INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
A. Khalid et al., Vol.13, No.2, June, 2023

Economic Analysis of a Solar Operated Irrigation Pump for Different Crops under Egyptian Climatic Conditions

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Received: 19.02.2023 Accepted:10.04.2023

Abstract- - The present investigation aims to analyze and compare the performance of a photovoltaic-powered submersible pump under three various climatic conditions in Egypt. The pump is employed to irrigate wheat and maize crops in a one-feddan farm by adopting the actual well depth and crop water requirement in the proposed locations. Furthermore, the total power of solar modules required to operate this pump is computed to reveal the auxiliary power needed for these crops at the proposed locations during their irrigation season. At the introduced weather conditions, an economic analysis is conducted to examine the feasibility of the solar powered pump versus that operated by traditional diesel generator. The results reveal that the net generated power via the PV panels to operate a pump used to irrigate wheat crop is 325, 495 and 17 kW and for maize crop is 1786, 1767 and 266 kW in Aswan, Alexandria and Giza cities, respectively. In Alexandria, Giza, and Aswan cities, utilizing solar PV panels as a power source for the pump used to irrigate wheat crop has proven its economic feasibility as it is expected to dramatically reduce the total cost by around 49, 46, and 76%, respectively and for maize crop cost is reduced by 47, 48 and 66% in the same locations compared to diesel generators.

Keywords: Water pumps; Irrigation system; Solar PV system; Diesel generator; TRNSYS.

1. Introduction

Food production and trade are strongly related to the global water crisis. Nowadays, agriculture is responsible for around 3200 billion cubic meters representing about 72% of international water demands [1]. Recently, farmers in Egypt have immigrated to the western desert to maximize usage of the huge areas of undeveloped land. Despite conventional diesel pumps are frequently employed for irrigation, rural areas have limited access to electric networks. Also, the adverse impacts of fossil fuels on the environment accompanied with using diesel pumps are a motivating factor for the renewable energy usage [2]. Thus, using photovoltaic panels (PV) to supply the required electrical power for the pump is an optimal solution that had proven its reliability and economic feasibility compared with diesel pumping systems particularly in areas of average daily solar radiation intensity more than 5 kWh/m^3/day, water demands less than 100 m^3/day, and medium water depths of l5 to 60 m [3]. Pumping systems could save approximately 223,800 million liters of fuel and eliminate yearly emissions by approximately 469.98 billion kg of carbon dioxide [4]. As a result, it contributes to resolving the challenges of resource depletion and global warming.

Numerous researchers were conducted in the past years on investigating the overall performance of solar pumping system by adopting different parameters.[5] achieved promising results in the study that concerned about the usage of PV panels in generating power for the pumping requirements of drip irrigation system. Additionally, different studies focused on systems with power requirements of about 1 kW in different sites such as Namibia, Jordan, India, and Morocco [6-8]. Also M.Kingsley established that the efficiency of the solar panel has a direct relationship with solar voltage and temperature [9] F.Javed improved the annual power production for a case study in Pakistan by using solar radiation tracker system to track sun for optimal amount of radiations.[10] Else, Hammad [11] presented a solar pumping water system using 14 wells spread across the Jordan east and south east desert that were eligible of pumping 30–100 cubic meters water/day to meet the living requirement in these remote areas.

M.Kingsley , R.Uhunmwangho , N.Nwazor , E.Mbounu and K.Okedu made a comparison between two conditions soot free and soot polluted condition in different locations to determine the effect of soot on the temperature of the PV panels resulting in that the present of soot reduces solar PV panels output by 27.8%[12]. K.Eguono , K.Okedu and R.Uhunmwangho presented a software using HOME software for hybrid optimization of multiple energy resources to evaluate a prototype model in different areas in Nigeria and this option provides opportunity of the lowest COE at 0.08 USD/kWh.[13].Also F.Alsharbaty and Q.Ali proved that adopted applications of smart grid can be handled successfully by secured wireless communications network (WCN) based on decentralized processing and self-powered.[14]

P. Narale, N. Rathore, and S. Kothari [15] analyzed the life cycle cost of the diesel and solar powered pumping system. They revealed that solar water pumping systems surpassed diesel water pumping systems. Also, Bhave [16] concluded that the solar PV pumping system is suitable for domestic water pumping in remote areas that facing a lack of electricity in India. It should be realized that the performance efficiency of solar water pumping system could be improved by using storage tank in order to be able to produce sufficient water in the cloud days [17,18]. Likewise,

Accordingly, the previous researchers revealed that the solar pumping systems are an appropriate choice compared to the conventional powered systems, as they have proven their effectiveness and reliability especially in rural locations. Nevertheless, further research is needed to examine the performance of the solar pumping system for different crops under various climatic conditions. But tiny minority of these studies demonstrated the variations of auxiliary required power for irrigation pump to cover the gap of the collected amount of water as the captured energy is not the same all over the day. However, no previous studies were found that focused on evaluating the cost of required auxiliary power to cover the gap of water required for irrigation, simultaneously with concentrating on the amount of stored water in tanks to be in the required range without pumping more water under different climatic data for summer and winter crops, aiming to eliminate the unused amount of water which is strongly related to the global water crisis.

Consequently, the current project seeks to estimate the exact water needs for irrigating a one feddan for the purpose of calculating the capacity of the photovoltaic modules needed to power the irrigation pump for this land under different Egyptian weather data. Thus, an economic analysis is carried out to compare solar and diesel-powered irrigation pumps for maize and wheat crops under the climatic conditions of Alexandria, Giza and Aswan.

2. System Description

In the present research, a comparison is conducted for a small farm using an irrigation pump operated with solar energy with that using diesel energy in different Egyptian climatic conditions. Also, the farm is proposed to be irrigated with underground water. The estimated farm is one feddan in size and is planted with summer as well as winter crops. Likewise, wheat and maize have been chosen as summer and winter crops, respectively, due to their optimal climatic growing conditions [19]. Table (1) indicates the quantity of irrigation water supplied to wheat and maize over the proposed three Egyptian weather conditions. Whereas the three regions in Egypt have been chosen to demonstrate various weather conditions. Thus, Alexandria represents the Nile Delta, Giza Middle Egypt, and Aswan Upper Egypt, as shown in these tables. The scenario analyzes the performance of the solar pump system used to irrigate wheat and maize crops at the three suggested climatic zones by adopting the actual well depth and water capacity required to irrigate the crops at each location.

Water requirements for wheat for one feddan is 1869, 2173 and 2431m^3 for Alexandria, Giza & Aswan but for maize crop is 2142, 2496 and 3394 m^3 for the same locations [20]. The number of irrigations from the date of planting to the date of harvesting is referred to as the seasonal number of irrigations. As a result, pre-planting irrigation is not included. Seasonal number of irrigations per season for wheat crop are 5, 9 and 7 irrigations at Alexandria, Giza and Aswan but for maize crop are 6, 9 and 8 for the same locations [21]. It should be indicated that the main ground water systems in Egypt includes the Nile aquifer system, Nubian sandstone aquifer, the fissured carbonate aquifer, the coastal aquifer, the Moghra aquifer and the hard rock aquifer. The three aquifers selected for the investigated locations in the present work are Moghra, Nile and Nubian aquifers, respectively, for Alexandria, Giza and Aswan cities with a vertical rise of water of 181, 16 and 114 m, in the suggested regions [22,24].

3. Transient Simulation

To evaluate the performance of the proposed solar operated pump system for irrigating wheat and maize crops transient simulation has been carried out using TRNSYS software. TRNSYS 16 is a complete and extendable simulation tool for PV system transient modelling. This software can be employed to verify and simulate innovative energy concepts. Also, TRNSYS software library offers several components that may be used to simulate various energy systems. Fig.1. shows the component and connections between the components modeled in TRNSYS software

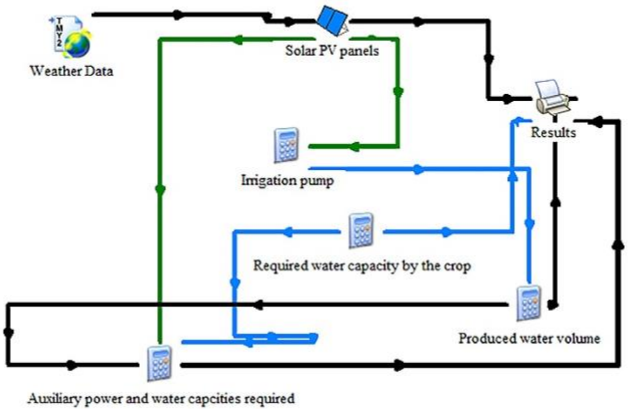


Fig. 1. TRNSYS components and connections of the proposed system.

Thus, the elevation head can be calculated by summing the aquifer depth and the tank height. Accordingly, the vertical rise of wells is 180.8, 16 and 114m, respectively, at Alexandria, Giza and Aswan cities. The three locations possess the same tank height which is assumed to be 3m. Consequently, the total dynamic head for Alexandria, Giza and Aswan is 186, 22, 120 meters. It should be mentioned that the total dynamic head can be computed by adding both the friction losses and the elevation head [25]. The supplied hydraulic power for the pump (W) can be dedicated as follows [26]:

$$P_h = Q\rho gh/(3600 \times 1000) \tag{1}$$

where Q is volumetric flow of water through the pump, ρ is water density (1000 kg/m³), g is gravity (9.81 m/s²) and h refers to the total head dynamic head. The water capacity required for one irrigation along with the number of days needed to fill the tank through one irrigation are illustrated on Table 1. Table 2. presents the number of irrigation hours per season and the average water volume per day. Accordingly, three different pumps are selected for Alexandria, Giza and Aswan cities with power of 2.3, 0.5 and 3kW, by using head and flow rate released from the data sheet of submersible pumps (Shakti manufacturer).

Table 1. Water capacity and number of days per single irrigation.

Crops	Water requirements for one irrigation (m^3)		
	Alexandria	Giza	Aswan
Wheat	374	242	348
Maize	357	278	425
Crops	Number of days to fill the tank for one irrigation		
	Alexandria	Giza	Aswan
Wheat	28	14	20
Maize	19	12	14

Table 2. Number of irrigation hours per season and average discharge m^3/h.

Crops	Total number of working hours between each irrigation – hours		
	Alexandria	Giza	Aswan
Wheat	308	154	220
Maize	209	132	154
Crops	Average Discharge m^3/h per day		
	Alexandria	Giza	Aswan
Wheat	1.21	1.57	1.58
Maize	1.71	2.11	2.76

A relation between pump power input and discharge flow rate is shown in Figure 2. This relation is tested on TRNSYS Simulation Studio to check the output flow rate from the pump at each location, where this amount of water is stored in storage tank that has dimensions relying on the required amount of water for each irrigation. But there is a gap in water capacity since the power is not steady during all hours of the day. The gap in water storage is calculated, then the auxiliary power needed for the pump is calculated to achieve required water gap for the crop at each location for every crop.
Figure 2 shows selected submersible pump for every location depending on three selected aquifers for each location [22,24] and total calculated dynamic head for Alexandria, Giza and Aswan which is 186, 22, 120 meters.

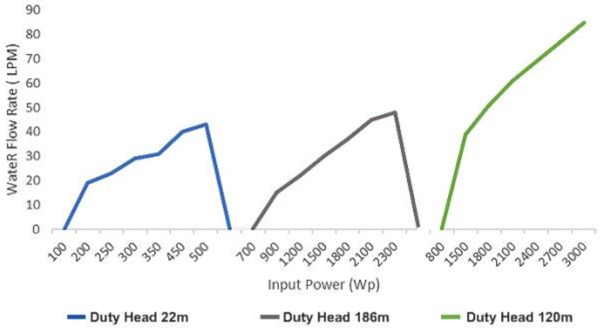


Fig. 2. Selected pumps performance for the three locations in terms of input power & output flow rate.

The current system utilizes 100W photovoltaic panels, where the selected number of panels is based on the input required to operate the pump. Then, the hourly flow rate is computed to analyze the relation between the energy coming from the PV panels and the flow rate obtained from the selected irrigation pumps. Thus, performance of the irrigation pump is evaluated while keeping in mind that the number of PV panels should not exceed the system requirements, since this may lead to additional costs and wasted energy, depending on the proposed location.

The number of PV panels by using TRNSYS software are 22, 3 and 11 for wheat crop at Alexandria, Giza and Aswan but for maize crop 18, 3 and 7 for the same locations. Moreover, an inverter of capacity 3220, 700 and 1200W, respectively, for Alexandria, Giza and Aswan towns. It should be mentioned that the inverter capacity is selected to have a power capacity 40% higher than that for the motor input power [25].

4. Life Cycle Cost Analysis

In this section, a cost analysis is performed for an irrigation pump operated by either a traditional diesel generators or photovoltaic panels. A promising technique for economic analysis is life cycle cost (LCC), which may be used to compare several alternatives, which are the solar PV panels and diesel generators employed in the current study, to identify which system is the most economical. This approach estimates the overall costs of each alternative and compares initial as well as running costs of alternatives over a period of time. Whereas, running cost includes onetime cost such as replacement cost, annual cost such as energy cost (fuel cost and its transportation), maintenance, operation and repair costs [26]. The life cycle cost of the proposed alternatives can be expressed as follows:

$$LCC = CC + PV\ recurring \tag{2}$$

where CC is the capital cost and PV running is the present value of recurring cost. Also, the present value of future cost can be calculated using Eq. (3).

$$PV = F_n/(1+d)^n \tag{3}$$

The present value of constant annual future cost can be computed from Eq. (4).

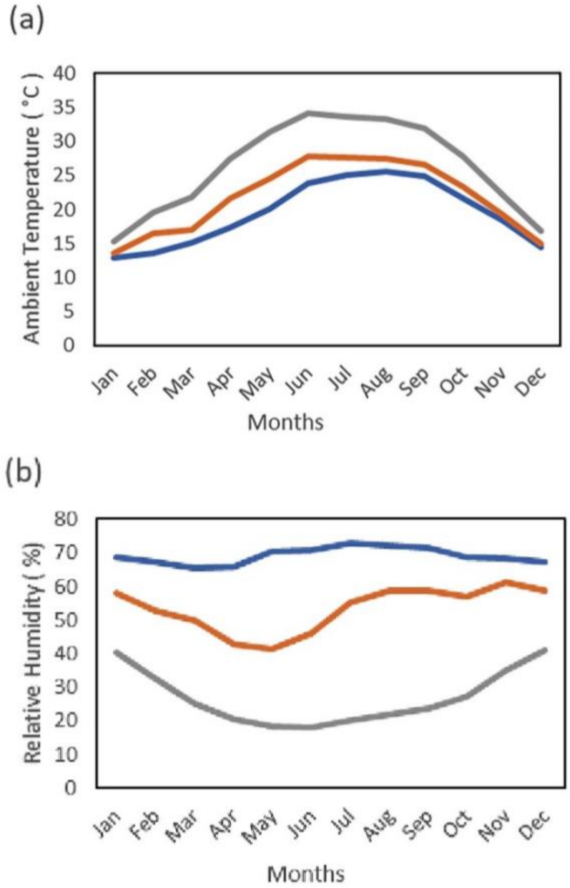
$$PV = (A_o)((1+d)^n - 1)/d\ X\ (1+d)^n \tag{4}$$

where n is the number of years, F_n refers to the yearly future cost, d is the discount rate and A_o is the constant annual cost. The discount rate is assumed to be 6% and the installation cost is assumed to be 1% of initial cost of diesel generator [26]. Moreover, the annual maintenance costs are 0.1 and 10% of the total capital cost for solar PV and gasoline generator systems, respectively. The annual cost of fuel for diesel generator can be computed by multiplying the specific fuel consumption, cost of gasoline fuel, total yearly operating hours and number of operating days per year.

5. Weather Conditions

The climatic conditions including the ambient temperature, relative humidity and solar radiation for Giza, Alexandria and Aswan cities are presented in this section. The selection criteria of these cities are based on testing and examining numerous climatic zones in Egypt. Where Alexandria, Giza and Aswan cities represent the Nile Delta, Middle Egypt and Upper Egypt zones, respectively.

Figure 3 illustrates the monthly variations of ambient temperature, relative humidity and solar radiations in Giza, Alexandria and Aswan towns. It is shown in Fig. 3 (a) that the highest monthly average ambient temperatures are achieved in Aswan followed by Giza and Alexandria cities, respectively. It can be noted that the highest temperatures for Aswan and Giza cities happen in July with values of 33.6 and 27.7°C, respectively, however the highest temperature value is 25.5°C which is found in August for Alexandria city. The monthly changes of relative humidity are presented in Fig. 3 (b). The lowest average relative humidity values occur in June for Aswan city followed by Giza city in May, then Alexandria city in March offering the following values, respectively, 17.9, 41.5 and 65.6 %. Moreover, the solar radiation varies yearly from about 456 to 1239, 467 to 1190 and 691 to 1253 W/m^2 for Alexandria, Giza and Aswan, respectively as is shown in Fig. 3 (c).



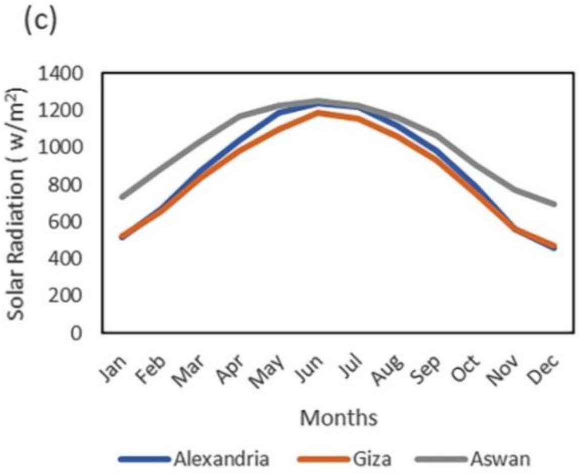


Fig. 3. Monthly Variations of weather conditions for three different cities in Egypt.

6. Crops Water Requirements

This section presents the water capacity required by each crop per season along with the storage tank capacity of each crop per one irrigation for the three proposed cities using the actual well depths in these sites.

It is obviously shown in Fig. 4 that the maximum water capacity for a crop per an irrigation season takes place in Aswan via the maize crop offering a value of 3394 m^3, whereas the wheat crop acquires the lowest value which is 1869 m^3 in Alexandria [20]. On the other hand, the highest storage tank volume per irrigation is found in Aswan through the maize crop, in addition the lowest capacity takes place in Giza via the wheat crop providing the following values, respectively, 425 and 242 m3, as seen in Fig. 5.

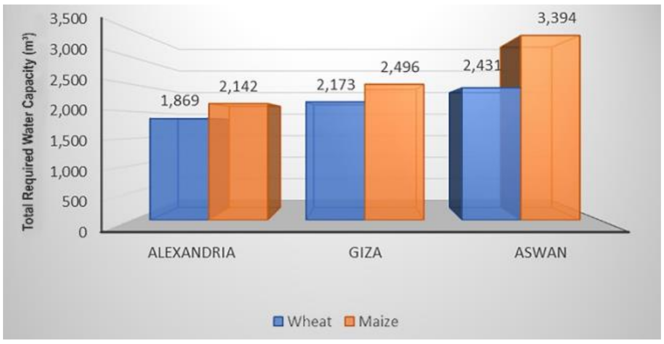


Fig. 4. Total required water for each crop per season at each location for one Feddan. [20]

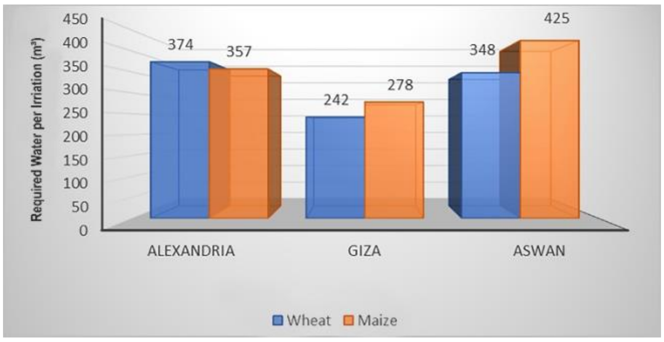


Fig. 5. Required amount of water for each irrigation for the crops at each location for one Feddan. [20]

7. Validation

The proposed mathematical model is verified with their numerical and experimental findings to examine the accuracy and validity of the developed numerical model. It is shown that average error for the generated electrical power from the PV module are approximately 5 and 4 %, respectively with the previous experimental and numerical studies under the same ambient and layout data that was performed by M.Slimani M. Amirat, I. Kurucz, S. Bahria, A. Hamidat and W. Chaouch, [27], as presented in Fig .6.

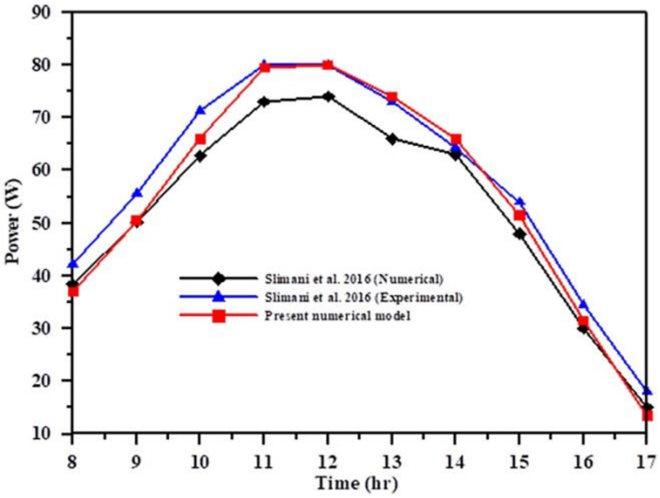


Fig. 6. Comparison between the present numerical results with the previous findings.

8. Results and Discussion

The present work aims to evaluate and compare the performance of a submersible pump powered by photovoltaic panels to irrigate wheat and maize crops using the weather conditions of Giza, Aswan and Alexandria cities. Else, the total power of photovoltaic modules needed to operate this pump is calculated to indicate the auxiliary power needed for these crops at the proposed locations for both the suggested crops during their irrigation season. Consequently, the water capacities required for both crops are determined to decide whether the produced water from the irrigation pump operated by the photovoltaic panels is sufficient for these crops or an additional amount of water is required. Finally, an economic analysis is conducted to determine the feasibility of the solar powered pump compared to that operated by traditional gasoline generator at the introduced climatic data.

7.1 Performance Analysis

This section is divided into parts, where the first one discusses the influence of using the actual operating conditions at each location by utilizing three different pumps on the system performance for wheat crop, but the system is evaluated for maize crops in the second part.

7.1.1 Wheat Scenario

In this case, the power generated from PV modules, the collected water capacities, and the solar fraction for the solar-operated pump system used to irrigate wheat and maize crops are assessed by adopting the proposed climatic data with different number of irrigations, well depth and water capacities based on the examined location.

The gap between the generated power from the PV panels and necessary auxiliary power for wheat crop irrigation in the presented sites is illustrated in Fig. 7. It is obviously clear that the greatest gap between the required power and generated power via the PV panels is in Alexandria followed by Aswan and Giza, respectively. Despite the solar radiation in Aswan and Alexandria are dramatically greater than that in Giza, the well depth in Giza is also considerably lower than that in Aswan and Alexandria acquiring values of 22, 120 and 186m, respectively. It should be mentioned that the lower well depth beside the required water capacity by the crop in Giza eliminate the effect of both the higher number of irrigations and lower solar radiation intensity compared to Aswan and Alexandria sites. Accordingly, the maximum net auxiliary power is revealed in Alexandria with a value of 495 kW, followed by Aswan and Giza cities, respectively, with values of 325 and 17kW. It should be realized that the last irrigation in the three locations possess the greatest generated power from the PV panels, as the solar radiation intensity in this period of irrigation marginally surpasses that occurred in the other periods during the irrigation season.

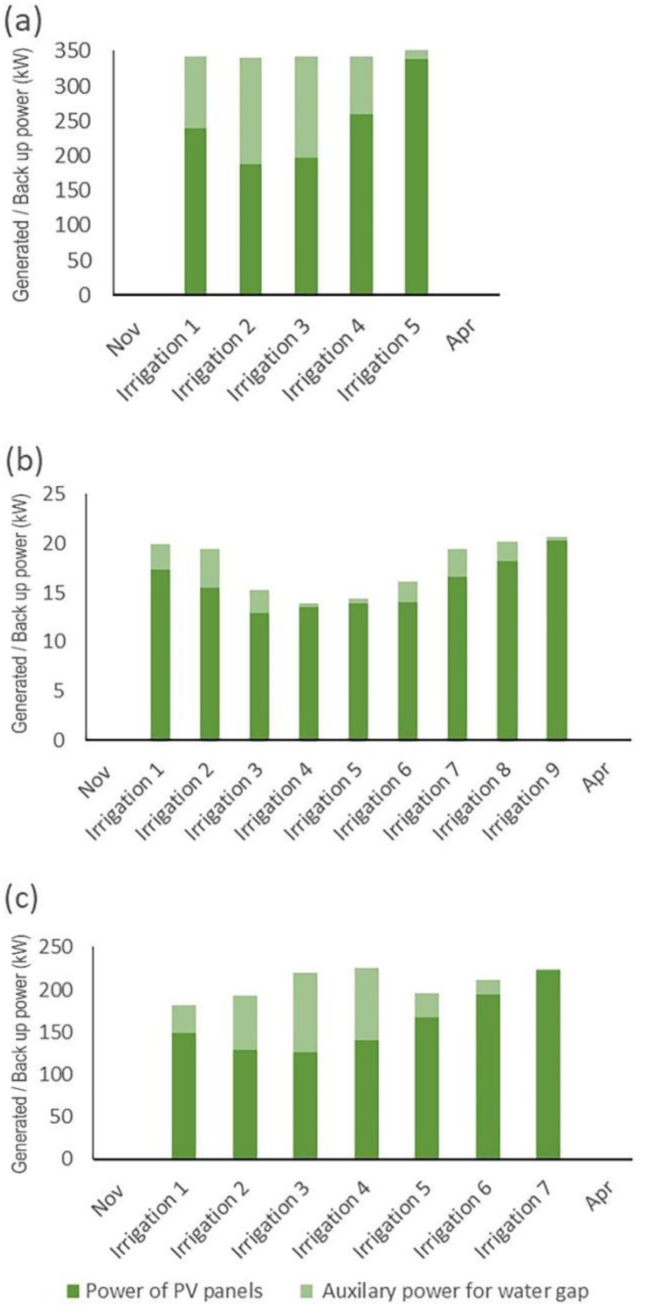


Fig. 7. The produced power from PV panels and the required auxiliary power for wheat crop in (a) Alexandria (b) Giza and (c) Aswan cities.

Figure 8 indicates the gap between the water capacity needed by the wheat crop throughout the irrigation season, which extends from November to April, and the water released by the solar-powered pump. Despite Alexandria reveals the maximum required auxiliary power, the highest gap between the produced and demand water capacities is found in Aswan.

The reason for this is that the number of irrigations for wheat crop in Aswan is marginally higher than that achieved in Alexandria by two irrigations. The gap in water capacities between the produced and demand along the irrigation season is 215, 733 and 746 m^3, respectively, for Giza, Alexandria and Aswan cities.

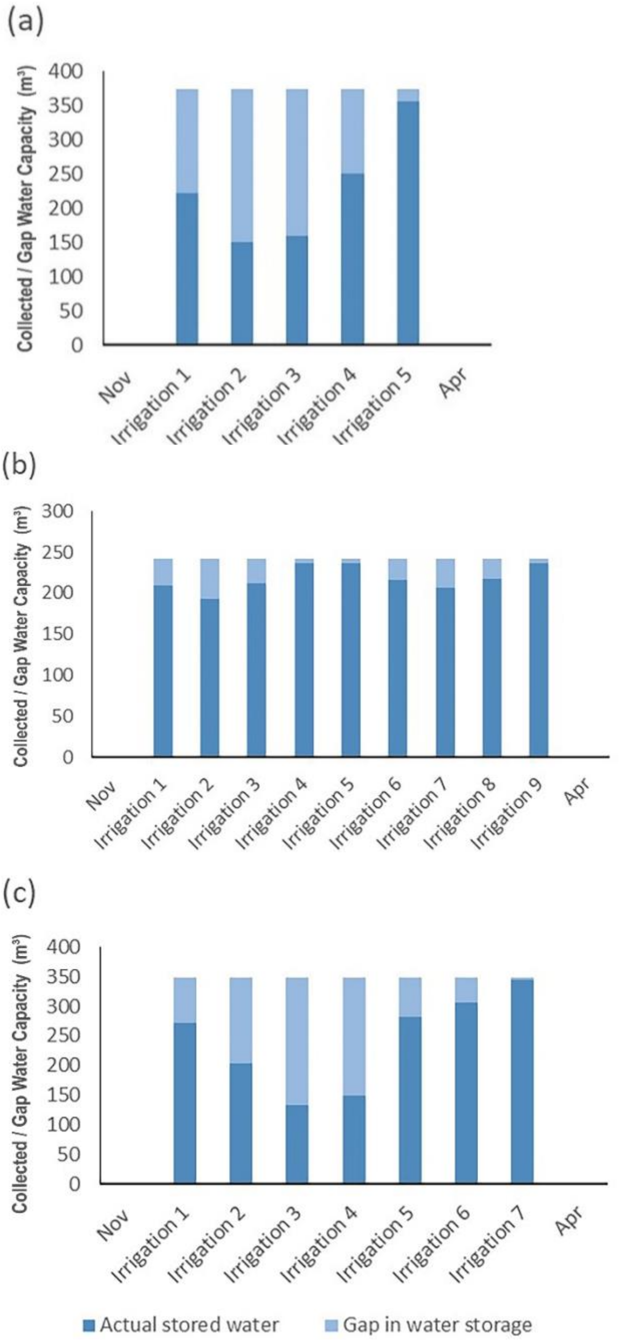


Fig. 8. The collected water capacity by the solar pump and the actual required capacity for wheat crop in (a) Alexandria, (b) Giza and (c) Aswan cities.

7.1.2 Maize Scenario

In the proposed sites, the power produced from the PV panels and the desired auxiliary power for maize crop during its irrigation season, which extends from May to September is depicted in Fig. 9. It is evident from this figure that the greatest difference between generated power from the PV panels and the net required power by the pump along the irrigation season is found in Aswan followed by Alexandria and Giza cities.

Although the solar radiation intensity is the highest in Aswan, both the well depth and the required water to irrigate the maize crop is also maximized in Aswan compared to the other locations. This leads to a dramatically higher auxiliary power needed by the pump to produce the necessary water capacity for the crop in Aswan compared to the other locations. Consequently, the total generated power through the PV panels is 1786, 1767 and 266 kW in Aswan, Alexandria and Giza regions, respectively.

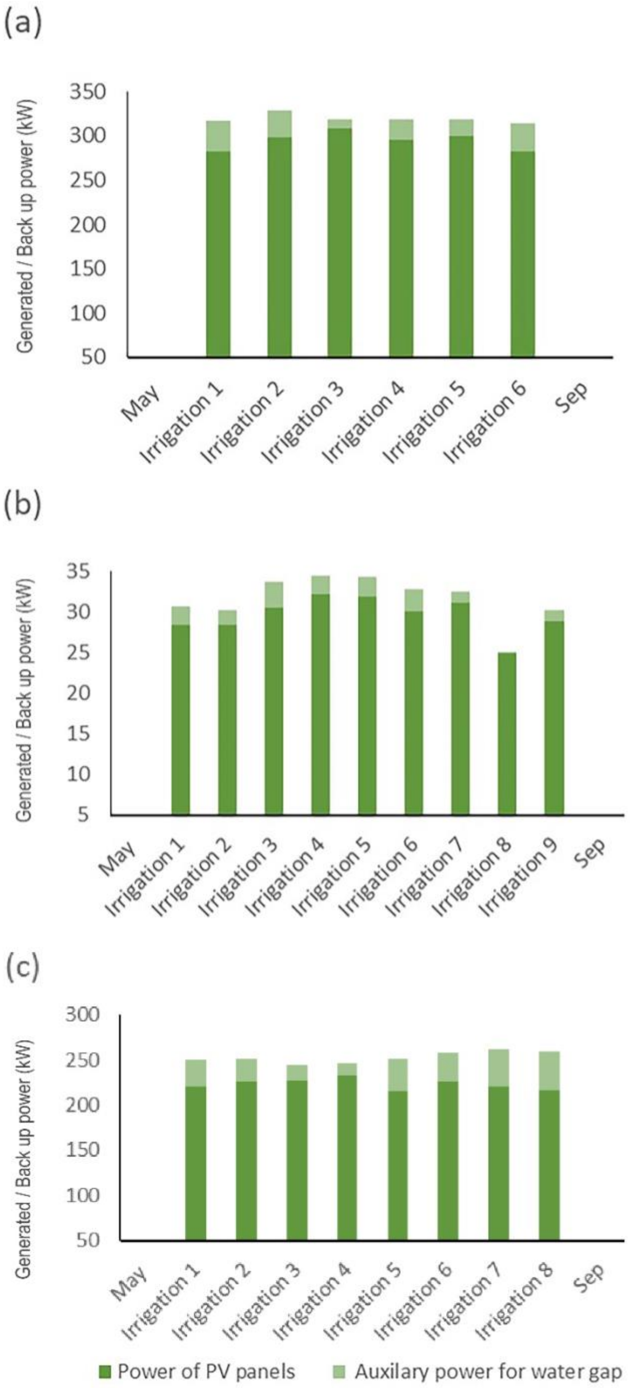


Fig. 9. Variations of generated power from PV panels and necessary back up power for maize crop in (a) Alexandria, (b) Giza and (c) Aswan cities.

Figure 10 displays the water capacity required and discharged by the solar-powered pump during the maize crop irrigation season in the proposed locations. Although Alexandria possesses a higher value of auxiliary power than that offered by Giza, the gap between demand and produced water capacities is slightly greater in Giza than Alexandria. This is because the number of irrigations for maize crop in Giza is higher than that in Alexandria by around three irrigations. Thus, the difference in water capacities between the provided and consumed during the irrigation season reaches to about 244, 220, and 546m^3 for Giza, Alexandria, and Aswan regions, respectively.

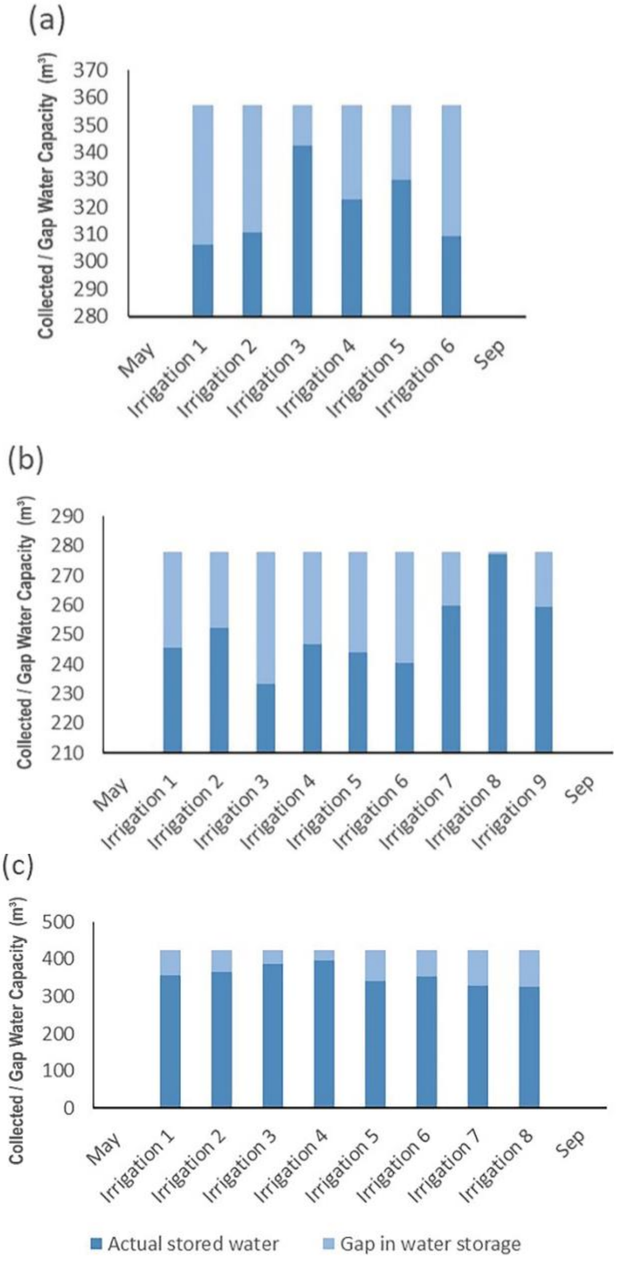


Fig. 10. The collected water by the solar pump and the actual required capacities for maize crop in (a) Alexandria, (b) Giza and (c) Aswan cities.

Figure 11 presents the solar fractions for both winter crop (wheat crop) and summer crop (maize crop) by utilizing the actual operating conditions at the investigated locations. The highest solar fraction occurs in Giza, then Aswan and Alexandria towns, with values of 0.89, 0.78 and 0.71, respectively, for wheat crop. On the other hand, the solar fractions obtained for maize crop irrigation are 0.92, 0.88 and 0.93, respectively, for Alexandria, Aswan and Giza cities. It should be noted that the solar fraction values are greatly related to the weather conditions, generated power from PV panels and actual operating conditions in the introduced locations for the previously discussed reasons in Figs. (7) and (9). Solar fraction is calculated by using Eq. (5).

$$SF = Generated\ power\ /(Generated\ power + Auxiliary\ power\ ) \tag{5}$$

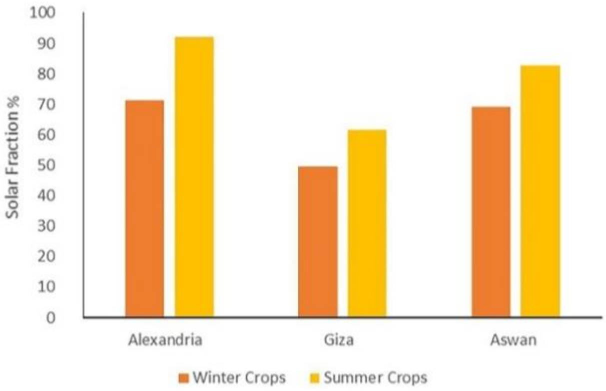


Fig. 11. Seasonal solar fraction at the proposed regions for maize and wheat crops.

7.2 Economic Analysis

A cost analysis is performed by adopting either traditional diesel generators or solar PV panels to generate the power needed for the submersible pumps. A comparative study is conducted using life cycle cost analysis to determine which system is more economically feasible for both the summer crop (maize crop) and winter crop (wheat crop) under the climatic conditions of Giza, Aswan and Alexandria using the real operating conditions for these regions.

Cost saving is calculated by dividing total cost of proposed method (solar PV panels) over total cost of conventional method (diesel generator) to get the total percent of saving as shown in Fig.12.

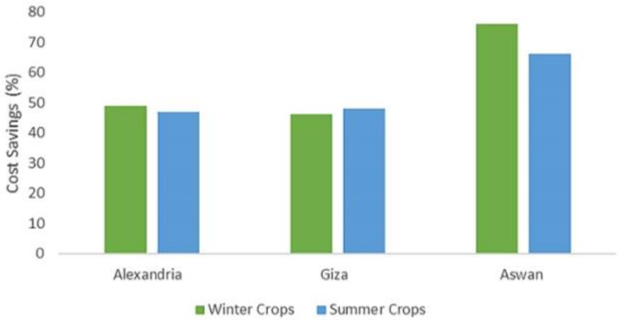


Fig. 12. Cost savings for summer & winter crops after using the proposed Solar PV panels method for a 20 years cost study

Table 3 and Table 4 present a comparison between solar photovoltaic panels and diesel generator as a power source to the irrigation pump at the investigated locations for wheat and maize crops during the project lifetime which is assumed to be 20 years.

It is clearly obvious from both figures that the capital cost of solar PV panels is slightly higher than that for the diesel generator system, but the total cost of the solar PV panels is marginally lower than that for the diesel generator due to the considerable declination in the running cost of the PV panels. Compared to the diesel generators, solar PV panels are predicated to save around 49, 46 and 76% from the total cost, respectively, in Alexandria, Giza and Aswan cities, for wheat crop. On the other hand, using solar PV panels are estimated to reduce the total cost by about 47, 48 and 66% compared to that for diesel generators used in Alexandria, Giza and Aswan regions, respectively, for maize crop.

Table 3. Initial, running and total costs of the power supply system to the irrigation pump at the proposed locations for wheat crop.

Crops	(Conventional method) Diesel Generator			(Proposed method) Solar PV panels		
	Alexandria	Giza	Aswan	Alexandria	Giza	Aswan
Capital Cost (LE)	135,320	125,688	115,044	175,833	131,320	129,695
Running Cost (LE)	314,469	121,549	568,963	53,477	2,449	31,242
Total Cost (LE)	449,719	247,237	684,007	229,310	133,769	163,867

Table 4. Initial, running and total costs of the power supply system to the irrigation pump at the proposed locations for Maize crop.

Crops	(Conventional method) Diesel Generator			(Proposed method) Solar PV panels		
	Alexandria	Giza	Aswan	Alexandria	Giza	Aswan
Capital Cost (LE)	168,951	110,227	184,046	204,206	115,547	206,689
Running Cost (LE)	248,811	115,547	508,359	19,097	2,501	27,416
Total Cost (LE)	417,762	225,774	692,405	223,303	118,370	234,105

9. Conclusions

A comparative study is conducted for a small farm in the present evaluation using an irrigation submersible pump operated with solar energy and that utilizing traditional diesel engine at different Egyptian climatic conditions. A farm of one feddan capacity is supposed to be irrigated by the designed water pumping system. Due to their great advantages and involvement as the main crops in Egypt's food security, winter crop (wheat crop) and summer crop (maize crop) are selected for the current assessment. To verify if the irrigation pump powered by the solar panels is delivering sufficient water for these crops or whether more water is required beside a cost analysis comparing between powering the submersible pump by Conventional method (diesel engine) and proposed method (solar PV panels) for a 20 years study, the water capacities necessary for both crops are estimated. The major findings can be summarized as follows:

1. The solar fraction in Alexandria, Aswan and Giza towns are 0.71 and 0.92, 0.78 and 0.88, 0.89 and 0.94, respectively, for wheat and maize crops.
2. Instead of utilizing diesel generators to run an irrigation pump for summer crop (maize crop) and winter crop (wheat crop), Alexandria, Giza, and Aswan regions are predicted to save 47, 48 and 66% of their total costs for summer crop (maize crop) and 49 , 46 and 76 % for winter crop (wheat crop) during 20 years study by switching to solar PV panels as a power source for submersible pump.
3. For Giza, Alexandria, and Aswan regions, the gap in water capacities between the produced and demand along the irrigation season is 215, 733 and 746 m^3 for irrigating winter crop (wheat crop) and is 244, 220, and 546 m^3 for irrigating summer crop (maize crop).

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