Future Sustainability
Open Access Journal
ISSN 2995-0473

February 2024| Volume 02 | Issue 01 | Pages 35- 46

Journal homepage: https://fupubco.com/fusus

https://doi.org/10.55670/fpll.fusus.2.1.4

Future Publishing LLC

Article

A techno-economic investigation for utilizing solar energy in irrigation of palm trees in Saudi Arabia

A.F. Almarshoud

Department of EE, College of Engineering, Qassim University, Saudi Arabia

ARTICLE INFO

Article history:
Received 06 October 2023
Received in revised form
08 November 2023
Accepted 14 November 2023

Keywords:
Sustainable irrigation, PV water pumping,
Solar energy water pumping,
palm date trees irrigation, solar energy economics

*Corresponding author
Email address:
dr_almarshoud@qec.edu.sa
dr_almarshoud@qu.edu.sa

DOI: 10.55670/fpll.fusus.2.1.4

ABSTRACT

This paper presents a techno-economic investigation for utilizing photovoltaic solar energy in water pumping applications for the irrigation of Palm trees in the Qassim region in Saudi Arabia. The Analysis has been done by applying four technical indicators and three economic indicators on a real farm of palm trees. The investigation took into account the varied water demand for palm trees over the years, meteorological data of the region, the characteristics of the borehole, and the local market prices of PV system components. The investigation has been done using two options of PV systems: grid-connected system and standalone system. The results showed the superiority of the grid-connected system in spite of the unfair price of energy exchange with the utility grid. The results achieved are the Levelled cost of energy, which is in the range from 0.013 to 0.019 $/kWh. The standardized cost of produced water is in the range from 0.011 to 0.013 $/m^3, and the simple payback time is in the range from 9.65 to 12.22 years. The results are considered to encourage farmers in the region to convert to solar energy utilization.

1. Introduction

Recently, the government of Saudi Arabia adopted a new tariff for consuming electricity and fuel. The percentage of rise in the new tariff ranges from 50% to 95%, depending on the type of fuel. However, the anticipated future energy prices are expected to increase even far beyond this level since the 2030 vision intends smooth liberalization of the fuels market. This rise in energy prices will affect mainly the agriculture sector, especially in water pumping costs, which mainly depend on electricity or diesel fuel. Finally, this extra energy tariff will reflect on the prices of produced crops. The agricultural sector in Saudi Arabia mainly depends on underground water, which requires a lot of electrical energy or diesel fuel for water pumping from deep wells. Due to the high tariff of electricity adopted recently in Saudi Arabia, and due to the rapid degradation in the cost of solar panels in the last few years, utilizing solar energy as an alternative source for providing the energy required for applications of water pumping and irrigation will be a promising option. Qassim region has more than 7.5 million palm trees [1], making it one of the largest producers of dates in the world. This huge number of palm trees consumes a significant quantity of energy to provide the required amount of water for the irrigation process. The region is rich in solar energy because it is located in the solar belt, as shown in Figure 1, so one of the appropriate solutions to minimize the consumption of fossil fuel is exploiting the relative property of the Qassim region, which is the abundance of solar energy. The water pumping system based on solar energy has some advantages such as easy installation, low maintenance, environmentally friendly, high reliability, and the operating process is simple with no cost. The disadvantages are high initial cost, and the water production depends on the availability of enough solar radiation. This study aims to investigate the technical performance and economic feasibility of using solar energy in water pumping for irrigating palm trees in the Qassim region. The economic feasibility of using solar energy for water pumping is affected by many factors, such as solar radiation, the type of pump used, borehole depth, daily water demand, the capital cost of equipment, and the cost of periodical maintenance. In this research, a comparison study will be performed for using solar energy instead of using a utility grid for water pumping. In addition, the Levelized cost of produced water per cubic meter is the cost of generated electrical energy per kWh. Finally, the payback period of the proposed system will be calculated. Moreover, the technical specification of the proposed system will be determined according to the case study requirements. The climatic condition of the Qassim region is a typical desert climate, known for its cold, rainy winters and for its hot, low humidity, and sometimes balmy summers with a long daily duration of sunshine [2]. Figure 1 shows the annual sum of global horizontal irradiance in the Qassim region, which reaches up to 2200 kWh/m^2 annually, while the average daily solar irradiance is about 6.08 kWh/m^2. The recorded meteorological data shows the viability of utilizing the solar PV systems in the Qassim region. Regarding the underground water resources, the Qassim region has a multi-aquifer system that consists of five main aquifers separated by semi-confining beds; they are Minjur, Jilh, khuff, Tabuk, and Saq. The deepest one is Saq which is the main productive aquifer, then Tabuk aquifer. The others are of limited productivity [3]. The static head of water in wells ranged from 130-165 m in 2015, according to the authority of water resources in the Qassim region.

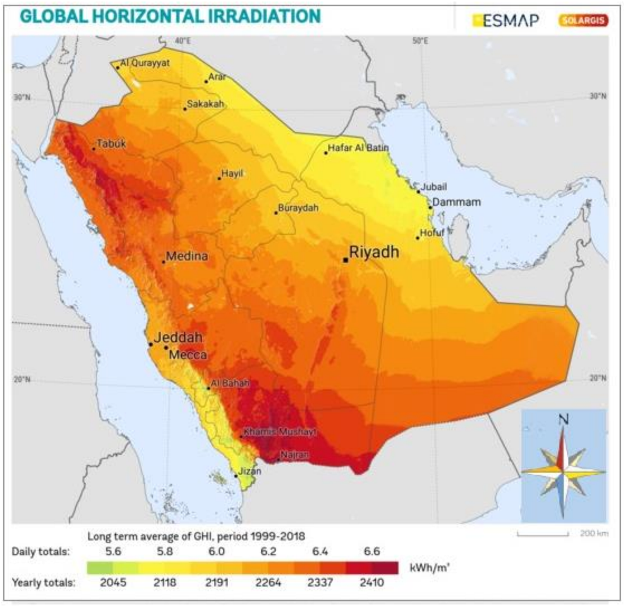

Figure 1. The annual sum of global horizontal irradiance in Saudi Arabia [4]

The published studies in the literature didn't achieve a consensus on a clear and effective methodology to investigate the performance and economic feasibility of Photovoltaic pumping systems. This study introduces a unified approach to investigating the techno-economic performance of PV water pumping systems. This study collected the diaspora scattered in many scientific papers and then extracted a unified approach to evaluate the technical and economic performance of water-pumping PV systems.

2. Literature review

Many attempts have been made in various countries around the globe to determine the optimum performance, economic feasibility, and environmental benefits of harnessing solar energy for the purpose of water pumping applications. The literature review below demonstrates the major recent research activities:

Elham and Hoseen et al. [5] presented a comparative study between solar PV systems and diesel unit sets for the use of underground water pumping where various parameters influencing the present value and the cost-effectiveness of both systems have been considered. Despite the use of PV batteries in their solar system, the authors concluded that the cost of water using solar energy is much less than using diesel systems. Pallav Purohit has developed a simple model to evaluate the economic feasibility of different renewable energy technologies such as solar water pumping, windmills, gasification, and biogas technology for water pumping for irrigation purposes in India. The developed financial framework is used to select suitable renewable energy technology. He estimated the unit cost of water produced compared to the cost of energy supplied by the various renewable energy systems and calculated the benefits obtained from saving electricity or diesel [6]. In line with the development of solar pumping applications, Ould-Amrouche et al. have developed a model based on experimental results to characterize the solar PV pump. In the developed model, a relationship between the water flow rate output and the electrical power at various heads is presented. The obtained experimental results by using different technologies and various motor pumps are used to verify the model. The measurement data and the result of the simulation are used to validate the proposed model. The model is simple and can be used for planning solar pumping systems and calculating the emission rate of CO_2 resulting from the use of diesel water pumping and the amount of carbon dioxide that can be saved by using solar PV water pumping systems [7]. Tamer Khatip [8] developed a mathematical relationship that uses the load matching technique to relate the solar radiation, solar module array, and the needed hydraulic power to satisfy the demand of the water pumping system. The study also reviewed the various existing commercial solar water pumps to ensure proper pump selection. Mokeddem et al. [9] conducted an outdoor experimental investigation to determine the actual performance of a solar water pumping system using a DC motor with a centrifugal pump having a PV array of 1.5 kW. Two static heads are considered to evaluate the system performance under various solar irradiance and operating conditions. The study applied an approximation for the frictional losses using an empirical factor depending on the Reynolds number. Sahin and Rehman performed the economic feasibility of solar water pumping systems to supply water from 50 m deep wells in five selected cities in Saudi Arabia. The conducted study revealed that the cost of solar water pumping is in the range of 2 -3 USD/m^3, which is assumed to be a relatively high cost [10]. A comparative study for cost-effectiveness between diesel engines and solar systems for pumping water in remote areas in Nothern Badia of Jordan is presented by Mohammad Al-Smairan; the study has considered different variables such as initial investment and prices of fuels. The obtained results are used to select the optimum alternative power source to operate the water pumping system [11]. The performance of a solar PV system for water pumping in four different locations in Tunisia was presented by Belgacem; the evaluation is based asynchronous motor coupled to a centrifugal pump. The obtained results of the different sites were evaluated [12]. A dynamic modeling tool correlating the pumping system, the demand for water, and the solar PV power for the water pumping system was developed by Elia et al. [13]. The proposed model is used to validate the design procedure between the water supply and demand. Shiv Lal et al. [14] conducted a performance analysis for the PV pumping system based on available solar radiation in Kota City in India, using a submersible pump for irrigation purposes. A feasibility study of solar PV systems for supplying drinking water in remote areas in Ethiopia is presented by Kabade et al. [15]; the study revealed that only a payback period of four years is needed to cover the overall cost of the system, which is considered a great economic advantage. Bouzidi has presented a method to design a solar pumping system based on the determination of Loss of Power Supply Probability (LPSP) and water cost [16]. The Analysis of the life cycle cost is applied by Sodiki to compare the cost-effectiveness of solar water pumping in various sites in Nigeria [17]. Farms irrigation study using solar water pumping systems in rural areas of Oman was conducted by Kazem et al. the optimum design of a PV pumping system based on meteorological data is determined using HOMER software and REPS.OM software [18]. Campana et al. [19] presented a procedure for the optimization process and economic investigation of the photovoltaic water pumping system, taking into consideration the PV system cost and the revenue from crop sales besides underground water level, amount of water produced, and water demand. Almarshoud [20] has investigated the reliability of the pumping system based on solar irradiance data, where the study revealed the importance of accurate sizing of PV array to satisfy the actual water demand and to avoid the additional cost resulting from oversizing.

3. Estimation of water requirements of palm date trees

Water requirements of palm date trees vary from one region to another due to many factors, such as the climate condition, Soil type, rainfall pattern, ambient temperature, the moisture of soil, wind speed, solar radiation, depth of tree roots, age of palm date tree, mature state of the crop. All these factors may affect the quantity of daily demand for water, which means the water demand varies from one month to another in the same area. There are some rough estimates made by different researchers in different countries such as, Iraq was found 115-306 m^3/ tree annually depending on the cultivar and climatic conditions [21], and Abu Khaled et al. [22] found the total annual water demand in Iraq nearly 18000 m^3/ hectare. In Tunisia, it was found that the total annual water demand was between 63-95 m^3/ tree [23]. In Saudi Arabia, there are some estimates for several regions, such as, in Qatif was found to be 13250 m^3/hectare/year [24], while in Hofuf region, the minimum daily water demand is between 2.3 m^3, 8.3 m^3/tree in January and August respectively. In another study done in the central region, it was found that the annual amount of sufficient water demand was 108 m^3/ tree [25].

In another study done in Najran, it was 136 m^3/ tree [26]. Alazba estimated the annual water demand per tree in both Eastern and Central regions; he found 137 m^3, and 195 m^3, respectively, for flood irrigation and 55 m^3, and 78 m^3, respectively, for drip irrigation [27]. Regarding the Qassim region, there are two studies that investigated the water requirements for palm date trees in case of applying drip irrigation; the first one was done by Kassim [28]; he reported the average water demand for each month as shown in Table 1, where the average daily demand was 44.795 m^3 / hectare. The second one was done by Al-Amoud et al. [29], who investigated the water requirements in the case of using drip irrigation for palm date trees in seven regions of Saudi Arabia. Qassim region is one of them. Also, in this study, the water demand was reported as average per month, as shown in Table 1, and the average daily demand was 65.71 m^3 / hectare [29].

4. Research objectives and methodology

This research aims to achieve the best design for a water pumping system that utilizes the potential solar energy and available water resources in the Qassim region to satisfy the water demand at the lowest possible cost. Also, a comparative study will be performed for utilizing solar energy instead of the utility grid for palm date irrigation. In addition to calculating some important economic indicators such as the Levelized cost of produced water per cubic meter, the cost of generated electrical energy per kWh, and the payback time of the proposed water pumping system. The investigation in this work will be done using two options of PV systems: a standalone PV system (the generated energy is consumed only by the pumping system) and a grid-connected PV system (Energy exchange with the utility grid is allowed). The investigation will follow the following methodology:

1- Collecting the required information about solar radiation data of the location, the characteristics of deep-water wells in the location, and the water demand of palm trees in the region based on previous studies.

2- Collect information about the specifications and prices of water pumping systems and solar PV arrays available in the local market.

3- Sizing the pumping system based on the water demand and well characteristics.

4- Sizing the PV system based on the size of the pumping system and the daily energy demand.

5- Determining the technical performance of the PV pumping system using the standard technical indicators.

6- Estimating the economic feasibility of the PV-pumping system using the economic indicators.

7- Analyzing the results and concluding the recommendations based on the energy market situation in Saudi Arabia.

Table 1. The average daily water demand using drip irrigation for palm date trees in the Qassim region (m^3/hectare)

Study	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kassim(2007)	18.6	23.41	39.5	49.89	59.85	72.5	72.9	67.4	53.54	34.91	26.4	18.62
Al-Amoud(2012)	27.5	37.5	55	74	91.5	101.5	103	94	76.5	58	40.5	29.5
Average	23.1	30.46	47.3	61.95	75.68	87	87.95	80.7	65.02	46.46	33.45	24.06

5. Case Study

Consider a palm date farm located west of Buraydah city in the middle of Saudi Arabia (26.34° N, 43.76° E); the area is 4 hectares, about 168 trees/hectare, the palm dates trees are uniformly distributed, the spacing between trees is 8 meter in both directions, the daily water requirement is according to the average quantity extracted from previous studies [28] and [29] and recorded in Table 1, using the drip irrigation method. The meteorological data of Buraydah City were collected from the Renewable Resource Atlas, which is part of the Renewable Resource Monitoring and Mapping (RRMM) program of King Abdullah City for Atomic and Renewable Energy [30]. The collected data represent the average of five years, from 2013 to 2018, and include the air temperature, wind speed, atmospheric pressure, Global horizontal irradiance (GHI), Global tilted irradiance (GTI), and the Clearness Index (K_t). Table 2 illustrates the detailed collected meteorological data. The depth of the well is represented by the Total Dynamic Head (TDH) of pumping which is 176 m. It is required to investigate the technical and economic performance of a PV water pumping system that can pump the daily demand over 25 years of its life using the chosen monocrystalline PV module; the specifications of the selected PV module are illustrated in Table 3.

5.1 Financial and economic data

The capital cost of the water pumping PV system includes the cost of the pumping system (pump, motor, pipes, cables, electrical panel, and installation cost), in addition to the PV System (PV modules, inverter, Balance of System cost), the Balance of System cost (BOS) includes mounting structures, infrastructure development, planning, DC cabling, switchgear, and installation cost. All the prices are taken from the local market.

The interest and inflation rates are 2.0 % and 2.5 %, respectively, as published by the Saudi Arabian Monetary Authority on its website. The discount rate was estimated at 9.0 %. Assume no debt as a part of the capital cost, and the life period of the project is 25 years, which is equal to the life cycle of the PV modules. The salvage value for the whole project at the end of its life is 20 % of the capital cost. Also, the same percentage was considered for the salvage value of the inverter and pumping system at the end of their life cycles. Table 4 shows the detailed cost according to the local market prices.

6. Results and discussion

The investigation will be done according to six steps: specifying the primary data, sizing the pumping system, calculating insolation on the tilted surface chosen, sizing the PV array, calculating the technical performance indicators, and calculating the economic feasibility indicators.

6.1 Step 1: Specifying the primary data

The primary data of the case under study, such as the metrological data, are given in Table 2. The water demand is shown in Table 1 as the monthly average per day for one hectare. Because the area of the case under study is 4 hectares, the water demand recalculated for the whole area, as shown in Table 5.

6.2 Step 2: Sizing the motor-pump system

The energy required by the pumping system is variable according to the variation of water demand, so, by using formula (1) below, the energy demand can be calculated [20]:

$$E_{pump}(Wh) = \frac{\rho g Q H}{3.6\, \eta_m\, \eta_p} \quad (1)$$

Table 2. Monthly average of daily weather data

Month	Ambient Temp.	GHI	GTI (26.34°)	Atm. Pressure	Wind speed	Clearness Index (K_t)
	°C	$kWh/m^2/d$	$kWh/m^2/d$	kPa	m/s	
January	14.25	4.24	5.72	94.21	3.08	0.66
February	16.3	5.34	6.63	94.06	3.25	0.65
March	22.44	5.70	6.25	93.76	2.46	0.58
April	26.48	6.25	6.20	93.65	3.25	0.61
May	32.22	7.10	6.53	93.44	3.15	0.64
June	35.04	8.15	7.16	93.15	3.70	0.72
July	36.6	8.13	7.26	92.92	3.20	0.75
August	36.78	7.54	7.25	93.04	2.05	0.71
September	34.16	6.68	7.09	93.39	2.58	0.69
October	28.5	5.61	6.70	93.78	2.63	0.66
November	20.44	4.37	5.73	94.06	2.83	0.62
December	15.2	3.83	5.27	94.31	3.07	0.60
Annual	26.53	6.08	6.48	93.65	2.94	0.66

Table 3. Specifications of the selected PV module

PV module	Sungold Co.	(SGM-50W)	mono-Crystalline
Peak power	350 W	Pout degradation/year	0.8 %
Rated Voltage	38.5 V	Open Circuit Voltage	46.9 V
Rated Current	9.09 A	Short Circuit Current	9.60 A
Efficiency	20.25 %	Dimensions	195 x 99.2 cm
Misc. losses	1.0 %	conditioning losses	2.0 %
NOCT	45 °C	Temp. Coefficient	-0.39 %

* Electrical data of PV module measured at STC (GHI: 1000 w/m^2, air mass: 1.5 g, Cell Temp.: 25 °C)

Where: H is the Total Dynamic Head (TDH) which is the sum of the static head of water in the well, discharge head, drawdown head, discharge pressure, and friction losses in the pipeline, ρ is the density of water (1.0 kg/L), g is the gravity acceleration (m/sec^2), Q is the daily demand of water (m^3), η_m is the motor efficiency, and η_p is the pump efficiency.

Table 4. Detailed cost according to local market

Item	Cost
PV modules	260 $/ kW
Inverter	$ 1200
BOS*	400 $/ kW
O&M / year	22 $/ kW
Pump	$ 3230
Motor	$ 2560
Pipes	$ 2400
Cables	$ 1860
Pump installation	$ 400
Exported energy**	0.01867 $/kWh
Imported energy**	0.04267 $/kWh

*BOS includes mounting structures, infrastructure development, planning, DC cabling, switchgear, and installation cost.

** The tariff of energy exchange is according to Saudi Arabia regulations issued on 26/12/2019.

The daily and monthly energy demand has been calculated and illustrated in Table 6.
The maximum energy required for pumping the daily water demand was 280.87 kWh/day in July, and assuming about 10 hours of sunshine daily in July, this requires a pump with a size not less than 28 kW. So, a highly efficient 30 kW AC submersible pump from Grandfous Co. driven by a three-phase induction motor has been selected; its full specification is illustrated in Table 7.
Also, an inverter of the same size has been chosen from Sako Co.; it is customized for solar pumping applications with a soft starting property; this property eliminates the need for batteries to support the starting current, also it is characterized by MPPT technology for regulating the operation of the pump automatically at maximum generated energy point of PV array to satisfy the requirements of the case under study, its full specification is illustrated in Table 8.

6.3 Step 3: Calculating the insolation on a tilted plane

Usually, the tilt angle of PV modules is chosen to equal the latitude of the location for achieving moderate generation over the year, but in this case, it is noted that the energy demand in summer may reach up to four folds of the energy demand in winter, so, the tilt angle should be chosen carefully to satisfy the maximum generation in summer.

Four tilt angles have been tested; 26.34°, which is equal to the latitude, latidude+15°, Latitude-15°, in addition to the horizontal case. The solar radiation has been calculated at these tilt angles and compared with the profile of energy demand, as shown in Figure 2.
It is clear from Figure 2 that the best matching between energy demand and solar insolation occurs when the tilt angle = zero. So, the following Analysis will be done considering the PV array fixed on the horizontal level.

6.4 Step 4: Sizing of the PV array

The daily output energy of the PV array may be given from the following formula [31]:

$$E_{pv}(Wh) = A_{pv}\,\bar{G}_t\,\eta_{pv}\,(1-\lambda_m)(1-\lambda_c) \qquad (2)$$

Where $\bar{G}_t$ is the global solar insolation on the tilted surface (W/m^2/day), A_{pv} is the area of the PV array (m^2), η_{pv} is the efficiency of PV array under operating condition, λ_m, and λ_c are miscellaneous losses of PV array and power conditioning losses respectively. Usually, the values of λ_m and λ_c are assumed from 1- 2 % for each. The sizing of the PV array could be done by matching the total energy needed daily by the pumping system (given by Eqn. 1) with the daily expected output energy of the PV array (given by Eqn. 2) as in the following:

$$E_{pv}(Wh) = \mathrm{E_{pump}(Wh)} \qquad (3)$$

Because the pumping system is connected to the PV array through the inverter, then Eqn. 3 could be modified as follows:

$$E_{pv} = \frac{E_{pump}}{\eta_{inv}} \qquad (4)$$

Or;

$$A_{pv}\,\bar{G}_t\,\eta_{pv}\,(1-\lambda_m)(1-\lambda_c) = \frac{\rho g Q H}{3.6\,\eta_m\,\eta_p\,\eta_{inv}} \qquad (5)$$

Where η_{inv} is the efficiency of inverter.
Then the size of the PV array required for the water pumping system may be obtained as follows:

$$A_{pv} = \frac{\rho g Q H}{3.6\,\bar{G}_t\,\eta_{pv}\,\eta_m\,\eta_p\,\eta_{inv}(1-\lambda_m)(1-\lambda_c)} \qquad (6)$$

The value of η_{pv} could be obtained as follows [31]:

$$\eta_{Pv} = \eta_r\,[1 - \alpha_p\,(T_c - T_r)] \qquad (7)$$

Where η_r is the PV module efficiency at the reference temperature (T_r = 25°C), and α_p is the temperature coefficient for module efficiency. T_c is cell temperature and related to the average ambient temperature T_a *as* follows [31]:

$$\mathrm{T_c - T_a} = \frac{219+832\mathrm{K_t}}{800}(\mathrm{NOCT}-20) \qquad (8)$$

where NOCT is the Nominal Operating Cell Temperature, and K_t is the clearness index.
The efficiency of the selected PV module given in Table 3 is based on STC condition, while in the case under study, the solar radiation and ambient temperature vary from one month to another.

Table 5. The monthly average of daily water demand (m^3)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
92.2	121.82	189.06	247.78	302.7	348	351.8	322.78	260.08	185.82	133.8	96.24

Table 6. Energy demanded by pumping system based on the water demand (kWh)

	kWh/day	kWh/month
Jan	73.61	2281.95
Feb	97.26	2723.26
Mar	150.94	4679.23
Apr	197.82	5934.72
May	241.67	7491.81
Jun	277.84	8335.14
Jul	280.87	8707.03
Aug	257.70	7988.79
Sep	207.64	6229.32
Oct	148.36	4599.04
Nov	106.82	3204.72
Dec	76.84	2381.94
Annual		64556.94

So, the efficiency of the PV module should be recalculated using formula (7) for two cases at least; one in winter where both insolation and temperature are low, and another in summer where both insolation and temperature are high, then getting an average value of efficiency to be used for sizing the PV array.

6.5 Sizing of the PV array according to the 1st option (Stand-alone system)

The sizing of the PV array has been done by applying Eqs. (2) to (8) and using the selected PV module after calculating the new efficiency (18.24 %), The resulted area of the PV array is 197.1 m^2 (102 modules), but, due to the degradation in the output power of PV modules, this size will not be able to supply the required energy in the last few years of the life cycle, so, the size could be increased to 105 modules. The total expected generated energy during the life cycle of the PV system (25 years) is 1815 MWh, taking into account the degradation factor stated by the manufacturer of the PV module (0.8% annually).

Figure 3 shows the degradation in output energy during the life cycle. It should be noted in the figure that the annual consumed energy at the end of life cycle does not exceed the expected generated energy, otherwise, the PV array wouldn't be able to generate the required energy at the end of the life cycle, so, in the case under study, the size of the PV array increased to 105 modules to satisfy this condition, which is apparent in Figure 3. This size (105 modules) can supply the maximum required load (July water demand); this means that the PV array will be oversized in other months. Hence, a part of the expected solar energy will not be exploited. Figure 4 shows the expected generated energy and energy demand over the year.

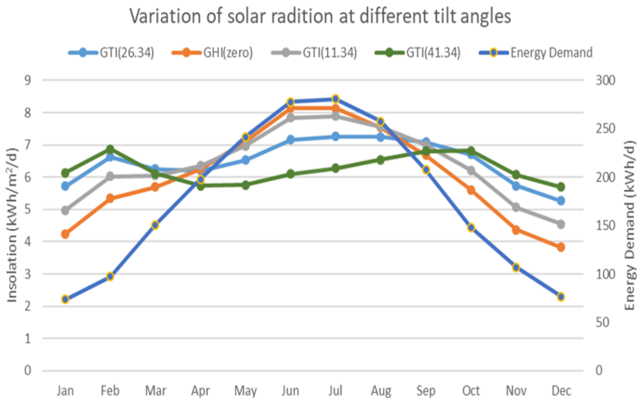

Figure 2. Variation of solar radiation at different tilt angles

The exact number of PV modules needed is restricted by the rated inputs of voltage and current of the inverter and the chosen connection layout of PV modules. So, the best connection layout of PV modules for the case under study is determined to be (15x7); 7 branches connected in parallel with 15 modules connected in series for each. In this case, the maximum input voltage will be 577.5 V, while the maximum input current will be 63.63 A. Figure 5 Shows the PV pumping system under study, and Figure 6 shows the connection diagram of the PV array.

Table 7. Specifications of the selected pumping system

Pump type	Multi-stage, submersible	Motor efficiency	85 %
Pump model	Grandfous (150S400-18)	Motor output power	30 kW
Pump efficiency	70.6 %	Rated Voltage	3x380 V
Pump rated head	195 m	Rated current	66.5 A
Pump rated flow	36 m^3/hour	Starting current	300 A
Pump speed	3450 rpm	Frequency	50 Hz
Motor model	MS6000QFT40	Power factor	0.87
*The expected life cycle of the Pumping system is seven years			

Table 8. Specifications of the selected inverter

Inverter model	SAKO Co.	(SKI650 30kW)	
Min Input Voltage	350 VDC	Rated output power	30 kW
Max Input Voltage	750 VDC	Rated input current	74 A
Output Voltage	380 V 3 Φ	Rated output current	60 A
Efficiency	98 %	Frequency	0 – 60 Hz
*The expected life cycle of Inverter is 15 years			

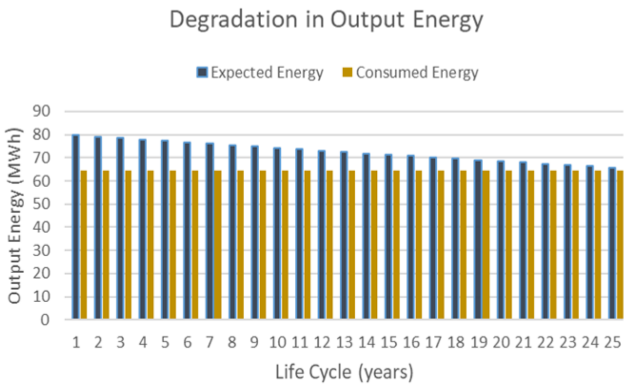

Figure 3. Degradation in the output energy during the life cycle

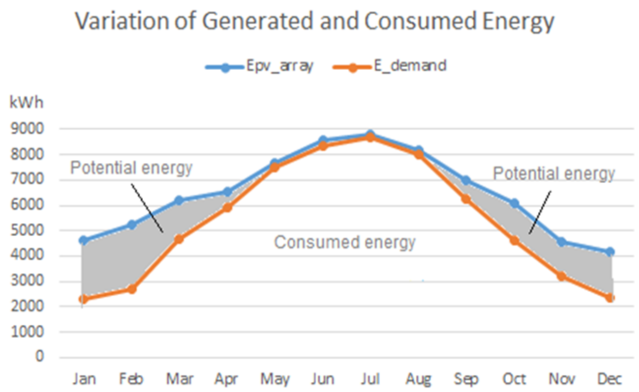

Figure 4. Variation of expected generated energy and consumed energy

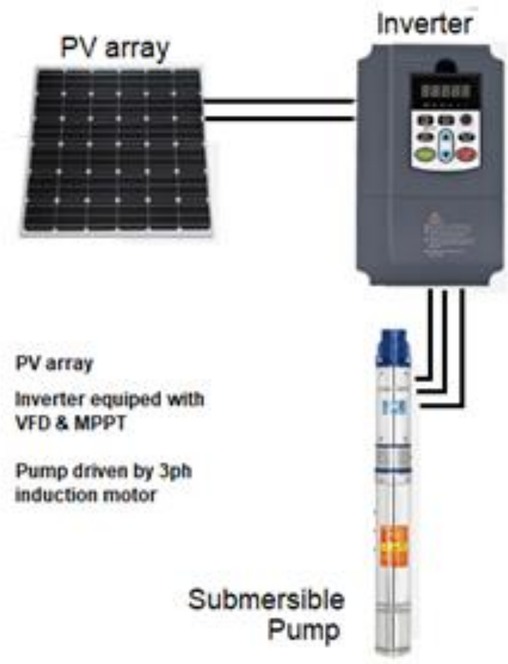

Figure 5. PV pumping system under study

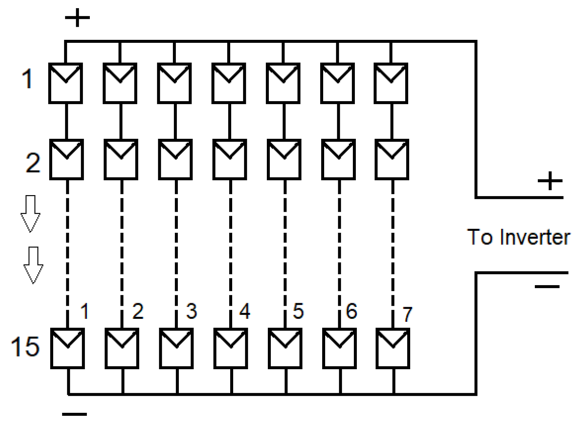

Figure 6. Connection diagram of PV modules

6.6 Sizing of the PV array according to the 2nd option (grid-connected system)

In the grid-connected system, the energy exchange between the PV system and utility grid is possible in both directions, so, in this case, it is not necessary to maximize the PV array to satisfy the maximum load; a smaller PV array may be used, and in case of peak demand, the extra required energy may be imported from the grid and vice versa in periods of an excess energy generation. So, the selection of the best size will depend on economic considerations, the price of exchanged energy, and the cost of the PV system. So, in this study, three sizes (80, 90, 100 modules) have been chosen to be investigated. Figure 7 shows the comparison between the energy demand and the generated energy of the selected sizes, and Figure 8 shows the periods of energy exchange in the case of using a PV array consisting of 80 modules.

6.7 Step 5: Calculating the technical performance indicators

The technical performance investigation of a PV water pumping system would be determined using the indicators proposed by the International Energy Agency (IEA) for evaluating the performance of photovoltaic energy systems [32]. These indicators concentrate on the energy absorbed by the grid (i.e., the useful energy) as defined by IEA, but in PV water pumping systems, the useful energy is the energy absorbed by the pumping system, so the concentration will be on the consumed energy by pumping system rather than the potential energy that may be generated by PV array. These indicators include the total output of energy (Energy yield), Yield factor, Capacity factor, and Performance ratio. The energy yield is the total amount of expected energy to be generated by the PV system. The annual energy yield for all cases is illustrated in Table 9, while the monthly energy yield for all cases is shown in Figure 9. The yield factor (YF) measures the productivity of a PV array under specific weather conditions, and it is defined as the annual, monthly, or daily consumed energy by the pumping system divided by the peak power of the installed PV array at standard test condition (STC), and it is given as following [33]:

$$YF = \frac{E_{Consumed}\ (kWh/year)}{PV_{array}\ (kW_{peak})} \quad (9)$$

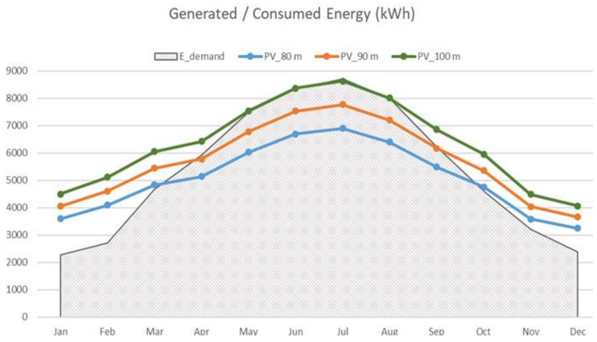

Figure 7. The generated energy of different sizes of PV array compared with the energy demand

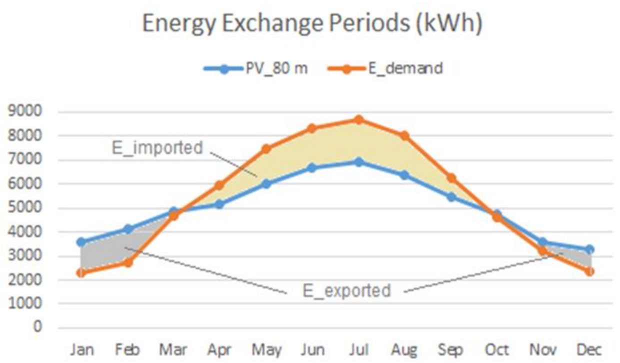

Figure 8. Periods of energy exchange in case of using 80 modules PV array

The grid-connected cases will have the same value of YF because, firstly, the YF is not related to the size of the PV array; secondly, the generated energy will be completely consumed by the pumping system, and in case there is excess energy, it will be absorbed by the grid, while in case of a standalone system, the PV array will generate the energy required by pumping system and still has some potential energy not generated. The annual YF is 2172 for grid-connected systems and 1757 for the standalone system. This value means that the PV array in this location under these weather conditions is capable of producing electrical energy equal to the YF times its rated power during one year. The monthly YF for both systems is shown in Figure 10. These values of YF are reasonable when compared with grid-connected PV systems worldwide. Capacity factor (CF) determines the percentage of usability of the PV system, and it is defined as the ratio of actual consumed energy to the amount of energy the PV system would generate if it is operated at its full rated power for 24 hours per day during the year, but, because the sun is available only about half the day, so, the ideal CF will not be more than 50%. The typical value of capacity factor is usually not more than 40% for most locations in the world; this is due to energy conversion losses and climate change. The CF is calculated as follows [33]:

$$CF = \frac{E_{Consumed}(kWh/year)}{\left(8760 * PV_{array}(kW_{peak})\right)} \quad (10)$$

$$CF = \frac{YF}{8760} \quad (11)$$

The resulting CF is 24.8 % for grid-connected cases and 20.1 % for the standalone case. This value of CF in the case of a grid-connected system is considered high, while it is not bad in the case of the standalone system when compared with other PV systems worldwide. Performance ratio (PR) is defined as the real amount of PV energy delivered to the pumping system in a certain period divided by the output rated energy calculated at the STC data of PV modules [34]. PR is independent of location or system size; it indicates the overall effect of losses on the array's nominal power as a result of; wiring mismatch, inverter inefficiency, PV module temperature, incomplete use of insolation due to soiling or snow, component failures, and system down-time [35, 36].

$$PR = YF \cdot G_{STC} / \sum \bar{G}_t \quad (12)$$

where G_{STC} is the irradiance at STC, and $\sum \bar{G}_t$ is the accumulative irradiance on the plane of PV array within a certain period (annual, monthly, or daily).

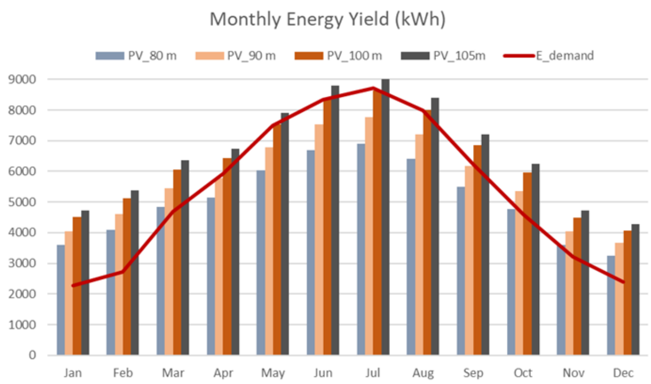

Figure 9. The monthly energy yield compared with the energy demand

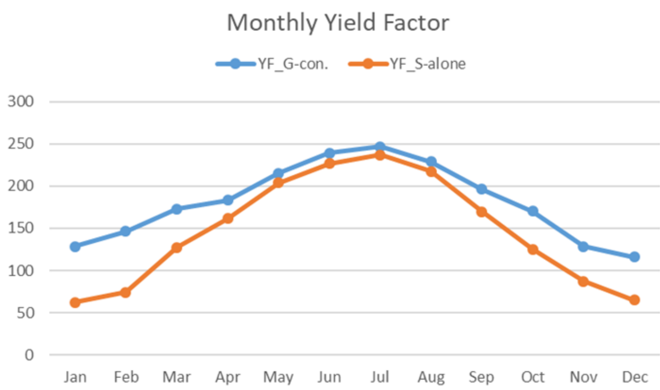

Figure 10. Variation of yield factor during the year for both options

The annual PR for the grid-connected systems is 97.8 %, and the monthly PR is expected to be the same value during the year because all generated energy will be consumed by the pumping system or exported to the grid. In the case of the standalone system, the annual PR is 79.2 %; this value of PR is considered high when taking into account that the potential energy is not included. The monthly PR is in the range of 47.2

% in January, where more potential energy is available but not exploited, up to 94 % in July, where most generated energy is consumed, as shown in Figure 11. The Exploitation factor (EF) is used for measuring the percentage of consumed energy to the potential energy that can be generated by a PV array, especially in standalone systems. This factor indicates the quality of the sizing of the PV array. For best sizing, it should reach near a hundred percent. The Exploitation factor may be calculated for a certain period (annual, monthly, or daily) and may be calculated as follows:

$$EF = \frac{E_{Consumed}}{E_{Potiential}} \quad (13)$$

The calculated annual EF for the standalone system is 80.87 %; this percentage indicates that about 19 % of the capacity of the PV array in the standalone case will not be exploited. The monthly EF is in the range of 48.27 % in January, where more potential energy is not exploited, and reaches up to 96.1 % in July, where most of the energy is consumed by the pumping system, as shown in Figure 11. The high value of EF in July, the month of maximum water demand, indicates the accuracy of sizing the PV array for the standalone system.

Regarding the reduction of GHG emission due to using the PV pumping system, GHG was estimated based on the type of fuel used in Saudi Arabia for generating electrical energy (crude oil & natural gas), considering the share percentage is 50% for each. The estimated reduction of GHG emission is in the range of 46 – 58 tons of CO_2 annually for all cases, as detailed in Table 9.

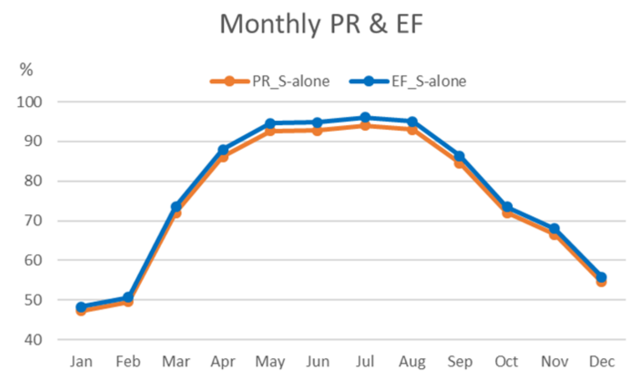

Figure 11. Monthly Performance ratio and Exploitation factor for standalone case

6.8 Step 6: Calculating the economic indicators

The economic feasibility would be investigated using three economic indicators: the Levelized Cost of Generated Energy (LCOE), the Levelized Cost of Produced Water (LCOW), and the Simple Payback Time (SPBT). The Levelized cost of energy (LCOE) is the average cost of energy generated ($/kWh) during the life cycle of the PV system. In other words, LCOE is the life cycle cost (LCC) of the PV pumping system divided by the amount of expected generated energy during the project life cycle.

The Levelized cost of water (LCOW) is the average cost of water produced ($/m³) during the life cycle of the PV pumping system, or in other words, is the life cycle cost (LCC) of the PV pumping system divided by the amount of expected produced water during the project life cycle. LCC is the sum of all expenses associated with the PV water pumping system over its life cycle in today's value of money, taking into account the effect of time on the value of money [37]. The purpose of applying the LCC is to bring back all expenses that are expected in the future to current year costs by discounting them. The life cycle cost is given as following [38]:

$$LCC = C_{capital} + \Sigma\, C_{O\&M} + \Sigma\, C_{replacement} - C_{salvage} \quad (14)$$

The capital cost ($C_{capital}$) of a PV system includes the initial cost for equipment, design of the system, engineering, and installation. The capital cost is always considered as a single payment paid in the first year of the project. The operation and maintenance cost ($C_{O\&M}$) is the sum of all scheduled operation and maintenance costs during the year. The cost of replacement ($Cr_{eplacement}$) is the sum of equipment replacement costs and the cost of all spare parts anticipated over the life cycle of the project. The salvage value ($C_{salvage}$) is the value of the equipment at the end of its life cycle period. Also, in the case of a grid-connected system, the cost/benefit due to energy exchange with the grid would be considered annually. All the anticipated expenses should be discounted to the present worth taking into consideration the inflation rate (i) and the discount rate (d).

The present worth (PW) of any future cost is given by [37]:

$$PW_n = \frac{C(1+i)^{n-1}}{(1+d)^n} \quad (15)$$

where *n* is the number of years.

The Levelized cost of energy (LCOE) can be calculated by dividing the life cycle cost value of the project by the expected generated energy during the project life cycle as follows [39]:

$$LCOE = LCC/\Sigma\, E_{generated} \quad (16)$$

The Levelized cost of water (LCOW) can be calculated by dividing the life cycle cost value of the project by the expected produced water during the project life cycle as follows:

$$LCOW = LCC/\Sigma Q_{Life\_cycle} \quad (17)$$

The simple payback time (SPBT) is considered one of the most requested indicators of the economic feasibility of renewable energy systems. Simple payback time calculates the number of years for the savings of energy from the renewable energy project to offset the initial cost of investment and is given as follows [40]:

$$SPBT(years) = \frac{Initial\ Cost(\$)}{(E_{generated}(Kwh/year)\cdot price(\$/kWh) - C_{O\&M}(\$/year))} \quad (18)$$

The economic analysis is investigated using formulae from 13 to 18 and by adopting the current prices of the local market. Table 4 illustrates the costs of all components according to the local market of Saudi Arabia. The LCOE & LCOW are calculated for the three cases of the grid-connected system in addition to the case of the standalone system. The resulting values are illustrated in Table 10.

The SPBT depends on the cost of energy avoided due to using the PV system instead of using the public grid for supplying the pumping system. The recent energy tariff for agriculture purposes in Saudi Arabia is 0.04267 $/kWh for consumption of less than 6000 kWh monthly and 0.08 $/kWh for more than 6000 kWh monthly [41].

Table 9. Summary results of performance indicators

Indicator	Grid-connected system			Standalone system
	80 modules	90 modules	100 modules	
Annual Expected Energy	60.82 MWh	68.42 MWh	76.03 MWh	79.83 MWh
Annual Consumed Energy	64.56 MWh			64.56 MWh
Annual Potential Energy	-	-	-	15.27 MWh
Annual exported energy	4.28 MWh	7.29 MWh	11.54 MWh	-
Annual imported energy	8.02 MWh	3.43 MWh	0.075 MWh	-
Annual YF	2172			1757
Annual CF	24.8 %			20.1 %
Annual PR	97.8 %			79.2 %
Annual EF	-	-	-	80.87 %
Generated energy during the Life cycle	1383.1 MWh	1556 MWh	1728.9 MWh	1613.92 MWh
Consumed energy during Life cycle	1613.92 MWh			1613.92 MWh
Annual GHG emission (0.76746 tCO_2/MWh)	46.68 tCO_2	49.88 tCO_2	58.29 tCO_2	49.55 tCO_2

Also, the tariff of energy exchange with the grid is not the same in both directions (0.01867 $/kWh for exported energy and 0.04267 $/kWh for imported energy). The SPBT has been calculated based on this pricing system, and the results for all cases are shown in Table 10. The economic indicators showed that the grid-connected system with 100 modules is the best for both LCOE & SPBT, while the standalone system came in the third position, as shown in Table 10. Note that the cost of the pumping system is excluded from the initial cost because the same pumping system will be used in both cases, supplying power from the PV system or from the utility grid. About 90% of consumed energy was priced based on the lowest tariff, but in the case of bigger systems, most of the energy will be priced based on the higher tariff, then the SPBT will go down dramatically. The approach followed in this research is applicable for its worldwide application if all the necessary data are provided. However, the economic viability depends on some factors such as; the quality of solar radiation, the depth of the well, the rate of energy exchange with the public grid. In addition, the irrigation pattern affects the economic viability; if the crop does not demand water all year, it will affect the economic viability badly unless the tariff of exported energy is encouraged.

Table 10. The economic indicators of the case understudy

Indicator	Grid-connected system			Standalone system
	80 modules	90 modules	100 modules	
LCOE ($/kWh)	0.01951	0.01579	0.01332	0.01653
LCOW ($/m^3)	0.01338	0.01218	0.01142	0.01323
SPBT (year)	12.22	10.42	9.65	11.2

7. Conclusions

In this study, the technical performance and economic viability of the use of solar energy in water pumping to irrigate palm trees have been investigated by applying a group of technical and economic indicators to a real case. The investigation was carried out taking into account the variation of water demand over the year, meteorological data of the region, and the characteristics of the borehole in addition to the local market prices of the PV system. The investigation has been done using two options of PV systems; grid-connected system, and standalone system. The investigation has been done through few steps; firstly determining the size of the pumping system based on water demand and characteristics of the borehole, then sizing the PV array based on the available meteorological data and the chosen PV module, then followed by calculating the technical performance indicators; the yield factor, capacity factor, performance ratio, and the exploitation factor. The last step is the estimation of economic feasibility by applying three economic indicators; the Levelized cost of energy (LCOE), the Levelized cost of produced water(LCOW), and the simple payback time (SPBT). The results of applying the technical and economic indicators showed the effectiveness and economic feasibility of the grid-connected system, especially the biggest one in spite of the unfair price of energy exchange with the utility grid. The economic indicators for all investigated systems seem encouraged, and they vary from 0.013 to 0.019 $/kWh for LCOE, 0.011 to 0.013 $/m^3 for LCOW, and from 9.65 to 12.22 years for SPBT. The calculation of SPBT is done based on the lower electricity tariff for agriculture application in Saudi Arabia. In case of using the higher tariff at bigger water demand, the SPBT will go down. Despite the difficult characteristics of the case under study in terms of the amount of water demand, or the borehole depth, as well as the cheap tariff of exporting surplus energy to the grid, the results came encouraging. This leads us to expect better results in areas with less borehole depth or with better solar irradiance, as well as in case of existing any supporting scheme from the government or in case of enhancing the tariff of exported energy. In general, the results are considered encouraging for farmers in the region to convert to solar energy utilization.

Ethical issue

The author is aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the author.

Conflict of interest

The author declares no potential conflict of interest.

References

[1] Arabia, G. A. (2019). Agricultural Production Survey Bulletin for 2019. Retrieved from https://www.stats.gov.sa/ar/1060-0

[2] P. Vincent, Saudi Arabia: an environmental overview., Taylor & Francis, 2008. https://doi.org/10.1201/9780203030882

[3] I. S. Al-Salamah, Develop a useful management tool for water resources allocation in the Saq aquifer in Al-Qassim Region, Saudi Arabia, Iowa State University, 2000. https://core.ac.uk/download/pdf/38905114.pdf

[4] GIS. (n.d.). Retrieved from GIS Data Solar Radiation Maps: http://solargis.info/doc/free-solar-radiationmaps-DNI

[5] Elham Mahmoud and Hoseen el Nather, "Renewable energy and sustainable developments in Egypt: photovoltaic water pumping in remote areas," Applied Energy, vol. 74, p. 141–147, 2003.

[6] P. Purohit, "Financial evaluation of renewable energy technologies for irrigation water pumping in India," Energy Policy, no. 35, p. 3134–3144, 2007.

[7] S. Ould-Amrouche, D. Rekioua , A. Hamidat., "Modelling photovoltaic water pumping systems and evaluation of their CO2 emissions mitigation potential.," Applied Energy, no. 87, p. 3451–3459, 2010.

[8] T. Khatip, "Design of photovoltaic water pumping system at minimum cost for Palestine: a review," Journal of Applied Sciences, vol. 10, no. 22, pp. 2773-2784, 2010.

[9] Abdelmalek Mokeddem , Abdelhamid Midoun , D. Kadri , Said Hiadsi , Iftikhar A. Raja, "Performance of a directly-coupled PV water pumping system," Energy Conversion and Management, no. 52, p. 3089–3095, 2011.

[10] hmet Sahin Z. and Shafiqur Rehman, "Economical Feasibility of Utilizing Photovoltaics for Water Pumping in Saudi Arabia," International Journal of Photoenergy, pp. 1-9, 2012.

[11] M. Al-Smairan, "Application of photovoltaic array for pumping water as an alternative to diesel engines in Jordan Badia, Tall Hassan station: Case study," Renewable and Sustainable Energy Reviews, no. 16, pp. 4500-4507, 2012.

[12] B. G. Belgacem, "Performance of submersible PV water pumping systems in Tunisia," no. 16, p. 415–420, 2012.

[13] Pietro Elia Campana , Hailong Li and Jinyue Yan, "Dynamic modelling of a PV pumping system with special consideration on water demand," Applied Energy, no. 112, p. 635–645, 2013.

[14] Shiv Lal, Pawan Kumar and Rajeev Rajora, "Performance analysis of photovoltaic based submersible water pump," International Journal of Engineering and Technology, p. 552–560, 2013.

[15] A. R. a. U. C. C. Asefa Kabade, "Solar Pump Application in Rural Water Supply - A Case Study from Ethiopia," International Journal of Energy Engineering, vol. 3, no. 5, p. 176–182, 2013.

[16] B. Bouzidi, "New sizing method of PV water pumping systems," Sustainable Energy Technologies and Assessments, no. 4, pp. 1-10, 2013.

[17] J. I. Sodiki, "Solar-Powered Groundwater Pumping Systems for Nigerian Water Sheds," International Journal of Renewable Energy Research, vol. 4, no. 2, pp. 294-304, 2014.

[18] Hussein A. Kazem, Ali H. A. Al-Waeli, Atma H. K. Al-Kabi, and Asma Al-Mamari, "Technoeconomical Assessment of Optimum Design for Photovoltaic Water Pumping System for Rural Area in Oman," International Journal of Photoenergy, pp. 1-9, 2015.

[19] Campana, P. E., Li, H., Zhang, J., Zhang, R., Liu, J., & Yan, J., "Economic optimization of photovoltaic water pumping systems for irrigation," Energy Conversion and Management, no. 95, p. 32–41, 2015.

[20] A. Almarshoud, "Sizing of PV Array for Water Pumping Application," in 32nd European Photovoltaic Solar Energy Conference, 2016. www.researchgate.net/profile/Abdulrahman-Almarshoud/publication/308204012_SIZING_OF_PV_ARRAY_FOR_WATER_PUMPING_APPLICATION/links/57ddb92208ae72d72ea98f8c/SIZING-OF-PV-ARRAY-FOR-WATER-PUMPING-APPLICATION.pdf

[21] A. Al-Baker, Date Palm Trees, Baghdad: Ministry of Higher Education, 1972.

[22] Abou-Khalid A, SA Chaudhry, S Abdel Salam, "Preliminary results of date palm irrigation in central Iraq," Date Palm J, no. 1, pp. 199-232, 1982.

[23] A. Al-Buzaidi, "Palm tree water requirement," in Training course in the cultivation and protection of date palms and dates in Tunisia, Baghdad, 1982.

[24] Mustafa SF Hussein, MS Kahtani, "Effect of frequency of irrigation and quantities of water required on the yield and quality of date fruits of the “Sukkari” cultivars grown in Gaseem, Kingdom of Saudi Arabia," Ministry of Agriculture and Water, Riyadh, 1976.

[25] Al-Amoud AI, Bacha MA. and Al-Darby, A. M., "Seasonal Water Use of Date Palms in Central Region of Saudi Arabia," Agricultural Engineering Journal, vol. 9, no. 2, pp. 51-62, 2000.

[26] H. Al-Ghobari, "Estimation of reference evapotranspiration for southern region of Saudi Arabia," Irrigation Sci, no. 19, pp. 81-86, 2000.

[27] A. Alazba, "Estimating Palm Water Requirements Using Penman-Monteith Mathematical Model," J. King Saud Univ, vol. 16, no. 2, pp. 137-152, 2004.
[28] M. Kassem, "Water requirement and crop coefficient of date palm trees" Sukariah CV"," Misr J. of Agric. Eng, no. 24, pp. 339-359, 2007.
[29] Alamoud AI, Mohammad FS, Al-Hamed SA, Alabdulkader, "Reference evapotranspiration and date palm water use in the Kingdom of Saudi Arabia," Intl. Res. J. of Agric. Sci. and Soil Sci, vol. 2, no. 4, pp. 156-169, 2012.
[30] K.A.CARE, "Renewable Resource Atlas," [Online]. Available: https://rratlas.energy.gov.sa/RRMMPublicPortal/?q=en. [Accessed 20 March 2021].
[31] RETScreen, "Photovoltaic Project Analysis," Natural Resources Canada , 2004. Available: https://unfccc.int/resource/cd_roms/na1/mitigation/Module_5/Module_5_1/b_tools/RETScreen/Manuals/Photovoltaics.pdf
[32] IEA-PVPS, "Analysis of Photovoltaic Systems," International Energy Agency PVPS Task 2, 2000. Available: https://iea-pvps.org/wp-content/uploads/2020/01/rep2_01.pdf
[33] E. Kymakis, S. Kalykakis, and T. M. Papazoglou, "Performance analysis of a grid connected photovoltaic park on the island of crete," Energy Conversion and Management, vol. 50, no. 3, p. 433–438, 2009.
[34] Ebenezer N. Kumi and A. Brew-Hammond, "Design and Analysis of a 1MW Grid-Connected Solar PV System in Ghana," in African Technology Policy Studies Network, 2013.
[35] McEvoy A, Markvart T, Castaner L, Practical Handbook of Photovoltaics: Fundamentals and Applications: Fundamentals and Applications, New York, USA: Elsevier, 2011.
[36] B. Marion, J. Adelstein, K. Boyle , H. Hayden, B. Hammond, T. Fletcher, B. Canada, D. Narang, D. Shugar, H. Wenger, A. Kimber, L. Mitchell, G. Rich and T. Townsend., "Performance Parameters for Grid-Connected PV Systems," in the proceedings of the 31st IEEE Photovoltaics Specialists Conference and Exhibition, Lake Buena Vista, Florida, 2005.
[37] S. A. Kalogirou, Solar Energy Engineering-Processes and Systems, 1, Ed., Elsevier Inc, 2009.
[38] Hussein A. Kazem, Tamer Khatib, "Techno-economical assessment of grid connected photovoltaic power systems productivity in Sohar, Oman," Sustainable Energy Technologies and Assessments, no. 3, p. 61–65, 2013.
[39] Holt, Thomas, Packey, Daniel J., and Short, Walter, "A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies," March 1995. [Online]. Available: http://www.nrel.gov/docs/legosti/old/5173.pdf.
[40] Benjamin S. Rashford, Natalie Macsalka, and Milton Geiger., "Renewable Energy Investment Analysis: What's the Payback?," 2013.
[39] Se.com.sa, "Saudi Electricity Company website," [Online]. Available: https://www.se.com.sa/en-us/customers/Pages/TariffRates.aspx
[40] B. Gastel and R. A. Day, How to Write and Publisher a Scientific Paper, New York, USA: Cambridge University Press, 2017.
[41] W. J. Strunk and E. B. White, The Elements of Style, IV Edition, Massachusetts, USA: Longman Publishers, 2000. ISBN 9780205313426