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Techno-economic study of a solar photovoltaic and diesel powered irrigation systems

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ABSTRACT

The paper presents the feasibility of photovoltaic water pumping system (PVWPS) to determine its suitability for irrigation purpose in Saudi Arabia. The study analyses an irrigation system for 4,900 m^2 land having 100 orange trees. Six distinct geographical locations have been considered to explore the feasibility of the proposed system. The study has discussed two scenarios for water pumping. In the first and second scenarios, water demands of 12 and 36 m^3/d have been considered. The proposed PVWPS fulfilled the water demands in both scenarios based on number of selected photovoltaic (PV) panels. The life cycle cost (LCC) analysis showed that for all the scenarios and cases, the total cost of PVWPS for 30 years was almost half of the total cost of diesel generator water pumping (DGWP) system. In scenario 1 (case 1), the capital cost of the DGWP was 1,600 US$ while that of PVWPS 3,173 US$ but the operation and maintenance and LCC costs were 6,240 and 14,320 for diesel and 3,637.7 and 6,804.7 for PVWPS, respectively. Overall, the larger PV systems were found economically more attractive. The subsidy played an advantageous role in making the system further economically attractive. Proposed systems can be deployed in Saudi Arabia and the regions having similar soil and climatic conditions.

Keywords: Photovoltaic; Diesel generator; Water pumping; Irrigation; Crop farming

1. Introduction

Production of crops is a challenge in Middle Eastern counties as most of the land is unsuitable or unfertile for farming. Therefore, the food security of these countries depend mostly upon importing foods from neighboring countries such as Turkey, Lebanon, Syria, Algeria, etc. One of the major issues for the production of crops is the lack of regular supply of water in these countries. Although underground water can be a partial solution for the issue under consideration but the irrigation still remains a problem as these farming lands are mostly far from power grid. The diesel pumping systems are being used widely to pump the water in the region due to low cost and easily available fossil fuel. However, such systems release harmful gases in the atmosphere which adversely affect the local environment and also contribute negatively to the global weather system. Furthermore, the diesel power

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generating sets create lot of noise, require fulltime skilled manpower attention, continuous supply of fuel, and need backup system in case of breakdowns. All these factors tremendously add to the cost of energy generation.

The photovoltaic water pumping system (PVWPS) have been used in various applications such as in hydroelectric power plants [1], ranch activities [2], and small scale irrigation [3]. Purohit [4] presented a simple framework for financial evaluation of renewable energy technologies such as photovoltaic (PV) pump, wind power pump, biogas, and producer gas-driven dual fuel engine pumps for irrigation. The unit cost of water and useful energy was presented. Campana et al. [5,6] proposed an optimized PVWPS by considering ground water level, water supply, crop water demand, and crop yield as variables and showed that PVWPS improved the production of forage to meet the local demand in China. Ramos and Ramos [7] reported that a renewable energy-based water pumping system was more cost-effective compared with conventional power system. Bouzidi et al. [8] compared the economic aspect of PVWPS with diesel generator water pumping (DGWP) in Ghardaia (south of Algeria) and concluded that large-scale projects should be considered with subsidy to make the system profitable. In another study, Bouzidi [9] developed a new method to optimize the design of PVWPS using loss of power supply probability and found that the tank size plays an important role and can reduce the size of the PV array.

Benyoucef [10] conducted a feasibility study to pump and supply drinking water in remote villages in Algeria using PV panels and showed that the performance of the PV pumping systems depends on the total head and the peak power of the PV array. Vick and Neal [11] analyzed a wind–PV hybrid system and compared it with each system alone in off-grid application and found that the hybrid system can pump 28% more water than each system alone. Al-Smairan [12] compared the present value cost of PV and diesel generator-based water pumping systems in Badia, Jordan, and found that the PV system was more cost-effective. Reca et al. [13] designed and analyzed PVWPS for greenhouse crops and concluded that the profitability and energy efficiency of the system can be improved if the excess energy of the PV system can be used for other purposes such as ventilation and cooling of the greenhouse.

Gao et al. [14] evaluated the performance of PVWPS by comparing with diesel pumping system in Qinghai province in China, and showed promising results to improve the grassland of 3.15 ha using PVWPS. Benghanem et al. [15] obtained an optimum PV array configuration to supply maximum quantity of water in the outdoor condition of Madinah, Saudi Arabia. Dursun and Özden [16] developed a PVWPS to reduce power consumption in the pumps by using the water efficiently in low moist area needing irrigation. The area was determined using artificial neural network method and managed to reduce 38% of power consumption. Kaldellis et al. [17] carried out experiments and calculated quantity of water and round trip efficiency of PVWPS which was close to 5%.

Kelley et al. [18] argued that PV irrigation is technically and economically feasible provided enough land is available for the installation of PV arrays. A number of studies [19–26] have been reported in the literature related to the hybrid, PV, and diesel power systems for water pumping for irrigation and desalination in the region. Saudi Arabia is geographically suitable for PV applications because it is located in the Sun Belt. Average solar irradiation exceeds 1.8 kW/m^2 [27]. Moreover, Saudi Arabia has an area of more than 2 million km^2 where many remote villages and settlements can benefit from solar energy applications [28].

This study presents a generalized method to determine the technical and economic feasibility of using PVWPS for irrigation in Saudi Arabia. Technical feasibility is determined as a function of geographic location, crop type, climate, land quality, and groundwater depth [29]. The main objective of this research is to compare the performance of diesel generator pumping system (DGPS) with solar PVWPS in different cities of Saudi Arabia. The study also includes the economic feasibility of using the proposed system at selected sites instead of the diesel systems. Technical aspects are discussed for six cities and the economic feasibility is conducted for only one city because the costs of all the equipment and materials of DGPS and PVWPS are considered the same for all the cities under investigation.

2. System description

The major components of the proposed PVWPS are shown in Fig. 1. It consists of PV modules, control system, submersible pump, overhead tank, fittings, and piping. For the mobile PVPWS the PV modules are installed on a tractor so that it could be mobilized from one farm to another. The DGPS consists of the same components except the power source which is a diesel generator instead of PV panels. The submersible pump is assumed to be different for the two systems. In this study, ALEO PV modules have been chosen for mobile PV power station. Table 1 illustrates the electrical characteristics of the poly-Si-ALEO S_16 165. Lorentz submersible

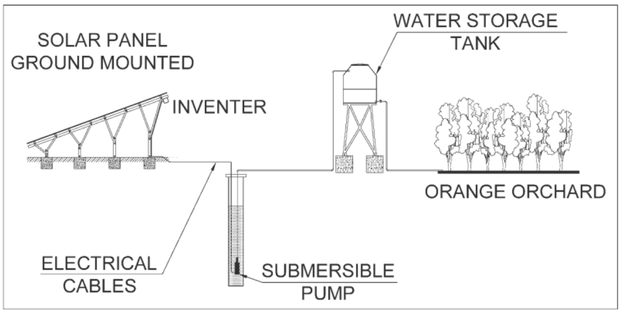

Fig. 1. Solar irrigation system.

Table 1
PV array power characteristics

PV array	
Description	ALEO S_16|165
Rated output (P_{MPP})	123 W
Rated voltage (U_{MPP})	21.5 V
Short-circuit current (I_{SC})	5.95 A
Open-circuit voltage (U_{OC})	27.4 V
Output tolerance	±3%

Table 2
Solar pump parameters

Pump system		
Pump system	PS200 HR	PS 600 HR/C
Maximum total dynamic head (m)	50.3	182.9
Maximum flow rate (m^3/h)	2.59	11.7

Table 3
Diesel generator specification

Diesel generator	
Model	JD186FAGE
Maximum AC output	5.0/5.5
DC output/V-A	12/8.3
Maximum power output (HP)	10
Operating noise level (dB)	70

Table 4
Diesel pump specification

Diesel pump system	
Pump system	BSI-3Kw
Maximum total dynamic head (m)	166
Maximum flow rate (m^3/h)	2.5

pumps (PS200HR, PS600HR/C) is selected to pump the water from the well to the irrigation system, described in Table 2. The diesel generator and pump specifications are provided in Tables 3 and 4, respectively.

3. System modeling

PV pumping has been widely used in remote areas due to its reliability, ease of operation and maintenance, and low costs. For proper and efficient design of a solar irrigation system, a number of parameters such as the amount of water required, the type of water source, the amount of solar irradiation at the site, the availability of technology and technical support have been considered. The mathematical relationship between the PV array power, solar irradiation, and the water flow rate is as follows [8]:

$$P = \frac{\rho \times g \times h \times Q \times \eta_r \times G_r}{G_T \times \eta_{pv} \times \eta_s} \quad (1)$$

where P is the PV array power (in watt-peak, Wp), η_r is the efficiency of the PV array at reference temperature ($T_r = 25°C$), G_r is the solar irradiation at reference temperature ($G_r = 1$ kW/m^2), G_T is the global irradiation on the tilted PV array plane (kWh/m^2/d), η_s is the subsystem efficiency (pump, the motor, and the inverter), Q is the daily amount of water required (m^3/d), h is the total pumping head (m), ρ is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), and η_{pv} is the efficiency of the PV array under operating conditions. The efficiency of PV array is calculated as follows [30]:

Table 5
Location of the cities in Saudi Arabia

Location	Latitude (°N)	Longitude (°E)
Al Baha	20	41.5
Al Taif	21.5	40.6
Tabuk	28.4	36.5
Al Ahasa	25.3	49.5
Madina	24.6	39.7
Al Kharj	24.2	47.5

$$\eta_{pv} = f_m\left[1 - \alpha\left(T_c - T_r\right)\right] \times \eta_r \quad (2)$$

where f_m is the matching factor (0.90), α is the temperature coefficient for cell efficiency, T_c is related to the mean monthly ambient temperature T_a as follows [31]:

$$T_c = T_a + \left(\frac{\text{NOCT} - 20}{0.8}\right) \times G_T \quad (3)$$

where NOCT is the nominal operating cell temperature and η_r, NOCT and α depend on the type of PV module considered. This study has focused on six different cities in Saudi Arabia where large farmable land and ground water sources are available. The locations of the cities are given in Table 5. Two scenarios, described below, have been investigated in this research work.

3.1. Scenario 1

A water pumping system with a mobile PV power station has been studied for 4,900 m^2 of an orange orchard in six different locations in Saudi Arabia. These regions consist of water aquifers with a depth of around 10 m. Orange trees need 100–120 L of water per day in summer season. Therefore, a total of 12 m^3/d is needed to be supplied for the proposed farm of orange trees. Pump flow rate of water is taken as 1.8 m^3/d. The total dynamic head is considered as 20 m to meet the irrigation requirement during May to October which is the suitable time for the crop of oranges. In this scenario, the orange trees are irrigated every day and a storage tank twice the capacity of the daily need of water is considered. Considering all the above technical and operational constrains, the required calculations have been made for six locations.

3.2. Scenario 2

A mobile PV system has been used for three farms of the same size as in scenario 1. One farmer gets the PV system for every 3 d. Individual farmers have to store water for every consecutive day to irrigate the land. In this scenario, initial cost is reduced for the farmer but the tank size is to be larger to hold water for 3 d. The PV pumping system must provide 36 m^3/d of water sufficient to irrigate three farms with an area of 4,900 m^2 each. Solar pump of PS600 HR/C is used in this case with higher flow rate. Flow rate and power consumed by the pumps are given in Table 2.

4. Results and discussion

The results of the above systems are discussed in details in the forthcoming sections. To further understand the economic sensitivity of the proposed system, the analysis is extended by considering the three cases (i) without an external funding, (ii) with an external funding of up to 25% of the capital cost, and (iii) with an external funding of up to 50% of the capital cost.

4.1. PVWPS system performance

The long-term monthly variation of solar radiation for the considered cities is illustrated in Fig. 2. Higher values of solar radiations were observed during summer time from April to September compared with other months at all the locations under investigation. Highest values of solar radiation are found at Tabuk and the lowest at Al Taif (Fig. 2). Maximum water production of 20.14 and 60.42 m^3/d was achieved in July at Tabuk and a minimum of 15.6 and 46.81 m^3/d at Al Taif corresponding to scenarios 1 and 2, respectively (Tables 6 and 7). The mounting angle of PV panels is used as 15° less than the latitude angle for all the locations to receive more solar insolation [32]. The water needs of the orange orchard and the amount of water to be pumped by PVWPS are illustrated in Figs. 3 and 4 for scenarios 1 and 2, respectively.

The water requirement and quantity to be pumped vary on the month and the location. On an average, the daily needs of water are around 12 m^3 in July as shown in Fig. 3. The proposed PV system can provide 15–21 m^3 of water daily depending upon the location in scenario 1. However, the water demand in scenario 2 is the same as in the previous case but the water availability varies from approximately 45 to 60 m^3/d in July (Fig. 4). In both the scenarios, the PV energy output is the highest in Tabuk and the lowest in Al Taif (Figs. 5 and 6). However, the highest values of energy are obtained in the months of June and July at all the locations, which coincide well with the higher water requirements for irrigation. The PV power requirement vary with month of the year with maximum values in January and December and minimum in June and July in both the scenarios, as observed from Figs. 7 and 8. Furthermore, relatively higher power requirements were found in Al Taif and lower in Tabuk and Madina between April and October. In this situation, to supply 12 m^3/d of water in scenario 1, a total of 0.14 kWp of installed PV capacity is required. On the other hand for scenario 2, a total of 0.42 kWp of installed capacity is required to meet daily water requirement of 36 m^3.

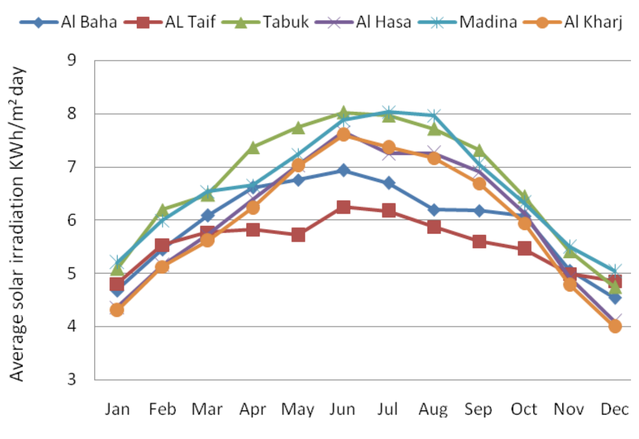

Fig. 2. Monthly solar irradiation for specified tilt angle of 15°.

4.2. Economic analysis

The LCC analysis method is widely used to estimate the cost-effectiveness of any project by comparing it with other similar methods and analyzing the effects over a specified duration of time. The profitability of the proposed PVWPS has been investigated using internal rate of return (IRR). IRR is defined as the discount rate at which net present value (NPV) of the cash flow of a project is zero. In case if the investment shows positive NPV, then the IRR will be higher than the market interest rate and this means the investment is profitable. The calculation of IRR gives the information about the income but the profit depends on the change in market within the specified period. Labor and fuel cost and market interest rates are the major parameters and play important role in the feasibility study calculations. Benefit to cost ratio (BCR) is another important parameter used in economic assessment of the projects. It is calculated by taking the ratio of benefit for chosen project to the total investment cost. The value of BCR is an indicator of whether the project is profitable or non-profitable. A value of BCR, less than 1.0 represents an uneconomic project, equal to 1.0 means that the expense are recovered, and greater than 1.0 indicates that the project is profitable. The reduction in greenhouse gases (GHG) emissions plays an important role in the economic analysis of the project by providing carbon credits.

The plant life is assumed as 30 years in the analysis. The three major components of the total investment include the costs of the PV array, motor-pump-control unit, and

Table 6
Performance of the PVWPS for six cities in Saudi Arabia for scenario 1

Performance of the system for various locations in the month of July						
Location	Al Baha	Al Taif	Tabuk	Al Ahasa	Madina	Al Kharj
Mean daily water requirement (m^3/d)	12	12	12	12	12	12
Mean daily water production (m^3/d)	16.92	15.60	20.14	18.33	20.30	18.61
Maximum flow rate (m^3/h)	1.97	1.81	2.34	2.13	2.36	2.16
Tilt angle of PV panel (°)	5.00	6.50	13.38	10.30	9.60	9.20
Mean daily solar radiation (kWh/m^2/d)	6.69	6.17	7.97	7.25	8.03	7.36
Nominal electrical power of PV panel (W)	133	144	112	123	111	121

Table 7
Performance of the PVWPS for six cities in Saudi Arabia for scenario 2

Performance of the system for various locations in the month of July						
Location	Al Baha	Al Taif	Tabuk	Al Ahasa	Madina	Al Kharj
Mean daily water requirement (m^3/d)	36	36	36	36	36	36
Mean daily water production (m^3/d)	50.76	46.81	60.41	3.52	60.89	55.84
Maximum flow rate (m^3/h)	5.90	5.44	7.02	0.41	7.08	6.49
Tilt angle of PV panel (°)	5.00	6.50	13.38	10.30	9.60	9.20
Mean daily solar radiation (kWh/m^2/d)	6.69	6.17	7.97	7.25	8.03	7.36
Nominal electrical power of PV panel (W)	399	433	336	369	333	363

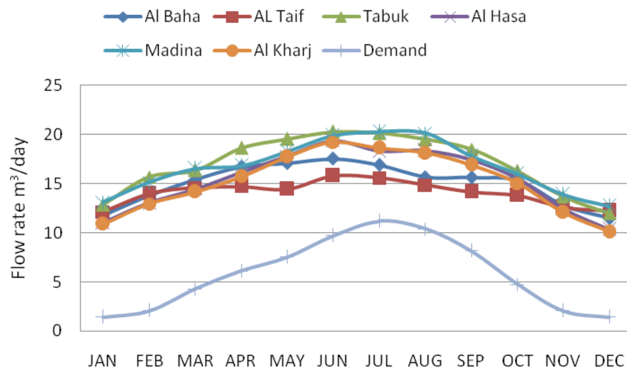

Fig. 3. Daily water demand and supply for scenario 1.

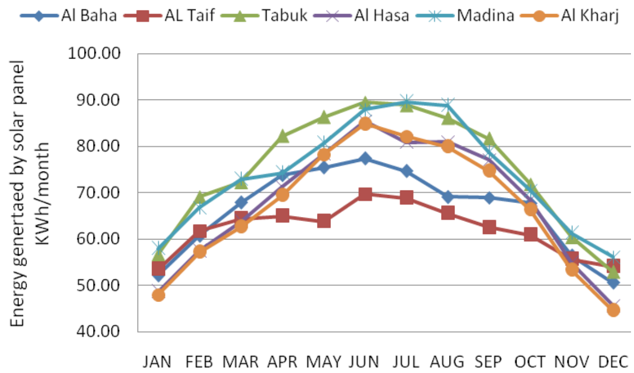

Fig. 6. Monthly energy generated for scenario 2.

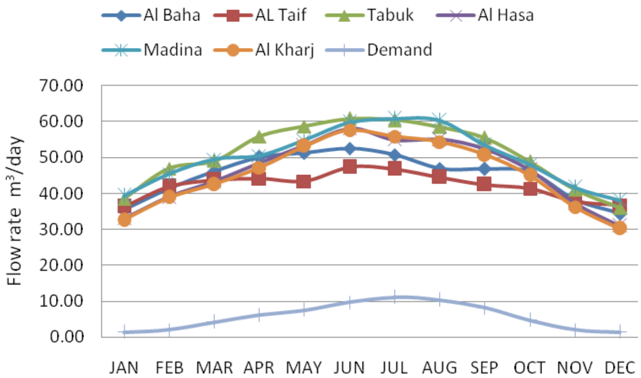

Fig. 4. Daily water demand and supply for scenario 2.

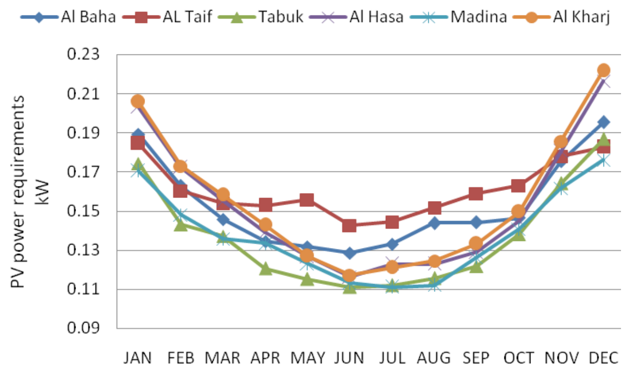

Fig. 7. PV power requirements for scenario 1.

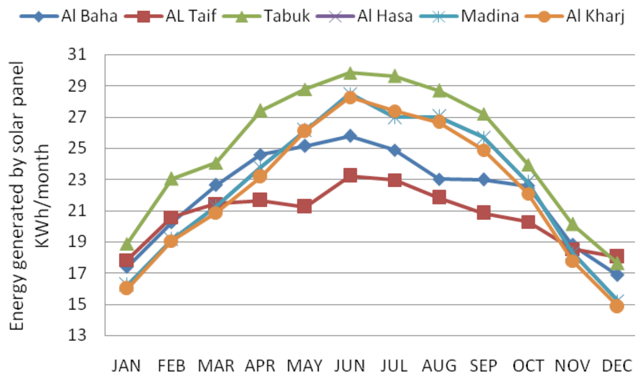

Fig. 5. Monthly energy generated for scenario 1.

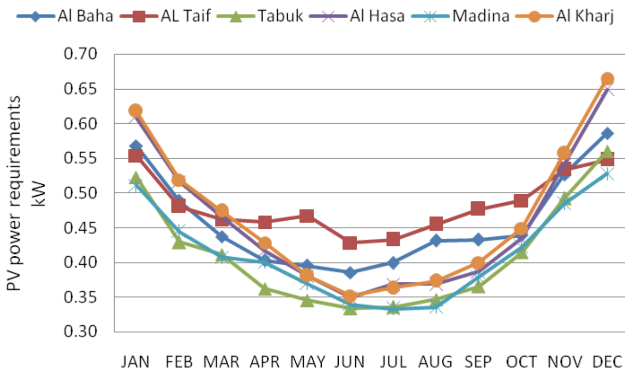

Fig. 8. PV power requirements for scenario 2.

installation. The system capacities and other relevant parameters are summarized in Table 8. The inverter and pump control units are assumed to have a periodic maintenance for every 15 years that costs 60% of its original costs. The greenhouse gas credit reduction fee is taken as 2% of the cost and the GHG credit rate is taken as 10 $/tCO_2$. The diesel generator replacement period is taken as 15 years by taking daily operational duration into account. The economic analysis of the proposed irrigation system is performed by considering the above assumptions and values for the following three cases:

- Without external funding;
- External funding up to 25% of capital cost; and
- External funding up to 50% of capital cost.

4.3. Case 1: without external funding

In this case, diesel and mobile PVWPS irrigation systems for both the scenarios are examined without any capital subsidy. The capital, total operational, and total PV and diesel generator life cycle costs (LCCs) are compared in Figs. 9 and 10 for both the scenarios. The capital cost of DGWP system for both scenarios in case 1 is less than the PVWPS but the corresponding operation and maintenance and LCCs of DGWP are much higher than the PVWPS. The total LCCs of DGWP systems are almost double and 2.5 times the respective LCC of PVWPS (Figs. 9 and 10). In the long run PVWPS proves to be more promising than the DGWP system. Cumulative cash flow (Fig. 11) shows that equity payback reaches at around 13 and 11 years for scenarios 1 and 2, respectively.

4.4. Case 2: external funding up to 25% of capital cost

In this case, the diesel and mobile PVWPS drip irrigation systems, for both the scenarios, are examined with 25% capital subsidy. PV module costs and water storage costs are supported by a subsidy program. This reduces the initial cost of the PV system and makes it more viable in the long run. The LCCs for the two scenarios and case 2 are analyzed in Figs. 12 and 13. In this case, again the capital costs of DGWP systems are lower compared with the PVWPS while the operation and maintenance costs and the LCC are much higher. The operation and maintenance costs of DGWP systems are almost double compared with the respective costs of PVWPS. Furthermore, the total LCC of the DGWP systems are around

Table 8
Plant technical specifications and costs

Description	Value	Comments
Plant life, year	30	
DGWP capacity, kW	3	Scenario 1
DGWP capacity, kW	10	Scenario 2
Head, M	20	
DGWP O&M cost, %	13	13% of the capital cost
Diesel cost/L, US$	0.12	Escalation 2%
PVWPS, kW	0.165	Scenario 1
PVWPS, kW	0.420	Scenario 2
PVWPS O&M cost, %	2	2% of the capital cost
PV panel efficiency, %	90	First 10 years
PV panel efficiency, %	80	Last 20 years

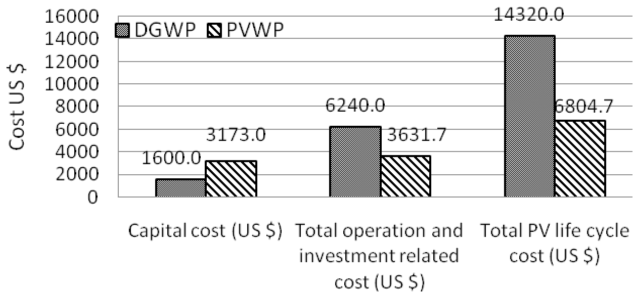

Fig. 9. LCC analysis scenario 1 case 1.

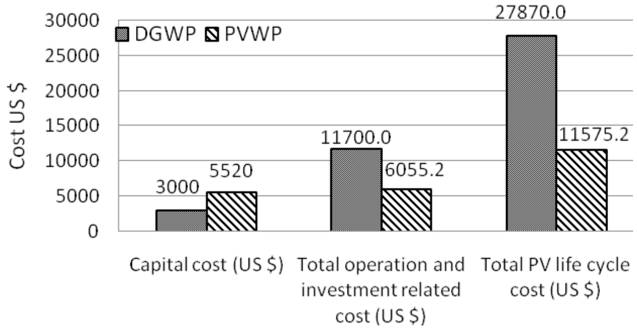

Fig. 10. LCC analysis scenario 2 case 1.

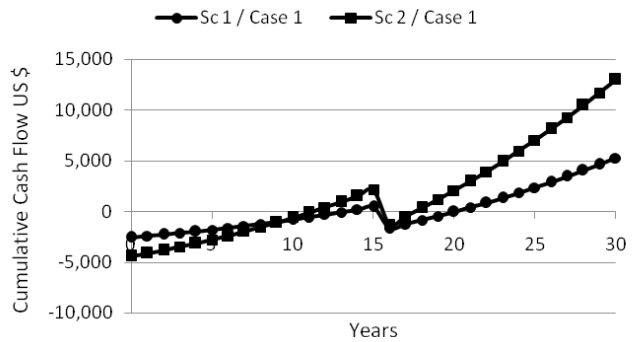

Fig. 11. Cumulative cash flow for case 1.

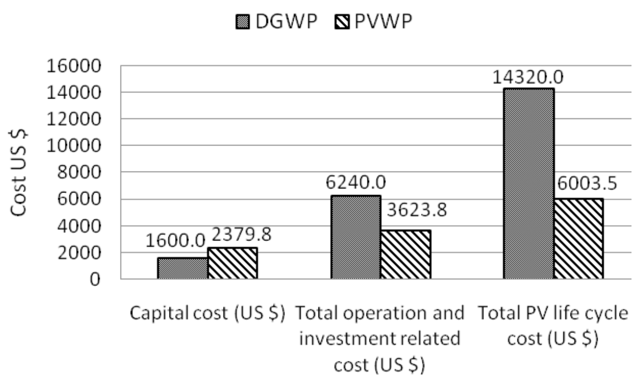

Fig. 12. LCC analysis scenario 1 case 2.

2.5 times those of PVWPS (Figs. 12 and 13) for scenarios 1 and 2, respectively. The cumulative cash flow (Fig. 14) shows that equity payback is estimated as 10 and 8.5 years for scenarios 1 and 2, respectively.

4.5. Case 3: external funding up to 50% of capital cost

In case 3, diesel and the mobile PV irrigation systems for both the scenarios are examined with 50% capital subsidy on PV module costs. It supports the water pumping equipment and solar equipment (solar modules, controller, etc.). It is evident from Figs. 15 and 16 that the capital costs of both the systems under both scenarios are almost identical. However, the operation and maintenance costs of the DGWP systems are almost two times that of the PVWPSs. The total LCC of diesel system is almost three times that of the PV system in scenario 1 and more than three times in scenario 2. The subsidy of 50% make the PV system further attractive compared with the diesel power system. The cumulative cash flow (Fig. 17) shows that the equity payback is around 7 and 5 years for scenarios 1 and 2, respectively. BCR shows that for all cases and scenarios (Fig. 18) the proposed PVWPS is an economical system in long-term. The IRR is around 2%, 3%, and 11% higher for scenario 2 compared with scenario 1 with zero, 25%, and 50% subsidy, as observed from Fig. 19.

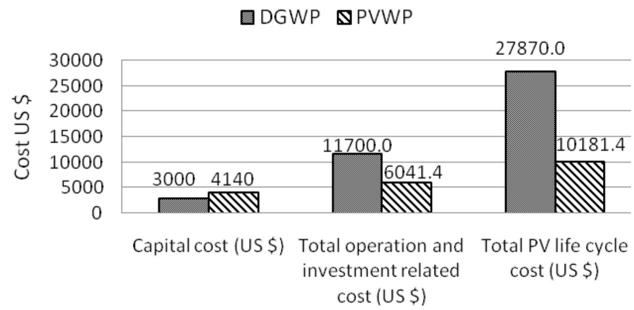

Fig. 13. LCC analysis scenario 2 case 2.

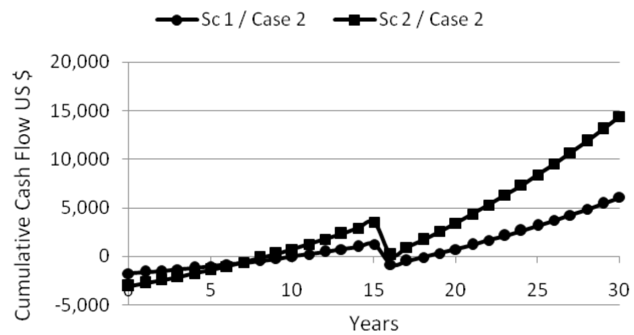

Fig. 14. Cumulative cash flow for case 2.

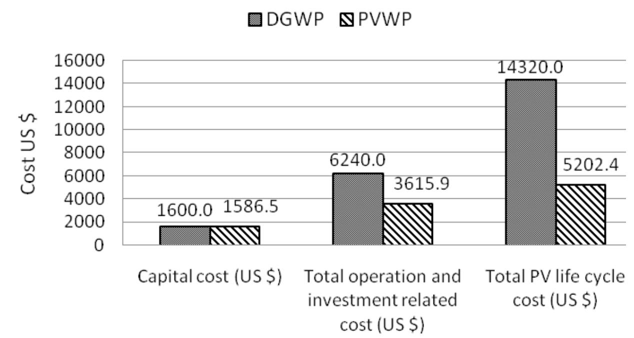

Fig. 15. LCC analysis scenario 1 case 3.

5. Conclusions

Most of Saudi Arabian land is not suitable for the production of crops due to sandy soil conditions. The extreme hot weather conditions further make agriculture farming a difficult and challenging task. As a result, the cities that have been selected for this study have underground water sources available, suitable soil conditions, and relatively mild weather conditions. This study concludes that the use of a

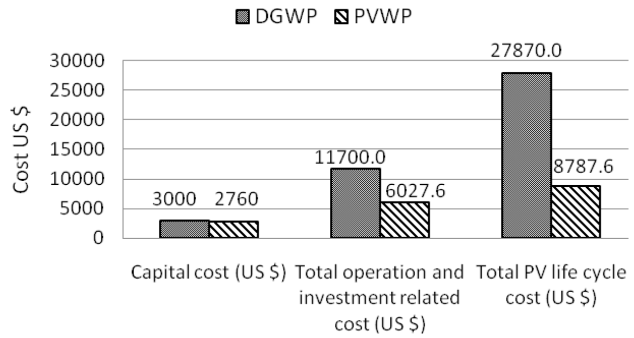

Fig. 16. LCC analysis scenario 2 case 3.

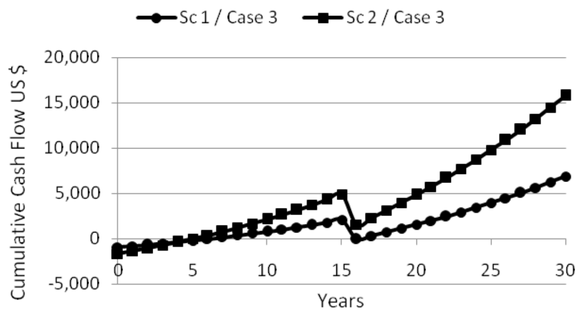

Fig. 17. Cumulative cash flow for case 3.

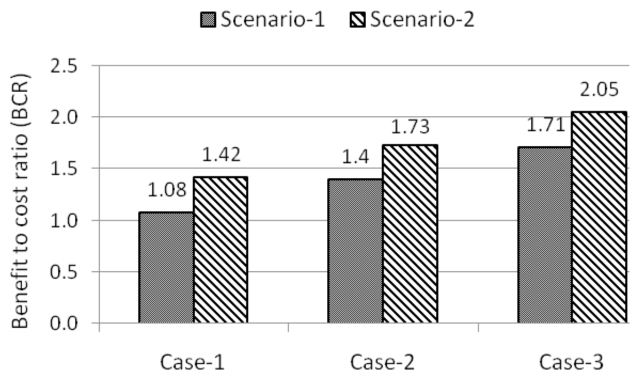

Fig. 18. Benefit to cost ratio.

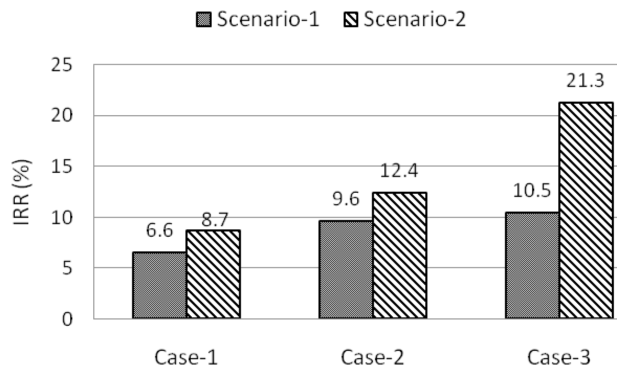

Fig. 19. Internal rate of return.

PV system is more cost-effective compared with the usage of existing diesel generators.

High solar insolation availability in Saudi Arabia is the major benefit of the PV array system to achieve the higher efficiency. Proper selection of the pump, PV array size, and the optimum tilt angle play an important role in optimizing the outcome of the PVWPS. It has been demonstrated in this study that the proposed PVWPS for both the scenarios are able to meet the water requirements of the orange orchard at all the locations. Hence, technically the proposed systems can be deployed comfortably in these sites and the sites having similar weather and soil conditions. On the economic front, the results showed that in long-term the overall cost (including the initial, maintenance, and miscellaneous costs) of the diesel system is comparatively much higher than the proposed PVWPS although having less initial capital investment. It has also been concluded that the provision of subsidy further makes the proposed PVWPS advantageous and economically attractive.

The comparison between the two scenarios showed that the larger systems have an economic edge over the smaller systems. The payback periods, IRR, and BCR demonstrated that scenario 2 is more attractive than the scenario 1 for all the three cases with zero, 25%, and 50% subsidies.

Symbols

A	—	Ampere
BCR	—	Benefit to cost ratio
DGWP	—	Diesel generator water pumping
g	—	Acceleration due to gravity
GHG	—	Greenhouse gases
h	—	Total pumping head
I_{SC}	—	Short-circuit current
LCC	—	Life cycle cost
kWh	—	Kilowatt hour
kW	—	Kilowatt
m	—	Meter
m^3/h	—	Flow rate
NOCT	—	Nominal operating cell temperature
PV	—	Photovoltaic
P_{MPP}	—	Rated output
PVWPS	—	Photovoltaic water pumping system
Q	—	Daily amount of water required
U_{MPP}	—	Rated voltage
U_{OC}	—	Open-circuit voltage
V	—	Volt
W	—	Watt
WT	—	Wind turbine

Greeks

ρ	—	Density of water
α	—	Temperature coefficient for cell efficiency

Subscripts

f_m	—	Matching factor
G_r	—	Solar radiation at reference temperature
G_T	—	Global irradiation on the tilted PV array plane
T_a	—	Mean monthly ambient temperature
T_c	—	Related to T_a
T_r	—	Reference temperature
η_r	—	Efficiency of the PV array
η_{pv}	—	Efficiency of the PV array under operating conditions
η_s	—	Subsystem efficiency

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