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Techno-economic Feasibility of Energy Supply of Water Pumping in Palestine by Photovoltaic-systems, Diesel Generators and Electric Grid

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ABSTRACT

The agriculture sector nowadays in Palestine relies mostly on conventional energy sources and traditional irrigation ways. Considering some factors such as high costs of fossil fuels and providing new electrical network, especially to remote areas and where grid electricity is either inaccessible or expensive to expand, therefore a solar photovoltaic (PV) powered irrigation system can be a practical choice for irrigating. In this paper, a PV-powered direct-current water pump system design for irrigation is presented, techno-economic feasibility of using solar PV systems for water pumping to replace a diesel engines and electric pumps also is presented. The PVSyst simulation software was used for convenience and monetary issues. Solar PV water pumping is found to be more economically in comparison to diesel or electricity water pumping in rural, urban and remote regions in Palestine. The investment payback for some PV water pumping systems instead of diesel is found to be around 1 year and around 7 years for replacement of electrical conventional pumps.

Keywords: Solar Water Pumping, Solar Photovoltaic, Techno-economic Analysis, Remote Areas
JEL Classification: Q42

1. INTRODUCTION

In rural areas in Palestine, many farmers are still using diesel generators for water pumping which are very expensive as well as unreliable due to the high cost of purchased fuel and insufficient maintenance and repair capabilities. The solar-powered pumping system can be used anywhere but it is appropriate for rural areas which is facing energy crisis. Due to geographical position, Palestine has good potential of solar radiation throughout the year which makes it ideal location for utilization of solar energy (Ibrik and Hashaika, 2019; Imad, 2019). Solar radiations in Palestine has an annual average of 5.4 kWh/m^2 day that fluctuates significantly during the day and all over the year, and approximately 3000 sunshine hours throughout the year.

A solar-powered pump is a normal pump with an electric motor. Electricity for the motor is generated on-site through a solar panel which converts solar energy to direct-current (DC) electricity, a solar-powered pump requires a DC motor if it is to operate without additional electrical components. If a pump has an alternating-current (AC) motor, an inverter would be required to convert the DC electricity produced by the solar panels to AC electricity. Due to the increased complexity and cost, and the reduced efficiency of an AC system, most solar-powered pumps have DC motors (Tamoli, 2017). Solar-powered pumps will naturally work best on sunny days, which is fortunate because farmers will need more water on hot, sunny days.

Photovoltaic (PV) water pumping system is one of the best alternative and feasible methods for irrigation in Palestine comparing with other systems as shown in Table 1. The use of this photo-irrigation system will be able to contribute to the socio-economic development especially in rural areas. It is the proposed solution for the present energy crisis for the Palestinian

Table 1: Comparison between diesel, PV and electricity

System type	Advantages	Disadvantages
PV powered system	Low maintenance Unattended operation Reliable long life expectancy (20+years) No fuel and no fumes Easy to install Low recurrent costs System is modular and closely matched to need	Relatively high initial cost Low output in cloudy weather
Diesel powered system	Moderate capital costs Easy to install Can be portable Extensive experience available	Needs maintenance and replacement Site visits required Noise, fume, dirt problems Fuel is expensive and supply intermittent
Electricity transmission lines	Transmit large amounts of electric power over long distances	High technical Voltage drop Expensive Maintenance required

PV: Photovoltaic

farmers. This system conserves electricity by reducing the usage of grid power and conserves water by reducing water losses.

In this paper, a performance analysis and feasibility of simple but efficient PV water pumping system is presented based on Palestinian environment.

2. LITERATE REVIEW

Solar PV technology for water pumping has been explored over 5 centuries ago. The conversion of solar energy into mechanical or electrical energy for water pumping is used since the 15th century, although the first reported PVWPS was installed in the Soviet Union only in 1964. The maximum power of the PV system installed at that time, to activate the water pump, was 373 W was developed in France (Pytlinsk, 1978). Initially, solar pumping systems with direct coupling with the water pumps were introduced; however, they presented limitations in the performance of the system, by not operating at the maximum power point of the PV generator. Despite this disadvantage, this type of system is considered to be simple, reliable (Kou et al., 1998), and also efficient for use in small scale irrigations (Kapadia, 2004). In the last decade, these systems have been improving their performance due to the addition of the maximum power point tracker (MPPT) and control systems (Katan et al., 1996).

The first generation of PVWPS was characterized by the use of centrifugal pumps driven by DC motors and variable frequency AC motors, whose hydraulic efficiency ranges from 25% to 35%. The second generation of PVWPS considered positive displacement pumps, characterized by low PV power (100 Wp-400 Wp) input, low capital cost and hydraulic efficiencies up to 70% (Protogeropoulos and Pearce, 2000). Currently, the PVWPS of the first and second generation are equipped with electronic control systems, pump speed and maximum power trackers, to increase the overall system performance (Chandel et al., 2015), who's hydraulic efficiencies reach values of 92% (Lorentz, 2017).

(Kolhe et al., 2004) analyzed the performance analysis of the directly PV-powered dc PM motor coupled with a centrifugal pump at different solar intensities and corresponding cell temperatures. It has been observed that the system operates most of the daytime because of its higher starting torque even at low solar intensities. The PV motor-pump system's electromagnetic torque–speed curve at low solar intensities should be steeper than at higher solar intensities. The load should have a torque–speed curve that increases as rapidly as possible in the operating region, which provides a good match between the characteristics of the PV array and the electromechanical system. Also, the load should have low starting torque. The manual tracking (i.e. changing the orientation of the PV array, 3 times a day to keep the arrays facing the sun) gives 20% more output compared to the fixed tilted PV array.

(Mokeddem et al., 2011) investigated the performance of a directly coupled DC powered PV water pumping system. The system operates without battery and electronic controls. The motor-pump efficiency did not exceed 30%, which is typical for a directly-coupled PV pumping system; yet such a system is suitable for low head irrigation in remote areas. The efficiency of the system can be increased by selecting the size of PV array, its orientation and motor-pump system.

(Eyad and Al-Soud, 2004) studied the potential of solar water pumping in Jordan and selected 10 sites based on the availability of solar radiation data under three categories: adequate, promising and poor and suggested other water pumping alternatives for these sites. (Sahin and Rehman, 2012) discussed components, basic operation and performance of water pumping and desalination in the remote areas of Saudi Arabia. The study reported that utilization of PV energy for water pumping and desalination is reliable and cost effective.

(Abdolzadeh and Ameri, 2008) Investigated the possibility of improving the performance of a PV water pumping system, by spraying water over the PV modules. The results show that spraying of water can achieve 12.5% mean PV efficiency. The mean flow rate at 16 m head on the test day was about 479 L/h in case of a system without water spray over PV modules whereas it reached 644 L/h for the system sprayed with water. Spraying of water on the PV modules leads to cooling of modules therefore improves the system and subsystem efficiencies.

3. SYSTEM MODEL

DC water pumps in general use one-third to one-half the energy of conventional AC pumps (Chandel et al., 2015). When a better output performance is required during low levels of radiation, the AC motor exceeds its performance capabilities compared to the DC motor. The solar water pumping systems in its simplest way, have the solar panels connected directly to the small DC motor that drives the water pump. These systems use centrifugal pumps, because of their ability to be matched to the output of the solar panels; the choice of a DC motor is attractive because PV arrays supply DC power. Solar water pumps are designed to use the DC provided by a PV array, solar DC water pumping systems, consists of solar PV modules, motor pump, water is pumped during day and stored in storage tanks, for use during day time, night or under cloudy conditions, as shown in Figure 1.

There are two types of DC pumps namely surface pumps and submersible pumps. All Surface pumps are centrifugal, while submersible pumps can be both centrifugal and helical rotor pumps. Table 2 shows comparison between the two types of DC pumps.

Batteries are usually not recommended for solar-powered livestock watering systems because they reduce the overall efficiency of the system and add to the maintenance and cost. Instead of storing electricity in batteries, it is generally simpler and more economical to install 3-10 days' worth of water storage to overcome the farmers water needs in nights and cloudy days, it is advantageous to store enough water using a higher sited reservoir during the sunshine time. Where there is not solar radiation, it will be distributed under gravity force in the time.

Figure 1: Schematic diagram of the photovoltaic water pumping system

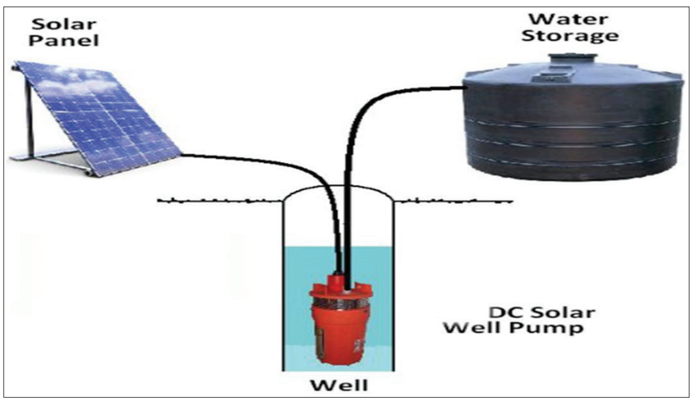


Table 2: Comparison between centrifugal and helical rotor pumps

Features	Centrifugal	Helical rotor
Suitable DC voltages	12 V-375 V	12 V-375 V
Maximum total dynamic head	170 m	350 m
Maximum flow rate	60 m^3/h	4 m^3/h
Maximum submersion	250 m	Unlimited

DC: Direct current

4. WATER PUMPING IN RURAL AREAS IN PALESTINE

Diesel generators used in most areas of the West Bank for the purpose of water pumping, especially in remote areas and villages, these engines require regular maintenance and high running cost in addition to that contribute to polluting the environment either through the gases resulting from the burning process or as a result of the oil leakage to water sources.

Main characteristics of the studied cases and their diesel generators were summarized in Table 3. These data were collected by distributing a questionnaire on a group of wells owners in North West bank areas (Salah, 2012).

As a case study we analyzed techno-economic analysis of replacing diesel pump to solar pump for deep well 2, in Jenin area in West Bank, with the following specification:

- Total dynamic head = 20 m
- Daily water consumption required: 60 m^3/day
- Diesel consumption = 36 L/day, needed diesel (L)/month = 1080 (L/month).

5. SOLAR PV SYSTEM DESIGN

Solar water pumping DC configuration as illustrated in Figure 2.

The design of PV system depends mainly on the values of average irradiation levels, in Palestine the average daily radiation is illustrated in Figure 3 (Energy Research Center, 2018).

Design elements of water pumping system by using the solar energy are as:

- The hydraulic energy (HE)

The HE can be calculated using Eq. (1).

$$HE\ (kWh/day) = 0.002725 \times Q \times TDH \quad (1)$$

Where: Q is water pumping rate (m^3/day) and TDH is total dynamic head (m).

For well No. 2 in Jenin city where average yearly water pumping rate was about 5 m^3/h, 12 operating hours and head of 20 m, the

Table 3: Data for some wells that operating by diesel generators in the WB

Well number city	Well 1 Jenin	Well 2 Jenin	Well 3 Qabatia	Well 4 Qalqilia	Well 5 Tulkarem	Well 6 Tulkarem
Depth (m)	180	70	200	60	180	50
Static water level (SWL) (m)	90	20	50	20	30	18
Dynamic water level (DWL) (m)	150	60	80	56	80	32
Water pumping (m≥/h)	7	5	12	3	15	12
Average number of pumping hours per day (hour)	24	12	24	12	24	24
Type of generator	Perkins	Perkins	Perkins	Lester	Perkins	Lester
Generator capacity (KVA)	16	7.5	16	10	16	15
Average daily consumption of diesel (L/h)	4	3	4	3	4.5	2.5
Generator cost $	2638.5	1847	3430	1583	3166.23	1055.4
Maintenance cost $/year	924	528	1055	528	660	1055.4

(HE) = 3.27 KWh/day, the annual HE is 1193 KWh/year, and the annual water pumping rate is 21900 m^3/year.

- PV generator selection

PV generator selection is based on the plans of PV sizing systems submitted by the performance of manufacturers, and different from an area to other.

The peak power of the PV generator (Ppv) is obtained as in Eq. (2).

$$Ppv = HE/(\eta s \times PSH) \quad (2)$$

Where PSH is the peak sun hours, ηs is the efficiency of the system components. For selected well No.2 the average PSH is 5.4 (Juaidi et al., 2016), ηs is 0.15, the calculated Ppv using Eq. (2) is 4 kW.

To install this power a PV module type Kyocera KD135SX – 135 Watt, with the specifications in Table 4 is selected.

The number of PV module required (Npv) is obtained as in Eq. (3).

$$Npv = Ppv/Ppv\ module \quad (3)$$

For Ppv is 4 KW and Ppv module is 0.135 KW then number of modules required can be calculated by Eq. (3) is 30 modules to get the required energy. The modules can be connected to give the desired Vdc which is 48 V, so the number of series modules required as in Eq. (4).

$$\text{Number of modules in series} = Vdc/Vmax \quad (4)$$

Vdc = 48 V, Vmax = 17.6 V, then the number of modules in series calculated by Eq. (4) is 3 modules.

Group of three modules connected in series to produce operating system voltage 48 V DC. Therefore, ten groups connected in parallel to produce 48 V DC system.

- Pump selection

Pump selection depends on the daily water pumping rate and the hydraulic head, (Q, H). For well No.2 where (Q = 5 m^3/h, H = 20 m), vertical multistage pump will be used, the resulting power of the pump (Pp) is: 2.82 KW. The motor power (Pm) can be calculated as in Eq. (5).

$$Pm = Pp/\acute{\eta} \quad (5)$$

ή is the pump efficiency and equal 0.85, then Pm is 3.32 KW.

The pump current (Ip) can be calculated as in Eq. (6).

$$Ip = (Pp \times 1000)/(\sqrt{3} \times V) \quad (6)$$

For a 3Ø system, V= 400 volt, then the pump current (Ip) will be 3.17 A. The motor current (Im) can be calculated by Eq. (7)

$$Im = (Pm \times 1000)/\acute{\eta} \times (\sqrt{3} \times V) \quad (7)$$

Im = 3.74 A

The selection elements for above wells are summarized in the Table 5.

6. SIMULATION OF PV WATER PUMPING SYSTEM

To be sure that the system performance and components are accurate, PV array and DC motor is modeled in PVsyst software (PVsyst Software) for performance verifications. PVsyst internal database and meteo data were utilized. The derived mathematical model was used to simulate the actual system. Using the various data and interchanging the values, the system was tested for real life feasibility, and the simulation result are shown in Table 6.

Figure 4 represents the monthly performance ratio for the system. The performance ratio relates the actual yield of the PV system (Yf) to the target yield (Yr) (Imad, 2019) and it is 0.614 for the simulated system.

Figure 2: Direct current direct configuration with storage tank

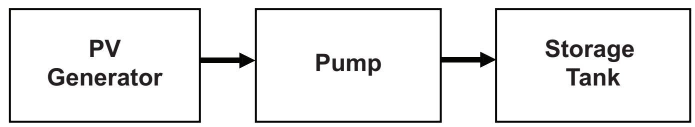


Figure 3: Monthly average solar radiation in North West Bank

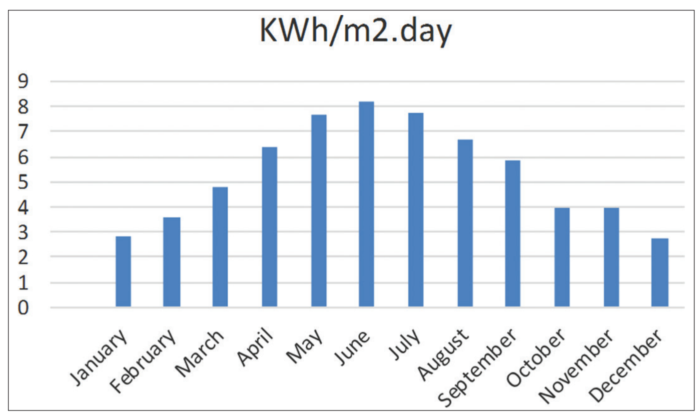


Table 4: Specification of Kyocera KD135SX module at standard conditions

Maximum power	135 W
Maximum power voltage	17.7 V
Maximum power current	7.63 A
Open circuit voltage (Voc)	22.1 V
Short circuit current (Isc)	8.02 A
Area	1.003 m²

Table 5: Selection elements of DC direct configuration with storage tank

Specification	Case study well
Module no.	30
Modules in parallel	10
Pump selected (kW)	3.32
Tank selected m³	5
Tank no.	3

DC: Direct current

Figure 4: Photovoltaic system monthly performance ratio (%)

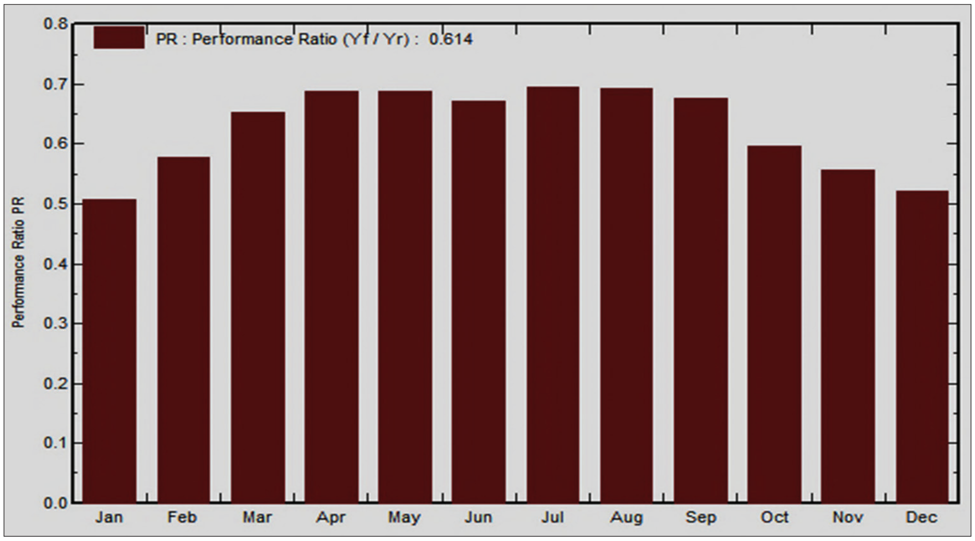


Table 6: Simulation results

Year	Incid. kWh/m² day	PV avail. kWh/day	PV needs kWh/day	PV excess kWh/day	Pumped W. m³/day	Missing W. m³/day	Missing %	Fuel L
January	4.5	17.1	22	0	46.7	14	23.4	106.3
February	4.6	17.5	22	0	47.8	11	18.4	75.4
March	5.7	21.5	22	0	58.7	2.8	4.6	20.9
April	6.3	23.9	22	0	65.1	0	0	0
May	6.8	25.7	22	2.5	63.2	0	0	0
June	7.4	27.8	22	5.8	60	0	0	0
July	7.4	28.1	22	6.1	60	0	0	0
August	7.4	27.8	22	5.8	60	0	0	0
September	7.5	28.4	22	6.4	60	0	0	0
October	7	26.5	22	4.5	60	0	0	0
November	5.8	21.7	22	1.4	55.5	0	0	0
December	4.5	17	22	0	46.5	8.6	14.3	64.9
Year	6.3	23.6	22	2.7	57	3	5	267.5

PV: Photovoltaic

7. ECONOMIC ANALYSIS

Life cycle cost (LCC) analysis is commonly used to evaluate the PV solar systems and help in the decision making of selecting the optimal configuration. Energy cost, simple payback period (SPBP) method also can be used to evaluate the feasibility of using solar PV water pumping systems instead of diesel or expanding of electrical network. The LCC includes the costs of the system during its life time period; it includes capital cost, the maintenance cost and the cost of the system components replacement.

7.1. Energy Cost

The fixed cost of selected PV water pumping configuration for well No. 2 in WB are summarized in Table 7.

The annual maintenance cost calculated is 6.4 $/year. Salvage value calculated is 960 $, the LCC of PV system illustrated in Figure 5.

The LCC of PV system = 6400 + 9.4(P/A i, n) –960 (P/F i, n) + 1600(P/F i, n) = 6811.83 $, and the equivalent annual worth is 741.38 $.

Table 7: The fixed cost for PV system with storage tank

Components	Quantity	Unit price ($)	Total price ($)	Life time (years)
PV module Kyocera	30	150	4500	20
Tank	3	300	900	10
Installations		1000	1000	20
Total			6400	

PV: Photovoltaic

The cost of 1 kWh from the PV generator is 0.086 $/kWh, while the cost of electricity for pumping of 1 m³ of water is 0.0356 $/m³.

7.2. The Energy Cost Comparison between Different Energy Sources

Economic results for comparison between different energy sources could be summarized as in the Table 8.

From Table 8, we note that the electricity cost of pumping water by diesel is more than water pumping using electricity or PV system knowing that the running cost for diesel is without fixed cost value, so if we take fixed cost then the LCC will rise more and more.

Table 8: Comparison of producing (1 KWh, 1 m³) between different energy sources

Configuration	Life cycle cost	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6
PV system with DC pump and storage tank	$/KWh	0.085	0.086	0.089	0.091	0.089	0.092
	$/m³	0.035	0.0356	0.0436	0.0383	0.03835	0.0391
Pumping by diesel	$/KWh	0.455056	0.457065	0.458723	0.461032	0.461816	0.462538
	$/m³	0.390894	0.395563	0.382229	0.392941	0.379485	0.382424
Pumping by electricity	$/KWh	0.18	0.18	0.18	0.18	0.18	0.18
	$/m³	0.074	0.0745	0.0882	0.0757	0.0774	0.0765

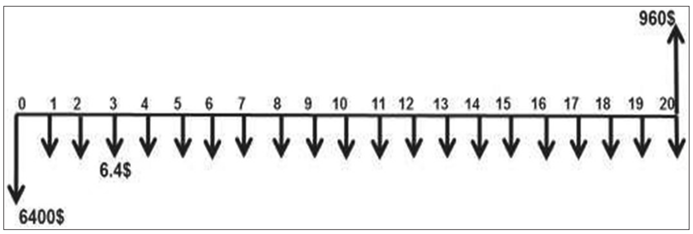
PV: Photovoltaic, DC: Direct current

Table 9: PV system yearly SPBP

Item	Diesel	Electricity
Saving ($)	7882.45	852.55
SPBP (year)	0.8	7.5

SPBP: Simple payback period, PV: Photovoltaic

Figure 5: Cash flow of photovoltaic system direct current direct configuration with storage tank for well no. 2



7.3. SPBP

SPBP is another technique can be used to analysis the project feasibility and it can be defined as the length of time required to recover the capital cost or the (LCC) of an investment. If the SPBP was lower than the project lifetime this mean the project is feasible otherwise is not. The SPBP can be estimated using Eq. (8).

$$S.P.B.P = Investment/Saving\ cost\ per\ year \quad (8)$$

Investment for well 2 = 6400 $

Saving/year = 7882.45 $, 852.55 $ for replacing diesel and electricity pumps respectively.

Using Eq. (8), the SPBP can be calculated and the results shown in Table 9.

This SPBP for using solar PV instead of diesel which as average equals to 1 year, means that all project cost will be recovered by the 1st year of the lifetime and the other years it will profit which mean also the project is feasible.

Also, replacement of diesel generator with PV have a significant environmental impact especially on air quality due to combustion process. For electricity the amount of CO_2 emitted per kilowatt-hour (kWh) depends on the method of generation; nuclear energy has no CO_2 emission or insignificant amount, while energy generated from coal produce a lot of CO_2 compared to gas.

8. CONCLUSION

This study presented a design of a standalone PV-powered irrigation system. For water pumping in rural villages in Palestine, usually using conventional electricity or diesel generated electricity. Solar water pumping minimizes the dependence on diesel, and electricity. The use of diesel based water pumping systems require not only expensive fuels, but also create noise and air pollution. The overall cost, including running cost, and replacement cost of a diesel pump are higher than a solar PV pump. Solar pumping systems are environment friendly and solving a problem with shortage of grid electricity in Palestine and mainly in rural and remote areas, solar PV pumping is one of the most promising applications. PV water pumping technology is reliable and economically viable alternative to electric and diesel water pumps for irrigation of agriculture crops. PV water pumping for rural areas is potential very feasible but is not still widely utilized in Palestine.

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