ELECTRICAL & ELECTRONIC ENGINEERING | RESEARCH ARTICLE

A comprehensive sizing methodology for stand-alone battery-less photovoltaic water pumping system under the Egyptian climate

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Abstract: This work introduces comprehensive sizing methodology to optimize a stand-alone battery-less PV water pumping system (PVWPS). The essential target for the battery-less PVWPS is storing water instead of electrical energy. The drawback of employing battery storage is requiring a complex control system. Accordingly it can considerably raise the cost and maintenance burdens of system. PV panel’s orientation has been investigated for achieving maximum incident radiation collected by PV panels at summer session, when large water quantity is demanded for irrigation purposes. The proposed technique is designed and is applied to estimate the optimal sizing of PVWPS for installing at Minya (Egypt). The obtained results demonstrated that, the PV panels should be horizontally oriented to achieve maximum collected energy during the season of peak water demand. Hence, the PV system offers much more water with a smaller PV cells area, i.e. lower cost of irrigation during summer season. This can be considered cost effective solution for agricultural purposes.

Subjects: Energy & Fuels; Power Engineering; Renewable Energy

Keywords: photovoltaic systems; stand alone; water pumping system; energy efficiency

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PUBLIC INTEREST STATEMENT
The main target of the battery-less photovoltaic water pumping system is storing water instead of electrical energy. The drawback of battery storage is requiring a complex control system. Accordingly it can considerably raise the cost and maintenance burdens of system. Employing battery storage must therefore be discouraged. This is due to the additional expenses added to PVWPS. Furthermore, complexity usually outweighs the obtained merits. A more effective and less expensive means of utilizing excess incoming solar energy is to substitute any deficit in water demand during cloudy days when there is no much insolation level to provide the starting current for the motor pump, and when the system is standby for further maintenance. PV panel’s orientation has been investigated for achieving maximum incident radiation collected by PV panels at summer session. A case study has been installed at Minya (Egypt).
1. Introduction
Energy demand has been increased by modern industrial society. This issue motivates investments toward alternative energy sources for improving energy efficiency (Benlarbi, Mokrani, & Nait-Said, 2004). Solar energy is freely available, abundant everywhere in the world and promising technology that can help mitigate CO2 emissions (Asumadu-Sarkodie & Owusu, 2016; Asumadu-Sarkodie, Sevinç, & Jayaweera, 2016). Furthermore, PV system became increasingly essential for generating electrical power. This is because PV system provides more securing clean power source (Dousoky, El-Sayed, & Shayama, 2011). Egypt has high solar irradiance. Annual global solar radiation of over 2,000 kWh/m²: Areas appear in red or pink (see Figure 1, including Egypt) (Dousoky, 2010; Rezk & El-Sayed, 2013). Moreover, Egypt has large-areas of low-cost land.

Numerous remote regions in Egypt were mainly powered using diesel. Diesel water pumping (DWP) has been considered attractive solution. This is because high power ranges of pumps. Furthermore, using DWP provides pumps and the availability of water when required (Senol, 2012). However, employing diesel generators is characterized by bad maintainability and high operating cost due to discounted fossil fuel costs together with difficulties in fuel delivery (Sawle, Gupta, & Kumar Bohre, 2016). Recently in Egypt the fuel price was doubled. Furthermore, the elaborate and skilled care requirement of the diesel motor turn DWP into a very expensive solution and therefore reduce the margin to be gained by farmers from irrigation. These factors have launched some modern alternative solutions.

One promising solution to overcome such problems is the photovoltaic water pumping system (PVWPS). PVWPS is one of the most interesting and potentially cost-effective solutions used to fulfill irrigation needs (Kaldellis, Meidanis, & Zafirakis, 2011). PVWPS has been considered mostly suitable solution for supplying water in isolated regions, it offer free source of energy, simplicity, reliability, low operating cost, unattended operation, low maintenance, easy installation, and long life for

![Figure 1. Annual solar irradiance (kWh/m²).](image)

![Figure 2. Configuration of PVWPS (www.solartech.net.cn).](image)
irrigation systems (Sawle et al., 2016). Such advantages considered very significant in isolated areas where unavailable electrical grid. The major advantage of PVWPS is that typically the solar resource matches the agricultural water needs. The solar radiation is usually high during the summer session when the water demand is also high (Vick & Neal, 2012).

On the other hand, high initial cost and variable water production in cloudy days and/or different seasons are the obvious drawbacks of the PVWPS. The main target of the current work is to introduce a technique for optimum sizing of stand alone PVWPS. Most PVWPSs operate without using battery storage. The essential target for battery-less PVWPS is storing water via water tank instead of storing electrical energy. PVWPS size should be carefully optimized for minimizing peak power demand and correspondingly total cost of PVWPS. Figure 2 shows the configuration of PVWPS, which consists of a PV array, solar pumping inverter, three-phase AC pump and water storage tank. The PV array is composed of many of PV modules in series and in parallel for meeting load demand. First, PV array converts solar radiation from sunlight into DC power. Then, inverter controls and regulates pumping operation and converts DC to drive AC pumps. After that, the AC pump is driven by a 3-phase induction motor to draw water from well. Finally, water is either stored in a storage tank or directly used for irrigation purposes (www.solartech.net.cn).

The following steps are used for designing PVWP systems.

2. Site description and load specification
The site under study is located at Minia, Egypt (28° N and 30° E). This location has high solar irradiance level. It receives average irradiance about 6.7 kWh/m²/day (http://www.nwp.gov.eg/). The load characteristics are required to start the sizing process (Mohamed, 2005). The farm under study consists of six land pieces with a total of 70 acres. The whole area is planted with olive trees. The water demand ranges between 350 and 500 m³/day in hot seasons and between 200 and 250 m³/day in winter season. The well has the following characteristics:

- Static water level: 40 m
- Well depth: 150 m
- Well discharge rate: 120 m³/hour

Among several available methods of irrigation used nowadays, drip irrigation techniques (DITs) have been considered most promising in Egypt. Integration between PVWPS and DITs was mainly appropriate for isolated regions where unavailable utility grid. DITs reach highest water efficiency about 90% (Mahmoud & El Nather, 2003). The required water demand per unit area irrigated depends on the crop, the climatic conditions, and the soil conditions as well. Figure 3 shows the monthly water demand for the farm under study.

![Figure 3. Monthly water demand (m³/day).](image-url)
3. Sizing different components of PVWPS

3.1. Storage water tank
The main target of the battery-less PVWPS is storing water instead of electrical energy. The drawback of employing battery storage is requiring a complex control system. Accordingly it can considerably raise the cost and maintenance burdens of PVWPS. Employing battery storage must therefore be discouraged. This is due to the additional expenses added to PVWPS. Furthermore, complexity usually outweighs the obtained merits (Morales & Busch, 2010). A more effective and less expensive means of utilizing excess incoming solar energy is to substitute any deficit in water demand during the cloudy days when there is no much insolation level to provide the starting current for the motor pump, and when the system is standby for further maintenance. Perfectly, water tank size must be equal to three-times of peak water demand (Morales & Busch, 2010). From the monthly water demand curve, the maximum daily demand is 500 m$^3$/day; subsequently the appropriate tank size is 1,500 m$^3$.

3.2. Design of the pump flow rate
The pump flow rate can be estimated via dividing daily water demands into PSH. PSH represents peak sun hours every day (Morales & Busch, 2010). Average solar irradiance (SI) in kWh/m$^2$/day represents SI that a certain site may receive it when Sun is shining with peak value for specified period. As peak SI equals one kW/m2, PSH will be equal to average daily SI. The pump flow rate can be determined as follows:

$$Q = \frac{D_{wd}}{n_{psh}}$$

where $Q$: flow rate, m$^3$/h, $D_{wd}$: daily water demand, m$^3$/day, $n_{psh}$: number of PSH per day, hour.

3.3. Estimation of the pump electrical rating
The pump should be selected using manufacturer’s pump data-sheets for ensuring that pump capable delivers desired flow for the known total head. Model of the pump specified via comparing calculated flow rate with pumping head using pump curve. The first step is positioning flow rate (70 m$^3$/h) on X-axis of pump curve (SAER Elettropompe, http://www.saerelettropompe.com/prod-list-EN.asp?c=1) (see Figure 4). Draw a vertical line and locate where this line intersects with a horizontal line representing a pumping head of 100 m. The intersection point shows that the appropriate model the pump (SAER S-151 c/11). Also from the pump curves, at 70 m$^3$/h flow rate the pump efficiency is 65%.

Accordingly, the maximum electrical power of desired pump was specified using water flow rate and total pumping head. It may calculated as shown below (Campana, Li, & Yan, 2013):

$$P_{pump} = \frac{2.725QH}{1000\eta}$$

where $P_{pump}$: Peak electrical power of the pump, kW, $H$: Total pumping head, m, $\eta$: Pump efficiency.

3.4. Sizing of PV system

3.4.1. Determination the best tilt angle of PV modules
Typically, fixed (non-adjustable) PV modules should be tilted toward south by angle equal to the latitude of the module’s location to capture the most year round solar energy (Mayfield, 2010). A tilt
angle of $\pm \delta$ degrees from latitude will increase energy production for the winter and the summer months. PV systems that are used for water pumping should be set to collect the maximum amount of energy in the summer, when water demand is high. However, to maximize energy for both summer and winter pumping, it is recommended that the tilt angle be adjusted.

3.4.2. Calculation of the radiation at different tilt angles
The average daily radiation on a tilted surface ($H_T$) is calculated, as addressed in (Klein, 1977; Liu & Jordan, 1961), at different tilted angles: $\beta$ is swept to identify the value that achieves the maximum collected every month: Sweeping of $\beta$ starts from 0 to $90^\circ$. Then the yearly energy ($E$) can be estimated as following:

$$E = \left( \sum_{n=1}^{12} H_T \right) \times 30.4$$

(3)
The above methodology was simulated using MATLAB software. After that it applied to case under study.

3.4.2.1. Input data to the program:

- The hourly solar irradiance on horizontal surface for case study. It is obtained from Egyptian Meteorological Authority (http://www.nwp.gov.eg/).
- Ambient temperature for site under study.
- Recommended average day (monthly average day).
- The monthly average day is the day in the month whose declination is closest to the average declination for that month (Klein, 1977).
- Monthly average daily extraterrestrial irradiance.

3.4.3. Estimation of optimum number of PV modules

3.4.3.1. Estimation of the daily energy produced from one PV module:

- The hourly produced power from one PV module is calculated as follows (Rezk & El-Sayed, 2013):

\[
P_m = A_m \times H_h \times \eta_m \times \left(1 + \alpha \left(T_c - T_{c, ref}\right)\right) \times \eta_{overall} \tag{4}
\]

\[
T_c = T_a + \frac{NOCT - 20}{800} H_h \tag{5}
\]

where \(A_m\): PV panel area, \(H_h\): Total hourly radiation, kW/m², \(\eta_m\): PV panel efficiency @STC, \(\alpha\): Temperature coefficient of power, \(T_{c, ref}\): Standard temperature (25°C), \(T_c\): Mean monthly ambient temperature °C, \(T_a\): Mean ambient temperature °C, \(NOCT\): Nominal operation cell temperature °C, \(\eta_{overall}\): Overall efficiency (Inverter efficiency, Mismatch and interconnection on module and safety factor for accuracy of radiation data).

- The daily produced energy from one PV module:

\[
E_m = n_{psh} \times P_m \tag{6}
\]

3.4.3.2. Estimation of the total number of PV modules: The total number of PV modules is calculated as follows:

\[
n_p = \frac{P_{pump}}{P_m} \tag{7}
\]

\[
P_{array} = n_p \times P_m \tag{8}
\]

where \(P_{array}\) is hourly PV array output power, kW

4. Results and discussion

The radiation at different tilt angles (from 0 to 90°) has been calculated. The change of solar radiation vs. the variation of \(\beta\) is calculated at all months (A sample is shown in Table 1, Figure 5 and 6). Moreover, the values of \(\beta\) that achieves the maximum collected radiation each month have been identified (illustrated in Figure 7).
Figure 5. Average daily total radiation under different tilt angles, kWh/m².

Figure 6. Total yearly collected radiation under different tilt angles.

Figure 7. Monthly best tilt angles.
Table 1. Sample of monthly average daily radiation under different tilt angle (β varied from 0 to 90°)

| Month    | β = 0° | β = 13° | β = 26° | β = 28° | β = 33° | β = 43° | β = 48° | β = 55° | β = 57° | β = 59° | H_opt | H₂   |
|----------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|-------|------|
| January  | 4.247  | 5.2701  | 6.0765  | 6.1786  | 6.406   | 6.7372  | 6.8383  | 6.9057  | 6.9089  | 6.9049  | 57°   | 6.9089 |
| February | 5.366  | 6.2909  | 6.9568  | 7.0339  | 7.1955  | 7.3819  | 7.4052  | 7.3589  | 7.3289  | 7.2914  | 48°   | 7.4052 |
| March    | 6.208  | 6.7674  | 7.0568  | 7.0762  | 7.0949  | 7.0048  | 6.8966  | 6.6764  | 6.5991  | 6.5156  | 33°   | 7.0949 |
| April    | 7.18   | 7.33    | 7.2013  | 7.1569  | 7.0179  | 6.624   | 6.3722  | 5.963   | 5.8348  | 5.7018  | 13°   | 7.33  |
| May      | 7.658  | 7.4534  | 6.9971  | 6.9056  | 6.6534  | 6.0557  | 5.7152  | 5.1995  | 5.0449  | 4.8876  | 0°    | 7.658 |
| June     | 7.856  | 7.484   | 6.8794  | 6.7670  | 6.4655  | 5.7821  | 5.4062  | 4.8505  | 4.6867  | 4.5213  | 0°    | 7.856 |
| July     | 7.143  | 6.8812  | 6.4022  | 6.3103  | 6.0608  | 5.4842  | 5.1621  | 4.6804  | 4.5373  | 4.3922  | 0°    | 7.143 |
| August   | 7.505  | 7.5043  | 7.2276  | 7.1611  | 6.9679  | 6.4718  | 6.1729  | 5.7036  | 5.5596  | 5.4115  | 0°    | 7.505 |
| September| 6.768  | 7.1963  | 7.3359  | 7.3311  | 7.2844  | 7.073   | 6.9019  | 6.5945  | 6.4927  | 6.3849  | 26°   | 7.3359 |
| October  | 5.289  | 6.0133  | 6.4974  | 6.5488  | 6.6494  | 6.7286  | 6.7066  | 6.6072  | 6.5642  | 6.5149  | 43°   | 6.7286 |
| November | 4.409  | 5.3732  | 6.118   | 6.2105  | 6.4143  | 6.6991  | 6.7779  | 6.8156  | 6.8107  | 6.7988  | 55°   | 6.8156 |
| December | 3.768  | 4.7250  | 5.4903  | 5.5884  | 5.8089  | 6.1382  | 6.2446  | 6.3262  | 6.335   | 6.3372  | 59°   | 6.3372 |
| H₂       | 2.23127| 2.37999 | 2.43927 | 2.4402  | 2.43269 | 2.37669 | 2.3286  | 2.23992 | 2.210165| 2.17853 | 59°   | 2.61799 |

Notes: H₂, Annual radiation, kWh/m², equal to 30.4 × monthly average daily radiation, where 30.4 is the average number of days per month.

* H_opt: Optimum tilt angle (vary each month), degree.

** H₂: Total radiation at optimum tilt angle, kWh/m².
From the table and figures it can be noticed that:

- Optimum fixed (non-adjustable) tilt angle is 28°. It is equal to the latitude of the site under study. At this angle, the total yearly collected radiation increased by 9.3% higher than total yearly collected radiation at horizontal plane.

- When PV modules are oriented with the monthly best tilt angle (β_{\text{opt}}\text{, adjustable}), the total yearly collected radiation increased by 17.33% higher than the total yearly collected radiation in case of horizontal orientation.

- Operating PV system at fixed tilt angel (latitude angle) or monthly best tilt angle it is very effective in maximizing the total yearly collected radiation of PV systems, either grid-connected or stand-alone systems.

- In case of operating PV system at fixed tilt angle of 28°, the total collected radiation in winter session has been significantly increased, compared with that when horizontal orientation, for example in December the increase is 48.31%. On the other hand in summer session, the collected radiation has different trend, for example July, it decreased by 11.65% less than radiation at horizontal orientation. Therefore, this method is not suitable for PVWPS since the water demand increases in summer session.

- The optimum for installing PVWPS in the site under study is the horizontal plane for PV panels to maximize the annual energy production in summer season.

- July is the critical month in summer season, which has a maximum water demand 500 m³/day and minimum average daily radiation 7.143 kW/m²/day.

The above discussion concludes that for PVWPSs, the PV panels should be horizontally oriented to achieve maximum collected energy during the season of peak water demand. Hence, the PV system offers much more water with a smaller PV cells area, i.e. lower cost of irrigation during summer season. This can be considered cost effective solution for agricultural purposes.

The characteristics of the selected PV modules are shown in Table 2 (www.talenpv.com/EnProductShow.asp?ClassID=5&ID=306). Solar pumping inverter has a maximum power point control system, compatible with 3-phase induction motors, adjustable-speed pump. The electrical characteristics of the inverter are shown in Table 3. The hourly output power and water flow rate for each month are calculated to ensure supply load demand. Samples of the calculation results are shown in Table 4 and in Figure 8. Table 5 illustrates the all components of PVSPS for the site under study and its initial cost.

| Table 2. Characteristics of PV module (TLPV-230P) |
|-----------------|---------|-------|
| Item            | Unit    | Value |
| Size            | m       | 1.62 × 0.992 |
| Rated maximum power | W       | 230 |
| Voltage at @ MPP | V       | 30.3 |
| Current at @ MPP | A       | 7.60 |
| Solar cell efficiency | %     | 15.8 |
| Module efficiency | %     | 14.1 |
| Open circuit voltage | V     | 37.2 |
| Short circuit current | A    | 8.2 |
| NOCT            | °C      | 45    |
| Number of solar cell per module | Cells | 60 |
| Solar cell technology | –    | Poly crystalline |
| Temperature coefficient of power | %/°C  | -0.40 |
| Product certificate | –   | IEC61215, IEC61730 |
| Price           | $       | 115   |
Table 3. Characteristics of the selected Solartech inverter (PB30KH)

| Item                        | Unit | Value |
|-----------------------------|------|-------|
| Rated power                 | kW   | 30    |
| Maximum DC voltage          | V    | 750   |
| Recommended MPP voltage     | V    | 530,600 |
| Rated output current        | A    | 60    |
| Output frequency            | Hz   | 0-50/60 |
| Output AC voltage           | V    | 3 PH 380 |
| Conversion efficiency       | %    | 98    |
| Price                       | $    | 10,000 |

Table 4. The hourly output power kW and water flow rate m³/h in July and December

| Time | $H_0$ W/m² | $P_{array}$ | $Q$ | $H_0$ W/m² | $P_{array}$ | $Q$ |
|------|------------|-------------|-----|------------|-------------|-----|
|      |            | July        |     |            | December    |     |
| 7    | 166        | 5.21        | 12.16 | 0          | 0           | 0   |
| 8    | 348        | 10.84       | 25.29 | 89         | 2.971       | 6.93|
| 9    | 536        | 16.57       | 38.67 | 244        | 8.07        | 18.83|
| 10   | 717        | 21.98       | 51.30 | 388        | 12.70       | 29.63|
| 11   | 838        | 25.52       | 59.55 | 528        | 17.10       | 39.911|
| 12   | 888        | 26.89       | 62.74 | 601        | 19.29       | 45.02|
| 13   | 897        | 27.02       | 63.11 | 600        | 19.14       | 44.67|
| 14   | 846        | 25.43       | 59.35 | 554        | 17.61       | 41.08|
| 15   | 727        | 21.84       | 50.98 | 434        | 13.78       | 32.15|
| 16   | 579        | 17.40       | 40.60 | 258        | 8.22        | 19.18|
| 17   | 394        | 11.87       | 27.71 | 71         | 2.26        | 5.28|
| 18   | 207        | 6.270       | 14.63 | 1          | 0.03        | 0.07|
|      | Total      | 211.7       | 506.1 |            | 121.2       | 282.8|

Figure 8. The hourly output power kW in July and December.
5. Conclusion
Conclusions can be summarized as follows:

• A comprehensive sizing methodology for PVWPS is introduced.
• The proposed system uses water tank for storing water to meet the water demand during deficit periods instead of storing electrical energy.
• The proposed methodology was applied to a certain case study and the detailed calculations are presented in this paper.
• In case of PVWPS, the PV modules are not recommended to be tilted by the site’s latitude angle ($\beta = \phi$). This case always does not achieve the maximum solar radiation in summer seasons compared with the other case ($\beta = 0$).
• The proposed PVWPS system is considered one of the best solutions to supply electrical power for water pumping applications in isolated areas.
• The achieved results represent a good framework for components sizing, system configuration and its cost and feasibility studies.

### Table 5. The overall components of the PVWPS and estimated initial costs

| Item | Description                                                                 | Estimated cost ($) |
|------|-----------------------------------------------------------------------------|--------------------|
| 1    | PV modules poly crystalline, 162 module (9 strings × 18 connected in series) | 18,630             |
| 2    | Cables                                                                      | 500                |
| 3    | Three-phase inverter                                                        | 8,000              |
| 4    | Main switch board                                                           | 500                |
| 5    | PV mounting system                                                          | 5,000              |
| 6    | Installation, commissioning and testing                                     | 1,500              |
| 7    | Water storage tank                                                          | 3,000              |
| 8    | AC pump with accessories                                                    | 7,500              |
|      | Total                                                                       | 44,630             |

Funding
The author received no direct funding for this research.

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Citation information
Cite this article as: A comprehensive sizing methodology for stand-alone battery-less photovoltaic water pumping system under the Egyptian climate, Hegazy Rezk, Cogent Engineering (2016), 3: 1242110.

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