Energy Conversion and Management 103 (2015) 311–320

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Techno-economic feasibility of the irrigation system for the grassland and farmland conservation in China: Photovoltaic vs. wind power water pumping

Pietro Elia Campana [a,*], Hailong Li [a], Jinyue Yan [a,b]

[a] School of Business, Society & Engineering, Mälardalen University, SE-72123 Västerås, Sweden
[b] School of Chemical Science & Engineering, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden

ARTICLE INFO

Article history:
Received 8 March 2015
Accepted 13 June 2015
Available online 3 July 2015

Keywords:
Photovoltaic
Wind
Water pumping
Irrigation
Crop yield
Simulation

ABSTRACT

Photovoltaic water pumping (PVWP) and wind power water pumping (WPWP) systems for irrigation represent innovative solutions for the restoration of degraded grassland and the conservation of farmland in remote areas of China. The present work systematically compares the technical and economic suitability of such systems, providing a general approach for the design and selection of the suitable technology for irrigation purposes. The model calculates the PVWP and WPWP systems sizes based on irrigation water requirement (IWR), solar irradiation and wind speed. Based on the lowest PVWP and WPWP systems components costs, WPWP systems can compete with PVWP systems only at high wind speed and low solar irradiation values. Nevertheless, taking into account the average specific costs both for PVWP and WPWP systems, it can be concluded that the most cost-effective solution for irrigation is site specific. According to the dynamic simulations, it has also been found that the PVWP systems present better performances in terms of matching between IWR and water supply compared to the WPWP systems. The mismatch between IWR and pumped water resulted in a reduction of crop yield. Therefore, the dynamic simulations of the crop yield are essential for economic assessment and technology selection.

1. Introduction

Grassland represents the largest ecosystem on the earth covering 52.5 million km^2 [1]. In China, the grassland area is nearly 4 million km^2, accounting for more than 40% of the national land area [2]. It plays a key and strategic role in achieving the sustainable development and enhancing the food security of the country since more than 100 million livestock is grown up in those areas. Grassland desertification in China has become one of the top socio-economic and environmental concerns, affecting 400 million people and producing an economic loss of about 8 billion US dollars [3].

Grassland irrigation based on the sustainable exploitation of the water resource can curb desertification, restore the pastures and enhance the local economies in rural areas [4,5]. Nevertheless, the major technical obstacle for irrigating is the lack of access to electricity in the remote pasture land areas. Photovoltaic (PV) technology and wind turbine (WT) are sustainable and cost effective solutions to provide electricity for off-grid pumping applications. They also represent a technical innovation to curb grassland degradation, as highlighted in the UN Convention to Combat Desertification [6]. This study is part of a large project which investigates the technical, economic and environmental feasibility of PV water pumping (PVWP) systems for halting grassland desertification and promoting farmland conservation in China [7–10].

Many studies have been conducted concerning PVWP and wind power water pumping (WPWP) systems. Campana et al. [11] focused on the PVWP system dynamic performances, in particular the match between water demand and water supply. Benghanem et al. [12] compared the performances of different PVWP configuration for different hydraulic heads. Stoppato et al. [13] proposed a new optimal managing strategy for PVWP systems equipped with hydro energy storage. Kelley et al. [14] studied the feasibility of PVWP systems for irrigation as a function of location. Rehman and Sahin [15] investigated the technical and economic performances of several small WTs to provide water in Saudi Arabia.

The performances of PVWP and WPWP systems have also been compared. Kumar and Kandpal [16] assessed the potential of PVWP and WPWP systems for irrigation in India. Bouzidi [17] compared PVWP and WPWP systems for the purpose of providing drink water in the Saharan regions. Even though the results showed that

* Corresponding author. Tel.: +46 (0)21 101469.
E-mail address: pietro.campana@mdh.se (P.E. Campana).

http://dx.doi.org/10.1016/j.enconman.2015.06.034
0196-8904/

Nomenclature

Abbreviations

AC	alternate current
DC	direct current
PV	photovoltaic
PVWP	photovoltaic water pumping
WPWP	wind power water pumping
WT	wind turbine

Symbols

B_a	annual revenues ($)
c	scale factor (m/s)
$c_{p,PV}$	specific cost of PV modules ($/W$_p$)
$c_{p,PVWP}$	specific costs of photovoltaic water pumping system ($/W$_p$)
$c_{p,WPWP}$	specific cost of wind power water pumping system ($/W$_r$)
$c_{p,WT}$	specific cost of the wind turbine ($/W$_r$)
CWR	crop water requirement (m^3/ha/day)
e_a	monthly average daily actual vapour pressure (kPa)
E_s	monthly average daily solar irradiation (kWh/m^2/day)
e_s	saturation vapour pressure (kPa)
ET_c	monthly average daily evapotranspiration in standard cultural conditions (mm/day)
ET_o	daily reference evapotranspiration (mm/day)
E_w	specific monthly average daily energy yield (kWh/-day/kW$_r$)
$f(v)$	probability density function of the wind speed (%)
f_m	matching factor
G	monthly average daily soil heat flux density (MJ/m^2/-day)
i	interest rate (%)
ICC	initial capital cost ($)
IWR	irrigation water requirement (m^3/ha/day)
IWR$_{t,m}$	total monthly average daily irrigation water requirement (m^3/ha/day)
k	Weibull shape factor
K_c	cultural coefficient
LR	leaching requirements (%)
m	month
max	maximum
n	total number of irrigated crops
η_{irr}	efficiency of the irrigation system (%)
η_p	efficiency of the pump (%)
omr	percentage of the annual operation, maintenance and replacement cost on the initial capital cost (%)
p	velocity-power proportionality
PBP	payback period (year)
P_e	effective precipitation (mm/day)
$P_{p,PVWP}$	photovoltaic water pumping system power peak (kW$_p$)
P_r	wind turbine rated power (W)
$P_{r,WPWP}$	wind power water pumping system rated power (kW$_r$)
P_v	power produced by the wind turbine in the power curve region comprised between v_i and v_r (W)
R_n	monthly average daily net radiation at the grass surface (MJ/m^2/day)
s	s-th irrigated crop
T	monthly average daily air temperature (°C)
t	time period (24 h)
T_0	reference temperature (25 °C)
T_{cell}	photovoltaic cell temperature (zC)
TDH	total dynamic head (m)
v	wind speed (m/s)
v_2	monthly average daily wind speed at 2 m above the ground (m/s)
v_i	cut-in speed of the wind power curve (m/s)
v_o	cut-out speed of the wind power curve (m/s)
v_r	rated speed of the wind power curve (m/s)
α_C	photovoltaic modules temperature coefficient (%/°C)
γ	psychrometric constant (kPa/°C)
Δ	saturation slope of vapour pressure curve at T (kPa/°C)

WPWP systems were the most competitive solution, this work did not consider the dynamic variation of the water demand. In addition, the work was focused only on a specific location, Adrar in Algeria. The findings could not be applied for other locations. Dıaz-Mendez et al. [18] presented a simple methodology to compare PVWP and WPWP for irrigation of commercial greenhouses in Spain, Cuba and Pakistan. Nevertheless, it focused mainly on the economic comparison between PVWP and WPWP systems for irrigation for three specific locations without taking into account the match between water demand and water supply and the effect of water supply on the crop yield.

The performances of PVWP and WPWP systems for irrigation are tightly bounded to the peculiar local climatic conditions and available energy resources. The WPWP system is even particularly dependent on the site specific factor, such as surface roughness, elevation and turbulence effects induced by obstacles. There is still a lack of general comparison between PVWP and WPWP systems. There is also a need to compare the two technologies for irrigation purposes. The irrigation water requirement (IWR) and the crop productivity vary notably at different sites affecting the economic feasibility of different water pumping systems.

This paper is to analyse and compare the performances of the individual PVWP and WPWP systems for irrigation based on dynamic simulations. In order to address the knowledge gaps identified in the literature review, a general approach is elaborated to design PVWP and WPWP systems for irrigation, with the consideration of IWR, solar irradiation and wind speed. The proposed approach correlates the PVWP and WPWP systems designed capacity and initial capital cost (ICC) as a function of solar irradiation and wind speed and represents a straightforward method to select the most cost-effective solution for irrigation. To compare the technical performances of PVWP and WPWP systems, dynamic simulations of IWR, pumped water and crop yield are conducted. Hails in Inner Mongolia is used as case study to verify the proposed design approach through dynamic simulations. The chosen site is located in the Mongolian Plateau, one of the world's largest grassland areas, and shows at the same time high irradiation and wind density: higher than 1620 kWh/m^2/year and higher than 200 W/m^2, respectively [19]. In particular, both the monthly average daily horizontal solar irradiation and wind speed in June, month marked out by the maximum IWR, are considerably high: 6.7 kWh/m^2 and 5.4 m/s (10 m above ground), respectively [20]. These characteristics make Hails a good candidate for comparing PVWP and WPWP systems for grassland irrigation.

This paper is organized as following: Section 2 provides a brief description of the PVWP and WPWP systems modelled in this paper; Section 3 deals with the methodology applied in this work to technically and economically compare PVWP and WPWP systems for irrigation. In particular, the design approach for PVWP and WPWP systems and the models adopted for simulating the