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Assessment of factors influencing the sustainable performance of photovoltaic water pumping systems

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ABSTRACT

In Yemen and in similar least developed countries (LDC), irrigation farming is a living principal in rural areas. Nowadays, Optimally Designed Photovoltaic Water Pumping Systems (PVWPS) are not only the most economic and environmentally adequate alternative to conventional sources but also the most economic feasible application of PV systems. However, the performance of PVWPS is a function of environmental conditions, manufacturing technology, design, and utilization. Evaluation of a sample of practically existing PVWPS in Yemen and similar LDC revealed that the performance of 60% of examined cases will decline at some time in the future. In addressing this, current study provides a comprehensive review and assessment of several factors that influence the performance of PVWPS such as: Solar Spectral Variation, Air Mass (AM), Angle of Incidence (AoI), PV cell temperature, soiling, shading, mismatch, degrading of PV modules, falling of bore-well depth, etc. This work aims to support the sustainable performance and a wide utilization of PVWPS. It will, also, benefits PVWPS researchers and practical designers, and contribute to the development of the socio-economic conditions of rural areas in LDC.

1. Introduction

The majority of the population in Yemen (75% [1]) as well as in many least developed countries (LDC) are rural residents who mostly rely on agriculture to survive. In Yemen, groundwater is a principal source for irrigation. In 2009, there were 70,000 of diesel Water Pumping Systems (DWPS) in Yemen. These were used to pump drinking and irrigation water, and had been consuming, nearly, 1.65 Gaga-Liter of diesel per annum [2]. However, recent fuel crisis has rendered most of them inoperable. Currently, PV Water Pumping Systems (PVWPS), in large [3] or in small scale [4], show economic and environmental superiority over water pumping systems that use other conventional types of energy. This is particularly clear for sites with high daily solar energy yield such as Yemen. Consequently, an increased number of PVWPS have been installed worldwide for instance, in Yemen [5,6], Ethiopia [7], KSA-Madinah [8], Algeria [9,10], Rwanda [11], etc. Though, analysis of a range of practically existing PVWPS cases (mostly in Yemen) suggests that many of these systems may suffer, in the future, from a considerable performance decline, due to a number of factors that may influence their sustainability because they have not been accounted for at the design stage or have been underestimated. Feasibly, performance sustainability is a multidimensional problem that related to the performance of: 1- PV subsystem 2- motor-pump subsystem 3-controlling systems (including Maximum Power Point Tracking (MPPT), variable speed control (VSC), inverters, and STS), 4- Optimal selection and matching between system's elements, and etc. This study focuses more on factors that affect the sustainable performance of PV subsystem, as the energizing unit of PVWPS. Factors that are frequently underestimated or forgotten by practical designers in the field of PVWPS include: 1-Degrading of PVMs output power that at first half span of modules life (12.5 years) could reach 12.5% of their initial peak power [9,12], 2-The effect of dust accumulation or soiling on the surface of PVM which varies from region to another, where in some cases it could cause more than 20% energy loss per day as in Malaga-Spain at long dry session. However, in southern Italy the loss could be as small as 0.04%/day, 3-Underestimating the effect of temperature by using ambient temperature Ta, or other values, instead of cell temperature T_C, 4-Neglecting the effect of shadowing and mismatching of PV modules, 5-The effect of incidence and tilting angles. 6-Overestimating the daily solar irradiation G_a, 7- Annual decline of well's depth (which, in the case of Yemen, ranges from 1 to 7 m per annum [2]), and so.

Economic feasibility of optimally designed PVWPS is acknowledged worldwide but disregard the influence of aforementioned factors will result in performance decline or failure of PVWPS and hence hinder wide spread of PVWPS in LDCs. This study is concerned more on the assessment of above-listed factors to assist practical designers, support a

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Nomenclature

Abbreviations

A	Area [m^2]
AM	Air Mass
AoI	Angle of Incidence
CAMS	Copernicus Atmospheric Monitoring Service
E	Energy [kWh]
G_i	Solar irradiation [kWh/m^2]
G	Global
g	gravity acceleration [m/s^2]
h	Hour(s) time
H	Borehole/Well Head [m]
I	Irradiance [(W/m^2) or kW/m^2].
I	Electric current [A]
n	Number of days
P	Power [W]
PID	Potential Induced Degradation
PR	Performance ratios
PV	Photovoltaic
PVC, PVM	PV cell, PV module
PVM	PV module
PVS	PV system and subsystem
PVGIS	PV Geographical Information System
Q	Water flow rate [m^3/s]
STC	Standard Test Conditions
STS	Solar tracking system
T	Temperature [°C or K]
ToA	Top of Atmosphere
V	Voltage [V].
V	Water volume per day [m^3/day]
VSS	Variation of Solar Spectrum.
1 × or 2 ×	One or two axes STS.

Greek symbols

α_p	Power temperature coefficient.
β	Solar tilt angle
ϒ	Azimuth angle
ζ	Angle of Incidence
η	Efficiency
θ_Z	Zenith angle.
ρ	Reflectance or Water desity
T or τ	Panel transmittance

Prefixes

a-; c-	Amorphous; crystalline
m-; p-	Mono; poly
Δ	Losses/Gain or increment

Subscripts

a	Ambient
act	Actual
av	average
C	Clear sky, cell or constant.
D, d	Direct; dust
EH	Horizontal surface at Extraterrestrial.
EN	Normal to sunrays at Extraterrestrial.
H (HC)	Horizontal (H at clear sky).
i, in	input
M	Module; motor or mismatch
MPP	Maximum power point
N (NC)	Normal to sun (NC at clear sky)
nom	Nominal value
o, out	output.
oc	open circuit.
op or opt	optimum
P	pump
PV	Photovoltaic
ref	Reference.
SC	Solar constant or short circuit.
sh	Shading; shadowing
XC	X axes STS at clear sky.

sustainable performance and wide utilization of PVWPS, particularly in Yemen and in similar LDCs, so as to enhance the social and economic conditions of rural residences. To achieve this, the study provides a comprehensive review of previous works, demonstrates and analyzes main factors that affect the performance of PVWPS, and evaluates a number of practically existing systems.

In addition to the introduction, the paper includes: a literature reviews and analyses of factors that may influence PVWPS performance, evaluation of practically existing systems, assessment of the performance of PVWPS, discussion, conclusion, and references.

2. Factors affecting the performance of PVWPS

The performance and sustainability of PV water pumping systems are affected by a variety of factors which will be reviewed and analyzed in following subsections:

2.1. Variation of solar spectrum

Different PV cells technology respond differently to the Variation of Solar Spectrum (VSS). Mambrini et al. [13] reported an annual difference in module short circuit current I_{sc} of 9.7% for amorphous silicon (a-Si) and a 6.6% for crystalline Silicon (c-Si) PV cells due to VSS. Similarly, D. B. Magare et al. [14] illustrated a 17%, 16.5% and 12.7% annual variation in Performance Ratios (PR) for polycrystalline p-Si, Heterojunction Intrinsic Thin-layer (HIT), and a-Si technologies respectively. While Ishii et al. [15] observed a minor influence of solar spectrum on the performance of c-Si modules whereas a-Si has been subjected to a variation of ± 20% due to the effect of VSS alone. Alonso-Abella et al. [16] studied the spectral responses of eight different PV cells of different technologies and found that a-Si and CdTe (cadmium telluride) cells to be the most affected modules by VSS, while monocrystalline m-Si and p-Si cells showed more stable performance. Similar results were reported by a number of researchers [17,18]. The minor influence of VSS on c-Si PVM comes in favor of PVWPS as commonly used PV devices in practical water pumping. In this paper, only PVWPS using c-Si PVMs are considered and therefore, the effect of VSS will not be examined further.

2.2. Effect of AM

The effect of scattering and absorbing of sunlight by earth atmosphere is known as the effect of Air Mass (AM). Previous researchers acknowledge the potential effect of AM on solar energy received by the earth. Mekhilef et al. [19] considered a unit increase in AM responsible for ΔI_S = 26.84%. Chen [20] confirmed a minimum of ΔG_S = 22% reduction under clear sky due to scattering and absorption. Similar, results were found in many PV literature [21,22]. Gouws and Lukhwareni [23], also believed that AM affects the performance and efficiency of PVWPS but no numerical measure was provided. E. Roumpakias et al.