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Economic optimization of photovoltaic water pumping systems for irrigation

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ABSTRACT

Photovoltaic water pumping technology is considered as a sustainable and economical solution to provide water for irrigation, which can halt grassland degradation and promote farmland conservation in China. The appropriate design and operation significantly depend on the available solar irradiation, crop water demand, water resources and the corresponding benefit from the crop sale. In this work, a novel optimization procedure is proposed, which takes into consideration not only the availability of groundwater resources and the effect of water supply on crop yield, but also the investment cost of photovoltaic water pumping system and the revenue from crop sale. A simulation model, which combines the dynamics of photovoltaic water pumping system, groundwater level, water supply, crop water demand and crop yield, is employed during the optimization. To prove the effectiveness of the new optimization approach, it has been applied to an existing photovoltaic water pumping system. Results show that the optimal configuration can guarantee continuous operations and lead to a substantial reduction of photovoltaic array size and consequently of the investment capital cost and the payback period. Sensitivity studies have been conducted to investigate the impacts of the prices of photovoltaic modules and forage on the optimization. Results show that the water resource is a determinant factor.

1. Introduction

Desertification, defined as land degradation resulting from both climatic-natural variations and human activities, is one of the most crucial worldwide environmental problems affecting food security, water security, eco-security, socioeconomic stability and sustainable development [1]. Photovoltaic water pumping (PVWP) systems, which can provide water for irrigation, have been considered a sustainable and economical solution to curb the progress of desertification [2].

There have been many studies regarding PVWP systems. For example, Bouzidi et al. [3] analysed the performances of such a system installed in an isolated site in the south of Algeria estimating the amount of water that could be supplied under different solar radiation conditions; similarly, Hrayshat and Al-Soud [4] studied the potential application of PVWP systems in Jordan; Bouzidi [5] compared PVWP systems with wind power water pumping (WPWP) systems to cover drinking water requirements in a specific location in Algeria; Ghoneim [6] developed a program for modelling each PVWP component to assess the performance of PVWP systems in Kuwait; Benghanem et al. [7] studied the effect of pumping head on the performance of PVWP systems using an optimal PV array configuration to drive a direct current (DC) helical pump; Mokeddem et al. [8] investigated the performance of a directly coupled PVWP system; Boutelhig et al. [9] compared two different DC pumps with the scope of selecting the optimal direct coupling configuration for providing water to a farm in Algeria; Hamidat at al. [10] presented the electrical and hydraulic performance of a surface centrifugal pump as a function of the hydraulic head and size of PV array for irrigation purposes in the Sahara region; Senol [11] focused on small and medium-size mobile PVWP applications for watering purposes in Turkey; Glasnovic and Margeta [12] elaborated an optimization model for small PVWP system for irrigation; Pande et al. [13] concluded that in order to achieve a successful design of PVWP system, the water supply and crop water requirements for orchards have to be carefully considered. Due to the extreme dynamic variability of the parameters affecting the functioning of PVWP systems, principally solar radiation, dynamic modelling is an important tool to evaluate

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their performances [14]. Campana et al. [15] modelled both the PVWP system and the crop water requirements to analyse the match between water demand and water supply. Model validation for both PVWP system and crop water requirement was presented in several works: Amer and Younes [16] validated long term performance of PVWP system using a simple algorithm; Hamidat and Benyoucef [17] validated PVWP system models based on the pump experimentation; Luo and Sophocleous [18] validated the models for assessing crop water requirements using a lysimeter. The technical advantages of a novel control system for achieving an optimal matching between crop water demand and water supply and for interfacing PVWP systems to the grid were analysed by Campana et al. [19]. The positive economic and environmental aspects of the proposed novel control system for PVWP applications was studied by Campana et al. [20].

Our effort focuses on the application of PVWP technology for irrigation to combat the grassland degradation and to promote the farmland conservation in rural areas of China. Previously, the estimation of the water demand for irrigation and the assessment of the groundwater resources were carried out by Xu et al. [21]. Yu et al. [22] assessed the most suitable areas for PVWP irrigation system in Qinghai Province and in the entire China. The groundwater resource has been identified as a crucial factor concerning the implementation of PVWP for irrigation [23]. The potential benefit of applying PVWP in the improvement of biodiversity of grassland [24], carbon sequestration [25], and energy and food security [26] were also investigated. A novel business model, which can be applied to integrated PVWP systems for grassland and farmland conservation, was proposed, including environmental co-benefits, agricultural products and social visualization of all benefits [27].

The PVWP technology is a well-developed technology with thousands of installations worldwide. The common approach for optimizing a PVWP system mainly deals with the improvement of effectiveness of various system components with the aim of minimizing the total cost. However, Glasnovic and Margeta [12] pointed out that this approach suffers from the lack of systematic quality and static quality. As a result it does not yield optimal results. Therefore, a new optimization method, which systematically integrated all relevant system elements and their characteristics, was developed. The objective function was still to minimize the PV size; whereas, the constraints were defined in a new way, which considered not only the water demand, but also the available water resource. The approach was tested at two areas in Croatia. Smaller PV sizes and thus lower PV costs were achieved. Nevertheless, the economic feasibility of PVWP is not solely determined by the investment cost of PVWP, it is also tightly related to the benefit from the crop. Even though the investment cost is linearly proportional to the PVWP size, the relationship between PVWP system size, crop yield and pumped water is nonlinear. Hence, it is essential to include that benefit in the optimization of PVWP systems. To the best knowledge of authors, there has not been any work regarding optimizing PVWP with the consideration of crop benefit.

The main objective of this paper is thus to develop a new optimization method taking into account the crop yield response to the supplied water and the revenue from selling the crop. As the price of PV modules follows a trend of decrease while the price of crops follows a country trend of increase, the sensitivity study will also be conducted in order to assess the influences of those prices on the optimization. Different from the work carried out by Glasnovic and Margeta [12] that statistic models were used for the simulation of PV system, pumped water and water demand, the following hourly dynamic models are employed in this paper: PV system, inverter-pumping system, water requirements, groundwater level and crop yield response to water. In addition, the hourly models of PVWP system, crop water demand and ground water level are validated against measurements, giving more accurate results. This paper is organized as follows: Section 2 presents the proposed optimization approach; Section 3 introduces all the models adopted to describe the operation of a PVWP system and provides the model validation; Section 4 shows the results of optimization; and Section 5 summarizes the important findings of this work.

2. Optimization approach and models description

Genetic algorithm *GA* has been used to find the optimal PVWP system size, as well recognized optimization technique [28]. The optimization problem finds the optimal size of PVWP systems for irrigation using one objective function under a prerequisite. The objective function is to maximize the annual profit, given by the balance between annual revenue R_{ann} ($), annualized initial capital cost ICC_{ann} ($) and annual operation, maintenance and replacement cost omr_{ann} ($). It thus (I) maximizes the crop yield Y_a (tonne DM/ha year) and consequently the annual revenue R_{ann} and (II) minimizes the PVWP system size and consequently the sum of annualized initial capital cost ICC_{ann} and the corresponding annual operation, maintenance and replacement cost omr_{ann}. The prerequisite is to have zero system failure or ensures the 100% reliability and sustainability of the PVWP system during the whole irrigation season. The PVWP system failure f is defined as the hourly drawdown s_h (m) (induced by the pumping system during the irrigation season) goes below the level of pump h_p (m) (measured from the static water level) or the daily water pumped volume $V_{p,d}$ (m^3) is larger than the daily sustainable pumped water volume $V_{s,d}$ (m^3). Different from previous optimization works, the following constraints are carefully considered in this work: the hourly decline of the groundwater level s and the daily pumped water limited by the water resource $V_{p,d}$. s and $V_{p,d}$ dynamically depend on the PVWP system capacity and water resource. If those two constraints are not taken into account in the optimization process, the PVWP system capacity can be oversized resulting in the dry-up of well, the broke-down of the pump, and the failure of sustainable water management. Furthermore, an oversized PVWP system also implies higher initial capital costs. The mathematical formulation of the proposed optimization approach is given by the following set of equations:

$$\max(R_{ann} - ICC_{ann} - omr_{ann}) \tag{1}$$

$$\sum f = 0 \ (f = \{0,1\}, f = 1 \text{ if } s_h > h_p \ or \ V_{p,d} > V_{s,d}) \tag{2}$$

The annual revenues R_{ann} from the forage sale depends on the actual forage yield Y_a and the specific forage price p_f ($/tonne DM) according to the following equation:

$$R_{ann} = Y_a p_f \tag{3}$$

The actual forage yield Y_a is a function of the pumped water and thus PVWP system capacity and it has been dynamically calculated according to the procedure described in Section 3.4. The specific forage price p_f has been assumed equal to 207 $/tonne DM [29]. The ICC_{ann} has been calculated from the initial capital cost ICC with the following equation:

$$ICC_{ann} = ICC\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{4}$$

where i and n are the real interest rate and the project lifetime assumed equal to 6.4% [30] and 25 years, respectively. The ICC of PVWP systems has been estimated from the capacity according to the data provided by a manufacturer company [31]. The PVWP system and components costs are depicted in Fig. 1 as a function of the capacity. The PV modules price has been assumed equal to 1, 1.5 and 2 $/W_p$ to conduct a sensitivity analysis. The specific inverter