrigation purposes, small electric tools and refrigeration. Part of the program was to finance small and medium enterprises to start businesses that would provide solar systems in rural areas. The loan limit for small and medium enterprises was set at 20,000–250,000 N$ (1 N$ = 0.067 US$) while the loan limit for solar home systems (SHSs) and solar pumping systems was set at 20,000 N$ and 40,000 N$, respectively [12]. The Namibian Ministry of Mines and Energy also developed a code of practice for the proper design and installation of SHSs [13].

SHSs are thus a technical and cost effective solution for generating electricity for households not reached by the electricity grid or for areas too sparsely populated in order to build a local mini-grid. A SHS typically consists of four main components: the PV module, the charge controller, the battery, and the electrical loads. The PV module converts solar radiation into electricity that is stored into a battery, which buffers the mismatch between electricity production and consumption. The charge controller matches the current and voltage between PV module and the battery preventing over-charge and over-discharge. The loads are directly connected to the charge controller if they are direct current (DC) loads. In case of alternate current (AC) loads, an inverter is installed between the loads and the charge controller.

SHSs programmes have been used as a viable solution for starting rural electrification in developing countries all over the world with different success levels. With 2.6 million SHSs installations bringing electricity to 9% of the population, the Bangladesh SHSs programme is a successful example implemented through setting renewable energy targets, introducing incentives and promoting the autonomy of independent agencies [14]. On the other hand, the SHSs programme conducted in Papua Nuova Guinea is a typical example of unsuccessful programme, due to a mix of technical (low quality PV modules, limited availability of SHSs components, logistics, and lack of training), economic (poverty, lack of capitals, and limited financing), political (poor institutional capacities of the government), and social (high end-users expectations and frequent cases of vandalism resulting in low acceptance) barriers [15].

The field interviews conducted in this study in Namibia revealed that the investigated SHSs installations were not performed properly. The main problems included incorrect design and installation that result in unsatisfied end-users, which was also highlighted in a study conducted by Azimoh et al. in South Africa [16]. The wrong design and installation was mainly due to two different aspects: the first was related to an inaccurate load estimation that most of the time is bounded to the limited awareness of the end-users on their own actual electricity consumption; the second was related to the service providers which have limited knowledge of solar power systems and in general a limited technical know-how [17]. From the conducted survey and through personal communications with local energy specialists, the encountered problems are very likely to affect the majority of the SHSs installations [17]. A study in Tanzania showed how inefficient loads and ignoring load demand estimation are common mistakes that lead to SHSs failure [18]. Moreover, the lack of solar power systems knowledge as a factor for SHSs failures has been investigated in a previous study conducted by Azimoh et al. in South Africa [19]. The study showed that the use of non-optimal tilt angle for the PV modules had negative consequences on the system reliability, lifetime and consequently on the related economic aspects. The quality of SHSs installations in Namibia has been improved since the Solar Revolving Fund (SRF), a credit facility established by the Namibian Ministry of Mines and Energy to support renewable energies penetration in rural off-grid areas, was introduced to fund SHSs installations [17,20]. Although the SRF has improved the quality of SHSs installations, many technical problems still remain, and further improvements can be done to support the utilization of SHSs in Namibia. For example, service providers have no access to advanced or commercial software tools during the design phase of SHSs which commonly results in rough size estimations without considering the Namibian code of practice. Hence, undersized PV modules or batteries will cause power shortages, undersized inverters or charge controllers will overheat and break, and undersized cables will cause high power transfer losses. Whereas, oversized SHSs components will result in unnecessary expenses for the usually poor households [17].

While most of the studies have been focused on optimization of power systems for rural areas, in particular hybrid power systems [21–23], few studies have focused on optimization of SHSs. Azimoh et al. studied the optimal SHSs tilt angle using the commercial software PVsyst® to maximize system reliability and lifetime, minimizing at the same time life cycle cost [19]. Kanyarusoke et al. presented an optimization model for finding the best SHSs components combination [24]. This optimization model is based on the SHSs daily simulations in TRNSYS® software and considers the following decisional variables: panel size, depth of discharge, charge efficiency, energy efficiency, battery capacity, number of batteries, and peak delivery current; and, the following two objective functions: minimizing panel size and utilizable storage capacity. The results of the optimization were also plotted on spatial maps of the entire Africa using Matlab® software. The spatial maps showed the spatial distribution of the SHSs components characteristics to minimize the battery storage capacity. A techno-economic assessment of SHSs with lithium-ion battery was conducted by Zubi et al. using the optimization software iHOGA® [25]. The study concluded that SHSs equipped with LED lights can have several economic, environmental and health advantages as compared to kerosene lamps.

In this study, we have developed an open-source MS Excel program written in visual basic (VBA) that optimizes the capacity of SHSs components. The developed model is a general model that can be applied everywhere in the world. The model is intended to help and support service providers to design optimal SHSs depending on the load profile construction and system components. The scope of developing this tool is to improve the function of SHS in Namibia and their reputation within the conducted electrification programmes. The program is based on an open-source genetic algorithm (GA) optimization model, called OptiCE, developed originally by Campana et al. [26,27] for research activities on photovoltaic water pumping system for irrigation and successively used to other applications such as hybrid power systems for residential applications [28–30], and shrimp farms [31,32].

Compared to the mentioned previous studies on SHSs, the novelty of this work lies in the following aspects: (a) the optimizations routines are run at hourly time step to appreciate the mismatch between solar power production and load power requirements,