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Research Article

Economical Feasibility of Utilizing Photovoltaics for Water Pumping in Saudi Arabia

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Energy and water are the two major need of the globe which need to be addressed for the sustenance of the human beings on this planet. All the nations, no matter most populous, developed and developing need to diversify the means and ways of producing energy and at the same time guarding the environment. This study aims at techno economical feasibility of producing energy using PV solar panels and utilizing it to pump-water at Dhahran, Riyadh, Jeddah, Guriat, and Nejran regions in Saudi Arabia. The solar radiation data from these stations was used to generate electricity using PV panels of 9.99 kW total capacity. Nejran region was found to be most economical in terms of minimal payback period and cost of energy and maximum internal rate of return whereas PV power production was concerned. Water-pumping capacity of the solar PV energy system was calculated at five locations based on the PV power production and Goulds model 45J series of pumps. Monthly total and annual total water pumping capacities were determined. Considering the capital cost of combined solar PV energy system and the pump unit a cost analysis of water pumping for a well of 50 m total dynamic head (TDH) was carried out. The cost of water pumping was found to vary between 2 and 3 US¢/m^3.

1. Introduction

Solar energy is a clean source of energy, and it does not risk human lives, environment, and economic disasters which may include oil and coal sludge spills, coal mine and devastating gas pipeline explosions, unforeseen nuclear accidents, and water supply contamination from natural gas fracking. Its utilization promotes better health through decreased coal plant emissions pollution.

Water pumps, powered by photovoltaic (PV) panels, are being used frequently to pump water for domestic usage, to irrigate crops and landscape, to cattle, and provide potable water. The advantage of using solar energy for pumping the water is that major quantities of water are required during day time and that too during time when the sun is on top of our head, and during these times the PV panels produce maximum energy and hence the water quantity. These solar pumps can be installed anywhere no matter it is a valley, remotely located farms, forest, or locations which are difficult to reach and are not connected to national electric grid. The utilization of solar water pump in developing countries is providing a workable solution to meet water needs of the people. At the same time, one can also save the environment by avoiding or minimizing the burning of fossil fuel for energy generation. The solar water-pumping technology is commercially available, has-proven record of reliability, require, minimal skilled manpower once in operation, and operation and maintenance cost is also very minimal and affordable.

Kingdom of Saudi Arabia is blessed with high intensities of solar radiations and longer durations of sunshine hours and vast open land with gentle topographical features in most of it and complex terrain in some part of it. According, Rehman et al. [1] global solar radiation varies between a minimum of 1.63 MWh/m^2/y at Tabuk and a maximum of 2.56 MWh/m^2/y at Bisha while mean value remained as

2.06 MWh/m^2/y. The sunshine duration varied between 7.4 and 9.4 h with an overall mean of 8.89 h or about a total of 3245 h in a year. The specific yield was found to vary from 211.5 to 319.0 kWh/m^2 with a mean of 260.83 kWh/m^2 [1]. The dwellings are spread all over the Kingdom with major concentrations in Dhahran on the eastern coast, Riyadh in the central part, Jeddah on the west coast, Guriat in the north most, and Nejran in the south part. Most of the major cities are connected to national electricity grid and the network of national and provincial highways. Still there are remote areas and smaller cities and towns which are not yet connected to national electricity grid and are dependent on power supply from diesel generating power stations and have isolated grids. Some of these dwellings are located in mountainous region where it is not only difficult to lay the grid but also economically prohibitive. Availability of water for domestic use and drinking purposes is a great challenge in such areas and areas which are far from the main cities or industrial regions. Ground water is available in most of these areas but they require electricity and equipment to pump the water for domestic usage, irrigation, and cattle.

Water pumping has regularly been a technical challenge, solving the problems of drinking water supply and regular irrigation was a prerequisite for the development of civilization in many of the ancient empires [2]. The PVPSs are being installed worldwide, and there were approximately 10,000 such systems in 1993 which reached to almost six time that is, 60,000 units in 1998, [3]. The ongoing efforts on performance improvement and modeling [4–9], system sizing and optimization [10–14], and performance of PV systems [15] on the basis of experimental measurements have resulted in commercially acceptable, economically affordable, and easily maintainable with least possible expertise. These developments have lead and are contributing to the improvement of the lives of remotely located dwellings.

J. S. Ramos and H. M. Ramos [16] used a pump of 154 W powered by a solar array of 195 watt peak (W_p) to pump water for village having ten families and consuming 100 L of water each with 6-day immunity period and 2% permissible loss of load at a cost of 1.06 €/m^3 and capital investment of 3019 €. Ould-Amrouche et al. [17] stated that the utilization of PV water-pumping systems helped both in improving the living conditions in remote areas and keeping the environment clean. Mahmoud and El-Nather [18] conducted the economical feasibility of using photovoltaic (PV) technology to pump the ground water in comparison with using diesel units. Their study proved that PV-battery system was economical compared to the diesel system. According to Kaldellis [19] the PV water-pumping systems (PVPSs) are environmentally friendly solution and contribute substantially to the satisfaction of remote communities' water consumption needs.

PV-powered water-pumping systems have been installed and are operational in various parts of the globe including Arabian countries, and some of these installation dates back to early 1990s. Some of these studies and installations have been reported in the literature like Bhave [20] for India, Alawaji et al. [21] for the Kingdom of Saudi Arabia, Hammad [22] for Jordan, Al Suleimani and Rao [23] for Oman, Al-Karaghouli and Al-Sabounchi [24] for Iraq, Manolakoset al. [25] for Greece, Kordab [26] for ESCWA member countries, Meah et al. [27] for, Sutthivirode et al. [28] for Thailand, and Chueco-Fernández and Bayod-Rújula [29] for Chile. In Saudi Arabia, the work has been reported on various aspects of solar energy such as radiation data prediction and estimation [30–37], photovoltaic-based cost of solar energy by generation Rehman et al. [38], availability of solar radiation and sunshine duration by Aksakal and Rehman [39], photovoltaic electricity for irrigation Rehman et al. [40] desert camping Al-Ali et al. [41], and solar radiation and sunshine duration maps by Mohandes and Rehman [42].

Table 1: Geographical coordinates of meteorological stations considered in this study.

Location	Latitude, (°N)	Longitude, (°E)	Elevation, (m)
Dhahran	26.3	50.2	17
Riyadh	24.7	46.7	620
Jeddah	21.7	39.2	17
Guriat	31.4	37.7	504
Nejran	17.6	44.4	1212

Table 2: Global solar radiation on horizontal surface (kWh/m^2/d).

Month	Dhahran	Riyadh	Jeddah	Guriat	Nejran
Jan	3.57	3.76	4.53	3.14	5.71
Feb	4.42	4.63	5.32	3.96	6.60
Mar	5.13	5.38	6.18	5.04	6.98
Apr	6.03	6.19	6.88	6.15	7.43
May	7.03	7.15	7.17	7.10	7.65
Jun	7.73	7.87	7.12	7.95	7.87
Jul	7.26	7.59	7.04	7.76	7.22
Aug	6.97	7.15	6.53	6.92	7.14
Sep	6.45	6.34	6.17	5.92	7.53
Oct	5.33	5.47	5.56	4.41	7.09
Nov	4.00	4.22	4.60	3.26	6.37
Dec	3.28	3.52	4.15	2.80	5.65
Annual	**5.60**	**5.78**	**5.94**	**5.37**	**6.94**

2. Input Data and Assumptions

The geographical coordinates and elevation above mean sea level of all the locations being considered in the present work are listed in Table 1. The global solar radiation values are summarized in Table 2 for Dhahran, Riyadh, Jeddah, Guriat, and Nejran. The isolated grid PV power system with 9.99 kW of installed capacity is considered for all the locations being reported in this paper. The PV systems consist of 54 modules of 185 W each with rated efficiency of 14.8%, module frame area of 1.24 m^2, nominal operating cell temperature of 45°C, temperature coefficient of 0.40%, and an inverter of 10 kW capacity with 90% efficiency. The miscellaneous losses in energy yield process are taken as 1%. For financial analysis, the capital cost is taken as 8US$ per W_p with 25 years of

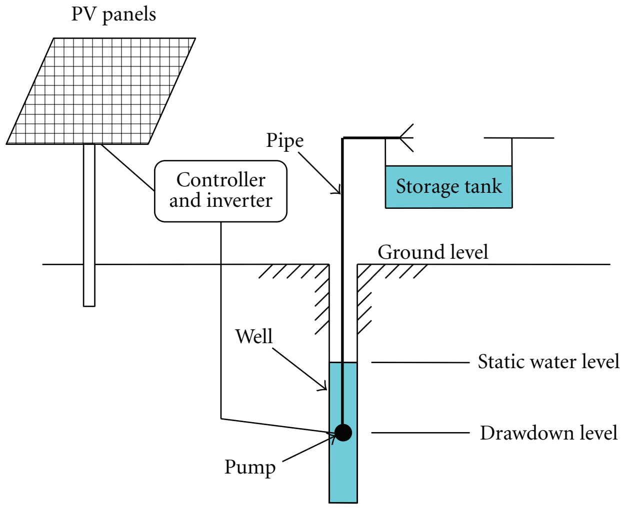

Figure 1: Schematic view of the solar photovoltaic water-pumping system.

operating life, inflation rate of 2%, debt interest rate of 7.0%, debt ratio of 70%, and debt term of 10 years. The total capital cost was calculated to be US$79,920, and it is assumed that it remains the same irrespective of location of the station. The total area covered by the PV panes was worked out to be 68 m^2. The schematic view of the solar PV water-pumping system considered in this work is shown in Figure 1.

3. Seasonal Variation of Solar Radiation on Horizontal Surface

Long-term monthly average global solar radiation intensities on daily basis for Dhahran, Riyadh, Jeddah, Guriat, and Nejran are summarized in Table 2. Highest intensities of 7.73, 7.87, 7.95, and 7.87 kWh/m^2/d were observed in the month of June at Dhahran, Riyadh, Guriat, and Nejran, respectively and of 7.17 kWh/m^2/d in May at Jeddah. It is also evident that relatively higher intensities were observed during April to September period which also correspond to higher-demand period for both power and water. Highest annual mean solar radiation intensity of 6.94 kWh/m^2/d was found at Nejran.

4. Solar Energy, Energy Density, and Greenhouse Gases Emission Analysis

The energy produced a PV array and delivered to the grid is estimated as follows:

$$E_P = S\eta_P\overline{H}_t, \quad (1)$$

where S is the area of the array, $\overline{H}_t$ is the daily total radiation on tilted surface, and η_P is the average efficiency of the PV array. The produced energy (E_P) is reduced by taking into consideration the miscellaneous PV array losses, (λ_p) and

Table 3: Values of PV module-related variables.

PV module type	η_r (%)	NOCT (°C)	β_P (%/°C)
Monocrystalline silicon (Mono-Si)	13.0	45	0.40
Polycrystalline silicon (Poly-Si)	11.0	45	0.40
Amorphous silicon (a-Si)	5.0	50	0.11
Cadmium telluride (CdTe)	7.0	46	0.24
Copper indium diselenide (CIS)	7.5	47	0.46

other power conditioning losses (λ_c). These losses are taken into consideration using the following equation:

$$E_A = E_P\left(1 - \lambda_p\right)(1 - \lambda_c), \quad (2)$$

where E_A is the PV array energy available to the load and the battery, if in use. The overall efficiency η_A is defined as follows:

$$\eta_A = \frac{E_A}{S\overline{H}_t}. \quad (3)$$

In (1), the average efficiency of the PV array (η_P) which is a function of average temperature of the PV module T_c is estimated using the following equation:

$$\eta_P = \eta_r[1 - \beta_P(T_c - T_r)], \quad (4)$$

where η_r is the PV module efficiency at reference temperature $T_r(= 25°\text{C})$ and β_P is the temperature coefficient for module efficiency. The module temperature T_c is related to the mean monthly ambient temperature T_a through Evan's [43] formula as given below:

$$T_c - T_a = \left(219 + 832\overline{K}_t\right)\left(\frac{\text{NOCT} - 20}{800}\right), \quad (5)$$

where NOCT is the nominal operating cell temperature and $\overline{K}_t$ the monthly mean clearness index. The values of η_r, NOCT, β_P, and depend on the type of PV module considered. For standard technologies and module the values of these variables are summarized in Table 3. The efficiency of photovoltaic cells varies with their operating temperature. Most cell types exhibit a decrease in efficiency as their temperature increases.

The monthly total energy estimated using (1) to (5) for all the locations is summarized in Table 4. This table also includes the energy density per unit area of the PV panel in kWh/m^2. At Dhahran and Riyadh the maximum energy of 1.569 and 1.596 MWh was observed in the month of October while at Jeddah (1.573 MWh), Guriat (1.517 MWh), and Nejran (2.057 MWh) in the months of March, August, and November, respectively. Similarly, the highest values of energy density of 23.07, 23.47, 23.13, 22.31, and 30.25 kWh/m^2 corresponding to Dhahran, Riyadh, Jeddah, Guriat, and Nejran occurred in the months of October, October, March, August, and November, respectively. Based on annual total energy output, maximum energy of 19.59 MWh was produced at Nejran while a minimum of 16.325 MWh at Dhahran, as can be seen from Table 4.

Table 4: Annual energy delivered and energy density for all the stations under consideration.

Month	Dhahran		Riyadh		Jeddah		Guriat		Nejran	
	MWh	kWh/m^2	MWh	kWh/m^2	MWh	kWh/m^2	MWh	kWh/m^2	MWh	kWh/m^2
Jan	1.303	19.16	1.362	20.03	1.536	22.59	1.288	18.94	1.961	28.84
Feb	1.277	18.78	1.326	19.50	1.443	21.22	1.230	18.09	1.768	26.00
Mar	1.383	20.34	1.435	21.10	1.573	23.13	1.472	21.65	1.719	25.28
Apr	1.319	19.40	1.336	19.65	1.417	20.84	1.444	21.24	1.464	21.53
May	1.354	19.91	1.353	19.90	1.324	19.47	1.478	21.74	1.325	19.49
Jun	1.313	19.31	1.312	19.29	1.195	17.57	1.463	21.51	1.198	17.62
Jul	1.318	19.38	1.347	19.81	1.250	18.38	1.509	22.19	1.204	17.71
Aug	1.416	20.82	1.428	21.00	1.298	19.09	1.517	22.31	1.343	19.75
Sep	1.505	22.13	1.461	21.49	1.384	20.35	1.493	21.96	1.628	23.94
Oct	1.569	23.07	1.596	23.47	1.540	22.65	1.401	20.60	1.966	28.91
Nov	1.341	19.72	1.408	20.71	1.404	20.65	1.206	17.74	2.057	30.25
Dec	1.227	18.04	1.312	19.29	1.439	21.16	1.184	17.41	1.957	28.78
Annual	**16.325**	**240.07**	**16.677**	**245.25**	**16.804**	**247.12**	**16.685**	**245.37**	**19.590**	**288.09**

Table 5: Summary of greenhouse gases avoided as a result of PV power utilization for water pumping in Saudi Arabia at different locations.

Location	GHG (tCO_2)/year	Gasoline saved (L/year)	During life time of the plant	
			(tCO_2)	L
Dhahran	3.3	1,420	82.5	35,500
Riyadh	3.4	1,451	85.0	36,275
Jeddah	3.4	1,462	85.0	36,550
Guriat	3.4	1,452	85.0	36,300
Nejran	4.0	1,704	100.0	42,600
Average	**3.5**	**1,498**	**87.5**	**37,445**

As a result of utilization of solar energy for water pumping in Saudi Arabia, on an average of 3.5 tons of CO_2 gas could be avoided from entering into the local atmosphere annually, as given in Table 5. Equivalently at Dhahran, Riyadh, Jeddah, Guriat, and Nejran a total of 1,420, 1,451, 1,462, 1,452, and 1,704 liters of gasoline could be saved from burning for energy production annually. On an average, during the life time of the PV panels in operation, in this case 25 years, around 87.5 tons equivalent of green house gasses could be avoided from entering into the local atmosphere, or 37,445 liters of gasoline could be saved from burning.

5. Economical Analysis of Solar Energy Production

The pretax internal rate of return (IRR) on equity (%) and assets (%), which represents the true interest yield provided by the project equity and assets over its life before income tax, is calculated using the pre-tax yearly cash flows and the project life and included in Table 6. In the present case, IRR has been calculated on a nominal basis that is including inflation. For a project to be considered financially acceptable, IRR is expected to be equal to or greater than the required rate of return of the investor. The simple payback (year) is the duration of time that it takes for a proposed project to recoup its own initial cost, out of the income or savings it generates. The simple payback method is the indicator that how desirable is the investment. Lesser the payback period better will be the investment. From economical analysis, it is evident that Nejran is the best location for the utilization of PV solar energy with maximum internal rate of return (IRR) of 14.0% and plant capacity of 22.4% and minimum simple payback period of 9.7 years and cost of energy of 16.32 US¢/kWh compared to other stations used in the present work. The other remaining locations are very near to each other whereas cost of energy and other economical indicators are concerned.

The effect of initial investment cost on cost of energy (COE) was also studied to check on the sensitivity. The initial investment costs of 8, 7, 6, 5, 4, 3, and 2US$ per peak watt (W_p) were considered while keeping all other interest rates the same. The resulting COE values for all the locations and initial investment rates are compared in Figure 2. It is evident that as the initial investment cost goes down, the COE also responds in the same manner. A decrease of US$1 per W_p in the initial investment cost (i.e., 7US$ instead of 8US$) causes a decrease of 12.5% in COE (i.e., 17.13 US¢/kWh instead of 19.58 US¢/kWh), and, for further decrease of 1US$, the COE decreased to 14.69 US¢/kWh or a decrease of 16.7%.

Table 6: Summary of internal rate of return (IRR) and cost of energy (COE) for all the stations considered in the present work.

Location	Pretax IRR (%)		Payback period (years)		Cost of energy (US¢/kWh)	Plant capacity factor (%)
	Equity	Assets	Simple	Equity		
Dhahran	10.3	3.2	11.7	13.1	19.582	18.7
Riyadh	10.7	3.5	11.4	12.9	19.169	19.1
Jeddah	10.9	3.5	11.3	12.8	19.024	19.2
Guriat	10.7	3.5	11.4	12.9	19.160	19.1
Nejran	14.0	5.2	09.7	11.1	16.319	22.4
Average	**11.3**	**3.8**	**11.1**	**12.6**	**18.651**	**19.7**

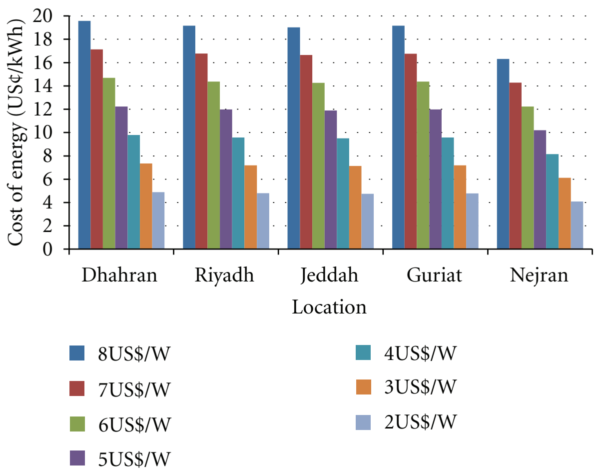

Figure 2: Effect of capital cost on cost of energy generated from 9.99 kW installed capacity PV power plant in Saudi Arabia.

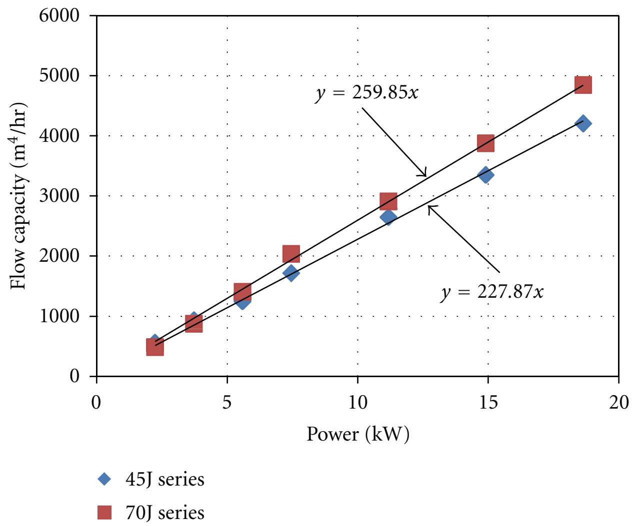

Figure 3: Flow capacity rate as function of pump size for two series of pumps.

6. Performance of Solar-Energy-Based Water Pumping

6.1. Water-Pumping Analysis. The power required for pumping water from underground P_{hyd}(W) can be determined by the expression

$$P_{hyd} = \rho g H Q (\text{W}), \tag{6}$$

where ρ is the density of water (kg/m^3), g is the gravitational acceleration (m/s^2), H is the total head (m), and Q is the volumetric flow rate of water (m^3/s). Assuming that the density and the gravitational acceleration do not vary significantly, the product HQ is found to be directly proportional to the pumping power requirement. HQ may be considered as the pumping capacity rate. Thus the equation can be rewritten as

$$HQ = \frac{P_{hyd}}{\rho g} (\text{m}^4/\text{s}) \tag{7}$$

to determine the pumping capacity rate HQ in m^4/s for any given available power P_{hyd}(W). Once the total head H (m) is available, the volumetric flow rate of water that can be pumped from underground Q (m^3/s) can be calculated. This expression indicates that a hydraulic power of $P_{hyd} = 1$ W is equivalent to a pumping capacity rate of 8.8 m^4/day. For the determination of the total pumping capacity for a given period of time, this equation can be written as

$$HQt = \frac{P_{hyd} \times t}{\rho g} (\text{m}^4), \tag{8}$$

where time t is time (s). Accordingly, a hydraulic energy ($P_{hyd} \times t$) of 1 kWh (i.e., 3600 kJ) is equivalent to a pumping capacity (HQt) of 367 m^4. On the other hand, the required pump size P(W) can be determined from

$$P = \frac{P_{hyd}}{\eta} = \frac{\rho g H Q}{\eta}, \tag{9}$$

where η is the pump efficiency.

6.2. Water-Pumping Capacity. Twelve models of water pumps at different sizes from Goulds Pump Company were selected in the present work. Six of these are from 45J series, and the remaining six are from 70J series high-capacity flat bowl 6-inch submersible pumps. Detail specifications of these pumps are given in Tables 7(a) and 7(b). The nominal flow rate of these pumps at best efficiency ranges from 45 to 70 GPM, and their motor size ranges from 3 to 25 HP. Depth of water for which the pumps operate ranges from

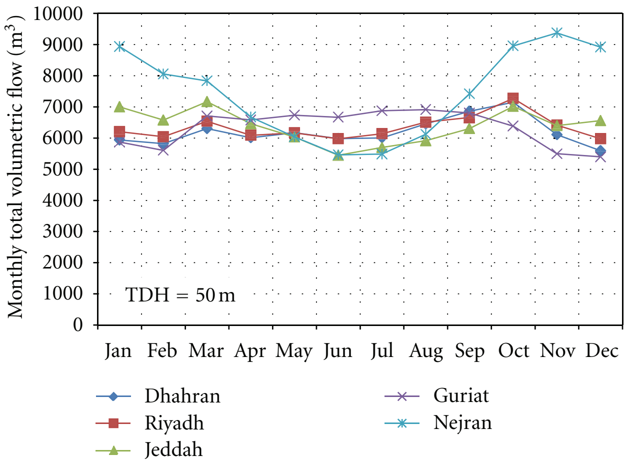

FIGURE 4: Monthly total volumetric flow of water from a well with total dynamic head of 50 m using solar PV-operated Goulds model 45J series pump for five different sites in Saudi Arabia.

100 to 1350 feet. Nominal flow capacity rate of each pump (in m^4/hr) is also given in the last column in Table 7.

Figure 3 shows the nominal flow capacity rate variation of the pumps at best efficiency point as function of the power consumption. As can be seen from this figure, the nominal flow capacity rate is almost linear with the power (or size) of the pump in each series of pumps. The least squares fit line for the data is shown on the figure for each series. The slopes of the lines are slightly different from each other as a result of different efficiencies of pumps. 70J series pumps are slightly more efficient (62% max) than the 45J series pumps (60% max). Accordingly, the relationship of nominal flow capacity rate and the power for each series of pumps can be expressed as follows:

Flow capacity rate (m^4/hr) = 227.87 × Power (kW) for 45J series

Flow capacity rate (m^4/hr) = 259.85 × Power (kW) for 70J series.

The flow rate in m^3/hr is obtained by dividing the flow capacity rate with the total dynamic head (TDH).

Monthly total volumetric flow of water from a depth of 50 m total dynamic head using solar PV-operated Goulds model 45J series pumps is shown in Figure 4. The maximum efficiency of the pumps in this series is 60%. Monthly total volumetric flow of water shows fairly uniform variation throughout the year except for the Nejran site. In Nejran site the volumetric flow is found to be considerably higher during the winter months as compared with that during the summer months. This is due to the high solar energy availability during the winter months in the site of Najran. Referring to Table 4, the yearly average solar electric power generation from the solar PV panels considered in the five sites, namely, Dhahran, Riyad, Jeddah, Guriat, and Nejran is 1.86, 1.90, 1.92, 1.90, and 2.24 kW, respectively. Therefore the most suitable pump model for the solar PV energy generator is the 45J03 model that comes with 5 hp (2.24 kW) motor

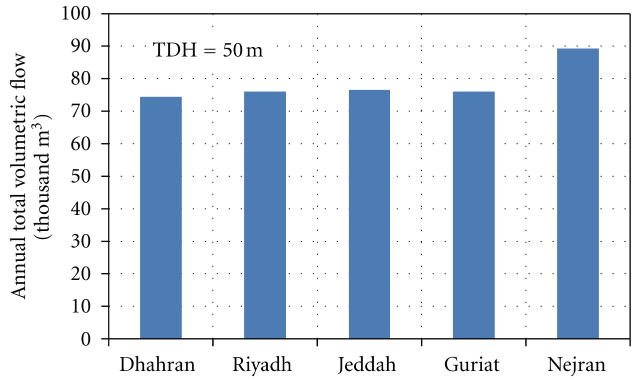

FIGURE 5: The annual total volumetric flow of water from a well with total dynamic head of 50 m using solar PV-operated Goulds model 45J series pump for five different sites in Saudi Arabia.

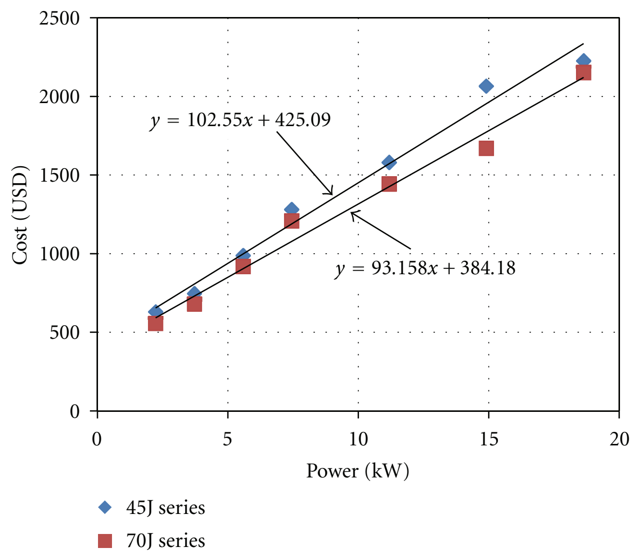

FIGURE 6: Cost of pumps as function of the pump size (power) for two series of pumps.

and efficiently operates with a TDH of 54.58 m as can be seen from Table 7(a). This is the reason why the TDH is fixed to be 50 m in Figure 4. The annual total volumetric flow of water for the same solar PV energy generator is shown in Figure 5 for the five sites considered. The variation of the annual total volumetric flow among the sites considered is minimal except for the case of Nejran site where the annual total volumetric flow is about 18% more than the other sites.

Figure 6 shows the cost (price) of water pumps considered in this study. The price of water pumps is found to increase with the size of the pumps. The variation shows a nearly linear trend for both series of pumps considered. This trend can be expressed in first-order approximation for both the pump series as

Price (\$) = 102.55 × Power (kW) + 425.09 for 45J series

Price (\$) = 93.158 × Power (kW) + 384.18 for 70J series of pumps.

Table 7

(a) Specifications of Goulds water pumps 45J series considered

Model	Price (USD)	Flow rate (GPM)	Power (hp)	TDH (feet)	Flow rate (m^3/hr)	Power (kW)	TDH (m)	Flow capacity rate (m^4/hr)
45J03	630	45	3	180	10.22175	2.2368	54.864	560.8061
45J05	745	45	5	300	10.22175	3.728	91.44	934.6768
45J07	987	45	7.5	400	10.22175	5.592	121.92	1246.236
45J10	1280	45	10	550	10.22175	7.456	167.64	1713.574
45J15	1580	45	15	850	10.22175	11.184	259.08	2648.251
45J20	2065	45	20	1075	10.22175	14.912	327.66	3349.259
45J25	2226	45	25	1350	10.22175	18.64	411.48	4206.046

Data at best efficiency (%60).

(b) Specifications of Goulds water pumps 70J series considered

Model	Price (USD)	Flow rate (GPM)	Power (hp)	TDH (feet)	Flow rate (m^3/hr)	Power (kW)	TDH (m)	Flow capacity rate (m^4/hr)
70J03	556	70	3	100	15.9005	2.2368	30.48	484.6472
70J05	680	70	5	180	15.9005	3.728	54.864	872.365
70J07	919	70	7.5	290	15.9005	5.592	88.392	1405.477
70J10	1208	70	10	420	15.9005	7.456	128.016	2035.518
70J15	1443	70	15	600	15.9005	11.184	182.88	2907.883
70J20	1670	70	20	800	15.9005	14.912	243.84	3877.178
70J25	2152	70	25	1000	15.9005	18.64	304.8	4846.472

Data at best efficiency (%62).

Table 8: Cost of solar PV water pumping from a well with 50 m TDH.

Location	Cost of water pumping with TDH = 50 m (US¢/m^3)
Dhahran	2.69
Riyadh	2.63
Jeddah	2.61
Guriat	2.63
Nejran	2.24
Average	**2.56**

Considering both of the relationships, a representative linear relation applicable for all the pump can be obtained by

$$\text{Price (\$)} = 98 \times \text{Power(kW)} + 405. \tag{10}$$

Considering the pump model 45J03, a cost of USD630 is added to the capital cost of solar PV system. Therefore the cost of water produced from a well of 50 m TDH becomes 2.69, 2.63, 2.61, 2.63, and 2.24 US¢/m^3 for Dhahran, Riyadh, Jeddah, Guriat, and Nejran, respectively, as shown in Table 8. The average pumping cost of water per cubic meter is found to be 2.56 US¢.

7. Conclusions

An economical feasibility study was carried out in relation to producing electrical energy using PV solar panels for pumping underground water at Dhahran, Riyadh, Jeddah, Guriat, and Nejran sites in Saudi Arabia. A solar PV energy generation system producing 9.99 kW of electrical energy was considered. The electrical energy generated was used to calculate the underground water-pumping capacity at each of the five sites. The following conclusions can be derived from the present work.

(i) The annual total energy output was found to be the maximum (19.59 MWh) at Nejran site while it was a minimum (16.325 MWh) at Dhahran site.

(ii) The Nejran site was found to be most economical in terms of minimal payback period and cost of energy and maximum internal rate of return.

(iii) Goulds model 45J series of pumps were found to be suitable to be integrated with the solar PV energy generation system.

(iv) Based on the solar PV electrical energy generation, monthly total water-pumping capacities were found to be nearly uniform throughout the year except for the Nejran site. Considerably higher water production capacity was observed during the winter months in Nejran.

(v) Annual total water-pumping capacities were almost equal in all the sites considered except for the Nejran site where the water-pumping capacity was %18 higher.

(vi) The cost analysis of water pumping system indicated that, for a well of 50 m total dynamic head (TDH), the cost of water pumping vary between 2 and 3 US¢/m^3 in all the five sites in Saudi Arabia.

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