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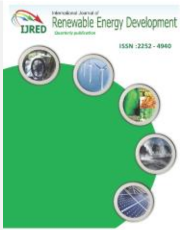

Production Economic feasibility of large scale PV water pumping applications utilizing real field data for a case study in Jordan

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ABSTRACT: Economic viability of photovoltaic, diesel and grid connected water pumping systems is investigated and compared for system capacities in the range 1500 m^4/day to 100,000 m4/day. Actual performance data from installed systems are considered in calculating systems outputs for base case scenarios. Sensitivity analysis is carried out to generalize results for other locations and conditions. Several scenarios of the effect of variation electricity tariffs, components prices, diesel fuel prices, operation cost and interest rate on the output water unit cost (US$/1000$m^4$) are investigated. Breakeven points of PV pumping systems are determined at certain input parameters.

Keywords: economic feasibility, equivalent hydraulic energy, interest rate, PV water pumping, water unit cost

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1. Introduction

Using PV pumps has several advantages over diesel systems. It avoids fluctuations in the availability and cost of diesel fuel, depletion of fossil fuel reserves, CO2 emissions and pollution. Diesel pumps require delivery of fuel oil, lubricants and spare parts to their often remote locations, and require trained operators and technicians. Experience has shown that once installed properly, PV pumps need only minimal attendance and often work unattended for long periods. For example, field experience of operating such systems in Jordan has demonstrated that energy generating components work for almost the entire life of the unit with little maintenance in comparison to diesel generators. Therefore, the operating costs of PV powered pumps are relatively low. However, the high initial capital cost of PV array remains the major barrier to their widespread use (Firatoglu and Yesilata 2004). The PV array cost constitutes around 70% of the total PV water pumping system capital cost. To date, the use of PV water pumps has been limited mainly to regions where subsidies have been available from either governments or aid agencies (Short and Oldach 2003). In remote applications, the greater reliability of PV pumping systems may offset its higher capital cost compared to diesel pumping system (Barlow *et al.* 1993). By using optical concentrators and developing more efficient pump/motor/controller subsystems, the cost can be reduced by a factor of between 2 and 3 (Whitfield *et al.* 1995).

Solar Photovoltaic programme in Jordan have been started in 1985 in cooperation with many international research and funding bodies. Several systems have been installed, tested and developed during the previous years. Jordan has participated in many international programmes to investigate, develop and promote PV electrification and water pumping applications. An example of these programmes is the International Program for Field Testing of PV- Water Pumps (PVP). This ambitious project has been sponsored by the German Agency for Technical Cooperation (GTZ, now a days called GIZ) and financed by German ministries (BMBF, BMZ) and implemented in seven different

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countries. Jordan was one of these countries who managed and participated in the installation, maintenance, monitoring, field test, evaluation and documentation of the project that included 8 PV- water pumping systems. Real data collected during this project have been used in this work to study the feasibility of the PV systems based on real output data.

As PV prices has been sharply decreased during the previous few years, it become more feasible to install larger PV applications. Most of previous studies has investigated small scale applications. It is believed that we are heading towards large scale applications in the next few years.

2. Literature Review

Internationally, it is estimated that more than a billion people in rural areas of developing countries enjoy no adequate access to clean drinking water (World Bank 1994). In a World Bank study, it was shown that PV pumping systems provided cheaper water than diesel pumping systems when the equivalent hydraulic energy was below 200 m^4day^{-1} at an insolation of 20 $MJm^{-2}day^{-1}$ (IT Power 1984). Equivalent hydraulic energy is defined as the product of head and volume of water delivered per day or year. For 200 m^4day-1 and PV costs of US\$ 18Wp^{-1}, US\$ 9W_p^{-1}, US\$ 6W_p^{-1}, and for an insolation of 20 MJm^{-2} day^{-1}, the cost of water was found to be 0.69, 0.43, and 0.4 US cents m^{-4} respectively (IT Power 1984). In a second World Bank study conducted nine years later it was found that PV pumping systems were competitive compared to diesel pumping systems for water requirements of up to 800 m^4day^{-1} at insolations above 10.08 MJm^{-2} day^{-1} (Barlow *et al.* 1993). Lasnier and Gang (1990) showed that the life cycle cost of PV pumping systems is less than that of diesel pumping systems for equivalent hydraulic energy range of up to 625 m^4day-1 and 13750 m^4day-1. The first case (625 m^4day^{-1}) applies for situations where low insolation of 14.4 MJm-2day-1, high interest rate of 20%, diesel generator lifetime of 9 years and diesel fuel cost of US\$ 0.25L^{-1} prevail. The latter (13750 m^4day^{-1}) is for an alternative case with (21.6 MJm-2day^{-1}, 5% interest, 3 years generator life time and US\$ 0.75L^{-1} diesel cost respectively). For seven countries (Argentina, Brazil, Indonesia, Jordan, the Philippines, Tunisia and Zimbabwe) it has been shown that PV pumping systems had a cost advantage over diesel pumping systems in the power range up to 4 kWp (Posorski and Haars, 1994; Posorski, 1996). In Jordan, a study that compared PV, diesel and wind pumps found that PV and wind water pumping systems are more feasible than diesel water pumping systems for sizes less than 10 kW (Hammad 1995). In another study of eight installations in Jordan, it was concluded that PV pumps were more viable than diesel pumps for equivalent hydraulic energy of up to 3800 m^4day-1 (equivalent to around 7.2 kWp) at an average insolation of 21.6 MJm^{-2} day-1 (Odeh *et al.* 1996). Brandt (2001) has stated that in remote areas and at equivalent hydraulic energy below 2000 m^4day-1 PV pumping systems are cheaper than diesel pumping systems. For irrigation, it was reported that PV pumping systems were becoming cost effective compared to diesel pumping systems where the equivalent hydraulic energy is less than 250 m^4day-1 at insolations above 14.4 MJm^{-2} day-1 (Barlow *et al.* 1993). Though PV powered systems are particularly useful in areas where it is not practical to extend an electricity grid, in locations where connection could be made to a grid, utilities have found it more viable to use PV pumps than to extend and maintain the electric grid (Kou *et al.* 1998).

In 2005, Odeh has concluded that for interest rate values of 0% (subsidized project), 10% (around average market rate in developing countries) and 20% (extreme market rate in some developing countries), PV water pumping systems have shown better economic viability than diesel water pumping systems for equivalent hydraulic energy capacities of up to 8000 m^4/day, 4100 m^4/day and 2600 m^4/day respectively. Considering pumping head of 50 m, for example, PV pumping systems hold a cost advantage for daily water volume capacity of 52 m3/day at interest rate of 20%, 82 m^3/day at interest rate of 10% and 160 m3/day at interest rate of 0%. The average equivalent hydraulic energy costs of the five systems considered increases from US\$ 3.1/1000 m^4 for PV and US\$ 6.13/1000 m4 for diesel at 0% interest rate to US\$ 7.12/1000 m^4 for PV and US\$ 6.65/1000 m^4 for diesel at 20% interest rate. This is equivalent to 130% increase on equivalent hydraulic energy unit cost of the PV pumping system and only 8.5% increase on the diesel case (Odeh *et al.* 2005).

3. Sources of Input Data

Data used for this work is of two main sources: system performance data and financial data. System performance data are considered based on actual performance data for 8 systems installed and tested over three continuous years. Financial data are collected based on market prices for the year 2012. Systems considered are of the AC type. It consists of a PV – generator, Inverter and Motor pump set. General specifications of these systems are shown in Table 1.

As an example of these systems, AL Hazeem station is located Near Azraq in Jordan (N 31.4, E 37.1) and it consists of 72 Siemens Solar mono-crystalline PV modules type M50S with a total peak power of 3.6 kWp, a 3.5 KVA-DC/AC inverter type Simovert-P-Solar, a 2.2 kW - 3 phase Franklin induction motor coupled to a centrifugal pump type KSB CORA 7/12 and 110 m^3 -

Table 1
General specifications of the eight PV pumping systems

System	PV		Inverter		Motor-pump set			Static head (m)	Location	
	Type	Peak power (W_P)	Type	Rated power (KVA)	Type	Motor power (kW)	No. of pumps		Latitude	Longitude
Ritem	M50S	4500	Simovert- P-Solar	3.5	KSB UPA 150-3-5	2.2	1	24	31.6 N	36.4 E
Hazeem	M50S	3600	Simovert- P-Solar	3.5	KSB CORA 7-56-12	2.2	1	20	31.4 N	37.1 E
Hasa	M50S	6300	Simovert- P-Solar	3.5	KSB CORA 4-89-22	2.2	2	80	30.8 N	35.7 E
Umruk	M50S	4500	Simovert- P-Solar	3.5	KSB CORA 7-56-12	2.2	1	50	30.6 N	35.3 E
Fidan	PQ10/40	4200	Solar- Verter 3	3.0	PLEUGER NE 44-12	2.2	1	40	30.4 N	35.3 E
Breekeh	PQ10/40	2800	Solar-Verter 3	3.0	KSB UPA 150-3-3	1.5	1	15	30.0 N	35.7 E
Jafr 1	PQ10/40	2800	Solar-Verter 3	3.0	PLEUGER NE 44-8	2.2	1	20	30.2 N	36.1E
Jafr 7	PQ10/40	4200	Solar-Verter 3	3.0	PLEUGER NE 44-12	1.5	1	30	30.2 N	36.1 E

Fig. 1 Sample picture of a typical PV powered water pumping station

Fig. 2 Sample picture of a typical PV powered water pumping station showing system components

-water storage tanks. The total area of the PV array (based on cell area) is 25.92 m^2. PV modules were arranged in 4 parallel sub-arrays each of which contains 18 modules in series. Figures 1 and 2 shows a sample system.

3.1 Data-Loggers and Measuring Devices

Three continuous years of testing and evaluation of all the systems have been carried out by utilizing high-tech Data Acquisition Systems connected to each pumping system. Data were collected using MODAS type 1220 data loggers shown in Fig. 3. All measuring devices have been supplied together with the data loggers in one set to avoid any mismatch between the data logger and the measuring devices. Eight data loggers were installed in the field (one for each pumping system) for a three-year period. Allocation channels are described in Table 2. Scanning rate for all measurements was two seconds.

Fig. 3 Data logger used

Table 2
Allocations of channels for the data loggers

	Channel	**Description**
Analogue channels with and without pre-insolation amplifier	1	DC voltage of the PV array
	2	DC current of the PV array
	5	Water level above pressure sensor
	6	Wind speed
	7	Global insolation on inclined plane measured by a Si-cell
	9	Global insolation on inclined plane measured by a pyranometer
	10	Calibration channel for insolation
	11	Global insolation on a horizontal plane measured by a pyranometer
	13	Ambient temperature
	14	PV cell temperature
Counter channels	17	Inverter / pump frequency
	18	Water output flow rate of pump
	19	Water consumption flow rate1
	20	Water consumption flow rate 2
Internal channel	21	Data logger accumulator voltage
Calculated channels	22	PV array DC power
	25	Dynamic water level
	27	Total delivery head
	29	Hydraulic power
	32	PV efficiency
	35	System efficiency
	38	Sum of water output since start of measurement
Spare	3, 4, 8, 12, 15, 16, 23, 24, 26, 28, 30, 31, 33, 34, 36, 37	Free

Insolation, ambient temperature, PV cell temperature, wind speed, PV voltage, PV current, water flow rate and dynamic water level of the well have been measured. The measuring devices used and their approximate errors are illustrated in Table 3. Measuring sensors specially the Pyranometers have been calibtrated on monthly basis using refrence standard Pyranometer.

Table 3
Measuring devices and their approximate errors

Parameter	**Device**	**Error**
Insolation	CM11 Pyranometer (Kipp&Zonen)	± 3%
PV Voltage	Voltage divider	± 0.5%
PV Current	Shunt resistance	± 0.5%
Flow rate	Counter with Reed-contact (SPX)	± 1% at > 0.1 m^3hr^{-1} ± 5% at < 0.1 m^3hr^{-1}
Water level in the well	Pressure sensor (GE Druck)	± 1%
Ambient temperature	Thermo resistance PT100	± 1 °C
PV cell temperature	Thermo resistance PT100	± 1 °C
Wind speed	Anemometer	± 2%

3.2 *Data Handling*

Measurements scanned every two seconds were averaged every ten minutes by the data logger and saved. Specialized software (MODAS12) installed on a laptop computer was used for: (i) calibration of the measuring devices, (ii) setting the storage interval from the wide range of options available: 2 seconds to 60 minutes, (iii) setting date and time of the data logger, (iv) programming the data logger, (v) resetting the data logger, (vi) display of instantaneous values of the measurements, (vii) transferring the data from the data logger to the laptop computer, (viii) time series graphical display of the physical measured data and (ix) production of ASCII-files.

A regular monthly monitoring program was implemented to transfer the data from the data logger to both a laptop computer and a CD, and to check the performance of the measuring devices. Reference devices were used for checking and calibration. In case of significant differences between the readings of the installed and reference devices, a new calibration factor would be obtained and entered to the data logger. These raw data were then transferred from the disk to an office computer using a specialized software called PVPEVAL that performed basic evaluation processes and converted the data from X-format (a data format used by the data-logger) to ASCII format to be used by other software for further analysis. ASCII data were then exported to MS-Excel spreadsheets for data analyses.

4. Methodology

Three different options of power supply is considered; PV solar, Diesel generator and electric grid. The idea for that is to compare the feasibility of these options and the breakeven points under different operation scenarios and different values for the input parameters. Input data for base case scenarios are taken from real system operation data and updated market prices.

One of the main parameter is the In-plane Insolation. This parameter has a significant effect on system sizing and performance of PV systems. The amount of insolation available for a PV array depends on the geographical location and the orientation of the PV array. Based on 10-minute average measurements over a three-year period, hourly, daily, monthly and yearly averages of insolation were processed for seven locations in Jordan.

Yearly Equivalent hydraulic energy is used in this work as the parameter that indicates system output. It is defined as the multiplication of the yearly accumulated water output in cubic meter by the total system pumping head as follows:

$$E = V \text{ X } H \qquad \textbf{(1)}$$

Where:
V: is the volume flow rate in m^3
H: is the total pumping head in m

Estimated system output (yearly equivalent hydraulic energy) used in the tables below are concluded based on the real output data from real installed systems in the field. Ratio of maximum field efficiency to standard modules efficiency (manufacturer's data at standard test conditions) was found to be 0.8 to 0.86. In this work, 0.8 was considered in calculating system output for proposed systems in this work. Other parameters are included in Table 4. In this work, four system sizes are considered and their correspondent data are depicted in Tables 4, 5, 6 and 7. These tables show technical and financial data for the three alternatives, PVP, Diesel and the electric grid respectively.

Table 4
Input parameters for the base case scenario of the economic analysis of the systems.

Designed Tilted irradiance (kWh/m^2/day)	6
Real interest rate	0.07
Motor-pump efficiency at fixed power input (Diesel)	0.55
Salvage values	0
Lifetime of the project (Years)	**20**
Distance from the public grid (m)	0
Cost of extending power lines ($/m)	30
Transformer cost	0
Electricity cost ($/kWhr)	0.12
Fuel Cost ($/L)	0.7
Maximum Motor-pump efficiency at variable power input PV-daily	0.55
Operator for diesel system $/year	5000
PV price $/W$_p$	0.9
Inverter price $/W$_p$	0.3
PV installation cost $/W$_p$	0.1
PV maintenance $/W$_p$/year	0.05
PV watchman $/W$_p$/year	0.05
Maintenance Diesel $/VA/year	0.02

5. Result and Discussion

Tables 5, 6 and 7 show that Diesel has the highest operating cost with a relatively low investment cost while PVP has negligible operating cost but with a high initial investment. Using the electric grid needs no initial investment and has a medium running cost.

Table 5
Financial data for PVP-systems

Specification, items	Unit	Sys4	Sys5	Sys6	Sys7	Lifetime
-Output equivalent hydraulic energy	m^4/year in million	3.2	5.04	17.68	35.36	
-Installed PV power	kWp	10	15	50	100	
-Specific module price	US$/Wp	0.9	0.9	0.9	0.9	20
-Specific price for structures	US$/Wp	0.2	0.2	0.2	0.2	20
-Total PV generator/structure	1000$	11	16.5	55	110	
-Inverter cost	1000$	3	4.5	15	30	7
-Cost of installation	1000$	1	1.5	5	10	20
Basement for PV modules	1000$	0.9	1.35	4.5	9	0
1.Total initial investment costs	**1000$**	**15.9**	**23.8**	**79.5**	**159**	
Watchman	$/year	500	750	2500	5000	
-Maintenance (yearly)	$/year	500	750	2500	5000	
2. Total operating costs	**1000$/year**	**1**	**1.5**	**5**	**10**	

Table 6
Financial data for the Diesel-systems

Specification/item	Unit	Sys4	Sys5	sys6	sys7	Life time
-Output equivalent hydraulic energy	m^4/year in million	3.2	5.04	17.68	35.36	
-Nominal power of diesel generator	KVA	12.0	18.0	60.0	120.0	
-Efficiency of diesel engine	%	34	35	37	40	
-Efficiency of generator	%	85	85	85	85	

-Efficiency of the pump-motor set	%	52	55	58	58	
-Overall efficiency	%	15	16	18	20	
-Specific hydraulic equiv. per lit. fuel	m^4/L	553	600	668	722	
-Specific fuel consumption	L/1000 m^4	1.8	1.7	1.5	1.4	
-Flow rate	m^3/hr	14.3	19.6	68.8	137.6	
-Total pumping head	M	95	110	110	110	
-Hydraulic energy discharge	m^4/h	1362	2157	7569	15138	
-Diesel consumption	L/h	2.5	3.6	11.3	21.0	
-Yearly diesel consumption	L/year	5759	8392	26461	48953	
-Diesel generator set price	$	2400	3600	12000	24000	7
1. Total investment costs	$	**2400**	**3600**	**12000**	**24000**	
-Fuel price + transportation cost	$/Wp	0.7	0.7	0.7	0.7	
-Fuel + transportation cost	$/year	4031	5874	18523	34267	
- Lubricant	$/year	90	100	120	150	
-Operators	$/year	600	900	3000	6000	
-Maintenance	$/year	240	360	1200	2400	
2. Total operating costs	$/year	**4961**	**7234**	**22843**	**42817**	

Table 7
Financial data for the Diesel-systems

Specification/item	Unit	Sys4	Sys 5	Sys6	Sys7
-Output equivalent hydraulic energy	m^4/year in million	3.2	5.04	17.68	35.36
Electric grid extension cost	$	0	0	0	0
1. Total investment costs	**$**	0	0	0	0
Yearly electricity bill	$	2396	3794	12483	23497
-Operators	$/Year	500	750	2500	5000
-Maintenance	$/Year	0	0	0	0
2. Total operating costs	**$/Year**	**2897**	**4545**	**14983**	**28497**

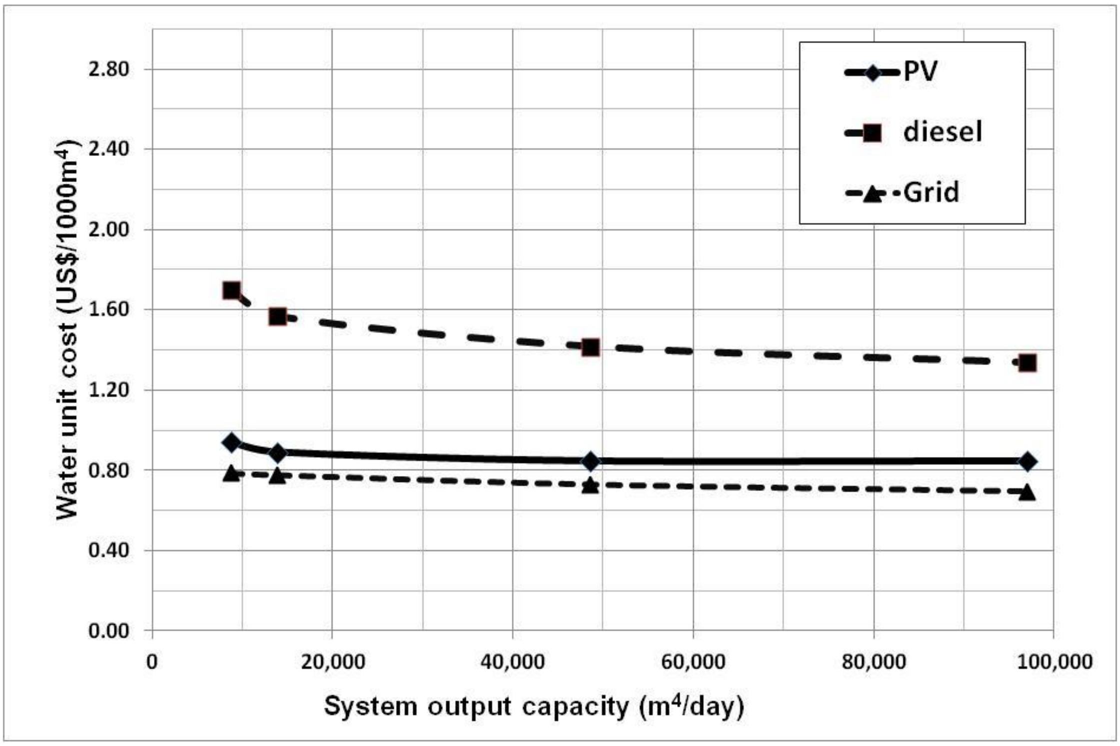

Fig. 4 Water unit cost vs. System output capacity at an electricity tariff of $0.1/kWhr.

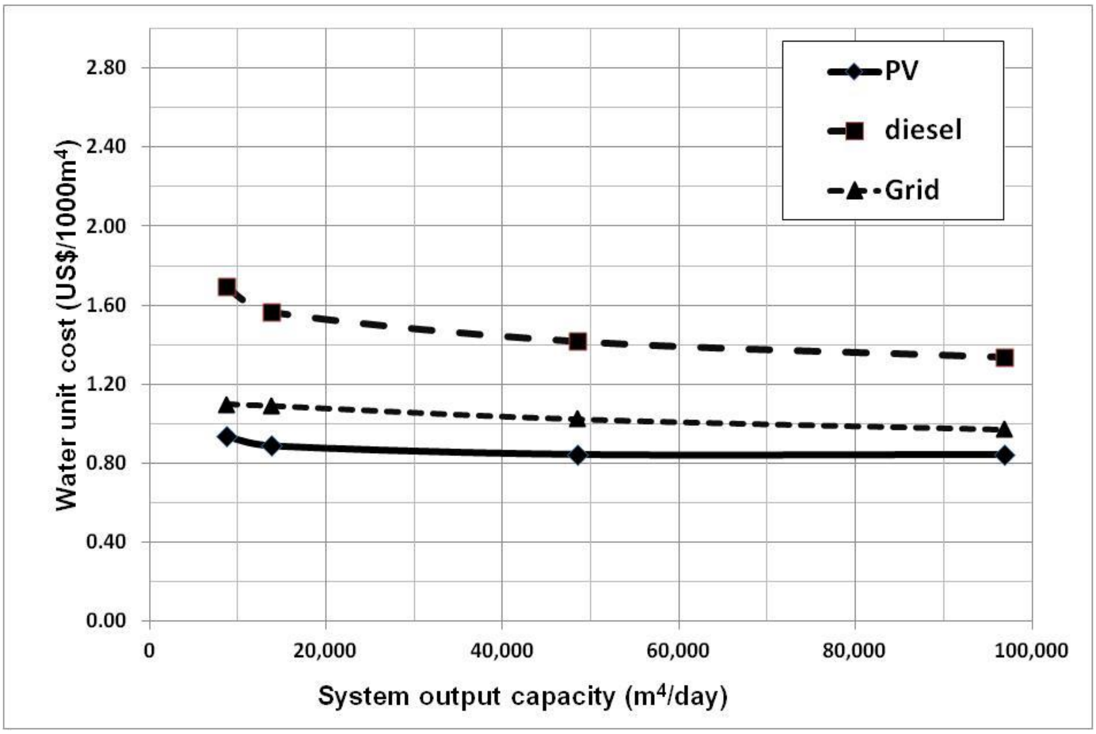

Fig. 5 Water unit cost vs System output capacity at an electricity tariff of $0.15/kWhr

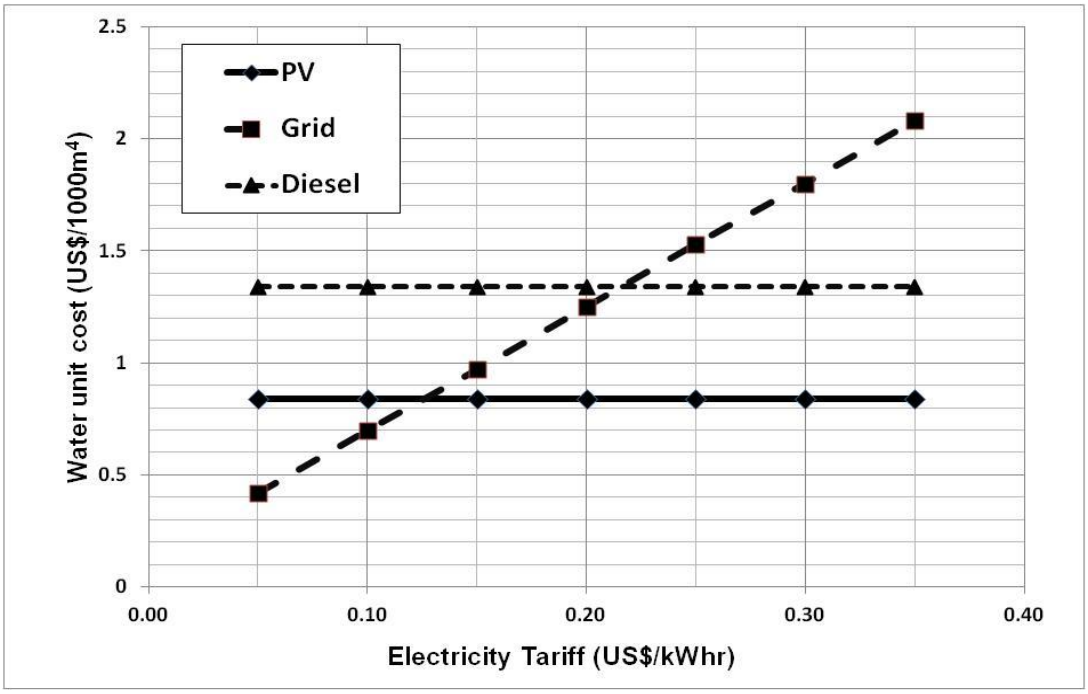

Fig. 6 Variation of water unit cost with electricity tariff considering: Interest rate = 0.07, Fuel price = $ 0.7/L, Irradiation= 6 kWhr/m^2.d

Fig. 4 and 5 show that for PV and diesel powered system, the water unit cost sharply decreases with increasing system sizes for small scale systems where it almost keep constant at large sizes above 15 kWp (13000 m^4/day). For electric Grid system the water unit cost is not highly affected with system size. Increasing electricity tariff from US$ 0.1/kWhr to US$ 0.15/kWhr has changed the economic feasibility of the systems dramatically.

Electricity tariff is an important parameters that determine the feasibility of a system and it highly affect the decision of technology selection for a new project. Fig. 6 clearly shows that PV systems are more economical than diesel systems for any electricity tariff. PV represents an attractive option when electricity tariff exceeds $0.12/kWhr which is considered as the breakeven point after which PV is the best economical choice. Diesel becomes more feasible than the Grid system at electricity tariff higher than $0.22 but not in any case compete PV systems.

To clarify the effect of interest rate on the system feasibility, water unit cost has been calculated for the three systems options at different interest rate values and depicted in Fig. 7. In this figure, the base case data has been used considering electricity tariff of $0.12/kWhr. From this figure it can be concluded that interest rate is an important parameter that affect the system feasibility. At interest rate below 6%, PV is the most economical choice. Increasing interest rate above 6% brings electric grid to competition considering electricity tariff of $0.12. This is due to the high initial cost of the PV system and considering electric grid system with no initial investment but with annual operation cost that is not affected by interest rate.

Solar radiation is a key parameter for PV system performance. Increasing irradiation increases PV output and thus increases water output volume for the installed system. In this study and for the base case, water unit cost has been calculated at different values of irradiation and depicted in Figure 8. This figure shows that at places that enjoys in-plane irradiation levels above 6.2 kWh/m^2.day, PV enjoys better economic feasibility than electric grid. At locations with Irradiation levels between 3.9 and 6.2 kWhr/m^2.day, PV is still more economical than Diesel but cannot compete the electricity grid at tariff of $ 0.12/kWhr.

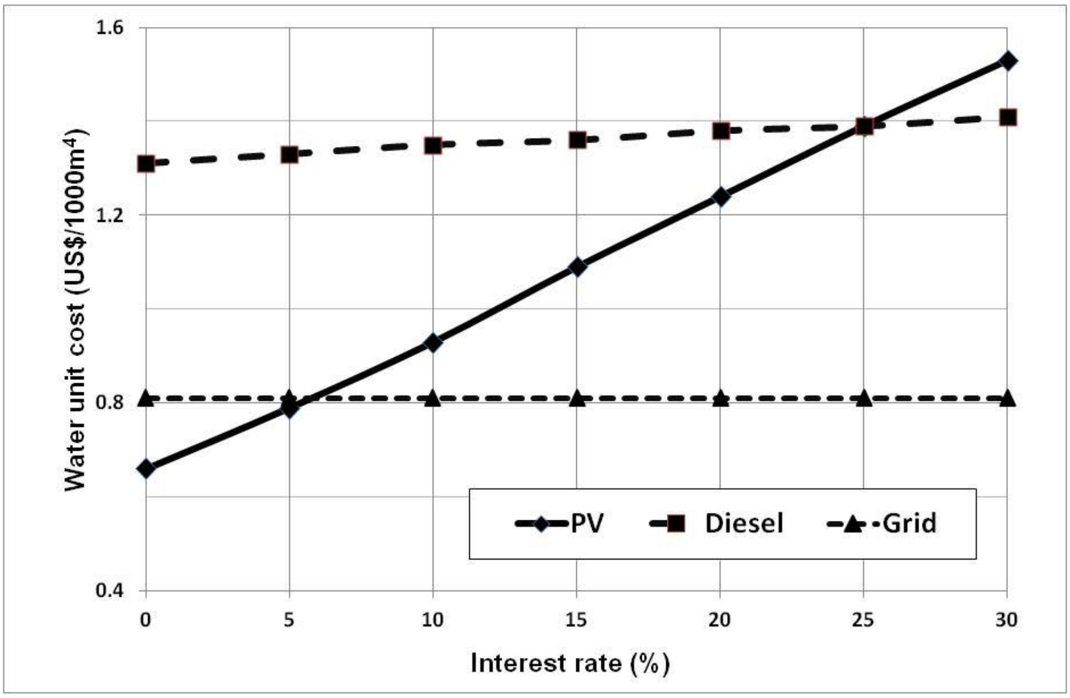

Fig. 7 Variation of water unit cost with interest rate considering Fuel price = $ 0.7/L, Electricity price = $ 0.12/kWhr, Irradiation= 6kWhr/m2.d

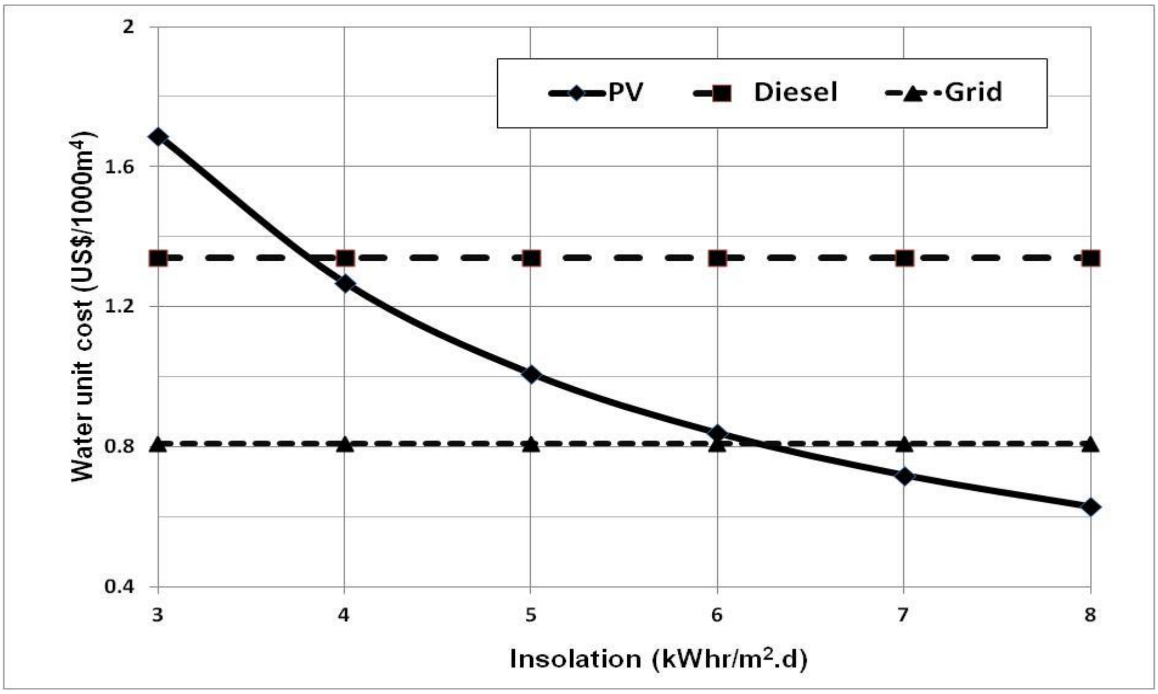

Fig. 8 Variation of water unit cost with insolation considering Fuel price = $ 0.7/L, Interst rate = 0.07, Electricity tariff = $0.12/kWhr

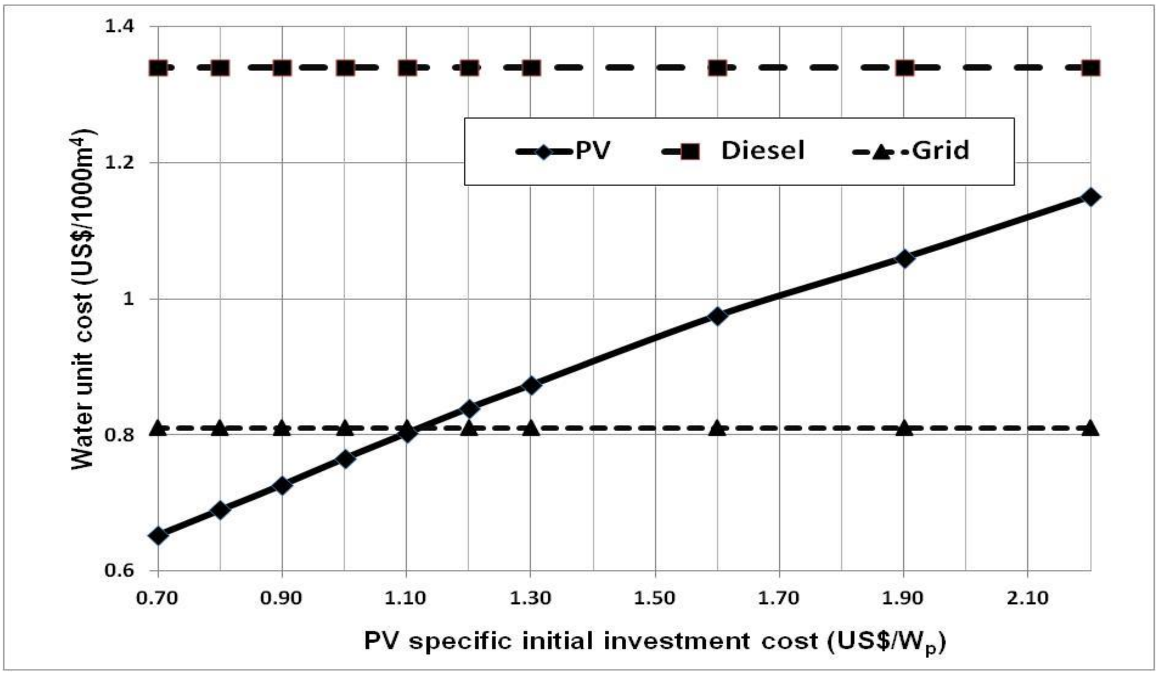

Fig. 9 Variation of water unit cost with PV initial investment cost considering: Fuel price = $ 0.7/L, Interst rate = 0.07, Electricity tariff = $0.12/kWhr, Insolation = 6 kWhr/m^2.d

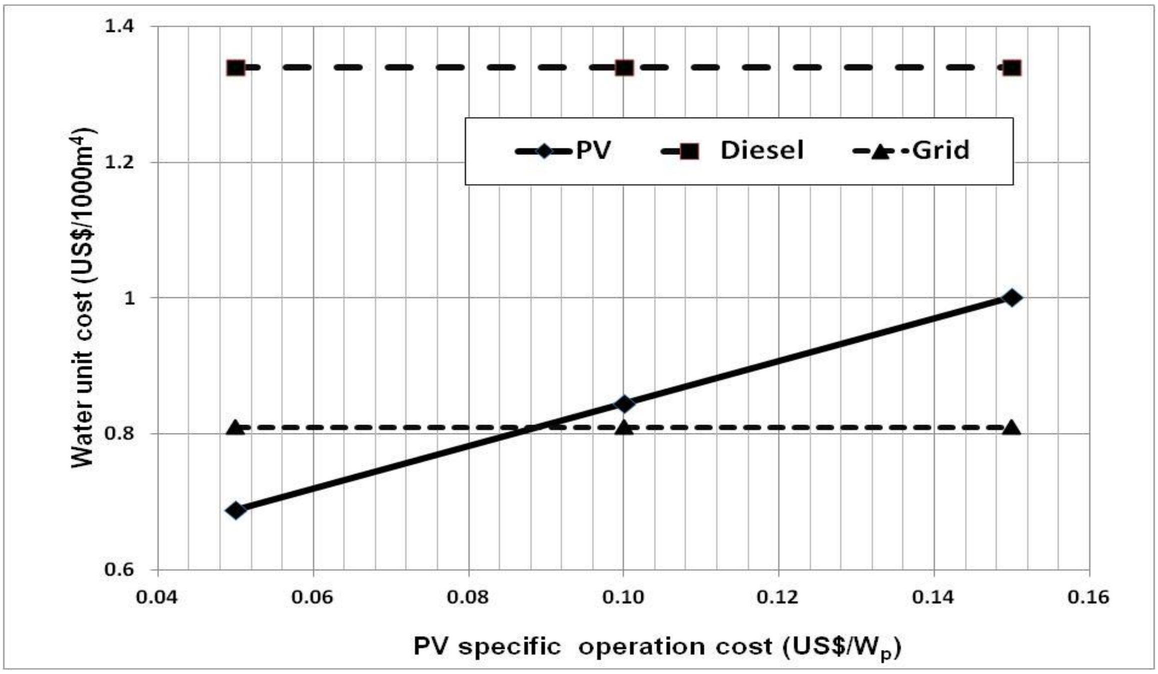

Fig. 10 Variation of water unit cost with PV PV specific operation cost considering: Fuel price = $ 0.7/L, Interst rate = 0.07, Electricity tariff = $0.12/kWhr, Insolation = 6 kWhr/m^2.d

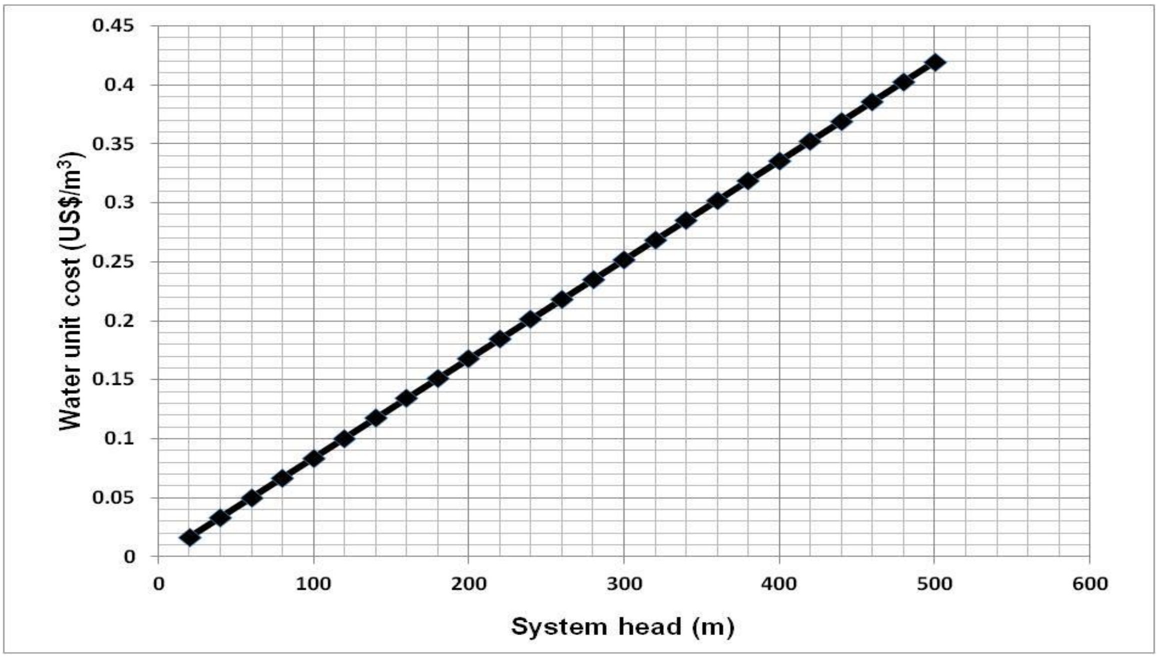

Fig. 11 Variation of water unit cost with system head considering: Interest rate = 0.07, Fuel price = $ 0.7/L, Electricity price = $ 0.12/kWhr, Irradiation= 6 kWhr/m^2.d, Cost = US$ 0.84 /1000m^4

Initial investment and operation cost effects on water unit cost has been studied and results are depicted in Fig. 9 and 10 respectively. For the base case scenario, PV is more economical than the electric grid at PV specific initial cost lower than US$ 1.13/Wp and at PV specific operation cost lower than US$ 0.088/Wp. To represent water unit cost in more readable and understood value, water unit cost in $/m3 has been calculated and depicted in figure 11 as a function of total pumping head. It is clear from this figure that cubic meter cost increase linearly with increasing pumping head.

6. Conclusion

The feasibility of using PV for pumping and electrification depends on a multitude of variables including; interest rate, average solar radiation, electricity and unit fuel prices. The more expensive electricity and fuel become, the more feasible it is to use PV to cover the electricity needs. PV water pumping systems are more economical than Diesel water pumping systems in Jordan under all situations considering fuel prices as US$ 0.7/L. This fact keeps valid until yearly average solar irradiation goes down below 3.8 kWhr/m2.day. Increasing irradiation levels by 10% over the case study value (6 kWh/m2.day) decreases water unit cost by 15%, while decreasing irradiation by same percentage increases water unit cost by 25%. The breakeven point for PV pumping with the grid connected systems happens when the electricity price is $0.12/kWhr, at an average daily solar irradiation of 6 kWhr/m2 and an interest rate of 7%. The equivalent output hydraulic energy unit cost is US$0.82/1000m4 and it can go down to US$ 0.65/1000m4 at zero interest rate. Decreasing PV prices by 20% can decrease output water unit cost by 12% and decreasing operation cost by same percentage will decrease output water unit cost by 8%.

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