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Design and Economics of a PV-based Pumped Hydro Storage Station in Rural Distant Areas in Egypt

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ABSTRACT

Although photovoltaic (PV) Energy is a viable solution and clean energy source, it is an intermittent source and certainly needs energy storage, particularly in the case of off-grid applications. Batteries are normally used as the common energy storage, despite all their demerits. This paper presents a preliminary design and cost estimate of a potential candidate for energy storage applications, which is the PV-based Pumped-Hydro Energy Storage (PHES). The proposal is suited for application in rural and distant areas, where the public electric grid is not easily accessible. The basic idea is that the required load demand is fulfilled by PV panels during the day. During the periods of high insolation, the PV panels are also used to pump water to a 31-m height tank. Then, at night or in periods of low insolation the water is allowed to flow downwards operating a hydro generator. Based on the average expected load (irrigation and domestic) of distant locations in Egypt, the PV panels and reversible pumps have been sized together with other system components. A cost estimate has been done to compare batteries and PHES for the average lifetime of the two systems. The cost estimate revealed that the PHES would be economically viable after 23 years of service. The system can be easy to extend to a larger scale by adding more reversible pumps and PV panels.

Keywords: photovoltaic; hydro storage; electric grid

1. INTRODUCTION

As the electricity demand increases continuously, research on reliable, efficient, and clean energy sources is advancing globally [1]. However, it is not an easy task to achieve the foregoing requirements because either fossil-fuel-energy or renewable-energy sources have their merits and demerits [2,3,4,5]. The basic challenge of renewable energy sources is their intermittent nature. Otherwise, they provide a clean and consequently an environment-friendly solution. To overcome this intermittent nature, two directions have been followed: construction of hybrid-energy source [6,7,8] and integration of efficient energy storage [9,10,11].

In the case of off-grid renewable energy sources, energy storage is not optional. There are many technologies of energy storages such as: Batteries, Ultra Capacitors, Flywheel [12,13,14], Superconducting Magnetic Energy [15,16,17], Molten Salt [19,20], Compressed Gases [21,22], and Pumped Hydro Storage Systems [23,24,25,26]. Batteries have been and still the most common option as storage for renewable energy applications [27,28,29]. However, their limited power ratings, regular replacement, and maintenance cost represent a challenge for the implementation of a long timescale [30,31,32,33]. Other technologies of energy storage have been also reported in the literature such as fuel cells and supercapacitors [33].

The decision on which energy storage to integrate into renewable energy systems relies on many factors such as Energy and Power Densities (W.h/kg, W/kg), Cycle Efficiency (%), Self-Charge/Discharge Characteristics, Life cycles (number of cycles), Chronological lifecycle and Power Ratings [34,35,36,37]. In some cases, the geographical location plays an important role in this issue [38,39] which favors the option of Pumped Hydro Energy Storage (PHES). Major advantages of PHES include long-time cost regain, high sustainability level, and its ability for large scale implementation. Moreover, PHES constitutes 94 % of the globally installed capacity of energy storage [40]. This paper presents such a situation in the east of Al-Owainat area, Egypt due to the fertility of its soil, the high availability of solar energy, and the presence hills and the Nubian sandstone reservoir in it [41,42].

The main aim of the paper is to present the preliminary design and cost estimation of a complete system that involves PV panels and PHES to feed electricity to 10 domestic users as well as irrigation of 50 acres as a case study to investigate its feasibility, compared to battery energy storage. Section II of this paper presents a description and layout of the site. In Section 3, the design guidelines of the whole system are presented. Section 4

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displays the cost estimation of the main system components with and without batteries. Results and discussion are presented in Section 5.

2. DESCRIPTION AND LAYOUT OF THE SITE

2.1. Site Location

Al-Owainat is in the southwestern part of the Arab Republic of Egypt, 365 km south of Dakhla, New Valley Governorate [43]. East Al-Owainat is one of the distinct areas in terms of soil type, suitability for cultivation, water quality and abundant quantity, in addition to the climate that allows the cultivation of the finest and most valuable strategic and economic cultivations such as alfalfa, wheat, corn, barley, palms, oil crops, medicinal and aromatic plants [44]. Fig. 1 displays a part of Egypt's map showing the area of East Al-Owainat (circled).

East Al-Owainat area is characterized by the presence of the Nubian sandstone reservoir, as it is one of the largest underground reservoirs in the world in terms of its horizontal and vertical extension as well. The saturated thickness of the tank ranges between 200 m in the east of Al-Owainat in the far south and gradually increases in the northern direction until it reaches more than 300 m in Farafra Oasis. The groundwater available in this reservoir is of good quality and the percentage of salts therein is lower [41,42].

2.2. Preliminary Site Layout

The site consists of 10 rural houses, 50 acres to be cultivated, a groundwater well, a storage tank for drinking and irrigation water, an electric machine for grinding agricultural cereals that be used during the day or at night, electric water pumps for irrigation by spraying that work at night, a hydroelectric power station as it is one the most efficient and effective energy solutions [45]. The hydroelectric power station consists of an overhead tank, a lower tank, water turbines. There is also a photoelectric (PV) station that consists of several photovoltaic modules - three-phase inverter and submersible pumps, three-phase electric transformer - automatic connection plate to separate and switching panel.

Figure. 1. Part of Egypt's map with the area of East Al-Owainat circled.

The groundwater well has submersible pumps to pump water from the underground well to the upper tank only once per day. The overhead tank is built next to the underground well over a hill. Water is pumped from the well to the overhead tank whenever the water level in the tank decreases due to evaporation. There is another lower tank built on the slope of the upper tank such that the water circulates between them in a closed-loop where the water is used to generate electricity during the night or when the PV output is not enough to feed the loads. The groundwater well feeds another reservoir to supply the area with the water needed for drinking, irrigation, household uses and irrigation as well as for rural animals.

3. SYSTEM DESIGN

3.1. Design Steps

The first step of the design has been the identification of a suitable location to employ its topography aiming to reduce the total capital cost of the project. As said in Section II, East Al-Owainat was selected due to explained reasons. Then, the required data regarding all water requirements and the electrical loads were collected to calculate: 1) capacities, heights, and locations of the two water reservoirs, 2) the power ratings of the PV panels as well as the hydraulic station. Subsequently, the capacities, numbers, and types of water turbines were identified. All required calculations were done to complete the design of the system as follows.

3.2. Calculations

3.2.1. Hydraulic Power Station

To minimize the system cost, a reversible pump is selected to play the role of a water pump and a water turbine as well. The use of reversible pumps in renewable energy applications has been reported in the literature such as [46,47,48]. The first step in the design was to estimate the daily energy consumption of an average rural house, for which the details are given in Appendix A, where a diversity factor was taken as 1.3 and group diversity factor was taken as 1.1 [49, 50]. Based on these calculations, the power required for 10 homes is 3252.7 W.

The next step is to determine the daily energy consumption of the whole site. There are two main loads: agricultural grain milling machine; Irrigation water pump for Fixed spraying. Details of these loads are given in Appendix B. Based on the assumed loads; the total power required for the selected electrical machines per day is 790.9 W. Consequently, the total power required is 3252.7+790.9=4043.6. Considering a power loss of 30 % in ally system components, the power required is then 4043.6x1.3= 5256.7 W. The water flow rate can be calculated using eq. (1) as [21]:

$$P = \eta \times \rho \times Q \times g \times H_{\text{net}} \qquad (1)$$

Where
P = generator output = 5256.7 W
η = Efficiency of generating units (turbine + generator), assumed as 90%
Q = Water flow through the turbine (Discharge) in (m^3/sec)
ρ = Density of water = 1000 kg /m^3
H_{net}=net head of water (the difference in water level between upstream and downstream of the turbine) =30 m
g = Gravitational acceleration = 9.81 m^2/s

Substituting all the above values gives Q = 0.02 m^3/s = 72 m^3/h. This implies that if the pumps work for hours, they will store 432m^3 of water. Assuming two autonomous days, they should be able to store 864 m^3 of water.

3.2.2. Pump Calculations

As the efficiency of Francis turbine is the highest among other turbine types and it is the most commonly used in hydropower plants [51], it is selected in this work. More precisely, Francis-type reversible pump-turbine has been selected to minimize the total cost, as stated in Section II. The pump must raise the water against the net vertical head in addition to the hydraulic losses due to friction. Such losses are expressed in meters and they depend on the diameter and length pipes as well as the shape of connections. However, as preliminary calculations, they can be taken as 5-10 % of the required water head. Thus, they were considered here to be 7% of the 30-m head. Consequently, the total required head by the pump is 30+0.07*(30+1) = 33.17 m, where one meter is added that represents the height of the water tank. The power of the pump is calculated using eq. (2) as follows.

$$P_h = \frac{Q\ \rho\ g\ H_{\text{tot}}}{3600 \times 1000} \quad (٢)$$

Where Q is the volumetric flow rate of water through the pump (m3 /h). H_{tot} is the total head required by the pump. In Egypt, the sun hours range from 6-10 hours [52]. A value of 9 hours is considered here for sun hours. Thus Q = 864/9 = 96 m^3/h. Then the pump power is 8.7 kW or 11.7 hp. Considering that the efficiency of the associated electric motor is 0.85 [53,54], the required electric power is 10.2 kW or 13.7 hp. As the nearest commercially available turbine is 6 kW [55]. Thus, two of these turbines are selected.

3.2.3. Calculations of the PV System

The PV panels are required to feed: 10 houses, water pumps for drinking and irrigation, and other electrical machinery in the site such as gain grinding machine and irrigation water pump for Fixed spraying.

3.2.3.1. Calculations of the water pumps

The design process of the water pumps follows the same procedure as the hydraulic turbine that was presented in Section B.2. First, the water flow rate must be determined. This necessitates the estimation of the daily water amounts of drinking and irrigation. All relevant calculations are given in Appendix C. Based on the calculations in Appendix C, the amount of water needed to be stored for irrigation and drinking is 210 m^3. As the sun hours are 9 hours as in Section B1, the water flow rate is 210/9 = 23.3 m^3/h. Knowing that the depth of the well is 30 m and the vertical height is 30 m, and considering 7 % hydraulic losses, the total dynamic head required by the pumps is 65.27 m. Reapplying eq. (3) to determine the power of the pump yields that the required pump should have a rating of 4.1 kW or 5.5 hp. Considering a motor efficiency of 85 %, the power rating of the required motor is 4.8 kW or 6.4 hp. Here, it is preferred (for repair and maintenance purposes) to have two submersible pumps, each of them is rated at 3.25 hp and 380 V.

3.2.3.2. Sizing of the PV Panels and Inverter

The PV panels will feed all the electrical loads as shown in Table 1.

Table 1. Electrical loads required energy for the site

Electric Loads	Power [W]	Quantity	Hours/day	Energy Wh/day
Power pump	5219.9	2	9	93958.2
Submersible pump	2423.5	2	9	43623
Agricultural grain milling machine	2237.1	1	1	22371
Total Required Energy for Electrical Machines				**139818.3**

The total amount of energy required from the PV panels is 139818.3 plus the energy of the 10 houses as in appendix A, i.e. Total energy = 139818.3 + 111162 = 251 kWh. Compensating for 30 % electrical losses, the required energy becomes 326.3 kWh. From Table 1, the total amount of power is 17.5 kW. Taking a diversity factor of 1.1, the required power for the electrical machines becomes 17.5/1.1 = 15.9 kW. Adding the power required for 10 houses gives the total amount of power as 15.9 + 3.25 = 19.15 kW.

The size of the PV panels is calculated (based on 9 sun hours) as 326.3/9 = 36.25 kW. Selecting a 260-W PV module yields the number of modules as 36.25/0.26 ≈ 140 modules. The characteristics of the selected module are given in Appendix D. The system voltage was identified as 400. Hence, the number of series modules = 400/30.8 = 13 modules, and consequently the number of strings is 140/13 ≈ 11. This gives a total of 143 modules.

The total amount of the required electric power is 19.15 kW. Adding a safety margin of 30 % gives the total power should be supplied with the inverter as 19.15x1.3 = 24.9 kW. The nearest commercially available inverter is 27 kW.

3.3. Batteries and Charge Controller

Although the proposed system is essentially a replacement or an alternative to the battery banks, the sizing of batteries and their charge controllers has been done for the sake of comparison between the two alternatives in terms of the total cost. The batteries are size based on the total energy required by all the operated loads, which in this case is 132.5 kWh according to the data given the appendices. Assuming 30 % electrical losses, the total energy would be 172.25 kWh. Assuming 2 days of autonomy, the total required energy by the batteries would be344.5 kWh.

If the allowed depth of charge is 50 % and the battery voltage is 12 V, then the total capacity of the batteries would be (344.5k/(0.5*12)) = 57417 Ah. Choosing a 200-Ah battery yields that the total number of batteries 57417/200 ≈ 288 batteries. Since the system voltage is 400 V and the battery voltage is 12 V, then the series batteries are 400/12 ≈34 batteries. Hence the number of battery strings is 288/34 = 8.47 ≈ 9 strings. This gives a total of 34x9 = 306 batteries.

The current rating of the charge controller(s) is directly related to the short-circuit current and the number of strings of the PV modules. According to the data given in Section 3.2 and allowing a 30 % safety margin, the current of the charge controller is calculated as Icc = 8.91 x 11x1.3 = 127.41 A. Selecting a 50-A charge controller implies that the number of needed charge controllers is 3.

4. ESTIMATION OF THE STORAGE-SYSTEM COST

In this Section, the cost of the storage system is estimated for the two alternatives: PHES and Batteries with charge controllers. The main objective of the Section is to able to compare the two alternatives and determine the number of years after which the PHES would be economically visible.

4.1. Cost of Batteries and Charge Controllers

4.1.1. Cost of Components

Most of the cost elements here are based on the local currency (LE) according to the local market in Egypt. However, some components are not available in local currency and only available in USA Dollars. So, the estimation may be slightly different due to the fluctuation of the Egyptian Pound against the USA Dollar. At the time of estimating the cost, it was 1 $ -US A = 15.8 LE.

The designed batteries in this work are rated 200 Ah and their number is 297 batteries as calculated in Section B3.3. According to [56], the price of a 200-Ah battery is 206 $ which is equivalent to 3254.8 LE. Then the total price of the batteries is 967k LE. Regarding the charge controllers and according to [57], the price of a 50-A charge controller is 11.30 $ which is equivalent to 178.54 LE. Hence the cost of 3 charge controllers is 535.62 LE, which is insignificant compared to the cost of batteries, i.e, the total cost of the storage system is 967k LE, approximately.

4.1.2. Cost of Maintenance of Batteries

To be able to estimate the total cost of batteries and the cost of a kWh produced by them, it is necessary to identify the lifetime of both batteries and PHES. According to [58], the lifetime of PHES ranges from 50 to 150 years at almost no deterioration of performance. In this work, the lifetime of PHES is considered 80 years as reported in [58]. On the other hand, the batteries are usually replaced every 5 years of service [59]. Normally, the batteries are nor replaced rather repaired. Thus, only the cost of replacement is considered. The price of battery increases by 5% every year as reported in [60]. Since the batteries will be replaced every 5 years, they would be replaced 16 times based on the assumed lifetime of the PHES. Although the technology of batteries is quickly developed, there is no reliable source that presents how the development of technology would affect their prices. Therefore, the cost replacement is calculated based on the current price. The replacement cost over the 80 years is calculated through the following steps.

1- The battery price (967 k LE) is multiplied by the increase rate of 1.05 and then the price is calculated each year till 80 years.

2- The prices of batteries in the 5th multiple years are summed. Hence, the replacement cost of the batteries is 206.5 M LE.

The replacement cost of the charge controller is calculated similarly and found to be 0.114 M LE. Hence, the total replacement cost is 206.64 M LE.

4.2. Cost of PHES

4.2.1. Cost of Two Tanks

The tanks are cylindrical with a diameter of 14 meters and a height of 6 meters. Based on the local market and resources, the cost of one water is 4 M LE, which implies that the total cost of the two tanks is 8 M LE.

4.2.2. Cost of Reversible Pumps

One three-phase, 380-V, 6-kW reversible pump costs 0.316 M LE [55]. Then, two pumps cost 0.632 M LE. As the reversible pumps are designed to withstand high pressures and continuous operation, there is no replacement cost [62,63]. However, according to [61], there is an operational cost of PHES that ranges from 6 to 43.3 US $ per kW per year. Adding the highest value of this cost yields the total cost of the PHES is to be 9.29 MLE over the 80-years lifetime.

5. RESULTS AND DISCUSSIONS

Two alternatives have been studied to store the energy during the day and deliver it during the night or in cloudy days: pumped hydro energy storage (PHES) and batteries with charge controllers. Table 2 shows a comparison between the two alternatives in terms of components and costs. It is important noting that the inflation rate of the currency was not considered in the calculations, as it would affect both alternatives equally.

Table 2. Comparison between PHES and Batteries

Item	PHES	Batteries
Components	• 2 reversible pumps, 6 kW, 380-V, three-phase • 2 water tanks	• 297 batteries, 200-Ah each • 3 charge controllers, 50-A each
Capital Cost in M LE	8.632	0.9667
Lifetime (years)	80	5
Replacement Time (years)	NONE	5
Replacement cost per year in M LE	NONE	5% increase. The first replacement cost is: 0.9667×1.05^5
Operational and Maintenance cost per year in M LE	0.0082	Included in the battery price
Total cost over the 80 years in M LE	9.29	206.64

It is clear from Table 2 that the cost of batteries increases exponentially as the time advances while the cost of PHES is almost constant. Plotting the two costs per 5 years as displayed in Fig. 2 indicates that 23 years is the time after which the PHES becomes economically better than batteries. Since the lifetime of PHES is moderately taken as 80 years, the PHES proves to be a valuable solution to the energy storage problem. One more advantage of PHES over batteries is the environmental impact where the disposal of batteries requires careful attention [64].

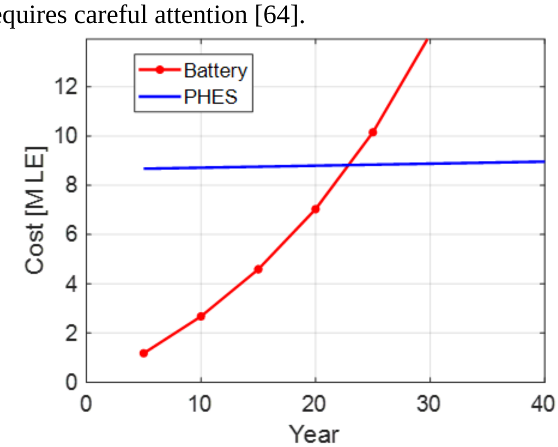

Figure. 2. Cost of PHES and Batteries per 5 years

6. CONCLUSIONS

The feasibility of a pumped hydro energy storage system (PHES) as an energy storage solution has been investigated for the implementation in Egypt for rural and distant regions. Exploring the topography of south Egypt has identified the Al -Owainat area as a potential candidate for the installation of PHES to feed 10 houses and irrigate 50 acres. The design of the PHES included two reversible pumps that have dual duties as a pump and water turbine for electricity generation. It also included the design of two water tanks. The PHES cost has been compared against the cost of an equivalent system of batteries and charge controllers. Preliminary calculations of the two systems revealed that 23 years is the break-even point after which the PHES becomes economically visible. Not only economic issues but also environmental impacts favour the PHES solution.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT:

Dr. Hilmy Awad: Conceptualization, Original draft, and Software
Nadia Shokri: Methodology, Calculations
Prof. Ahmad Atalla: Supervision and Guidance
Dr. Hassan Mahmoud: Field Data and Guidance

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A: Daily loads of an average country-side house

To determine the daily energy consumption of a country-side house, the data given in [65] was considered as shown in Table A.1.

Table A.1. Daily loads of an average country-side house

Electric Loads	Power [w]	Quantity	Hours per day	Total Power [W]	Energy per day [Wh]
Washing machine	200	1	1	200	200
Refrigerator	200	1	24	200	4800
TV + Receiver	35	1	8	35	280
Fan	100	3	12	300	3600
Blender	400	1	1	400	400
Led Lamps	9	6	12	54	648
iron	1000	1	0.25	1000	250
radio	10	1	12	10	120
Led Lamps	24	3	12	72	864
			Total	**2271**	**11162**

The Average power required for a single home = 11162 / 24 = 465.08 W

Considering a Diversity factor = 1.1 and a Group Diversity factor = 1.1 [49,50], the average power required for a single home =465.08 / 1.3 =357.8 W and the power required for 10 homes = 10 × 357.8 / 1.1 = 3252.7 W

Appendix B: Electrical Machines of the site

The site contains:

1. Electric agricultural grain grinding machine

The electric grain grinding machine has a power rating of 3 hp and grinds all types of grains such as corn, barley, broad beans, fodder, and farm wastes. It grinds from 150 to 200 kg per hour [19].

2. Fixed spray irrigation water pump

When growing the main crops such as (wheat - barley - alfalfa - peanuts - sunflower - corn - sesame), irrigation with fixed sprinklers is preferred.

It is used to irrigate 10 acres (185 x 250) meters. We need a pump for irrigation water with engine POWER of at least 20 hp [20], that is, we need 5 engines to irrigate 50 acres with total POWER= 100 hp = 74569.99 watts.

Table B.1. Daily consumption of the selected electrical machines

Agricultural machinery	Power [W]	Quantity	Hours/ day	Po wer [W]	Ener gy day [Wh]
Agricultural grain milling machine	2237.1	1	1	2237.1	2237.1
Irrigation water pump for fixed spraying	14914	5	0.25	3728.5	18642.5
			Total	6015.6	20879.6

The average power required per day = 20879.6/24 = 869.98 W. Then, the total power required for the selected electrical machines per day is 869.98 / 1.1 = 790.9 W.

Appendix C: Water Needs

C.1. Daily water needs for irrigation

Specific crops were identified based on the nature of the site and the inhabitants. These crops and their water needs are shown in Table C1 [66].

Table C1: Water needs for irrigating the selected crops

Crop	Water [m^3/acre]	Water [m^3/acre/year]	Water [m^3/acre/day]
Barley (Winter)	321.9	659.7	1.8
Peanuts (Summer)	337.8		
Municipal Beans (Winter)	217.8	916.7	2.5
Yellow corn (Summer)	698.9		
Alfalfa (permanent)	238.6	283.6	0.65

The crops are distributed in acres and their needed amounts of water per day are shown in Table C2.

Table C2. Distribution of Crops through 50 acres

Crops	Acres	Water [m^3/day]
Barley + Peanuts	20	36
Municipal Beans + Yellow Corn	20	50.2
Alfalfa	10	6.5
The total amount of water for 50 acres		92.7

C.2. Daily water needs for Drinking

These amounts of water include both individuals and some rural animals are shown in Table C3 [C1].

Table C3. Water requirements for a country house

Item	Average Consumption (Liters/head/day)	Quantity	Total Consumption (Liters/day)
Rural Family	190	4	760
Dairy cow	114	2	228
Sheep and goats	8	10	80
Calf	41	1	41
Poultry	0.45	50	23
Cattle	57	1	57
Rabbit	0.2	10	2
Total consumption for 1 house = 10 x 1191 Litres/day = 11.91 m^3/day			

Thus, the total amount of water for irrigation and drinking is 92.7 + 11.91 = 104.6 ≈ 105 m^3/day. Considering two days of autonomy, then the amount of water becomes 210 m^3. To store such amount of water, a cylindrical reservoir will be built with a diameter of 10 m and a height of 3 m.

Appendix D: Characteristics of the selected PM module

Maximum Power (P_{max})	260 W
Open Circuit Voltage (Voc)	38.10 V
Short Circuit Current (I_{sc})	8.91 A
Maximum Power Voltage (V_{mp})	30.87 V
Maximum Power Current (I_{mp})	8.42 A