Optimum Design and Evaluation of Solar Water Pumping System for Rural Areas

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Abstract- Sultanate of Oman like the rest of GCC countries is a fossil-fuel-rich country that highly depends on the production of natural gas which exists in massive amounts of its land, which makes electricity generation through natural gas a cheap solution. However, power transmission to rural areas costs the government massive amounts of money. The need of electricity for rural areas, especially for water pumping systems, is crucial to farmers. One solution is to use diesel generators for water pumping; however this solution is costly over the long run and not environmentally friendly. This paper studies the use of PV-powered water pumping system (PVWPS) instead and shows techno-economic and environmental studies comparing both PV and Diesel pumping solutions.

The PVWPS showed to be more cost-effective for Oman than the diesel generator over the lifetime of the system and having 0 carbon emissions, making it the obvious choice for such issue. The optimum COE found for the PV-powered pumping system is US$ 0.4743/kWh while the COE for Diesel-powered pumping system is US$ 0.6092/kWh.

Keywords Photovoltaic, solar water pump, rural area, technical, economic, environment.

1. Introduction

In nations such as the Sultanate of Oman, farming has been a cultural staple for generations, and even a mainstay of their economy. In spite of the latter description, agriculture today is no longer sufficient to improve the economic situation of the country. As the industrial revolution the world has opened up new prospects for employment. At the same time it increased the global demand for energy, especially fossil fuels such as oil and natural gas. In Oman, these revolutions began during the late 1970's and depended mostly on two resources: Oil & Natural Gas, which remain the biggest economic players to this day, constituting 44.9% of Oman's gross domestic product (GDP) in 2010 [1]. This situation paved the way for the Sultanate's expansion into industries. Despite these facts, however, both oil and natural gas have been unreliable at times as sources of revenue (considering they are the prime sources of income to the Sultanate) due to the volatile nature of their international markets, especially in recent times. Fig. 1 shows the overall trends in oil prices (specifically the American WTI & European Brent crudes) over the past 30 years [2].

As seen in Fig. 1, the greatest and fastest fall in prices before 2015 was during the 2008 global financial crisis. Following the relatively slow recovery over the next few years, oil prices fell again during the last quarter of 2014, and despite a minor recovery during 2015; prices fell even further by the end of the year. Global oil prices were at a 12-year record low by late January & early February 2016 [1]-[2]. Oman's economy was hit hard as a result of these price falls, as well as that of its crude oil, ending 2015 at US$31.21/bbl., and falling even further in January 2016, reaching a record low price of US$23/bbl [3]. All three oil standards have slightly recovered in their prices since then, but with how volatile this market can be, the Sultanate can't afford to keep as much focus on oil & natural gas as it has in the past [4].

The Omani government has already made, and continues to make, plans over the past several years to ensure that the ramifications of scenarios like this could be avoided, yet they require time in a view to planning and enforce. These plans range from setting up industries (apparent in the 9.1% increase in its sector's GDP share between 2000 & 2010, telecommunications services, power production, and more, including the now-diminished agricultural sector. However, there is one dimension that, despite much research, has yet to be significantly implemented in most of these areas: Renewables [1]-[3].

The agricultural sector, for example, would benefit from the use of renewables. An important part of agriculture is farming, which requires water pumping systems to pump water from water wells (which are abundant in the sultanate) and irrigate their crops. Due to the nature of the Omani economy in the past, local diesel prices have been low, and due to the difficulty and high costs involved in the installation of transmission lines to deliver power to farms in rural areas, diesel generators have become the most attractive option to power these pumping systems. However, they may not be as good of an option anymore, whether due to a possible increase in local diesel prices, an accompanying increase in the cost of generators and other equipment, etc. [4]. As such, renewables can be used instead to power these systems, both as a large-scale proof-of-concept in its impact on the Sultanate's future strategies, as well as a long-term cost-cutting measure (which will be discussed later). Before that, however, those two options must be compared to smaller scale projects to verify their feasibility and capabilities [5].

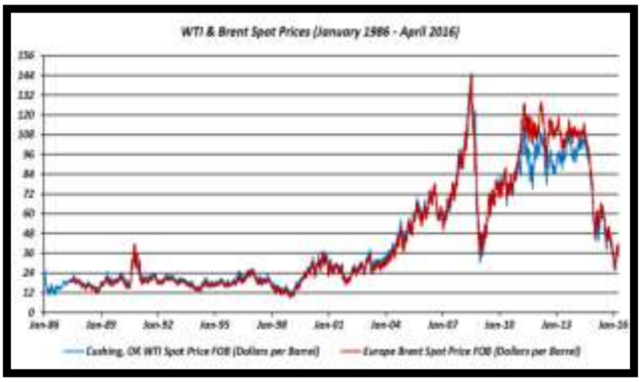

Fig. 1. WTI & Brent oil prices from January 1986 to April 2016 in dollars per barrel

2. Literature Review

With the limitless potential available from solar energy, and the continuous decrease in PV module/system prices due to the improvement in their operation & manufacturing efficiencies (as will be discussed later). The research into building and improving PV systems for different applications has bloomed over the last decade, especially in countries which have a high solar potential, such as Indonesia, Kuwait, Algeria, and so on.

Ghoneim [6] mentioned that one of the best applications of photovoltaic systems is their use as a power source for pumping water. The advantages of utilizing water pumps powered by PV systems are low maintenance, ease of installation, reliability, the matching between the powers generated and the water usage. Also, the system can use water tanks instead of batteries in this system. The researcher used TRNSYS (Transient System Simulation Tool) to simulate the performance of the PV pumping system with maximum power point tracker. The model confirmed its success after it was compared with the manufacturer's PVCAD program. The costs of PV equipment and water pumps are expected to decrease more and more over the years. Also, the PV arrays life cycle materials are 20–25 age, whereas those of engine and pump are eight years.

Prasetyaningsari [7] designed an optimum solar powered aeration system for fish ponds in Sleman Regency, Yogyakarta. HOMER (Hybrid Optimization Model for Multiple Energy Resources) proposes a 1 kW Photovoltaic, eight batteries of 200 Ah, a 0.2 kW Inverter and COE of about US$0.769 /kWh for the given requirements of these ponds.

Ajao [8] explained the cost analysis of a wind turbine solar hybrid system in comparison with utility power supply costs. The results indicated that the hybrid system is not economically cheap. Also, the system payback time was thirty-three years. If the investment cost per kilowatt reduced due to the installation of many instances of this hybrid system in a farm, a wind-solar cell hybrid energy system would be cost effective. Its availability, sustainability, and environmental friendliness make it a desirable source of energy supply.

Salam [9] designed and analysed a PV system that provides lighting to a renewable energy lab. Using HOMER, the optimal results of the system were found using 12V, 140W PV modules which are connected in series to get 24 V as well as four batteries of 6 V, 360 Ah capacities. The results obtained from the optimization gives the initial capital cost as US$ 13,500, while operating cost is US$817/year. Total NPC of the system is US$23,939, and the COE is 1.354 US$/kWh.

Elhassan [10] discussed the use of HOMER for designing an efficient and economically viable hybrid PV/Wind electrical power supply system for residential areas in Khartoum, Sudan. This plan was to take advantage of the vast expanses of desert in Sudan as well as their extremely prevalent sunshine and to design an economically viable way of building large-scale solar power plants. The researchers depended on the NASA global average radiation data, and the monthly averaged measure data for wind factors from SEI were used. HOMER was utilized in the design process and simulation. HOMER's optimizations and simulations demonstrated that the NPC of the grid/renewable energy source (RES) hybrid configuration is comparable to that of a grid-only supply. The resulted payback time was 14 years (at 2004 prices) and a 65% reduction in greenhouse gas emissions can be achieved.

Kazem [11] designed a stand-alone PV system to be used for the electrification of Omani rural areas at an optimal efficiency. It specifically dealt with critical aspects such as the PV array's orientation & cell temperatures. The requisite simulations were performed by HOMER software, resulting in a system that satisfies a 33 kWh/day load at a COE of US$0.044/kWh.

Similarly, Kumar [12] proposed a system based on photovoltaic technology to satisfy some of Caledonian College of Engineering's electrical needs (15 kWh of energy on a daily basis, specifically for lights within one of the campus's buildings). The resulting configuration had a capital cost of US$23,400 & an expected LCC of about US$40,500, leading to a COE of US$0.3946/kWh, assuming a 12-year lifespan. While it was under-utilized throughout the testing period, the system was proved to be able of satisfying higher loads at high efficiencies, considering improvements and optimizations were introduced.

Kazem [13] designed a 9 kW solar system to power an Omani health clinic which demanded 42.307 kWh/day. The authors used the highly accurate numerical method (via the program HOMER) to design the system, and detail the costs involved the resulting COE. The optimal system resulted in an affordable COE of US$0.418/kWh, as opposed to the simulated COE of a diesel generator powering the same load, which is US$0.5581/kWh. When the two systems were compared, it is found that despite the PV system's higher NPC, it's still a more feasible solution than its diesel-based counterpart in the long-term due to the latter's high volume of harmful gas emissions and maintenance costs.

Lastly, Chaichan [14] proposed powering road lights using a hybrid PV/Wind/Battery system, while comparing this to a similarly capable diesel generator based design. The authors utilized the numerical analysis software HOMER to find the optimum system design. The resulting system COE was US$ 0.400/kWh. As for the diesel generator system, HOMER's simulations resulted in design with a 7000 kW generator having a COE of US$ 3.164/kWh. The results of the previously mentioned researches are summarized & tabulated in Table 1.

From the literature review, it's observed that HOMER is the most commonly used system building/analysing software when it comes to both non-renewable and renewable power systems in the surveyed papers. This signifies its flexibility, accuracy, capabilities, and robustness across such scenarios. As such, for the task of simulating these systems with the desired inputs, HOMER will be used, specifically the HOMER Pro® (courtesy of HOMER Energy LLC) trial version [15].

It's also observed; regarding preconceptions towards renewables-based technologies, PV systems historically represented higher base costs, and in the same time, lower maintenance costs when compared to their non-renewable energy-powered counterparts, usually resulting in lower life cycle costs. The PV arrays remain to do so to a far lesser extent, as the technology continues to grow and improve with decreasing costs [16].

This study aimed to design and evaluate solar water pumping system in term of cost and pollution. By using HOMER software, many simulation analyses have been proposed to find and optimize different technologies that contain solar photovoltaic and diesel in combination with storage batteries for electrical generation. There are four different power systems were proposed, diesel generators only, solar PV/battery with and without battery, and with and without storage tanks. The results to be discuss and analysed in term of cost of energy pollution.

3. Solar Energy Source

The Sultanate of Oman locates in the south-eastern part of the Arabian Peninsula located between latitudes 16°40' & 26°20' north and between longitudes 51°50' and 59°40' east. Deserts mostly cover the sultanate land, with high humidity near its 1700 km-long coast. Many researches carried out to investigate the solar potential in the sultanate, determining that the sultanate experiences the sunshine for 8.0–10.5 hours daily, 6.0–6.5 of which is peak sun-hours. Oman has 342 days of sunny days in the year, resulting in an average solar radiation of 5.197 kWh/m^2/day [17].

The sultanate's economy is constantly evolving, and the increasing growth of the population leads, expectedly, to an increased demand for energy sources. From a technical point of view, as per the previously mentioned interest from the sultanate in diversifying its economic portfolio, there is an ever-increasing need for power to satisfy the variety of large projects that are being implemented, as well as for those currently in their planning phase. From a residential point of view, remote areas and communities, such as the Valley of Haba and others, need a source of electricity [18]. To connect the national electrical grid to these areas is a very expensive proposition, especially because it is so far from any power plants of an adequate size. As such, both the residents and the Omani government need alternative sources of energy to deliver electricity to these areas at a lower cost and a higher efficiency. The best possible systems that could be applied here are those that would utilize solar energy for electrical generation. This would not only make perfect economic sense as they would help in reducing governmental expenses over the years. If such projects continue to be built, these would certainly assist the sultanate in becoming a hub of solar energy of some kind, at least on the Arabian Gulf scene, if not beyond that and onto the global fray [19].

4. Load Profile and Water Pumping System Design

Photovoltaic Water Pumping System consists of two systems, the PV, and the Pump systems. The pumping system can be described with its basic components as follows:

1. Water pump, which is the most important element of the system. Its design is essential to meet the watering requirements. Pumps vary in types depending on where they are installed and how are they used. A submersible centrifugal pump is proposed in this paper.
2. The power source provides AC current to the water pump for operation. It can be any energy source that can be used by the pump. Diesel generators or photovoltaic systems may be employed. Diesel generators produce AC directly to provide AC current; the PV system must be linked to an inverter.
3. The storage tank is used to simplify the process of pumping the water from the source, which may be a well for example. There are different types of tanks such as vertical and horizontal tanks (both are simulated in the HOMER Pro).
4. The irrigation system can be a series of sprinkler systems, tapped pipes, or any similar system (from the storage tanks) may be used for the actual irrigation of crops. This is if the system is used for agricultural purposes, as usual. If its purpose is not agricultural, it may be replaced with a delivery system for residential applications.
5. Additional features may contain filtration or treatment mechanisms when pumping water from

the well (or other sources) to the storage tank depending on the quality of water source. Float switches can also be installed in the reservoir(s) if there is a risk of tank overflow. Also, pump controllers could be fitted.

The PV system (when used as power source for the pump system) can also be described by its components, which are listed as follows:

Table 1: Summarizing the literature review

Reference	System	Year	Location	Tool[s]	Total NPC (US$)	COE (US$/kWh)
Ghoneim [6]	PVWPS	2006	Kuwait	TRNSYS	-	-
Prasetyaningsari [7]	Solar powered aeration system	2012	Indonesia	HOMER	7,032	0.769
Hamidat et al.	PVWPS	2002	Algeria	Intuitive software	-	-
Ajao et al. [8]	Wind turbine-solar hybrid system	2011	Nigeria	HOMER	4,251	1.74
Salam et al. [9]	Solar powered lighting system	2013	Oman	HOMER	23,933	1.354
Elhassan et al. [10]	PV/Wind power supply system for residence	2012	Sudan	HOMER	-	-
Khatib [20]	PVWPS	2010	Palestine	-	-	-
Kazem at al. [11]	PV system for rural area	2012	Oman	HOMER	27,397.6	0.044
Kumar et al. [12]	PV system to supply college requirements.	2011	Oman	-	-	0.3946
Kazem et al. [13]	PV system for health clinic.	2013	Oman	HOMER	96,470	0.418
Chaichan et al. [14]	hybrid system for lighting street	2016	Oman	HOMER	63,696,652	0.400

1. PV cells are the simplest elements in the PV system which are made of semiconductors and are used to turn light into electricity but with little output power and so it is connected with other cells to form modules and these modules are connected in series and parallel to create arrays with higher power output. PV arrays will feed the system, and they must be sized to meet the load requirements as well as covering all the losses in the system (Khatib, T., 2010).

2. Batteries are the storage units of the PV system which are usually selected based on their usable capacity. The number of batteries purchased depends on the amount of backup energy needed which also depends on the number of no sun days of the location in which the system is installed.

3. Charge controller/regulator is a device that has a similar function to the voltage regulator as it regulates the voltages between the PV arrays and the batteries. This invention provides protection to the batteries when used in a PV system. Charger controller protects the batteries from overcharging or highly discharging which will damage the batteries. The formerly mentioned devices introduce loses, and so their selection must be based on their efficiency. Controller will switch off the PV array partially or entirely if the battery's State of Charge (SOC) is full. If the battery is discharged below the current level of its SOC, then the charger controller will disconnect the entire load, and so it is important for the charger controller to measure the state of charge of the battery. Another aspect of the charger controller is the overall protection it provides as it provides reverse current protection by not allowing the current to flow from the battery through the charger to the PV arrays during night time and blocking diodes are also implemented to remove these unwanted currents.

4. Inverters are devices that are used to convert the DC current into AC current using various methods depending on the type of the inverter and the required output waveform. Inverters are selected based on the AC load and the DC input from the battery or the PV array, and the output waveform varies depending on the conversion technique used, and so inverters are a key element to supplying AC loads in a PV system.

The combined systems operate starting from the solar cell, as the sun strikes the PV array it will produce a DC current which will be directed to the batteries for storage. When the pump is needed to be used, the battery will supply DC current to the inverter, which will turn the current into AC and supply the pump. Once the pump operates, it will start pumping water from the well into the storage tank. Delivery or sprinklers will be used to irrigate the crops or soil using the water from the reservoir. Variations of these combined systems can be made. The combined systems require a control board, which will use timers to specify the time in which the pump will operate and a time period for operation process (irrigation time).

The numerical analysis (using HOMER Pro) is a crucial element to the study, bearing in mind that the design constrains critical to solidifying this design from other designs of PVWPS's around the world. Specific input variables have been chosen suited to the Sultanate of Oman such as location, inflation rate, and discount rate. The system is planned to be installed in Sohar, Oman, which is located at

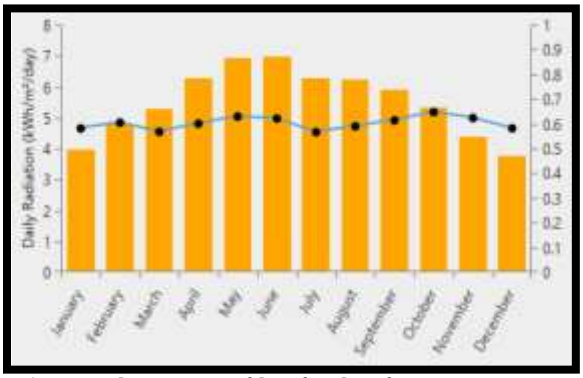

Fig. 2. Solar GHI profile of Sohar from NASA

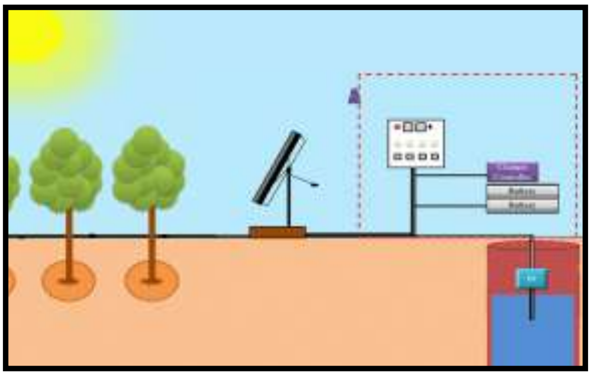

Fig. 3.a. A schematic drawing of the PVWPS with batteries for direct field irrigation

Besides, the annual operation & maintenance cost thought US$10, assuming minimal maintenance for the systems. As for the diesel system, a price of US$0.7/W for the generator and US$0.42/liter for the diesel fuel (the February 2016 global price) were considered.

Four cases (scenarios) were considered when modeling the pumping system using HOMER, Three cases for PVWPS and one case for DGWPS.

1. PVWPS with a backup battery system for direct field irrigation.
2. PVWPS with a backup battery system with a horizontal pumping solution.
3. PVWPS with a backup battery system with a vertical pumping solution.
4. DGWPS for direct field irrigation.

The first scenario considers the water-well as the water tank and directly pumps water to the sprinklers and uses batteries, fig. 3a (on the left) shows the schematic drawing of the system and fig. 3b (on the right) shows the schematic diagram using HOMER.

The considered prices for every component were: US$2.00/W for the PV modules (assuming a lifetime of 25

24°21' North & 56°43' East. The discount & inflation rates were considered at the January 2016 rates of 2% & 0.2%, respectively (Sultanate of Oman. National Centre for Statistics & Information, 2016).

The solar irradiance profile (input to PV system) of Sohar, which was obtained from NASA, is illustrated in fig.2, where it highlights the monthly average solar Global Horizontal Irradiance (GHI) data, which shows the irradiance peaking in June with 6.95 kWh/m^2/day.

years, a 90% derating factor (10% reduction in power due to the dust), and a 24° tilt angle in agreement with the site's latitude). The batteries cost assumed US$140 for the 6V, 167 Ah (1 kWh rating, considering a lifetime throughput of 3000 kWh). The inverter requires US$0.5/W (assuming 90% total efficiency).

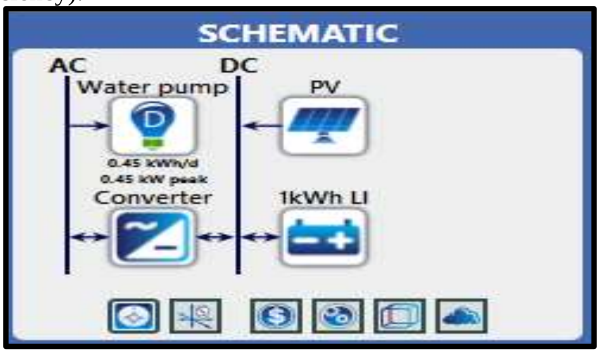

Fig. 3.b. A schematic diagram of the PVWPS scenario #1-HOMER Pro.

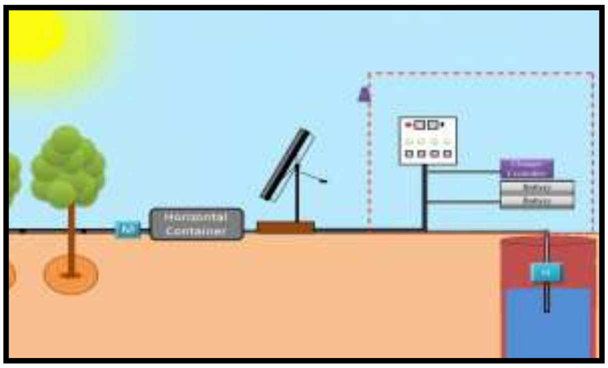

Fig. 4.a. A schematic drawing of PVWPS with batteries for horizontal pumping solution

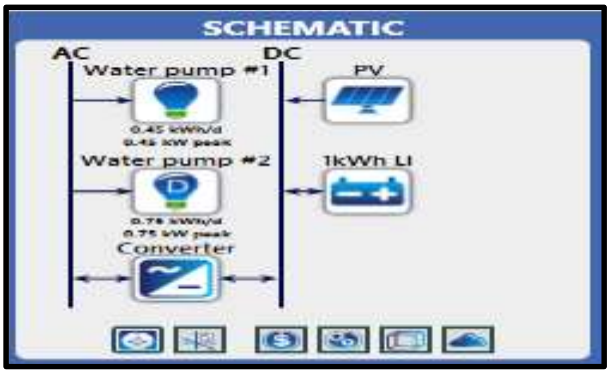

Fig. 4.b. A schematic diagram of the PVWPS scenario #2-HOMER Program

The second scenario, the horizontal pumping solution was used. Fig. 4a (on the left) shows the schematic drawing of the system while Fig. 4b (on the right) shows the schematic diagram using HOMER.

The third scenario, the vertical pumping solution was used, fig. 5a (on the left) shows the schematic drawing of the system and fig. 5b (on the right) shows the schematic diagram using HOMER.

The fourth scenario replaces the PV system with a diesel generator system for direct field irrigation. Fig. 6 shows the schematic diagram using HOMER.

The water pumping system design includes two main designing schemes, the pumping system (the load) and the PV system (the supply).

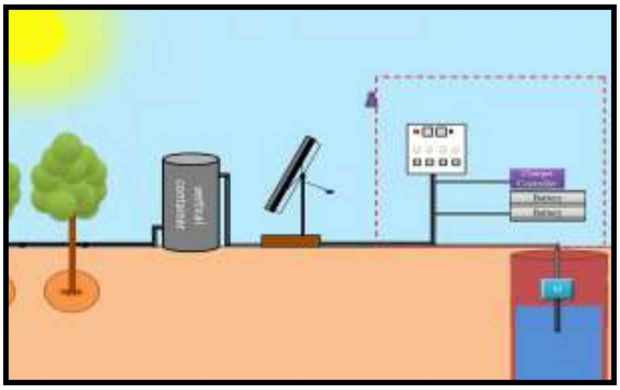

Fig. 5.a. A schematic drawing of the PVWPS with batteries for vertical pumping solution

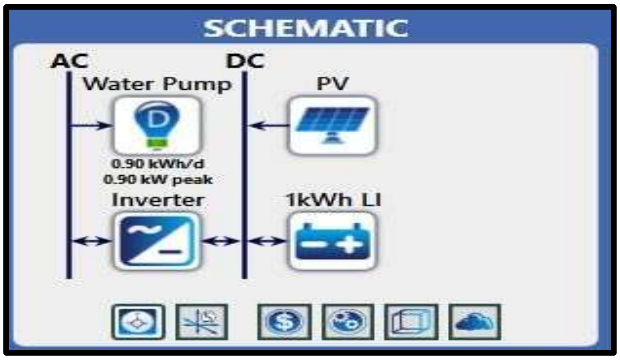

Fig. 5.b. A schematic diagram of the PVWPS scenario #3-HOMER Pro.

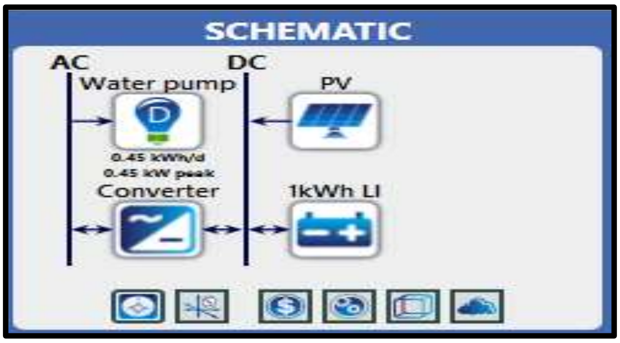

Fig. 6. A schematic diagram of the PVWPS scenario #4-HOMER Program.

The first parameter to tackle has to be the load, in which the PV system will be designed to meet. The capacity proposed is a submersible centrifugal pump that is planned to be installed in a water-well at Sohar University campus (green area near the HR center), and it is considered a small irrigation system. The sizing of the pump requires the use of the following formula (Kazem, et al., 2015):

$$P_{pump} = \frac{\rho g (h + \Delta H) Q}{\eta_b \cdot \eta_e} \quad (1)$$

Where ρ=fluid density (1000 kg/m^3 for water), g= gravitational acceleration (9.81 m/s^2), $h + \Delta H$ = total pumping head and hydraulic losses in m (17 m from the well to the plants), Q = required flow rate for irrigation (4.5 m^3/hr = 0.00125 m^3/s), and $\eta_b = \eta_e$ = pump & motor efficiencies (0.85, considered as a general average for efficiency) (Kazem, et al., 2015).

The calculate pump power that is required for this system is about 288.53 W to irrigate. This model has not been chosen, as this particular size has not been found in the market and so the closest pump size found is a 450 W pump. The 450 W pump (centrifugal pump) will be considered as the primary load to the system as it will be submerged within the water-well. A pump of 750 W was chosen to pump water from the water tank (of the second scenario-horizontal pumping solution) into the field while a 900 W water pump will be used to pump water from the well (of the third scenario-vertical pumping solution) into the field.

A higher pump power is chosen for the vertical pumping solution (third scenario) instead of the direct field irrigation or horizontal pumping solution. The reason was that the vertical water tank's input is from the top of the reservoir (and the output is at the bottom, depending on the gravitational powers) which will require more pumping head. Hence, more power is needed. Two solutions were considered, one of which is to pump water for a longer period, and the other is to increase the power of the pump. The second solution has been chosen, in order to unify the time of pumping for all scenarios. The irrigation time is chosen based on the field requirement, as it is known that the flooding process depends on the soil-water relationship. The longer time for irrigation does not mean better irrigation. As more water could lead to oversaturation the soil and crops which could damage the plants, as well as waste both water and power (Evans et al, 1996). Farmers have a better understanding of the time it is required to irrigate the field correctly, consulting a farmer can help to decide an appropriate irrigation period. One hour was proposed for such small area with small amount of crops. It can be noted that no study of the suitable time have been made as this is a techno-economical & environmental study of the PVWPS.

5. Results and Discussions

The results of the simulations ran by HOMER shows great potential in the PVWPS design schemes in comparison to their DGWPS counterparts. However, the main issue relies on the capital costs of the PV powered pumping solutions as they are higher than those of the DGWPS. Despite that, the simulations show that the overall costs of the PVWPS are less than those of a comparable DGWPS. From Table 2, the first PVWPS has a COE of US$0.4743/kWh, an NPC of US$1,553.7 and an operating cost of US$38.44/yr, whereas the DGWPS has a COE of US$0.6092/kWh, an NPC of US$2,000.9 and an operating cost of US$82.55/yr. The corresponding values of the other scenarios are as shown in the table.

The graph shown in Fig. 7 (and the associated table 2) illustrates the breakdown of costs across the four simulated scenarios. It can be seen that in 3 out of 4 cases (all of which are PVWPS cases), the capital costs far exceed the rest of the costs (operation & maintenance, replacement, fuel costs, etc.). One of the biggest issues driving users away from PV-powered pumping solutions is the higher capital costs when compared to a diesel-powered option. As the figure reveals, despite having a higher capital cost the PV system presents itself as a better option economically due to the requisite operational & maintenance costs of its diesel-powered counterparts. The second PVWPS scenario exhibits higher costs across the board from the other PVWPS scenarios, thus giving the impression that the horizontal pumping solution is the most expensive one. The cheapest solution is the right field irrigation WPS, where instead of using a water tank, the water-well itself is considered as the tank, saving further costs.

Table 2: Results of scenarios simulated by HOMER

Costs (in US$)	PVWPS 1	DGWPS	PVWP 2	PVWP 3
NPC	1553.7	2000.9	3680.3	2970.2
COE	0.4743	0.6092	0.4223	0.4534
Annual operating cost	38.44	82.55	84.02	63.01
Total O&M	489.96	1277.4	1039.12	779.93
Total replacement	386.64	0	888.12	666.09-185.82
Total salvage	-107.86	-87.84	-247.76	

Furthermore, Fig. 8 shows the capital costs breakdown (cost of each element in the system) of each scenario, which helps in understanding why the PVWPS scenarios exhibit higher capital costs than those of the DGWPS. The figure shows that both the inverter and battery are the primary reason for the increase in the expenses (except the PV array which has a higher cost per watt, but is neglected due it being the power source and the most important element of the configuration). Two points of note are that inverters are indispensable to the system and can't cause chemical hazards, as opposed to batteries. The one advantage of DGWPS is that it only uses one element which is the generator itself (producing AC current without the need of an inverter). The annualized cash flow for both PVWPS (first scenario) and DGWPS are compared in Fig.'s 9 and 10, respectively.

The bulk of the costs in both cases (as previously discussed) are the capital costs with a secondary mass investment in the fifteenth year of the PVWPS's life-cycle. Despite that fact, the overall cost across the age of 25 is in the favor of the PVWPS (US$1,553.7 vs. US$2,000.9 for the DGWPS). These two figures take into account both the inflation and discount rates of Oman (0.2% and 2% respectively).

Above all, both technologies can be compared concerning their environmental impact, as observed through the following points:

1. Generated noise (causing a disturbance).
2. Visual impact.
3. Greenhouse gas emissions.

Table 3 illustrates the greenhouse gas emissions for all of the simulated scenarios. The PVWPS solutions emit 0 kg of emissions in its total lifetime. As opposed, over the DGWPS's lifetime just over 3.7 tons of emissions is emitted (at a rate of 148.55 kg/yr), with Carbon Dioxide constituting 97.4% of the emissions, bearing in mind that it's the most impactful of the greenhouse gases.

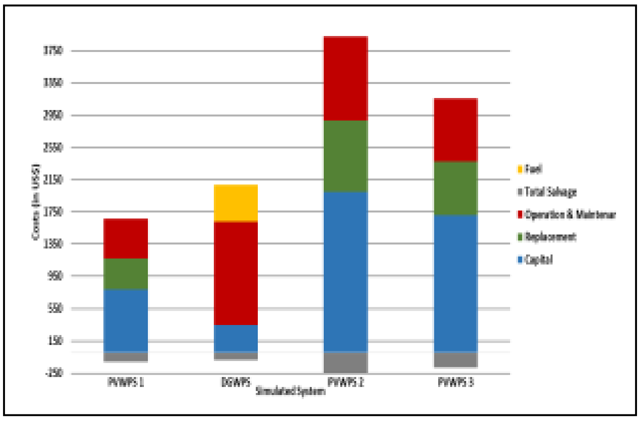

Fig. 7. Graph showing costs breakdown between the simulated scenarios.

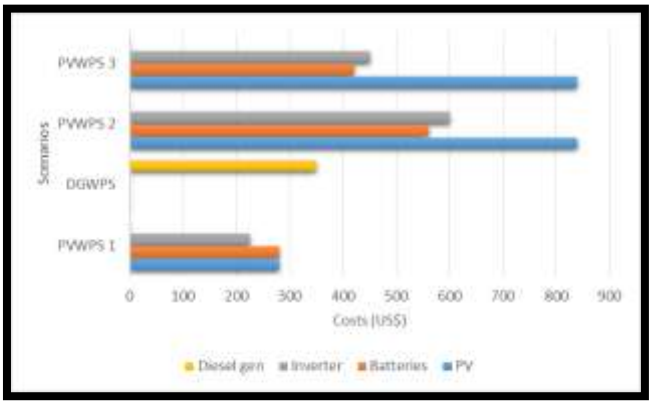

Fig. 8. Cost per element of the four scenarios

6. Conclusion

The PVWPS is a feasible solution for Oman considering its location and solar resources. Four scenarios were taken into consideration, with three of them being PV-based solutions and the final one being a diesel-based solution. A comparison has been made to cover both the techno-economic and environmental aspects. The results have shown that the optimum cost of energy for the PV-based right field irrigation system is US$0.4743/kWh, with an NPC of US$1,553.7, while a diesel-based solution had a COE of US$0.6092/kWh & an NPC of US$2,000.9. The second PV-based scenario had a COE of US$0.4223/kWh at an NPC of

US$3,680.3 while the third & final PV-based case had a COE of US$0.4534/kWh at an NPC of US$2,970.2. These results show that the PV-based solutions are more cost-effective than comparable diesel-powered solutions. The analysis shows that replacing diesel generator by a PV system will protect the environment from greenhouse gas emissions. These emissions include 144.64 kg/yr of CO2, 0.36 kg/year of CO, 3.19 kg/yr of NOx, 0.04 kg/yr of HCs, 0.29 kg/yr of SO2, and 0.03 kg/yr of suspended particles.

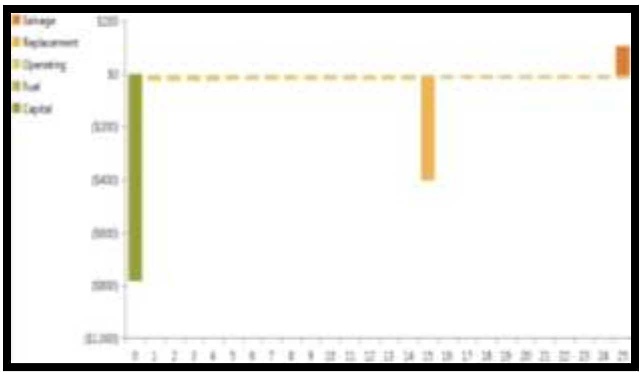

Fig. .9. The PVWPS's annualized cash flow

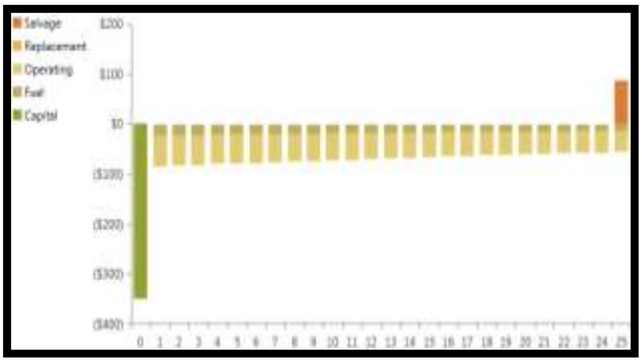

Fig. 10. The DGWPS's annualized cash flow

Table 3: Results of scenarios simulated by HOMER

Gas	Annual emissions (kg/yr)			
	PV WPS#1	DG WPS	PV WPS#2	PV WP#3
Carbon dioxide	0	144.64	0	0
Carbon monoxide	0	0.36	0	0
Unburned hydrocarbons	0	0.04	0	0
Particulate matter	0	0.03	0	0
Sulfur dioxide	0	0.29	0	0
Nitrogen oxides	0	3.19	0	0

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