Applied Geography 94 (2018) 41–57

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Suitability mapping framework for solar photovoltaic pumps for smallholder farmers in sub-Saharan Africa

Petra Schmitter[a,*], Kefyalew S. Kibret[b,c], Nicole Lefore[d], Jennie Barron[e,1]

[a] International Water Management Institute, Addis Ababa, Ethiopia
[b] Institute of Plant Production and Agro-ecology in the Tropics and Subtropics, University of Hohenheim, Garbenstr. 13, Stuttgart, Germany
[c] Hawassa University, School of Natural Resource and Environmental Studies, P.O. Box 128, Shashemene, Ethiopia
[d] International Water Management Institute, Pretoria, South Africa
[e] International Water Management Institute, Colombo, Sri Lanka

ARTICLE INFO

Keywords:
Irrigation
Ethiopia
GIS
Multi-criteria analysis
Solar
Sub-Saharan Africa

ABSTRACT

As solar panels become more affordable, solar photovoltaic (PV) pumps have been identified as a high potential water lifting technology to meet the growing irrigation demand in sub-Saharan Africa (SSA). However, little is known about the geo-spatial potential of solar based PV pumping for irrigation taking into account not only solar radiation but also the availability of water resources and linkage to markets. This study developed a suitability framework using multi-criteria analysis in an open source GIS environment and tested it in the case of Ethiopia. The accessibility of water resources was the driving factor for different scenarios. Suitability results following the groundwater scenarios showed good agreement with the available referenced well depth data. Comparing the suitability maps with available land use data showed that on average 9% (96 10^3 ha) of Ethiopian irrigated and 18% (3739 10^3 ha) of rainfed land would be suitable for solar PV pump irrigation. Furthermore, small solar PV pumps could be an alternative water lifting technology for 11% of the current and future small motorized fuel hydro-carbon pumps on smallholder farms (2166 10^3 ha). Depending on the technical pump capacity, between 155 10^3 ha and 204 10^3 ha of land would be suitable for solar PV pumps and provide smallholder farmers with the option to either pump from small reservoirs or shallow groundwater. With the ongoing interest in development for smallholder irrigation, the application of this model will help to upscale solar PV pumps for smallholder farmers in SSA as a climate smart technology in an integrated manner.

1. Introduction

Irrigation is one of the key pathways for smallholder farmers to build resilience towards climate change (Alemayehu & Bewket, 2017). The increasing variability of rainfall and its effect on rainfed agricultural productivity in sub-Saharan Africa (SSA) has led to several studies attempting to estimate the availability and/or sustainable use of surface and groundwater resources in irrigation (Altchenko & Villholth, 2015; Ashton, 2002; MacDonald, Bonsor, Dochartaigh, & Taylor, 2012; Pavelic, Smakhtin, Favreau, & Villholth, 2012; Xie, You, Wielgosz, & Ringler, 2014; You et al., 2011). Surface and groundwater resources are highly variable throughout sub-Saharan Africa (SSA) and the latest climate scenarios suggest that variability and uncertainty will continue to increase (Gan et al., 2016; Vörösmarty, Ellen, Green, & Revenga, 2005). According to Arnell et al. (2016), under the A1b emission scenario, 127 million people in SSA will be exposed to a decrease in water resources whereas only 28 million will have access to increased water resources. Hence, with the increasing demand for resilient agricultural solutions in the context of food security and the promotion of irrigation throughout SSA, irrigation technologies are an essential component of climate smart agriculture. Climate smart agriculture is defined as technologies that ensure sustainable increases in productivity and income, increased climate adaptation and reduced greenhouse gas emissions below "business as usual" (FAO, 2013).

In sub-Saharan Africa, a wide variety of manual (e.g. treadle pumps, rope and washer and other hand pumps) and motorized lifting technologies (e.g. petrol and diesel pumps) have been tested (Kamwamba-Mtethiwa, Weatherhead, & Knox, 2016 and references therein; Schmitter et al., 2016). Whilst the adoption of manual water lifting technologies remains rather site specific, the use of fuel based motorized pumps has risen exponentially over the past decade in SSA (Giordano & de Fraiture, 2014; Namara, Hope, Sarpong, De Fraiture, &

* Corresponding author. Present: International Water Management Institute, Yangon, Myanmar.
E-mail address: p.schmitter@cgiar.org (P. Schmitter).
[1] Present: Dept. Soil and Environment, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden.

https://doi.org/10.1016/j.apgeog.2018.02.008
Received 7 October 2017; Received in revised form 11 February 2018; Accepted 12 February 2018
0143-6228/

Owusu, 2014). Furthermore, combining surface and groundwater, the use of motorized pumps could increase small scale irrigable land by 30 million ha benefiting 180 million people and result in an annual net revenue of 22 billion USD (Xie et al., 2014). However, the access to hydro-carbon fuel remains a challenge in several SSA countries (Amjath-Babu, Krupnik, Kaechele, Aravindakshan, & Sietz, 2016). Additionally, the use of hydro-carbon energized motorized pumps would not fulfil the climate smart criteria of reducing emissions in agriculture. Furthermore, rural electrification is particularly poorly developed in SSA, which significantly reduces the potential of electricity based pumps as an alternative to hydro-carbon pumps, unlike for example, smallholder farming in India (Amjath-Babu et al., 2016).

As solar panels become more affordable, solar photovoltaic (PV) technologies, with their low carbon footprint, have been identified as high potential solutions for rural electrification as well as water extraction for both domestic and irrigation purposes in sub-Saharan Africa (Chandel, Nagaraju Naik, & Chandel, 2015; Jäger-Waldau, 2017; Mohammed Wazed, Hughes, O'Connor, & Kaiser Calautit, 2018; Muhsen, Khatib, & Nagi, 2017). As such, solar PV pumps for smallholder farmers have become an emerging technology in SSA (Burney, Woltering, Burke, Naylor, & Pasternak, 2010; Burney & Naylor, 2012; Kamwamba-Mtethiwa et al., 2016; Mohammed Wazed et al., 2018). A review by Chandel et al. (2015) shows that solar PV based pumping can be more economically viable in urban and rural areas compared to both hydro-carbon energized and electrical pumps. The continuous improvement of the technology and the reduction in capital investment required, which remains a challenge in SSA, could make solar PV pumps an affordable alternative to hydro-carbon fuel and electrical pumps in smallholder irrigation (Chandel et al., 2015; Mohammed Wazed et al., 2018). However, the economic viability is highly dependent on water supply meeting the water demand (Muhsen et al., 2017; Odeh, Yohanis, & Norton, 2006).

GIS based mapping has been used effectively to assess suitability and feasibility of renewable energy, water resources or specific crop systems (Akyol, Kaya, & Alkan, 2016; Palmas, Abis, von Haaren, & Lovett, 2012; Szabó, Bódis, Huld, & Moner-Girona, 2013, 2011; Venkatesan, Krishnaveni, Karunakaran, & Ravikumar, 2010; Worqlul, Collick, Rossiter, Langan, & Steenhuis, 2015; Worqlul et al., 2017; Yalcin & Kilic Gul, 2017). Multi-criteria decision making (MCDM), first developed by Saaty (1977), and a wide range of related methodologies offer a variety of techniques and practices to uncover and integrate decision makers' preferences into "real-world" GIS-based planning and management solutions (Ascough et al., 2002). Various applications of MCDM have been used to assess the potential of agricultural water management strategies for smallholder farmers. For example, Worqlul et al. (2017) used MCDM in Ethiopia to identify 7.5% to 12.4% of potential suitable irrigable land that could be irrigated using groundwater resources. Food and Agricultural Organization (FAO, 2012) have developed and used a multi-criteria GIS framework to map the potential for investments in agricultural water management in SSA.

The existing suitability analysis methodologies can be adapted for the suitability analysis of solar PV pumps for smallholder irrigation. However, a multi-criteria GIS based platform has not yet been developed to assess the suitability of solar based PV pumps for smallholder irrigation (i.e. < 1 ha) in Africa taking into account available water resources, despite the availability of solar irradiation estimates such as those from the European Commission, Joint Research Center (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php) (Huld, 2017; Huld, Müller, & Gambardella, 2012). In India, remote sensing has been used to quantify solar irradiation and then combined with data on elevation and land use to map suitability for concentrated solar power and centralized solar photovoltaic systems (Mahtta, Joshi, & Jindal, 2014). The gap in suitability maps for solar based PV pump irrigation suggests the need to develop and test such methodologies in Africa. Therefore, this study sought to (i) develop a GIS based methodology using open source software to evaluate the potential of solar based PV pumps using shallow groundwater and surface water, and (ii) test the performance of the model in Ethiopia. Identifying suitable locations for solar based irrigation is particularly urgent as various investors consider out-scaling the systems. The suitability mapping can be integrated into planning for overall sustainable irrigation development in SSA, and more specifically, to evaluate possible investments in solar pump business models.

2. Material and method

2.1. Study site

Ethiopia was chosen as the pilot case to develop the multi-criteria model given the wide range of altitude (−125 m a.s.l. to 4550 m a.s.l.) and corresponding diversity of agro-ecological zones (Fig. 1). The agro-ecological zones are characterized by differences in topography, solar irradiation, rainfall, geology, and hence soil types as well as land uses. Hence, the complexity and variety of these agro-ecological zones provide a great opportunity to develop and test a multi-criteria environment.

Approximately 85% of the population and 75% of livestock live in rural Ethiopia covering approximately 76.3 million ha (45% of the total land area) (Dejene, 2003; Leta & Mesele, 2014). Many of the highly populated towns are located in the wet and moist zones of the mid-highlands. Therefore, road infrastructure is dominant in the mid-highland agro-ecology. Whilst the majority of agricultural land is purely rainfed, 1.3% is estimated to be under smallholder irrigation (Sheahan & Barrett, 2017). Recently the Agricultural Transformation Agency (ATA) has estimated that approximately 11 million ha would be suitable for irrigation of which 48% could be irrigated using groundwater (Agricultural Transformation Agency (ATA), 2016). Moreover, Ethiopia places high priority on irrigation development within its Transformation Agenda to sustainably intensify agriculture and improve food security.

2.2. Data and pre-processing

Data selection focused on biophysical parameters as well as two indicators representing market access. The latter is considered a critical factor providing economic incentives for investment in irrigation development. The input maps selected for the analysis were based on their accessibility (i.e. preferably open source), resolution and relevance for the multi-criteria tool development. Five main categories of data were identified to assess the potential for solar PV pumps for surface and shallow groundwater based irrigation: i) topography and soil suitability, ii) rainfall, iii) surface and groundwater resources, iv) land use and protected areas, and v) road infrastructure, towns and population. The GRASS GIS modules (*r.sun, r.reclass*, and *r.mapcalc*) were used to pre-process the input data (Table 1). The vector data layers including road, river, land cover and national park were converted to raster data.

The digital elevation model (STRM 30 m resolution) was used to derive the elevation class, aspect and slope information with the same resolution. The annual rainfall data (resolution 900 m) was obtained from WorldClim (WorldClim, 2005). The agro-ecological zones were derived using annual rainfall and the elevation classes based on the criteria defined by Hurni (1998) (Fig. 1).

As the main objective of the study was to assess the feasibility of solar PV pumps rather than the suitability of irrigable land, the soil suitability input was restricted to the depth of the soil profile by using the depth to bed rock (resolution 250 m). Soil suitability for irrigated agriculture is complex and would entail a full assessment of the various soil types. Furthermore, no specific crop was chosen as to not constrain the model to a specific crop water demand and hence application of irrigation.

Irradiation maps from PVGIS with a coarse resolution of 2000 m were obtained (see Table 1). However, the data is too coarse to consider the slope and aspect conditions of smallholder farms (i.e. 1 ha and