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Design of a Solar-Powered Water Pumping System for Irrigation in Sukkur, Pakistan

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***Abstract*—**This paper presents the design of a solar-powered water pumping system that would be used for irrigation in Sukkur, Pakistan. A dependable model of the pumping system as well as the solar system is designed in PVsyst and HOMER softwares to establish the practical and economic viability of solar-powered water pumping system at the site. The proposed system consists of a submersible centrifugal multistage deep well pump and sixty 480 W solar modules. For the purpose of evaluating the backup system's viability, a battery backup system is also connected to the system. The obtained results show that the proposed solar-powered water pumping system is a potential candidate and a viable option for employment at the selected site and at other sites that have the same conditions for water pumping and irrigation. Moreover, when compared to the cost of using nonrenewable resources, operating and maintenance costs for renewable energy systems are more manageable.

***Keywords*—** Solar-powered pumping system; HOMER; PVsyst; Renewable energy; Pakistan.

1. INTRODUCTION

One of the main causes of climate change due to carbon emissions and air pollution is the burning of fossil fuels to produce electricity [1-3]. In many regions of the world, the development of renewable and sustainable sources of clean energy has gained prominence as a result of factors such as rising prices for fossil fuels and the requirement to attain energy self-sufficiency [4-7]. Due to the high energy requirements of agricultural irrigation, the use of solar powered pumping system (SPPS) has been proposed as a prospective application. For SPPS irrigation to be a practical option, it must be technically and economically feasible, just like any other use of alternative energy. In [8], the authors have investigated the potential for harnessing solar energy in Pakistan's Upper Indus Basin region based on the suitability of the climate and topography. They estimated the suitability of an overall 12.1% slope index of three Hindu Kush-Karakoram Himalaya ranges for the feasibility of a solar-powered irrigation system.

Rana et al. in [9] investigated the financial and environmental impact of the solar power irrigation system, specifically for Boro rice in Bangladesh. They investigated the possibility of reducing more than one million carbon emissions into the atmosphere from agricultural sources by replacing half of the diesel-powered irrigation systems. Furthermore, they found that the change in the price of irrigation has not shown to have a significant impact on the demand for irrigation, revealing that the irrigation system is highly inelastic.

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Grant et al. proposed a solar-powered drip irrigation system [10]. They simulated its seasonal performance to reduce the life-cycle cost of the system while maintaining operational reliability. They investigated the proposed system in a Moroccan olive orchard to demonstrate the model theory by examining the optimal design's sensitivity to field area, system reliability and weather conditions. Furthermore, some studies have shown the climatic impact of solar power irrigation systems.

Because of their low environmental impact and low maintenance needs, SPPS are increasingly becoming the norm. There is a heavy reliance on nonrenewable energy sources like diesel engines in Pakistani irrigation [11]. Using these nonrenewable sources, on the other hand, is not only expensive but also detrimental to the health of the environment [12-18]. Rahman et al. [19] investigated the synergies of solar-powered irrigation as a drought-mitigation strategy in a particularly sun-deprived region of northwest Bangladesh. They argued that many of the benefits of climate adaptation - such as the formation of informal social groups, increased financial security and new employment opportunities - are indirect, less obvious and long-term. The feasibility of installing a small-scale solar-powered irrigation system in Uganda was examined in [20] from both a technical and ecological perspective. They calculated that initial irrigation system costs could be cut by 20%.

In [21], the authors presented the technical viability of using solar power to induce irrigation in Pakistan, offering an alternative to conventional irrigation systems that are based on fossil fuels. They examined five agricultural exports: wheat, maize, rice, sugarcane and cotton. They found that for a rice field that covers one hectare, the average amount of solar panels needed to power a 4hp motor pump and keep the flow rate at 68 m^3/day is 14 units with a 320 W capacity each.

Using HOMER Pro [22], Iqbal et al. planned a photovoltaic (PV) water pumping system that could function independently on a real farm data. An inverter for a pumping system with a capacity of 20.7 kW was part of the system, along with 60 batteries and 78 solar panels. Through the use of MATLAB and Simulink, a dynamic model of the system is simulated. The maximum amount of PV power that can be extracted is made possible through the use of perturbation and monitoring. In the simulations, it was found that both the voltage and the frequency were consistent.

Here, we look at the feasibility of installing a PV water pumping system in Sukkur, Pakistan. Compared to the current systems in Pakistan, this one could work. Unlike the rest of the country, the lower part of Pakistan - as seen in Fig. 1 [11] - receives an abnormally high level of solar radiation. Hence, SPPS irrigation is better than both renewable and nonrenewable water supplies. Using PVsysyt [23], we propose a model for an SPPS for irrigation. The next step is to use HOMER Pro [24] to conduct a comprehensive cost-benefit analysis that factors in all relevant technical, financial, and economic factors.

The organization of the paper is as following: the specifics of the location are discussed in section 2. In section 3, the specifics of the proposed design produced by PVsyst and HOMER softwares are dissected and discussed. Section 4 contains the presentation and discussion of the obtained results. Section 5 compares the proposed system with other nonrenewable system, and section 6 provides the summary and the conclusions.

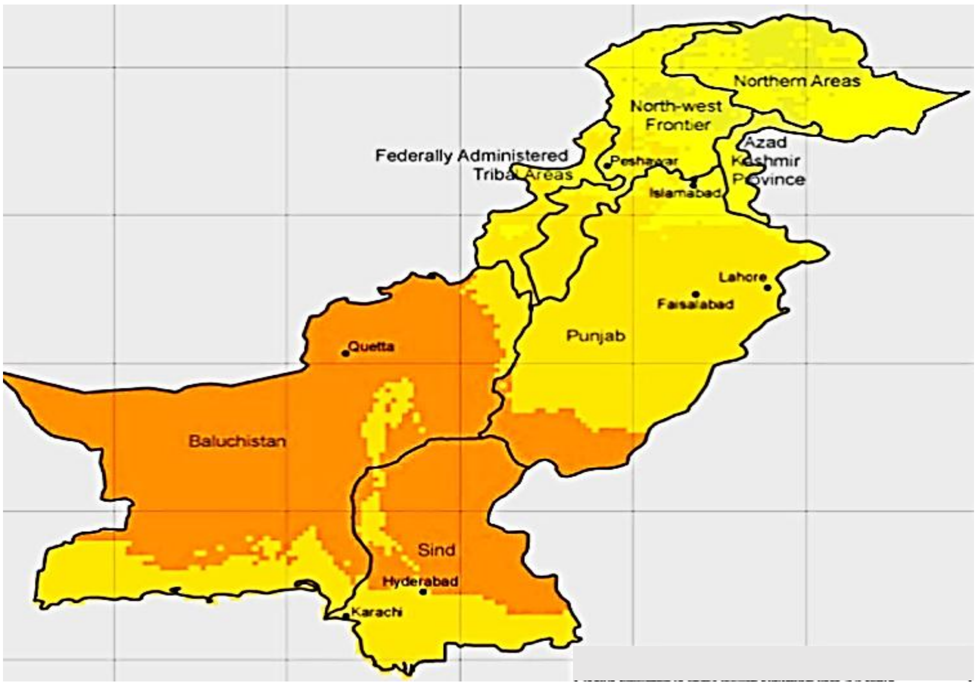

Fig. 1. Pakistan global horizontal solar radiation [11].

2. SITE DESCRIPTION AND RESOURCE ASSESSMENT

2.1. Site Description

A farm located in the tehsil of Saleh Pat in the district of Sukkur, Pakistan, of 20 acres in size has been chosen as the location for the project. The GPS coordinates of the selected location are 27.481784, 69.051130. The position of the facility is shown on Google Maps in Fig. 2. Date palms have been planted across the land, each one spaced out by 20 feet by 20 feet. On the farm, there are around one thousand plant, all of which are in varying phases of development.

Fig. 2. Location of the site on google map.

2.2. Solar Radiation at the Selected Site

One of the most crucial aspects of a site's viability is the quantity of solar irradiance it receives. Measured solar irradiance is the amount of energy from the Sun that is received at a given location and distance from the Sun. From 3.64 to 6.73 kWh/m²/day, as depicted in Fig. 3, radiation from the sun is readily available throughout the year at the site. The clearance index is a measurement of how well one can see through the air. Similarly, Fig. 3 depicts this for the location. Its annualized rate of change is between 0.550 and 0.640, and it has never been higher than 1. The sun's horizon line at the chosen location is shown in Fig. 4.

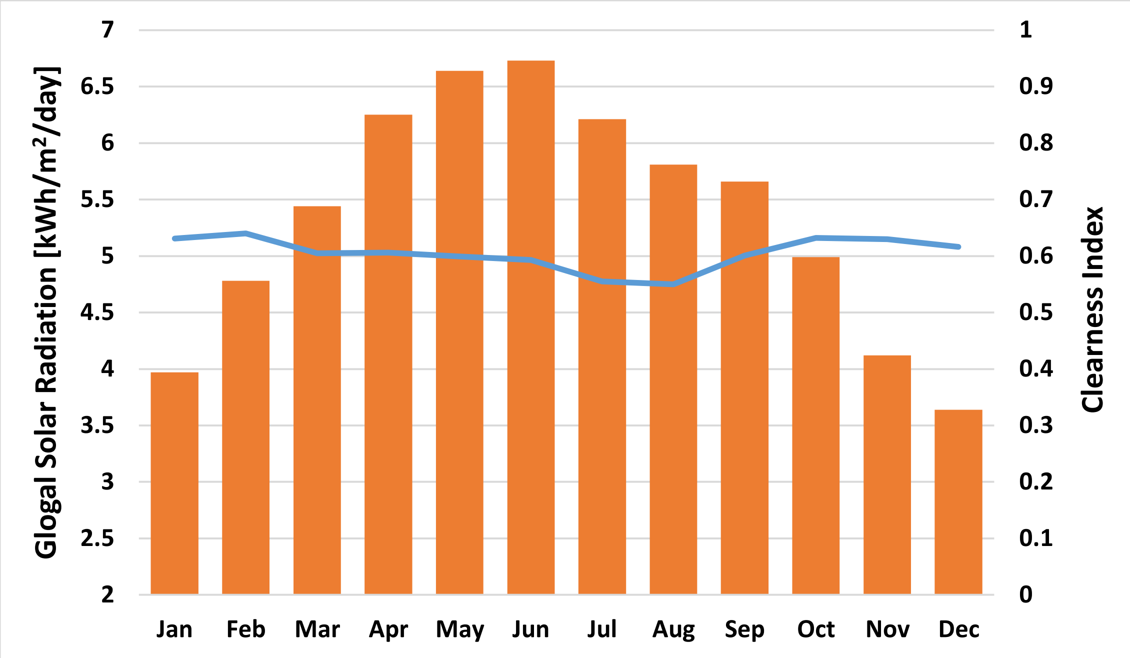

Fig. 3. Monthly variation of solar radiation and clearance index at the site.

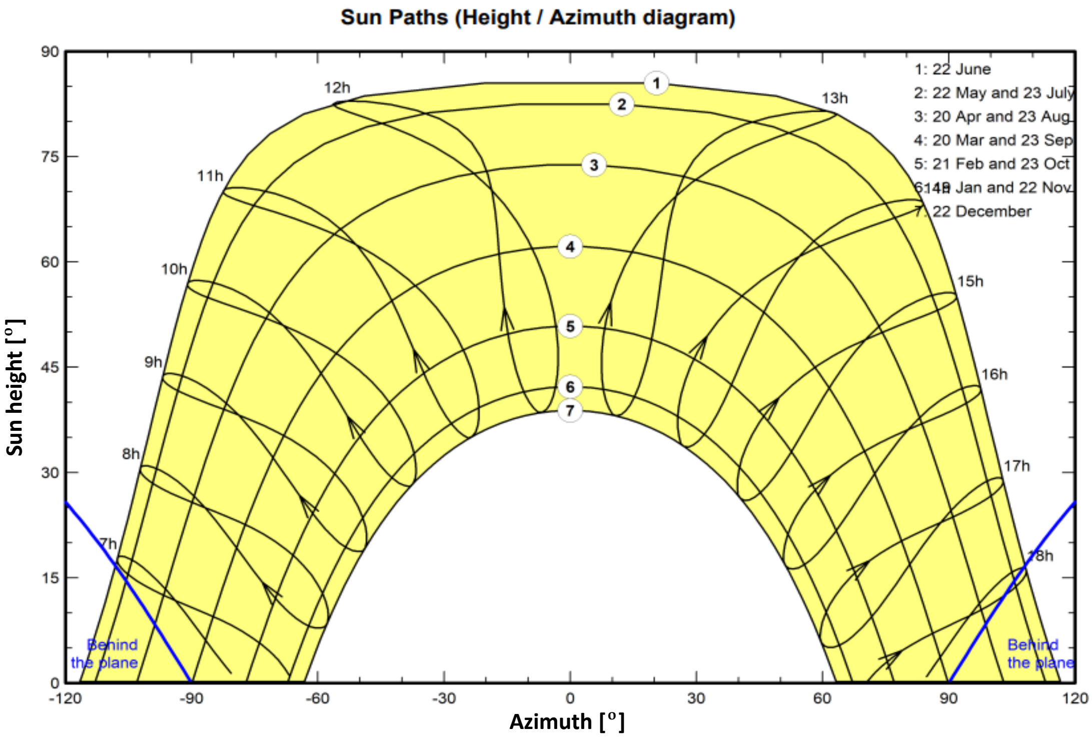

Fig. 4. Sun horizon line at the selected site.

2.3. Calculation of the Load for the Water Pump

For the solar water pump load, the site data collected is as follows:

Water required by date palm tree = $287\ L/day$ [22] (1)

Water required by 1000 date palm trees = $287\ m^3/day$ (2)

Flow rate for 24 hours = $11.958\ m^3/h$ (3)

The amount of time spent in direct sunlight that is ideal each day is between six and eight hours. As a result, a higher flow rate is necessary in order to keep the pump operating for 6–8 hours in order to collect the necessary amount of water. The increase in flow rate will be calculated as 24 hours divided by 6 hours, which is equal to four times. So,

Flow rate = $11.958 \times 4 = 47.8\ m^3/h$ (4)

Water depth = $100\ feet = 30.48\ m$ (5)

Total dynamic head = $35\ m$ (6)

Hydraulic power of the water pump (P_h) is calculated as:

$$P_h = \rho \times g \times h \times \frac{Q}{3600} = 4557.5\ W \quad (7)$$

where ρ is the water density, g: gravitational acceleration $[m/s^2]$, h: dynamic head and Q: water flow $[m^3/hour]$.

Motor efficiency (η) is estimated to be 80%. Therefore, motor power (P_m) will be:

$$P_m = \frac{p_h}{\eta} = \frac{4557.5}{0.8} = 5696.82\ W \quad (8)$$

The pump efficiency is estimated to be 50%, so: required power (P) is calculated as:

$$P = \frac{5696.82}{0.5} = 11.394\ kW \quad (9)$$

Since a motor is required in horsepower, therefore, the required pump is estimated to be $15.27\ hp$.

3. DESIGN OF THE PV BASED WATER PUMPING SYSTEM

The PV based water pumping system that would be used for irrigation was designed with the help of PVsyst software [23]. Pvsyst's primary focus is analyzing and improving PV systems as well as sizing them. The estimated design cost is then calculated using the Hybrid Optimization Model for Electric Renewables (HOMER) software [24]. To get the best possible results from using HOMER, we must optimize its economic costs.

3.1. Design of the PV Based Pumping System in PVsyst

For PVsyst to determine the system's output, it needs the system's location (including GPS coordinates) and solar irradiance data (obtained from the Meteonorm database). The specified location is covered by these statistics for the years 1996 through 2015. After that, we detail how much water will be needed, as well as the features of the PV modules and the pump that will allow them to work together. The following discussion will elaborate on the specifics of these demands.

3.1.1. Water and Pumping Requirements

The water level in the well is stable at a depth of about 30.5 m, and the rate of drawdown is 1 $m/m^3/h$. So, a pump that can be submerged to a depth of 90 m is needed. A submersible centrifugal multistage deep well pump, namely Grundfos SP 95-3 is selected.

Using a three-phase alternating current (AC) motor, this multistage centrifugal deep well pump can lift water at a variety of depths..

Considering that 287 m^3/day is the annual average, a water storage tank with a capacity of 574 m^3/day is required to store enough water for two days. The schematic of the proposed system is shown in Fig. 5.

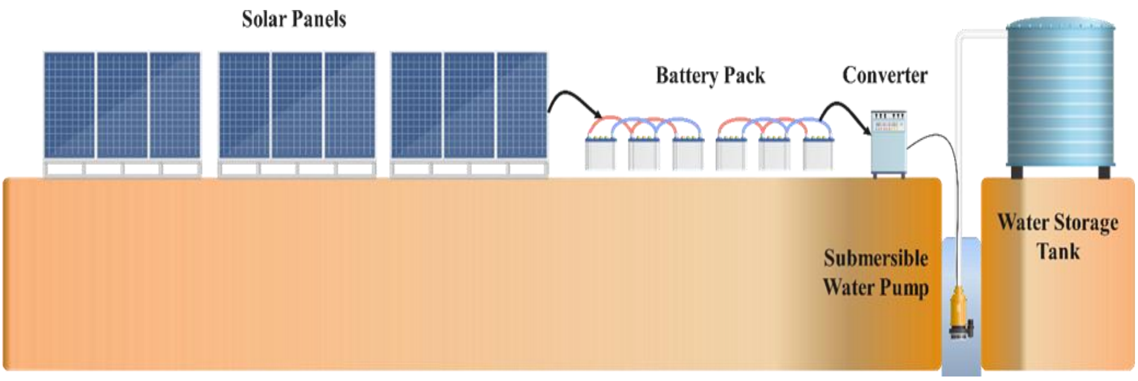

Fig. 5. Schematic of the proposed PV based pumping system .

3.1.2. The PV System

Although the calculated electrical power is 11.39 kW, PVsyst suggested using an AC pump with a capacity of 13 kW. This means that a PV system with a capacity of 15.36 kW is recommended for installation to account for any potential electrical losses. However, because of this, 54% of the water was wasted. This means that a PV system with a capacity of 28.8 kW should be installed. Therefore, the water shortage issue was resolved to the extent that it dropped from 54% to 14.7%.

The proposed PV system features sixty individual modules of solar panels, each of which have 480 W of power. The ENN Solar EST-480 PV model serves as the basis for the proposed system. A total of four 15-strings would are connected to the module in a series configuration.

The recommended tilt angle for the summer season is 140°, while the recommended tilt angle for the winter season is 440°. It has been determined that the azimuth angle is 0°. In addition to that, you will need an AC-MPPT converter, which stands for maximum power point tracking, and it must have an efficiency of 97 % or higher. Fig. 6 shows the configuration of the utilized PV system.

3.2. System Configuration in HOMER

A comma-separated values (CSV) file containing information about the system's electrical consumption is read by HOMER. HOMER uses this information to calculate the optimal dimensions for the PV module and the battery storage. The, it gives the selected setup a score. The evaluation will take into account the levelized cost analysis in addition to the net present cost (NPC). For a year, HOMER will have access to the provided site data. Modelling the same PV system with an 11.39 kW nominal load yields the same results. Because of the abundant solar insolation, the pump is expected to run for a total of 6 h/day. An average daily load of 68.36 kWh will be incurred due to the 6-h period of operation. Additionally, a backup battery system has been built in. As a result, there is a better chance of having power on days with precipitation or cloud cover. Moreover, it might come in handy late at night if absolutely necessary.

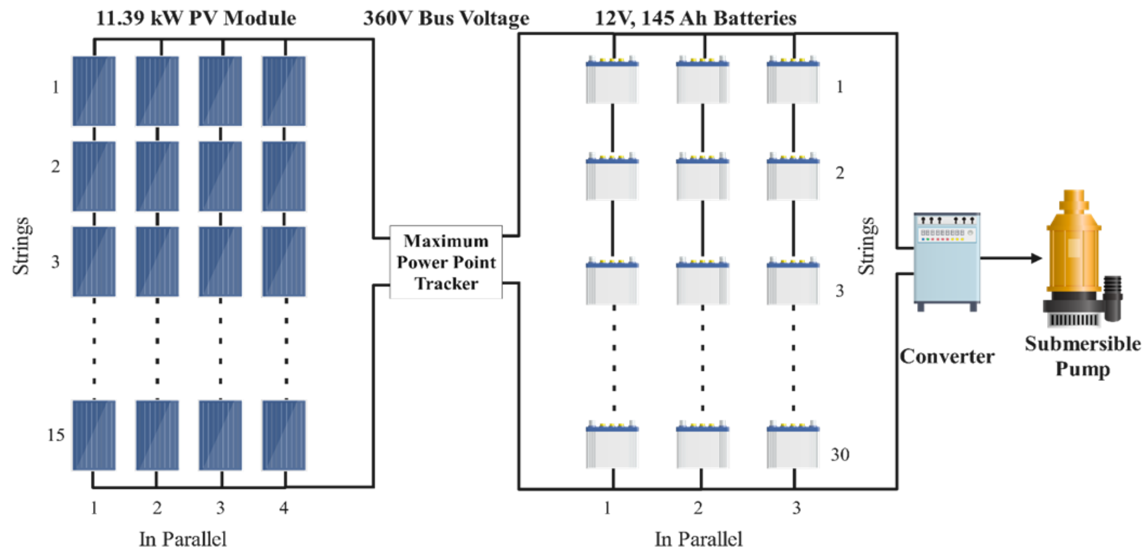

Fig. 6. Configuration of utilized PV system.

3.2.1. NPC

The NPC of a component, also known as its life-cycle cost, is calculated by taking the present value of all the costs associated with installing and operating the component over the course of the project's life-time, subtracting the present value of all the revenues that the component generates over the course of the project's lifetime, and then multiplying the result by one hundred. The net present cost of each component in the system, as well as the total cost of the system, is determined by the HOMER.

3.2.2. Levelized Cost of Energy

The levelized cost of energy (COE), is what HOMER refers to as the average cost incurred per kWh of usable electrical energy generated by the system.

3.2.3. Annualized Operating Cost

The annualized operating cost is the value of all costs and revenues, excluding those associated with initial capital expenditures.

4. RESULTS AND DISCUSSION

4.1. PVsyst Design Results

PVsyst delivers the simulation results for the PV system that is coupled to the water pump. The proposed system will produce a total of 89,321 m^3 worth of water over the course of a single year. Fig. 7 depicts, over the course of one year, results of simulating the proposed system in PVsyst. It shows that the overall efficiency of the system is 79%, whereas the efficiency of the pump is 43.5%. Table 1 provides on a monthly basis, the production of renewable energy and the consumption of water over the course of a year. This breakdown is presented in conjunction with the consumption of water.

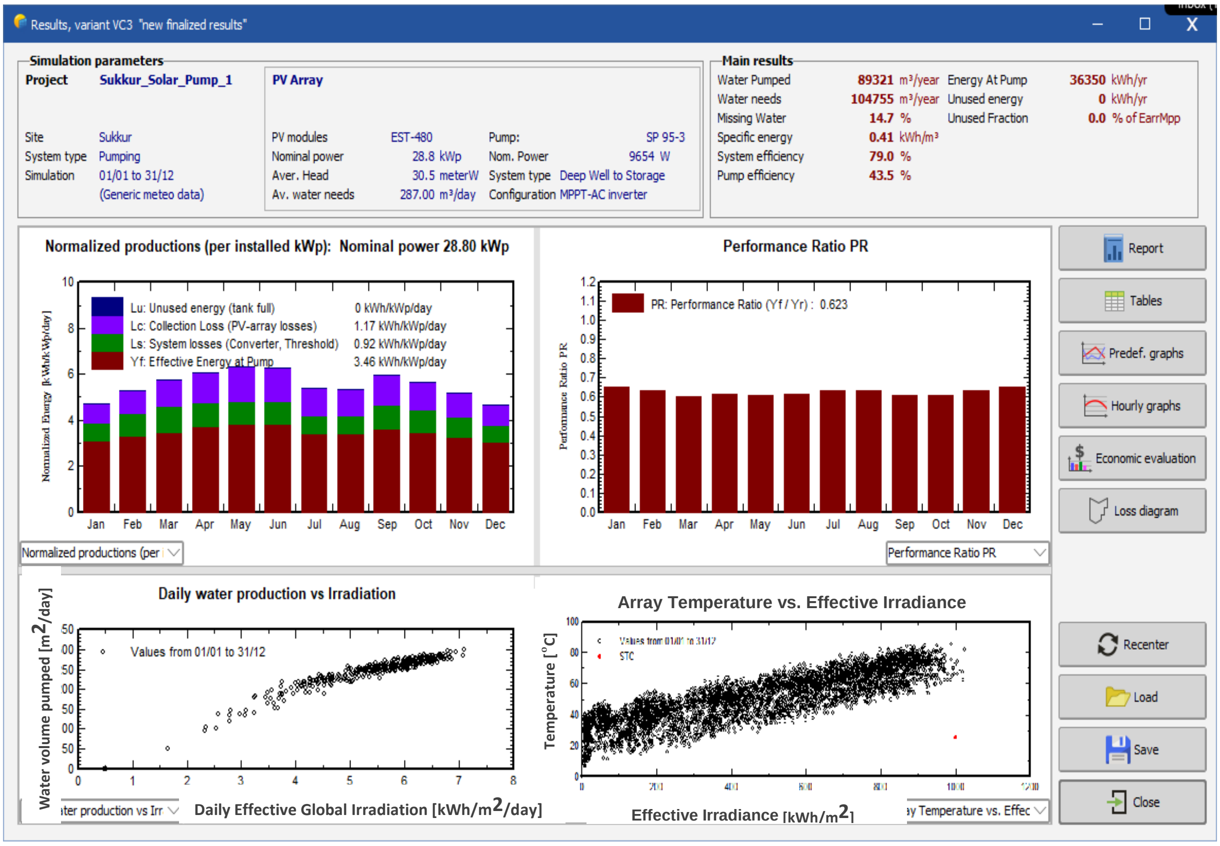

Fig. 7. Simulation results of the proposed system in PVsyst.

Table 1. Monthly production of renewable energy and water production and consumption for a 1-year cycle.

Month	Global radiation [kWh/m²]	Array energy at MPP [kWh]	Pump operating energy [kWh]	Average total pump at head [mW]	Water volume pumped [m³/day]	Water used [m³/day]	Missing water [m³/day]
January	144.1	3471	2767	61.46	220.6	228.2	58.83
February	144.7	3458	2688	62.64	239.1	239.1	47.89
March	174.2	4096	3109	62.56	249.8	249.5	37.53
April	177.1	4098	3201	61.17	261.8	261.2	25.82
May	190.5	4313	3410	60.97	269.8	270.3	16.72
June	184	4182	3330	60.58	271.3	271.4	15.6
July	163.2	3729	3047	58.88	237.2	236.7	50.27
August	161.6	3731	3040	59.18	237.8	238.6	48.36
September	174.8	4022	3127	61.19	255.9	255.3	31.67
October	172.5	3980	3084	61.04	243.8	244.2	42.77
November	153.2	3583	2834	62.34	234.4	234.5	52.51
December	141.6	3371	2712	61.08	215.9	217.7	69.34
Year	1981.6	46033	36350	61.03	244.7	245.5	41.5

It is estimated that the proposed system will have an efficiency of 1981.6 kWh/ m³ for the amount of power it produces per area. The total energy produced by the array when it operates at its maximum power point is estimated to be 46 MWh/ year, while the energy produced by the pump when it is in operation is 36 MWh/ year. Furthermore, it is estimated that the total head of the pump is 61 mW on average. While the proposed system pumps an average of 244.7 m^3, the user will draw an average of 245.5 m^3 of water from the system on a daily basis. This results in an average loss of water of 41.5 m^3, which is referred to as the missing water.

4.2. HOMER Design Result

Block diagram of the utilized PV system that was simulated in HOMER is depicted in Fig. 8. One AC bus and one bus carrying direct current (DC) are necessary to realize the design in its full potential. The DC bus is connected to the PV system and a battery backup. There is a connection between the pump and the DC-AC converter via the AC bus.

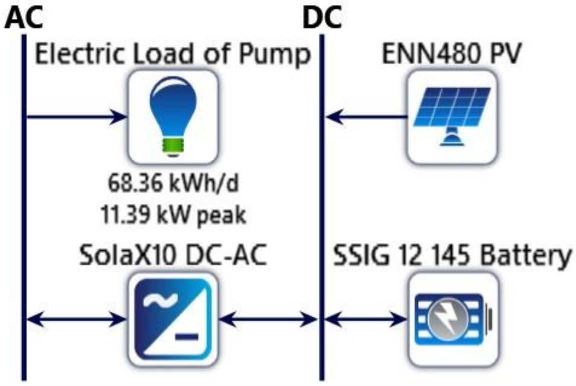

Fig. 8. Block diagram of the PV system in HOMER.

The foundation for the PV system is the same as that used by PVsyst; it is the ENN Solar Energy480EST-480 system. The feasibility of using a backup system is also evaluated by connecting a battery to the system. To power the system, readily available Trojan SSIG 12 145 batteries were incorporated into the blueprints. Homer's PV setup and battery pack specifications are listed in Tables 2 and 3, respectively.

Table 2. Parameters of the ENN solar energy 480 EST-480.

Parameter	Value
Rated capacity	29.9 kW
Mean output	5.51 kW
Daily mean output	132 kWh/day
Capacity factor	18.4 %
Total annual production	48,271 kWh/year

Table 3. Specifications of the Trojan SSIG 12 145 battery bank.

Specification	Value
Number of batteries	90
String size	30 batteries
Number of strings in parallel	3
Bus voltage	360 V
Autonomy	44.3 H
Nominal capacity	158 kWh
Annual throughput	3,059 kWh/year
Lifetime throughput	43,650 kWh

The itemized cost of the proposed system - utilized in Homer simulations - is provided in Table 4. The annualized initial cost of PV panels is $717.77 while operating and maintenance (O&M) cost is estimated to be $508.85 per year. There is no replacement cost of the PV panels. The DC-AC converter initial cost is $34.66 while annual O&M cost is $36.66. The battery pack initial cost is approximated to be $681.22 while O&M cost is $17.10 per year. There is a replacement cost of $8,714.36 in the 15th year and estimated to be $298.17 per year.

Table 4. Cost parameters of the PV system's components.

Component	Capital [$]	Replacement [$]	O&M [$]	Salvage [$]	Total [$]
ENN Solar Energy480EST-480	$717.77	$0.00	$508.85	$0.00	$0.00
SolaX X3-hybrid10 DC-AC	$34.66	$0.00	$36.66	$0.00	$0.00
Trojan SSIG 12 145 Battery	$681.22	$298.17	$17.10	$0.00	-$40.09
System	$1,433.65	$298.17	$562.61	$0.00	-$40.09

The NPC, as shown in Fig. 9, is worth $29,142.90 on the open market and will incur operating costs of $820.68 per year. NPC is currently worth $29,142.90, compared to an initial investment cost of $18,534. The COE per kWh is found to be $0.09036. Fig. 10 shows the estimated total cost of the proposed system. The proposed system's cash flow is depicted in Fig. 11. According to the cash flow analysis, the total cost is $18,533, with the cost of replacing the battery being estimated at $8,714.36 every 15 years. It is estimated that the project's salvage value will be $2,163.64 after 25 years.

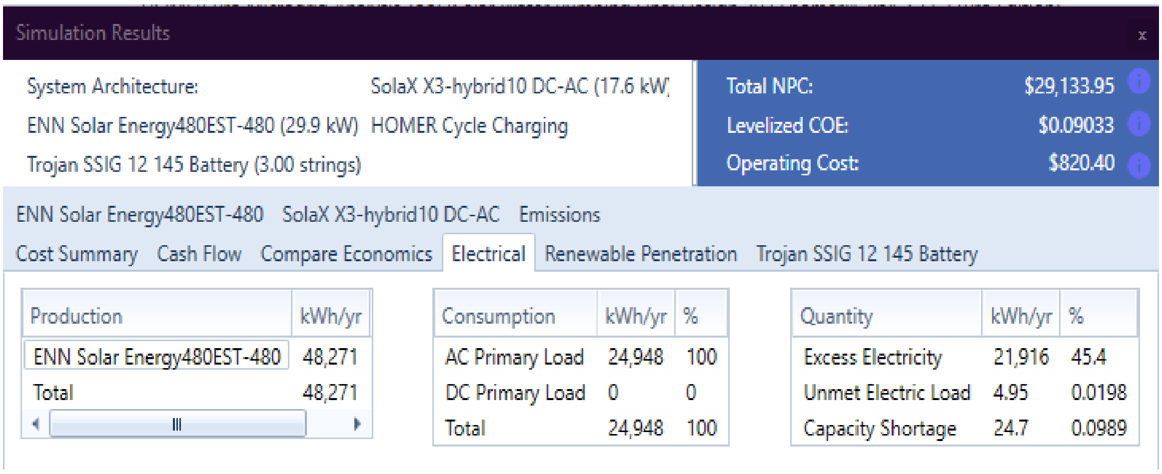

Fig. 9. Simulation results of the proposed system in HOMER.

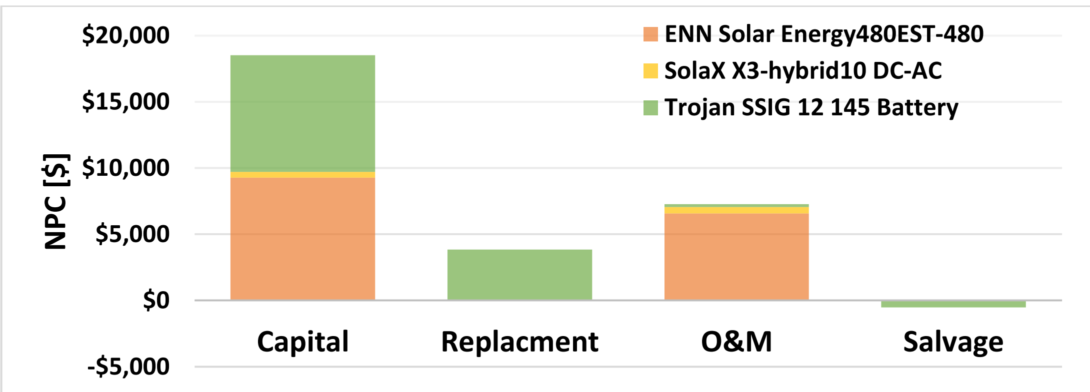

Fig. 10. Cost summary of the proposed system.

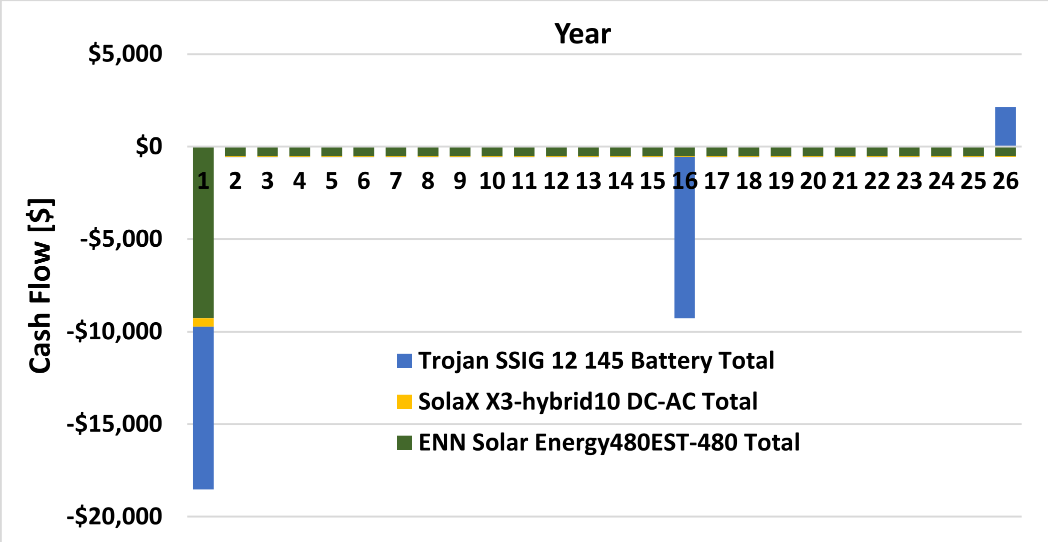

Fig. 11. Cash flow of the proposed system for the priod of 25 years.

5. COMPARISON OF THE PROPOSED SYSEM WITH NONRENEWABLE SYSTEMS

We have compared our model with two other generators that use non-renewable resources, such as diesel and natural gas generators, as well as grid-connected systems [25, 26]. The analysis of non-renewable resources can be found in Table 5. In comparison to diesel-powered, natural gas-powered, and grid-connected systems, the initial investment cost of our proposed model is significantly higher; however, overall, it results in significantly reduced costs for both operation and maintenance. In addition, the proposed system requires only a moderate O&M cost in contrast to other non-renewable resources.

Table 5. Comparison of the proposed system with non-renewable systems.

	Solar powered	Natural Gas powered	Diesel powered	Grid connected
Initial investment	High	Low	Low	Low
O&M Cost	Low	Medium	High	Medium
Maintenance	Medium	High	High	Medium
Environmental impact	Eco-friendly	Emits medium pollution	Emits high pollution	Emits medium pollution

We have run simulations of our model alongside natural and diesel generator sets and compared all of these to rechargeable energy sources. We have simulated PV systems with backup, as well as PV systems with natural gas or diesel generators with backup, and PV systems with generators but without battery backup. Table 6 presents an illustration of the comparison of the simulated models. It shows that the proposed system has lowest NPC when only PV system and battery backup system are used. The NPC is determined to be $29,142.90 while PV along with battery backup and with non-renewable sources is between $29,635.27 and $31,323.40. If the same PV system is used without battery backup, the system is quite inefficient. However, if we add a non-renewable system with PV only and no battery backup is used, the NPC ranges from $97,256.29 to 105,632.71 which is quite high. Therefore, the PV system with battery backup is the recommended system when compared to other options.

Table 6. Comparison of the prposed system with diesel and natural gas gensets.

	Only PV with backup	PV with backup and natural gas genset	PV with backup and diesel genset	PV without backup and natural gas genset	PV without backup and diesel genset
Capital investment	$18,533.53	$15,900.68	$18,836.64	$45,807.24	$41,423.11
Replacement	$3,854.60	$4,440.46	$5,476.92	$709.22	$858.65
O&M cost	$7,273.09	$6,541.86	$6,618.87	$29,765.33	$26,642.43
Fuel cost	$0.00	$3,143.79	$1,224.12	$21,272.36	$36,857.03
Salvage	-$518.32	-$391.52	-$833.15	-$297.85	-$148.53
Total (NPC)	$29,142.90	$29,635.27	$31,323.40	$97,256.29	$105,632.71

Furthermore, we have simulated a model that includes a grid-tied system with net metering, despite the fact that there is currently no chance that the grid will be extended to the location of the project. The comparison is detailed in Table 7. It is clear that the project will actually become profitable with a negative NPC once the proposed system is connected to the grid. On the other hand, connecting to the grid in the near future is unlikely to happen.

Table 7. Cost comparison of the proposed system with a grid-tied system.

Cost	System	
	Only PV	Grid-tied PV
Capital investment	$18,533.53	$25,696.27
Replacement	$3,854.60	$0.00
O&M cost	$7,273.09	-$36,196.79
Fuel cost	$0.00	$0.00
Salvage	-$518.32	-$678.49
Total (NPC)	$29,142.90	-$11,179.01

6. CONCLUSIONS

An irrigation water pump powered by renewable energy sources is modelled after this study's findings. After showing how to design a submersible AC pump according to a site's water requirements in Sukkur, we used HOMER Pro to estimate the system's up-front and recurring costs. Specifically, 60 PV panels (4 strings of 15 panels) will be connected in series to provide the necessary 29.9 kW of PV capacity for the system. In addition, 90 12V 145Ah batteries connected in 3 strings of 30 in series are needed for the system to function properly. We have analysed how the proposed system stacks up against conventional energy sources like natural gas and diesel generators. From our testing, we have learned that the net present cost of a solar-powered pumping system is significantly lower than that of a system that relies on non-renewable energy sources. The proposed system becomes financially viable with a negative net present cost if the same system can be connected to a net metered grid. After conducting extensive research and optimizing the system with HOMER, it was determined that the O&M costs are fair when weighed against those of non-renewable energy sources.

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