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Optimal grassland locations for sustainable photovoltaic water pumping systems in China

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Abstract

Grassland is of strategic importance for food security of China because of the high number of livestock raised in those areas. Grassland degradation due to climate change and overgrazing is thus regarded as severe environmental and economic threat for a sustainable future development of China. Photovoltaic water pumping (PVWP) systems for irrigation can play an important role for the conservation of grassland areas, halting degradation, improving its productivity and farmers' income and living conditions. The aim of this paper is to identify the technically suitable grassland areas for the implementation of PVWP systems by assessing spatial data on land cover and slope, precipitation, potential evapotranspiration and water stress index. Furthermore, the optimal locations for installing PVWP systems have been assessed using a spatially explicit renewable energy systems optimization model based on the minimization of the cost of the whole supply chain. The results indicate that the PVWP-supported grassland areas show high potential in terms of improving forage productivity to contribute to supplying the local demand. Nevertheless, the optimal areas are highly sensitive to several environmental and economic parameters such as ground water depth, forage water requirements, forage price and CO_2 emission costs. These parameters need to be carefully considered in the planning process to meet the forage yield potentials.

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Keywords: PV water pumping; irrigation; grassland; forage; supply chain; optimization.

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

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security of the country since 100 million livestock are raised in those areas [1]. In recent years, PVWP technology for grassland and farmland conservation has been 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 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 [3]. Moreover, PVWP systems are an economically suitable technology to provide electricity for irrigation both in off- and on-grid areas, avoiding also a further pressure on the energy requirements in the pastoral-farming sector [6].

There were previous attempts to identify feasible locations for the implementation of PVWP technology 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 area for the installation of irrigation systems. According to previous studies 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 comprised between 300 to 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 1400h, 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. Whereas, the constraint of the 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 system could be achieved in areas marked out by 350 to 400 mm of precipitation [2, 3].

The previous studies omitted to take into account the availability of water resources in identifying the technically suitable grassland areas for implementing PVPW systems. Moreover, the conducted optimization neglected all the costs related to the supply chain and the co-benefits of implementing PVWP system for grassland and farmland conservation. The aim of this paper is to identify the most technically suitable areas for implementing PVWP technology for forage irrigation including the availability of water resources in the assessment. A better approach for identifying the areas that require irrigation has been also adopted. Once identified, these areas are subject to the selection of the optimal locations for PVWP units, using an optimization model that minimizes the supply chain costs of forage production using PVWP systems as irrigation technology. The co-benefits of implementing PVWP system for irrigation, such as CO_2 emission saving and sequestration, are also included in the optimization model.

2 Methodology

For this article, the analysis of the technically suitable grassland area for the implementation of PVWP systems has been conducted by using GIS-supported spatial analysis including some relevant differences compared to the previous works [2, 3]. The following spatial data were taken into account: grassland distribution, slope of terrain, precipitation, potential evapotranspiration and water stress index. Similarly to previous works, grassland distribution and slope of terrain have been used to identify the technically suitable grassland areas for the installation of irrigation systems. Different from the previous assessments, the areas where irrigation is required have been estimated considering the difference between precipitation and potential evapotranspiration (a difference lower than 0 means that irrigation is required). Moreover, the spatial distribution of the water stress index (WSI), defined as the ratio between water demand to sustainable water resources, has been used to remove in the suitability analysis those areas marked out by a high water stress [7]. Thus, in identifying the technically suitable locations for PVWP irrigation technology, only the areas marked by a low WSI have been taken into account (WSI<0.1) to provide the most conservative results. This assumption has been taken based on the fact that water security is one of the main environmental and economic threats for China. Table 1 shows the spatial data taken into account to identify the technically suitable areas for implementing PVWP systems for grassland conservation, both for the current and previous approach.

Table 1: Spatial data used for the assessment of technically suitable grassland areas for PVWP irrigation systems.

Definition	IIASA approach	Previous approach [2, 3]
Grassland area	Grassland distribution [8]	Grassland distribution [8]
Area suitable for irrigation	Terrain slope (<9°) [9]	Terrain slope (<9°) [9]
Area where irrigation is required	Precipitation [9] - Potential evapotranspiration [10, 11] (<0)	Precipitation (300-600mm) [9]
Constraint	Water stress index (<0.1) [8]	Temperature (<20°C) [9] Sunshine duration (>1400 hours) [12]

The assessment of the feasible grassland areas for the implementation of PVWP systems has been a starting point for the search of the optimal areas. Spatial data on the sunshine duration has been derived from interpolation of weather station data available in a global meteorological database [12]. The optimal locations for PVWP units have been estimated using BeWhere, an optimization model for renewable energy systems developed at the International Institute for Applied System Analysis (IIASA) [13-16]. BeWhere is a mixed linear integer program written in GAMS® that minimizes the costs of the entire supply chain, including e.g. feedstock harvest, transportation, conversion and delivery of final energy products. For the specific purpose of searching for the optimal areas for PVWP systems, the original version of BeWhere has been adapted in order to minimize the supply chain costs for forage production in China, considering the technically suitable grassland areas as supply locations. The BeWhere model minimizes the costs of the entire forage production chain including the costs of PVWP system installation, costs of feedstock management, transportation and additional forage to meet the forage demand. When minimizing the supply chain costs, the following revenues are also taken into consideration: revenues due to PVWP system electricity surplus sales as well as carbon trading. Indeed, the application of PVWP systems lead to a substantial reduction of CO_2 emissions due to the surplus of PV power production during the non-irrigation period and carbon sequestration through grassland improvement conditions, as shown in [6, 17]. The negative effects of CO_2 emissions due to forage transportation have been also taken into account.

The assessment of the feedstock production has been conducted from the spatial data of net primary productivity (NPP) [18], using the approach described in [19]. In our specific case, Alfalfa (*Medicago Sativa*) has been used as reference crop as it is one of the most widely used forage crop. To study the effect of irrigation on NPP and consequently on the Alfalfa yield, the experimental relationship between annual average irrigation and NPP increase, proposed by [20], has been used. The average irrigation has been computed from the spatial data of reference evapotranspiration and precipitation applying the procedure described in [21]. To avoid soil salinity issues from irrigation, an 18% leaching requirement has been considered in the assessment of irrigation water requirements. The forage demand has been assessed from the FAO spatial data about livestock density [22], assuming an average fodder intake differentiated between small and big ruminants [23, 24]. The PVWP system capacity and the corresponding investment costs have been calculated from the spatial data of solar irradiation, irrigation water requirements and depth of the groundwater resources [25, 26], considering the specific costs provided by a PVWP systems manufacturer company [27].

This study is restricted to the grassland areas in China. Therefore farmland areas have not been taken into consideration in the forage supply chain. China has been covered with a grid of cells with a half-degree (equals 50x50 km at the Equator) spatial resolution. Thus, the original maps spatial resolution has been aggregated to half-degree resolution. Only 1% of each cell grid has been considered as forage supply area to avoid high pressure on the available water resources.

3 Results and discussions

Suitable areas for PVWP irrigation technology

The comparison between the calculated suitable areas identified by IIASA in this study and the previous approach is depicted in Fig. 1 in the form of a disagreement map. The common areas of both approaches are also highlighted. Despite the fact that the total technically suitable area is almost similar, there is a significant disagreement in the spatial distribution, especially with respect to the central provinces of China. On the basis of the previous approach, the technically suitable areas for grassland irrigation in China are mainly locate within a zone reaching from the northeast to the southwest of China. On the contrary, the technically suitable areas of the present IIASA approach are located in the northeast of China, in particular in the northeast part of Inner Mongolia, as well as in the southwest of China, mainly in Qinghai, Sichuan and Tibet. This significant difference is mainly due to the WSI that has not been taken into account by the previous approach.

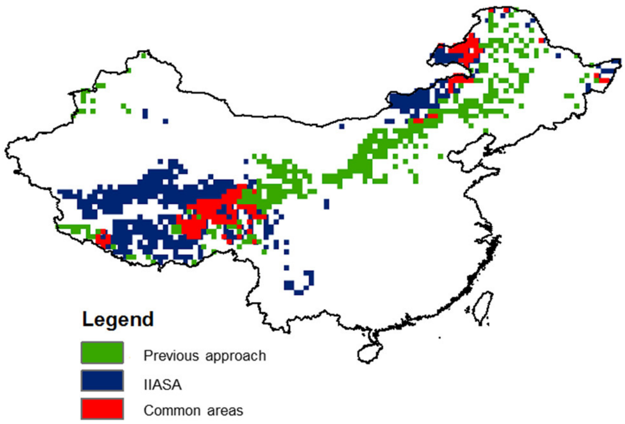

Fig. 1. Disagreement map for the areas suitable for PVWP technology identified by the IIASA and previous approach.

Based on the assumptions made, the calculated potential forage production is 4.1 Mtonne DM (dry matter), corresponding to about 1% of the total livestock fodder demand in China. At the same time, this potential is about forty times higher than the Chinese 2013 Alfalfa import volume, equal to 100 ktonnes DM [28].

Optimal locations for PVWP irrigation technology

Fig. 2 shows the results of the optimization process carried out with the BeWhere model in terms of forage production as a function of the forage market price to meet the forage local demand. Four different scenarios have been considered: 1) business as usual (BAU) (forage sale is the only income connected to the PVWP systems operation); 2) 50% initial capital cost (ICC) (a subsidy for the 50% of the IC is taken into account); 3) electricity + incentives (the surplus of electricity and the corresponding incentives for renewable power production in China are considered as part of the revenues of the base case); and 4) carbon trading (the CO_2 emission reduction and sequestration are considered as offsets at 100\$/tonne CO_2). BeWhere starts to select the optimal locations, and thus takes into account the corresponding potential forage production, when the PVWP forage cost is competitive with the market forage price required to fulfil the local demand. The higher the market forage price is and higher the number of locations selected is and the higher the PVWP forage production is. Most of the locations are selected when the forage price ranges from 150 to 300 $/tonne DM. The results indicate that the forage price from PVWP irrigation is already competitive at the import price. The price of Alfalfa import varied from 200 to 400 $/tonne DM between 2009 and 2013 [23] with the United States as the major exporter. It is interesting to highlight that the import prices are also likely to increase due to the high Alfalfa water requirements and the drought periods that have affected United States during the past years [29].

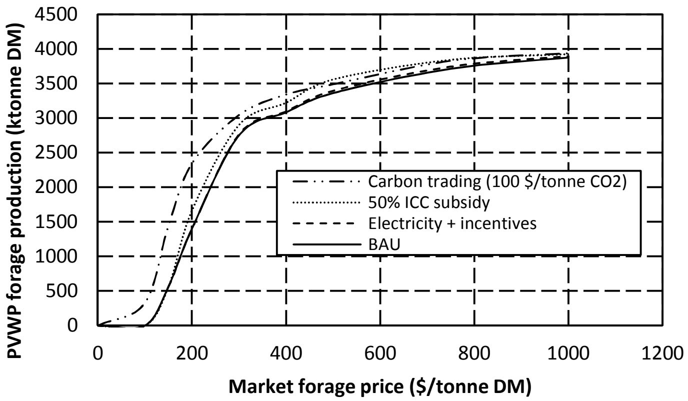

Fig. 2. PVWP forage production as a function of the market forage price for different studied scenarios.

The results show furthermore, that grassland irrigation can play a key role for the sustainable future of China and at the same time for enhancing the rural economies. Grassland irrigation can hence increase the internal forage supply to meet the internal demand for livestock or at least substantially reduce the forage imports. The effects of investment reduction shows only a slight effect on the optimization process. This can be explained by the fact that the majority of the locations selected are characterized by low water requirements and shallow groundwater level and thus a low PVWP irrigation capacity. Correspondingly, the surplus of electricity sales and incentives play a marginal role in the search of the optimal locations. Taking instead the offsets generated by carbon trading into consideration, the competitiveness of PVWP systems for forage irrigation can be enhanced, but only at high CO_2 prices. Fig. 3 shows a sensitivity analysis on how the optimal location selection, and thus forage production, is affected by varying CO_2 prices.

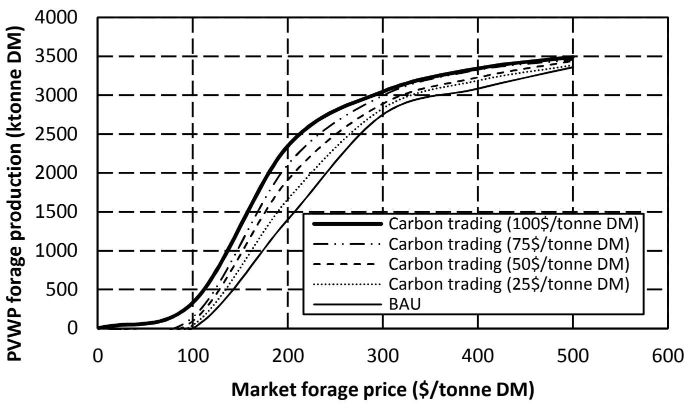

Fig. 3. PVWP forage production as a function of the market forage price and CO_2 price.

The PVWP system can also offer additional benefits, i.e. CO_2 emission offsetting for grassland [11, 12]. The identification of the optimal locations and thus the corresponding forage production is also sensitive to the potential NPP and to the potential improvement of NPP through irrigation.

4 Conclusions and future works

PVWP systems are a renewable energy-based solution to support the sustainable development of the pastoral and agricultural sectors in China. The potentials of PVWP systems for grassland conservation and increasing its productivity are substantial for China. The optimal locations are sensitive to several environmental and economic parameters such as forage potential yield, forage water requirements, ground water depth, forage price and CO_2 price that need to be carefully considered with the selection of the most technically suitable areas and locations. This work can be considered a first attempt to analyse and optimize the entire food supply chain in China, from irrigation and fodder production for livestock to the meat final consumer. Through the present study it became obvious that the developed methodology, i.e. the combination of GIS combined with modelling and renewable energy technology, can be applied in many countries and regions in the world. Particularly interesting for future applications appear regions marked out by severe sustainability issues.

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Biography

Pietro Elia Campana graduated in Environmental Engineering at the University of Perugia, Italy. Currently, he is PhD candidate in Energy and Environmental Technology at Mälardalen University, Sweden.