ARTICLE IN PRESS

Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Suitable and optimal locations for implementing photovoltaic water pumping systems for grassland irrigation in China

P.E. Campana [a,*], S. Leduc [b], M. Kim [c], A. Olsson [d], J. Zhang [e], J. Liu [b,f,g], F. Kraxner [b], I. McCallum [b], H. Li [a], J. Yan [a,d]

[a] School of Business, Society & Engineering, Mälardalen University, SE-72123 Västerås, Sweden
[b] International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria
[c] Department of Environmental Science and Ecological Engineering, Korea University, 136-701 Seoul, Republic of Korea
[d] School of Chemical Science & Engineering, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden
[e] Department of Geographical Sciences, University of Maryland, MD 20742 College Park, USA
[f] School of Environmental Science and Engineering, South University of Science and Technology of China, 518055 Shenzhen, China
[g] School of Nature Conservation, Beijing Forestry University, 100083 Beijing, China

HIGHLIGHTS

- A new approach to assess the grassland sites for PVWP irrigation systems is proposed.
- A spatial explicit optimization model is used to assess the optimal locations.
- The potentials of PVWP systems for grassland conservation are substantial.
- The potential of PVWP in carbon emissions reduction is significant.

ARTICLE INFO

Article history:
Received 15 September 2015
Received in revised form 25 December 2015
Accepted 2 January 2016
Available online xxxx

Keywords:
Photovoltaic water pumping
Grassland
Irrigation
Optimization
Spatial analysis

ABSTRACT

Grassland plays a key role for the food security of China because of the large number of livestock raised in those areas. Thus, grassland degradation due to climate change and overgrazing is considered as one of the most severe environmental and economic threat for the future sustainable development of China. Photovoltaic water pumping systems for irrigation can play a fundamental role for the conservation of grassland areas.

This paper investigates the geospatial distribution of the technically suitable grassland locations for the implementation of photovoltaic water pumping systems. The technically suitable grassland areas were taken as starting point to assess the optimal locations. The assessment of the optimal locations was conducted using a spatially explicit optimization model of renewable energy systems based on the cost minimization of the whole forage supply chain.

The results indicate that the photovoltaic water pumping systems provide high potential for improving forage productivity, contributing to meet the local demand. The optimal areas are highly sensitive to several environmental and economic parameters such as increased forage potential yield, forage management costs, forage water requirements, ground water depth, forage price and CO_2 price. Most of the optimal areas are selected when the market forage price ranges from 300 to 500 $/tonne DM, indicating that the forage produced using PVWP technology for irrigation is already competitive compared to the imported forage.

1. Introduction

In China, grassland covers nearly 4 million km^2, accounting for more than 40% of the national land surface. Furthermore, grassland plays a key role in achieving sustainable development and enhancing food security of the country since 100 million livestock are raised in those areas [1]. In recent years, photovoltaic water pumping (PVWP) technology for grassland and farmland conservation was successfully implemented in different pilot sites in China: Qinghai [2,3], Inner Mongolia [4] and Xinjiang [5]. The combination of PVWP technology with water saving irrigation techniques and

* Corresponding author.

http://dx.doi.org/10.1016/j.apenergy.2016.01.004
0306-2619/© 2016 Elsevier Ltd. All rights reserved.

sustainable water management showed that it is technically feasible to improve grassland productivity in areas without access to the grid. The grassland productivity can be increased up to 20–30 times using PVWP systems for irrigation, without imposing a severe threat to the available water resources [2]. Moreover, PVWP systems are an economically suitable technology to provide electricity for irrigation both in off- and on-grid areas, also avoiding a further pressure on the energy requirements in the pastoral-farming sector [6].

Identification of feasible locations were studied for the implementation of PVWP technology for grassland and farmland conservation in China [2,3]. In these studies, the feasible grassland areas for implementing PVWP irrigation technology were evaluated through the combination of a set of spatial data on land cover and slope, precipitation, temperature and sunshine hours. The spatial data regarding the land cover and terrain slope were considered to assess the suitable grassland areas for the installation of irrigation systems. According to previous recommendation, the slope must be lower than 2–5% for furrow irrigation and lower than 5–9% for micro-spray irrigation to avoid runoff, soil erosion, and water and energy wastage [2,3]. The suitable annual precipitation for PVWP irrigation systems was between 300 and 600 mm on the basis of grassland water demand [2,3]. The suitable annual ambient temperature and sunshine hours should be lower than 20 °C and greater than 1400 h, respectively [2,3]. The constraint of the annual ambient temperature was related to the effect of temperature on the evapotranspiration and thus on the grassland water demand. The temperature constraint was also set to avoid an excessive decline of the PV modules working efficiency. However, the constraint of the annual sunshine hours was an indirect measure of the solar energy resources required to drive the PVWP systems. System optimization was carried out considering the incremental benefit of irrigation, assessing the rate of the investment return in relation with the precipitation. The authors concluded that the highest economic benefits of PVWP systems could be achieved in areas marked out by 350–400 mm of precipitation [2,3].

Nevertheless, an in-depth analysis considering the detailed availability of water resources in identifying the technically suitable grassland and farmland areas for implementing PVWP systems was not addressed in the previous studies [2,3]. Moreover, the costs related to the supply chain and the co-benefits of implementing PVWP systems for grassland and farmland conservation were not thoroughly considered in the conducted optimization [3].

The aim of this paper is to identify the most technically suitable grassland areas for implementing PVWP technology for forage irrigation, taking into account the availability of water resources in the assessment. A more comprehensive approach for identifying the areas that require irrigation was also adopted. Once identified, these areas were subject to the selection of the optimal locations for installing PVWP systems, using an optimization model that minimizes the supply chain costs of forage production. The co-benefits of implementing PVWP systems for irrigation, such as CO_2 emission reductions and carbon sequestration, were also included in the optimization model. Another contribution of this work is that the forage supply chain in China using PVWP technology as mean to provide water for irrigation was studied for the first time. The results provide a better understanding on how PVWP technology can be a solution for the sustainable development of the pastoral and irrigation sectors in China.

This paper is organized as follows: Section 2 provides a general overview of the methodology applied in this work to assess the suitable and optimal grassland areas for implementing PVWP irrigation systems. The corresponding subsections address the methodologies applied in details; in Section 3, the results of the spatial assessment and optimization are presented and discussed; Section 4 summarizes the outcomes of this study pointing out the directions for future works.

2. Methodology

The conceptual framework applied in this study to identify the suitable and optimal grassland areas for the implementation of PVWP systems for irrigation is depicted in Fig. 1. The methodology is divided into two main parts: the first is the spatial analysis, focusing on the assessment of the technically suitable areas and on the primary spatial input data used for selecting the optimal locations in the optimization tool (such as PVWP system capacity, increased forage yield due to irrigation, forage demand, and transportation distances); the second part deals with identifying the optimal locations among the technically suitable locations using BeWhere model [7–10].

The suitable grassland areas were assessed using the following spatial data: grassland distribution, terrain slope, precipitation, potential evapotranspiration, and water stress index (WSI). The approach used in this study to assesses the suitable areas for implementing PVWP irrigation systems, hereafter called "Approach 2", was compared to a previous approach developed by Yan et al. [2] and Yu et al. [3], hereafter called "Approach 1". A detailed description of Approaches 1 and 2 is given in Section 2.1. The suitable grassland locations represent the main spatial input data for the optimization model and the optimal locations were selected among the suitable ones during the optimization process.

The spatial distribution of the PVWP system capacity was calculated using the spatial data of solar irradiation, groundwater depth, and irrigation water requirement (IWR) which is related to the reference evapotranspiration ET_o. Solar irradiation, groundwater depth, and IWR represent the main design parameters for PVWP irrigation systems assuming groundwater as the water source. The PVWP system design map was used to calculate the spatial distribution of the PVWP initial capital costs (ICC).

To estimate the effect of irrigation on the forage yield, the spatial data about IWR was used along with an experimental relationship between annual average irrigation and NPP increase. The increased forage yield is the main economic benefit produced by the implementation of PVWP irrigation systems, thus representing one of the main spatial input data for the optimization model.

The forage demand was assessed using the spatial data of livestock density, taking into account the average forage intake of small and big ruminants.

The road and rail networks were utilized to assess the transportation distances between grassland forage supply locations and livestock forage demand locations. Accordingly, the transportation distances are fundamental to assess the transportation costs and emissions.

The spatial data, together with techno-economic parameters (i.e. PVWP system specific ICC, forage management costs, market forage price, road and railway specific transportation costs, electricity price, incentives for renewable power generation, and CO_2 offsets) were used as the input data to identify the optimal location using the BeWhere model. This model was originally developed to determine the optimal locations of bioenergy production facilities, such as biomass CHP plants or biogas plants. In this work, the original version of BeWhere was adjusted to identify the optimal PVWP system locations for forage production.

2.1. Feasible grassland areas

In this article, the analysis of the technically suitable grassland areas for the implementation of PVWP systems was conducted using GIS-supported spatial analysis including some relevant differences as compared to "Approach 1" [2,3]. The following spatial data were taken into account: grassland distribution, terrain slope, precipitation, potential evapotranspiration and WSI. The grassland

Please cite this article in press as: Campana PE et al. Suitable and optimal locations for implementing photovoltaic water pumping systems for grassland irrigation in China. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.01.004