Custom sizing and cost analysis of a PV-battery system: Dual-purpose application for residential load and agricultural water needs

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Abstract

This study conducts a technical and economic assessment of a solar water pumping system integrated with an electricity generation system used for a rural house and a farm. For the purpose of application, the location is Bandar-Abbas, a provincial capital in southern Iran. The study incorporates loss of power supply probability (LPSP) and water shortage probability (WSP) concepts along with users' tolerance levels for shortages. A custom code in MATLAB was developed, taking into account a particular energy usage pattern for a household and an irrigation water usage profile for a small-scale citrus farm. The results emphasize the substantial influence of LPSP and WSP thresholds on the system's size and cost. Notably, it was observed that increasing the LPSP tolerance from 0% to 3% could lower the levelized cost of energy (LCOE) by roughly 55% and reduce the WSP by about 36%. Hence, the key factor in such an installation is not technical, but rather human as the tolerance to the risk of service disruption is the key aspect that determines the overall cost, i.e., capital expenditure (CAPEX) and LCOE of a project.

Keywords: Solar water pumping, Photovoltaics, Loss of power supply, Water shortage

1. Introduction

Energy demand is growing due to increases in both population and per capita energy consumption (Key World Energy Statistics, 2021). In response, renewable energy sources are being increasingly adopted by both private and public sectors. Solar photovoltaic (PV) systems, first developed in 1954 by Chapin et al. (1954) have seen significant efficiency improvements.

One of the many applications of PV systems is water pumping and there are many studies in this particular field. However, it is worth noting that few studies focus on the dual application of residential load demand and agricultural water needs. For this combined application, Bhayo et al. (2019) examined a solar PV system designed to power a rural household's electricity requirements of 3.2 kWh per day. The study found instances where the system produced more energy than needed, which was then allocated for water pumping. It was shown that excess energy generation is common and can be redirected to secondary applications like water pumping. However, the study did not evaluate the tolerance level of the users in terms of water shortage probability (WSP) and loss of power supply probability (LPSP), and the effect of those factors on the sizing and cost of the system. In another study, Gualteros and Rousse (2021) developed an open-source software library designed to support various aspects of prefeasibility studies, system sizing, optimization, maintenance, and financial assessments. The software aimed to assist individuals with limited knowledge of solar water pumping systems in remote rural regions. They introduced the concept of WSP as a specific variation of LPSP to measure a community's tolerance for water shortages. The study demonstrated that this tolerance significantly impacts the system's size and cost.

The current study aims to examine technical and economic aspects of a PV-battery system for a farm by incorporating the concepts of LPSP and WSP. The objective is to demonstrate how the selection of appropriate values for LPSP and WSP can influence the overall system cost, highlighting that CAPEX and LCOE are highly dependent on the user-defined thresholds for these two parameters.

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2. Methodology

2.1. Mathematical modelling

Equations (1) to (3) are utilized to calculate the output power of the PV array (Bhayo et al., 2019; Ibrahim et al., 2017; Bukar et al., 2019):

$$\mathrm{P_{PV}(t) = N_{PV} \times I_{PV}(t) \times V_{PV}} \quad \text{(eq. 1)}$$

where the current of the panel and the effect of irradiation on the panel's temperature are defined as:

$$\mathrm{I_{PV}(t) = I_{PV,r} \times \left(\frac{G(t)}{G_{STC}}\right) \times (1 + \alpha \times (T_C(t) - T_{C,STC}))} \quad \text{(eq. 2)}$$

$$\mathrm{T_C(t) = T_{amb} + \left(\left(\frac{NOCT - 20}{800}\right) \times G(t)\right)} \quad \text{(eq. 3)}$$

The state of charge (SOC) of the batteries is determined using equations (4) and (5) (Bukar et al., 2019):

$$\mathrm{SOC_{Charging}(t) = SOC(t-1) \times (1-\sigma) + \left(P_{PV}(t) - (\frac{P_l(t)}{\eta_{inv}})\right) \times \eta_{bc}} \quad \text{(eq. 4)}$$

$$\mathrm{SOC_{Disharging}(t) = SOC(t-1) \times (1 - \sigma) - \frac{\left(\left(\frac{P_l(t)}{\eta_{inv}}\right) - P_{PV}(t)\right)}{\eta_{bd}}} \quad \text{(eq. 5)}$$

where σ represents the hourly self-discharge rate, and P_l indicates the load power. Additionally, η_{bc} and η_{bd} refer to the battery's charging and discharging efficiencies, respectively. The values for σ, η_{bc}, and η_{bd} are 0, 0.97, and 1, respectively (Bhayo et al., 2019).

Furthermore, the yearly loss of power supply probability (LPSP) and water shortage probability (WSP) are defined as:

$$\mathrm{LPSP = \frac{\sum_{t=1}^{t=8760} LPS(t)}{\sum_{t=1}^{t=8760} P_l(t)} \times 100} \quad \text{(eq. 6)}$$

$$\mathrm{WSP = \frac{\sum_{d=1}^{d=365} WS(d)}{\sum_{d=1}^{d=365} IWR(d)} \times 100} \quad \text{(eq. 7)}$$

For economic evaluations, the levelized cost of energy (LCOE) of the project was investigated in the study and is defined as (Bhayo et al., 2019):

$$\mathrm{LCOE_{\ Discounting} = \frac{Life\ cycle\ cost}{\sum_{t=0}^{Lifetime}(\frac{EP_t}{(1+r)^t})}} \quad \text{(eq. 8)}$$

where EP_t represents the annual electricity production. Here, the discount rate (r) was considered to be 15% as in the study by Nikzad et al., 2019 (Nikzad et al., 2019). The life cycle cost is defined as:

$$\mathrm{Life\ Cycle\ Cost = CAPEX_{0-PV} + CAPEX_{0-pump} + CAPEX_{0-else} + O_t + M_t + R_t + F_t} \quad \text{(eq. 9)}$$

$CAPEX_0$ refers to the initial investment or capital expenditure for the components. The operational cost (O_t) and fuel cost (F_t) are assumed to be zero. Furthermore, the maintenance cost is considered to be 2% of the initial cost of the combined water pumping system and PV arrays (Bhayo et al., 2019; Li and Sun, 2018). The replacement cost for the lifetime of the project (30 years) is determined as follows (Bhayo et al., 2019):

$$\mathrm{R_t = CAPEX_{0-battery}} \times \left(\sum_{i=1}^{i=5} \frac{1}{(1+r)^{5i}}\right) + \mathrm{CAPEX_{0-inverter}} \times \left(\sum_{j=1}^{j=2} \frac{1}{(1+r)^{10*j}}\right) \quad \text{(eq. 10)}$$

To simulate pumping, it's necessary to determine π, the system's pumping power. The subsequent equation is used for this calculation:

$$\pi = \rho * g * \dot{V} * H \quad \text{(eq. 11)}$$

It is assumed that the water would be pumped directly from the pump to the farm, and no reservoir is used in the system. This set of equation is sufficient to carry out the results of the calculations presented in section 3.

2.2. Schematic of the system

The schematic of the system, including its main components, is shown in Fig. 1. As can be seen, the system provides electricity for a home and the batteries are used in case the generated energy is insufficient to meet demand. Finally, the pumping system is powered by energy exceeding domestic needs. It can partially or fully meet the farm's irrigation needs. The blue arrows represent AC current while the red ones are associated with the DC counterpart. Hence, Fig. 1 clearly illustrates that an AC water pump is used and that the house is also operating on alternative current. This is not a limitation and the rationale behind these choices is that the most efficient large-size water pumps are operating on AC and most residences involve AC appliances.

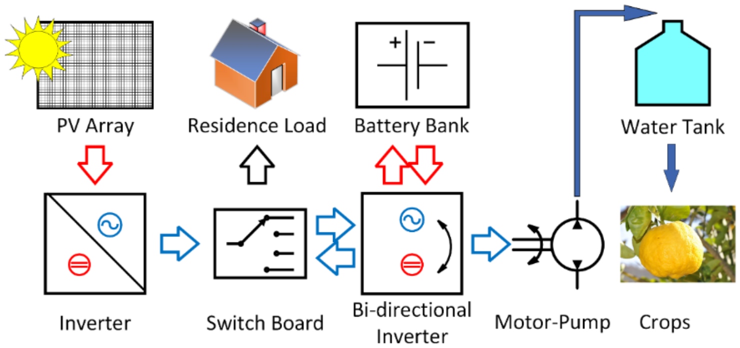

Fig. 1: Schematic of the dual-purpose electrification and water pumping system.

2.3. Algorithm of the study

The algorithm used in the design of the MATLAB code is depicted in Fig. 2. Initially, the algorithm determines the tilt angle for which the total annual irradiation is maximum. Then, it first takes in charge the load demand of the residence. When this electricity demand is met, the system starts charging the batteries, and finally, when there is still excess power, it is used to drive a pumping system. The motor pump is incorporated to provide water for a citrus farm with specific water irrigation requirements. The format of this conference paper does not allow a complete description of the algorithm as it would become overly lengthy. However, the interested reader should contact the authors for more details on the subject.

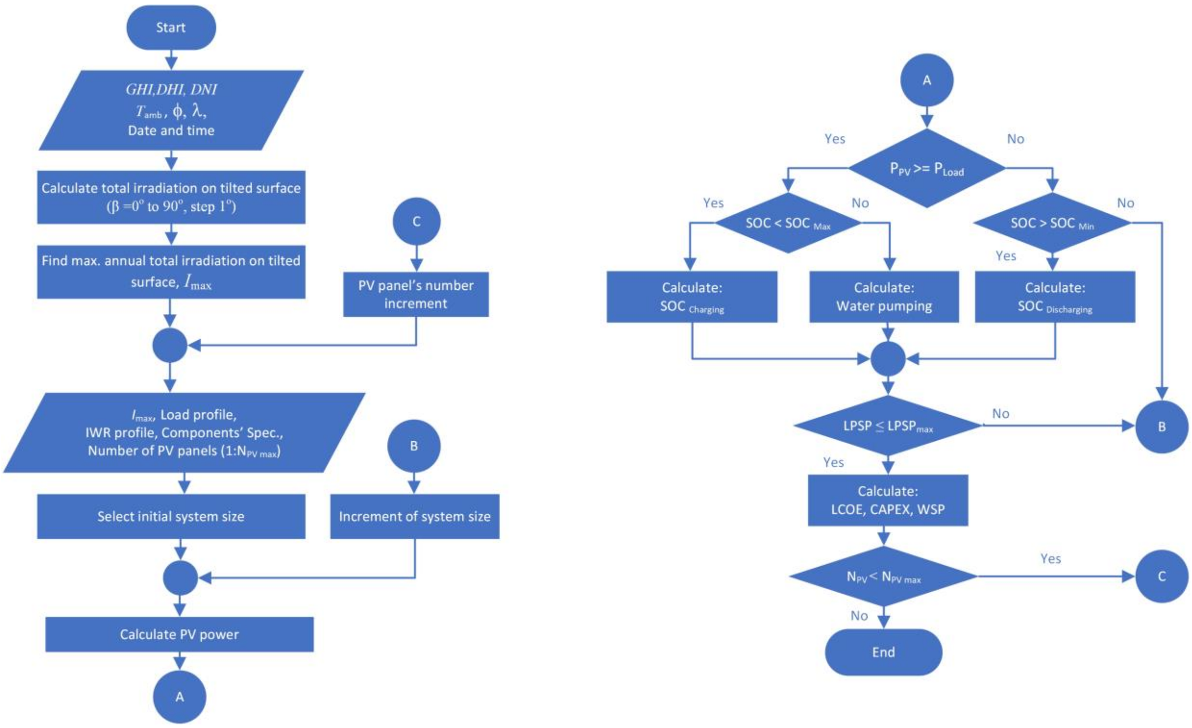

Fig. 2: The algorithm developed for the current study

2.4. Key component specifications

The specifications for all the main components are needed to provide a complete picture of the problem. These specifications are given in Appendix I, based on reference (Bhayo et al., 2019). Among other details, the batteries have a service life of 5 years, after which they are considered to have no residual or salvage value (Numbi and Malinga, 2017; Bhandari and Stadler, 2009; Ndwali et al., 2020). Furthermore, it is assumed that the inverters will have a service life of 10 years. The panels are anticipated to remain operational for the full 30-year term of the project without any performance loss, which is a rather optimistic assumption.

2.5. Case study

The city of Bandar-Abbas, the capital of Hormozgan province in Iran, is selected for the investigation. Bandar-Abbas is located in the southern part of the country. The Crop water requirement (CWR) and Irrigation water requirement (IWR) are shown in Fig. 3. The CWR reaches a maximum in summer with more than 250 mm of water needed while the IWR peaks at slightly more than 150. The needs are much less in winter.

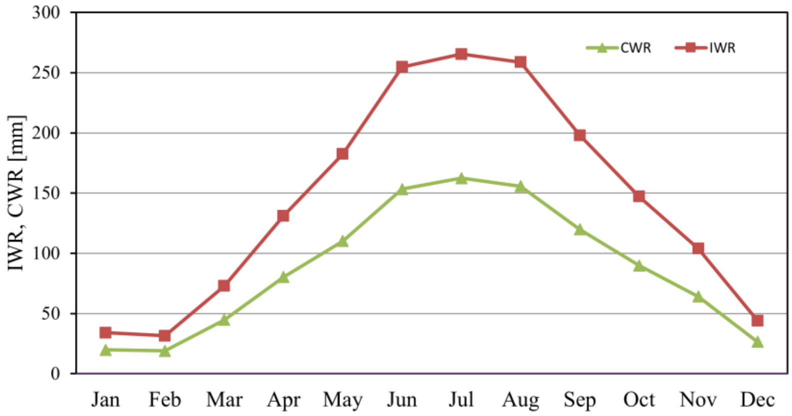

Fig. 3 Crop water requirement (CWR) and Irrigation water requirement (IWR) for a typical citrus orchard located in Bandar-Abbas, Iran (Bazrafshan et al., 2019).

A typical rural Iran electricity load profile for a house is shown in Fig. 5. The needs are basic with a lunchtime maximum of a bit more than 300 W between 12h and 14h and a 255 W consumption from 18h to 23h.

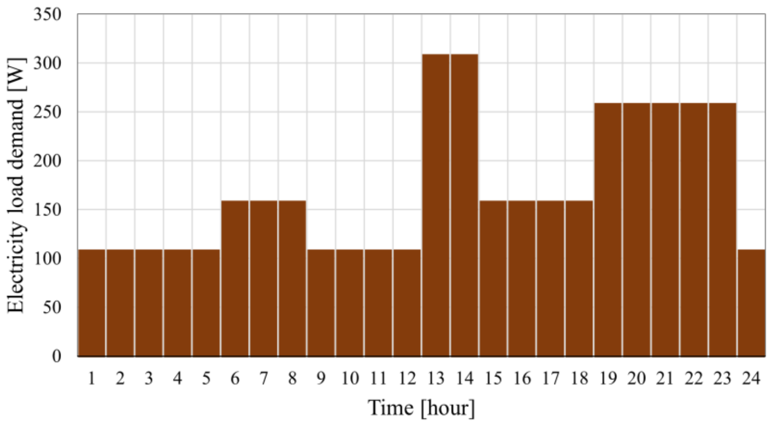

Fig. 4: Typical average hourly load profile in W as a function of the hour of the day used in the study.

3. Results and discussion

Selected simulation results for the proposed system are presented here, focusing on water shortage probability (WSP), levelized cost of energy (LCOE), and capital expenditure (CAPEX) across three loss of power supply probability (LPSP) scenarios. The initial objective is to find the optimal tilt angle for the south-facing panels. For this city, the optimal angle for maximizing total annual irradiation is about 17°, though angles between 10° and 28° offer similar performance.

The result is shown in Fig. 5 for a LPSP threshold of 0% (top), 1% (middle), and 3% (bottom). Please note that the range of the Y-axis is not the same for the three plots in this figure.

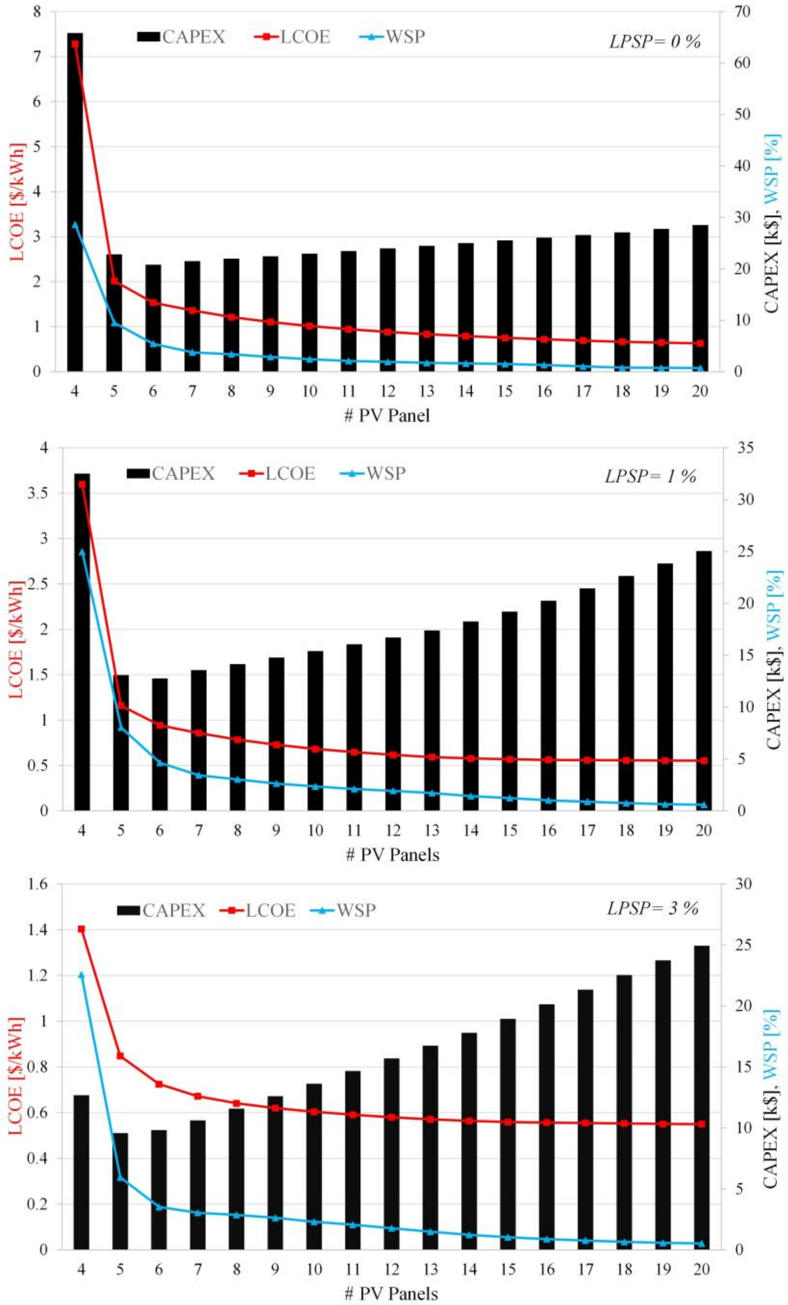

Fig. 5 : PV panel number versus CAPEX, WSP, and LCOE for different LPSP values.

LPSP=0% indicates 100% system reliability, providing uninterrupted electricity to the residence year-round. In this study, LPSP is set according to the tolerance of the house residents, and the minimum PV panel number and the capacity of the battery bank are determined based on this value. In LPSP=0%, a system with 4 panels involves a capital cost of $66,000, a WSP over 28%, and an LCOE above $7/kWh, largely due to the high battery capacity requirement. However, adding more panels quickly reduces both WSP and LCOE. The LCOE reaches around $1/kWh with 10 panels, beyond which further increases in panel numbers have little effect on LCOE but raise CAPEX.

Similar trends are seen with LPSP=1%, where 10 panels result in a 33% lower LCOE compared to LPSP=0%. A higher LPSP significantly reduces CAPEX; for example, CAPEX for a 10-panel system drops from $23,000 to $15,000 as LPSP increases from 0 to 1%.

When a larger tolerance is acceptable (LPSP=3% or about 263 hours per year), a 10-panel system shows a

40% LCOE reduction, with CAPEX as low as $14,000. It can be seen that the system's capital cost has a minimum value at different LPSP levels (6 panels for LPSP=0% and 1%, and 5 panels for LPSP=3%). This is because while adding panels increases system size and investment, a very low number of panels requires substantial battery capacity to meet LPSP thresholds, leading to high CAPEX driven by battery costs.

What this study does not mention is that when the situation requires it, the owner of the farm who tolerates a LPSP of 3% could lower his needs, he could postpone the use of water at the farm or distribute it at 80 or 90% of the curve presented in Fig. 3. He could use an alternative or complementary water storage tank for these hours only, etc.

4. Conclusion

In this paper, for the first time, the effects of the tolerance level of users in terms of WSP and LPSP (i.e., the reliability) on system size and price are evaluated for a dual-purpose hybrid PV-battery standalone system that produces electricity for a rural home and pumps water for a farm. It was shown that accepting a slight increase in the chance of power outages can significantly reduce the size of the system and its LCOE, with only a minor effect on the likelihood of water shortages. This indicates that communities or households with budget constraints might benefit from exploring additional measures to ensure they don't run out of water for irrigation. Finally, there is a point in the CAPEX versus PV panels number plot where additional increases in the number of panels result in only minor changes to WSP and LCOE. This occurs because the demand for battery storage rises significantly after reaching a certain number of panels, which are comparatively more affordable. It is expected that in a near future, when battery storage cost will decrease, the threshold shown in Fig. 5 will shift to the right.

5. References

Bazrafshan, O., Zamani, H., Ramezani Etedali, H., Dehghanpir, S., 2019, Assessment of citrus water footprint components and impact of climatic and non-climatic factors on them, Scientia Horticulturae, 250, 344-351.

Bhandari, R., Stadler, I., 2009, Grid parity analysis of solar photovoltaic systems in Germany using experience curves, Sol. Energy, 83, no. 9, 1634–1644.

Bhayo, B. A., Al-Kayiem, H. H., Gilani, S. I., 2019, Assessment of standalone solar PV-Battery system for electricity generation and utilization of excess power for water pumping, Solar Energy, 194,766-776.

Bukar, A., Tan, C., Lau, K., 2019, Optimal sizing of an autonomous photovoltaic/wind/battery/diesel generator microgrid using grasshopper optimization algorithm, Solar Energy,188, 685-696.

Chapin, P., Fuller, C., Pearson, G., 1954, A New Silicon p-n Junction Photocell for Converting Solar Radiation into Electrical Power, J. Appl. Phys, 25, no. 676.

Gualteros, S., Rousse, D. R., 2021, Solar water pumping systems: A tool to assist in sizing and optimization, Solar Energy, 225, 382-398.

Ibrahim, I., Khatib, T., Mohamed, A., 2017, Optimal sizing of a standalone photovoltaic system for remote housing electrification using numerical algorithm and improved system models, Energy, 126, 392-403.

"Key World Energy Statistics 2021," International Energy Agency, September 2021.

Li, H., Sun, Y., 2018, Operational performance study on a photovoltaic loop heat pipe solar assisted heat pump water heating system, Energy Build., 158, 861-872.

Ndwali, K., Njiri, J.G., Wanjiru, E.M., 2020, Multi-objective optimal sizing of grid connected photovoltaic batteryless system minimizing the total life cycle cost and the grid energy, Renew. Energy, 148, 1256–1265.

Nikzad, A., Chahartaghi, M., Ahmadi, M. H., 2019, Technical, economic, and environmental modeling of solar water pump for irrigation of rice in Mazandaran province in Iran: A case study, Journal of Cleaner Production, 239-118007.

Numbi, B. P., Malinga, S. J., 2017, Optimal energy cost and economic analysis of a residential grid-interactive solar PV system- case of eThekwini municipality in South Africa, Appl. Energy, 186, 28–45.

6. Appendix I: Key component specifications

The details presented here are provided for the researcher who would like to benchmark their results for the same problem. Here Tab.1 provides PV, batteries, inverter specifications and the details that pertains to the water system.

Tab. 1: Key component specifications

Feature	Value
PV panel specifications	
Maximum power	305W
Optimum voltage	32.70 V
Optimum current	9.33 A
Temperature coefficient	−0.37 % / °C
Nominal operating temperature	42 °C
Cost	201$
Battery specifications	
Nameplate voltage	12 V
Capacity	104 Ah
Service life	5 years
Cost	362$
PV inverter specifications	
Output power	2000 W
Efficiency	97 %
Service life	10 years
Cost	867 $
Bi-directional inverter specifications	
Output power	2200-2400W
Maximum efficiency	94 %
Service life	10 years
Cost	992 $
Pumping and storage system specifications	
O&M cost	0.02 of investment cost
Total head	8 m
Service life	30 years
Cost	2.4 $/W