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The Economic Sizing of Hybrid Energy System and Reducing GHG Emissions for Drive a Small RO Plant in NRC Noubarya Farm, Egypt

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ABSTRACT

Hybrid Renewable energy system water desalination systems is gaining popularity due to increased demand for water and energy, as well as a desire to reduce carbon emission. The main aime of this paper is to design a renewable energy system capable of meeting the electrical load requirement of a small-scale reverse osmosis desalination plant (65m^3/d), in NRC Noubarya Farm, Egypt as well as to determine the ideal sizing and assess the techno-economic and environmental feasibility of various off-grid power system configurations. Also designs a new hybrid renewable energy system (HRES) for this RO plant by conducting simulations using the HOMER (Hybrid Optimization of Multiple Energy Resources) software. three power systems configures investigated and analyzed based on economic and environmental bases: (PV/ Wind turbine (WT)/DG), (PV/ WT/DG/Battery). The comparisons result of hybrid configuration systems shows the optimal hybrid power system configuration is PV/WT/DG/Battery, which has the lowest COE of 0.274$/kWh, Renewable Fraction (RF) as 87.1%, Net present cost(NPC) is about 66,081.46 $ and CO$_2$ emissions as 417,752 kg/year.

1. Introduction

The continued emphasis on economic advancement, combined with rapid Urbanization has a considerable impact on world energy usage [1]. As a result, negative consequences, CO$_2$ emissions Traditional energy sources are limited and decreasing, prompting the need for alternative alternatives [2]. Contemporary essential considerations include cost-effective, sustainable, and environmentally acceptable primary energy supply solutions with minimal greenhouse gas emissions, especially in the power and industrial sectors [3, 4]. To transition away from fossil fuels, it's vital to find a renewable and secure clean energy alternative.

Reliance on fossil fuels is minimized by renewable energy sources, which reduces their negative effects on the environment and carbon dioxide (CO$_2$) emissions. The use of an integrated energy system for saltwater desalination appears to be a potential strategy for ensuring coastal communities' access to clean drinking water [5]. Desalination has become an attractive option as the need for clean drinking water has recently increased. However, employing typical energy sources for desalination may not always be feasible or affordable. As a result, desalination plants now operate by sustainable and clean alternative energy sources, such renewable energy [6]. There are various factors that influence seawater desalination. These considerations include renewable energy availability, salinity, energy costs, and desalination process efficiency. In areas with abundant renewable energy sources, such as solar and wind power, hybrid energy systems can be an affordable and dependable choice for desalination facilities. Furthermore, developments in desalination technology have increased process efficiency, lowering energy usage [7].

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Egypt's outlying regions face serious shortages of both electricity and drinking water. In these remote areas, the demand for freshwater is mostly satisfied by the use of water tanks, which incur expensive costs that can surpass 10€/m^3 [8]. The optimization of renewable energy systems, such as wind [9–11] and solar [12–14], has been the subject of numerous academic studies. In their analysis of solar systems used to power reverse osmosis water desalination, Ahmad et al. [15] examined the impact of the slope and azimuth angle of photovoltaic (PV) panels on the permeate flow rate. Qiblawey et al. [16] examined the combination of reverse osmosis water desalination and photovoltaic energy generation with auxiliary battery storage. The efficiency and dependability of desalination systems could be improved by hybrid renewable energy sources (HRES) [17]. On a smaller scale, HRES-powered desalination systems can be created by using the energy produced by wind turbines (WT) and solar (PV) collectors to run high-pressure pumps in RO units. Smaller-scale desalination systems powered by HRES can be developed by utilizing energy from solar photovoltaic collectors and wind turbines to drive high-pressure pumps in reverse osmosis units. Energy storage systems are necessary to keep the system operating when the supply of renewable energy is limited.

Enhancing PV-wind hybrid systems to supply energy to reverse osmosis (RO) desalination facilities has been the subject of several previous studies. For optimal performance remote hybrid RO desalination plants that are powered by solar and wind electricity, were investigated by Mokheimer et al. [18] created modelling software that is appropriate for the environment of Saudi Arabia. Their findings demonstrated that in order to reduce the Levelized Cost of Electricity (LCOE), several wind turbines are required. In order to run a standalone RO desalination plant in Iran, Zhang et al. [19] introduced an optimization framework for a comprehensive system that combines PV, wind turbines, and battery storage. In order to better optimize their model, they first used a harmonic search approach and then included a chaotic search algorithm. The PSO-GWO optimization technique was presented by Abdelshafy et al. [20] in order to ascertain the optimum RO desalination hybrid system size, taking into account the possibility of hydrogen or battery storage. Kumar et al. [21] used the Biogeography-Based Optimization (BBO) technique to determine the ideal size for PV/wind hybrid energy systems in order to reduce overall costs and guarantee the supply of electricity in remote locations.

An improved version of the Bees algorithm was created by Maleki [22] to optimise the scale of hybrid renewable energy systems. Ghaithan et al. [23] sized grid-connected photovoltaic wind installations using mixed-integer programming with the goal of lowering the overall cost, greenhouse gas emissions, and grid dependence for RO desalination in a residential region of Saudi Arabia. Using a genetic algorithm, The significance of novel evolutionary heuristic techniques in the design of hybrid PV-wind systems with batteries and RO technology in Tunisia was emphasized by Bourouni et al. [24]. For the desalination plant in Tunisia, Kumarasamy [25] created an autonomous hybrid renewable energy system with the goal of maximizing both profitability and efficiency. The cost-effectiveness of the coordinate sizing method for microgrids with RO systems was demonstrated by Prathapaneni and Detroja [26]. With an emphasis on economical energy distribution, Anoune et al. [27] optimized PV wind hybrid system options for Tunisia using TRNSYS. Acuna et al. [28] highlighted the significance of employing renewable energy to increase system dependability by introducing a fresh reliability metric for hybrid systems. A Mixed Integer Nonlinear Program for desalination plants was presented by Klaimi et al. [29] in order to reduce costs while achieving particular carbon emission targets. To find the most effective HRES for freshwater production, Peng et al. [30] used a range of optimization techniques, such as Harmony Search, Simulated Annealing, Particle Swarm Optimization, Bees Swarm Optimization, Chaotic Search, and Tabu Search.

The ideal HRES size for RO desalination has recently been determined using a variety of techniques. In their study of dispatch strategies for the best HRES configurations, Liu et al. [31] concentrated on lowering the dependability index, LCOE, capacity shortfall cost, and net annual cost. Saboori et al. [32] suggested a novel linear formulation for the simultaneous optimization of the desalination system and its power supply components in order to lower the Levelized Cost of Water, precisely size the system, and lower carbon emissions. Their study offers insightful information for further research on water cost mitigation.

2. Methodology

The NRC Noubarya farm in Egypt has a small-scale Reverse Osmosis (RO) facility, and these HRESs are carefully crafted to meet its electrical load requirements. Therefore, using Homer Pro software, an approach that includes optimization and feasibility analysis is used to find viable HRES alternatives. A number of critical measures, such as Net Present Cost (NPC), Cost of Energy (COE), and the environmental effects related to carbon emissions, are integrated into the performance evaluation of each alternative. Furthermore, Homer simulation methods are used to identify the best power system configuration. The suggested hybrid energy system, which consists of a PV module, a wind turbine, a diesel generator, and a battery bank, is schematically represented in Figure 1.

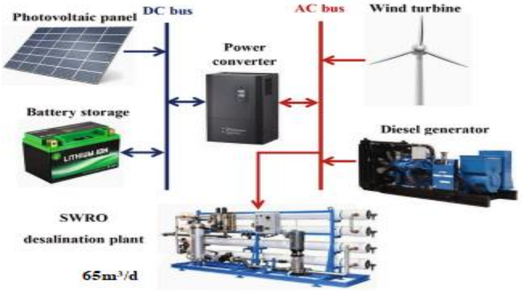

Figure 1: proposed RO unit hybrid energy system

3. Location and weather data description

3.1. Location

Generally, the site should be carefully chosen. The National Research Centre (NRC) farm, situated in the remote locality of Noubarya, Egypt, is positioned at a Latitude: 30^{o}40′ 0″ and Longitude: 30^o 40′ 0″, has been chosen as the location. It is unstable electricity grid, suitable solar radiation, and suitable wind speed and water source. Figure 2 illustrates the geographical representation of Noubarya [33].

Figure 2: Geographical Map of Noubarya, Egypt [34]

3.2. Solar Energy

The mean monthly solar radiation data is derived from NASA's HOMER software [34]. The yearly mean solar radiation in Noubarya is approximately 2 KWh/m2 per day. Figure 3 depicts the annual radiation profile for Noubarya, Egypt. From this illustration, it is evident that August experiences the highest radiation levels throughout the year.

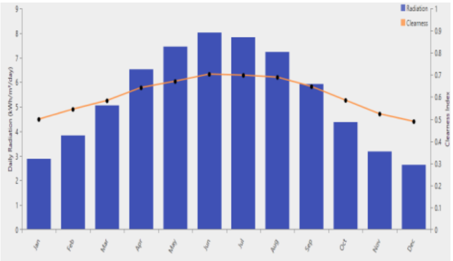

Figure 3: HOMER Results of radiation profile during the year at NRC Noubarya farm.

3.3. Wind speed

According to NASA's HOMER program, the average monthly wind speed data at NRC Noubarya Farm in Egypt is roughly 5.78 m/s [34]. Figure 4 displays the annual wind speeds at NRC Noubarya farm in Egypt. The highest wind speed of the year is observed in February.

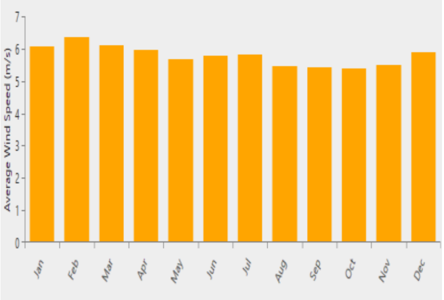

Figure 4: Homer results of wind speed profile along the year at NRC Noubarya farm.

4. Load Profile Curve

The load characteristics of a reverse osmosis desalination unit DU is powered by energy produced by HSES. The capacity of the desalination unit is about 65 cubic meter daily. In the context of this load profile, the high-pressure pump, the distribution pump, and the feed pump operate concurrently, thereby establishing a peak load requirement of approximately 6.6 kW. The reverse osmosis desalination unit NRC- farm and load profile curve are presented in Figs 5 and 6respectively.

Figure 5: Real photo for a case study of RO water desalination plant in NRC farm located in Noubarya

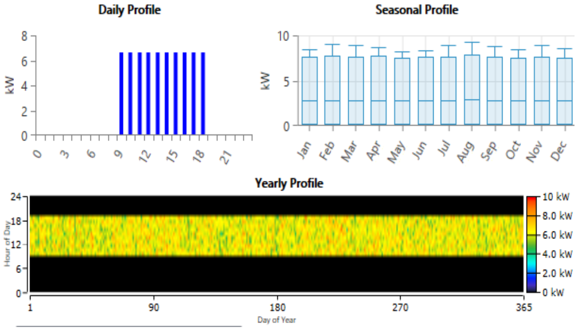

Figure 6: Daily, seasonal and yearly load profile for desalination plant

5. Mathematical modeling and simulation

HOMER software has been used to construct a hybrid energy system model that includes a diesel generator, photovoltaic solar panels, a wind turbine, and a battery storage system. The next sections outline the model's inputs and underlying assumptions, which include weather information, the availability of energy resources for the specified location, community load demand, and component specifications.

5.1. PV module

The amount of solar radiation that strikes the PV array's surface determines the system's maximum power output, which is then immediately turned into electrical power. The PV array's output power is computed using HOMER software [35]. The following formula determines the computed power:

$$P_{pvout}(t) = P_{PVrated} \times \frac{G(t)}{1000} \times [1 + \alpha t\,((T_{amb} + (0.0256 \times G_t))) - T_{ref}] \quad (1)$$

In this context, $P_{pvout}(t)$ denotes the output power (W) of the photovoltaic module, G(t) signifies the solar radiation value (W/m²), P(PVrated) refers to the nominal power of the photovoltaic system under standard conditions, at represents the temperature coefficient calculated by (23.7 x 10^-23 (1/C)), Tref is designated as 25°C, which corresponds to the reference temperature under standard conditions, while Tamb indicates the ambient temperature (°C).

The PV module's technical specifications and cost are shown in Table 1.

Table 1 Economical characteristics of the PV module used in this study

PV system	
Model	Peimar SG290NFB
Peak power	1 KW
Capital cost	640$
Replacement cost	640$
Life time	25 years

5.2. Wind turbine

The power output generated by a wind turbine is commonly evaluated utilizing equation (2) [36]. A height of ten meters is conventionally adopted at meteorological stations for the deployment of an anemometer to assess wind speed.

$$P_{WT} = \begin{cases} 0 & v(t) \le v_{cut-in} or v(t) \ge v_{cut-out} \\ p_r \times \frac{v(t) - v_{cut-in}}{v_r - v_{cut-in}} & v_{cut-in} \le v(t) \le v_r \\ p_r & v_r \le v(t) \le v_{cut-out} \end{cases} \quad (2)$$

In this formulation, P_{WT} represents the output power of wind turbines, P_r denotes the rated power of the wind turbine, while the associated speed v(t) (m/s), $v_{cut-out}$ (m/s) signifies the cut-out speed of the wind turbine, v_{cut-in} (m/s) indicates the cut-in speed of the wind turbine, and v_r represents the rated speed of the wind turbine. Table 2 presented the specifications and costs of Wind turbine.

Table: 2 Economical characteristics of the wind turbine used in this study.

Wind turbine	
Model	Bergey BWC XL.1
Peak power	1 kW
Capital cost	2300 $
Replacement cost	1500 $
Life time	20 ears

5.3. Battery bank

Given the stochastic characteristics of battery storage and the inherent variability of outputs from photovoltaic cells and wind turbines, it is imperative that the battery is accurately modeled to fulfill load requirements. The batteries undergo charging when the energy generated by renewable resources surpasses the total load demand. Conversely, to address the energy deficit, batteries are discharged when the load demand exceeds the generated power [37]. In situations where the load demand is not adequately met by the cumulative power produced from all sources, the battery storage bank will activate to supply the requisite energy. Consequently, the battery storage bank initiates the discharge process. Batteries serve the function of storing excess energy generated by renewable energy sources; however, the capacity of these batteries must be constrained. It is not feasible to achieve large-scale energy storage with this particular battery storage bank. A percentage representation of the maximum allowable depth of discharge (DOD) is indicated. Complete discharge of a battery is impractical. In this study, it was presumed to be 80% in order to minimize the required battery storage capacity, as per equation (3) [38, 39].

$$E_{BSmin} = (1 - DOD) \times E_{BSmax} \quad (3)$$

E_{BSmin} represents the minimum permissible capacity of the battery bank, E_{BSmax} denotes its nominal capacity, and DOD is defined as the depth of discharge. The costs and technical details are presented in the Table 3.

Table 3: Economical characteristics of the Battery data used in this study

Generic 1kWh lead acid (ASM)	
Voltage	6V
Capital cost	300 $/unit
Replacement cost	300$/unit
O&M cost	20$/year
Life time	15 years

5.4. Diesel generator

In a hybrid energy system, a diesel generator compensates for the inadequacy of power output from photovoltaic or wind energy sources alongside a battery bank. Regular maintenance and repairs are generally recommended to prolong the operational lifespan of the generator. Equation (4) articulates the fuel consumption of a diesel generator, which is entirely contingent upon the power output of the generator.

$$F(t) = a_{dg} \times P_{DG}(t) + b_{dg} \times P_r \qquad (4)$$

The following are the corresponding DG parameters in this instance: P_r stands for average power, F(t) for fuel consumption (L/h), and $P_{DG}(t)$ for power generation at hour t (kW). In the meantime, the constant numbers a_{dg} and b_{dg} (L/kW) represent the standardized fuel consumption characteristics, which are 0.246 and 0.08415, respectively [38]. The generator costs data are listed in Table 4

Table 4 Economical characteristics of the Diesel generator used in this study

Diesel Generator	
Voltage	Auto size Gen
Capital cost	500 $
Replacement cost	500 $
Life time	15,000 hr

5.5. Converter

For a hybrid energy system to function properly, it needs one or more power converters. Inverters are electronic devices that convert direct current to alternating current. Here, a converter is used, which may act as both a rectifier and an inverter, depending on which way the electricity flows. Equation (5) can be used to calculate the inverter's input power Pinv [40].

$$Pinv(t) = P_l^{max} / \eta_{Inv} \qquad (5)$$

In this case, P_l^{max} (t) stands for peak power demand, or the maximum power that the load might possibly need at that particular time. The invert's efficiency is represented by η_{inv}. Table 5 contains data on the inverter.

Table 5: Economical characteristics of the Converter used in this study

Converter	
Voltage	1 kW
Capital cost	300$/kW
Replacement cost	300$/kW
Life time	15 years

6. Results and discussion

This study examines the results and provides a thorough analysis of the optimization outcomes of the RO plant in NRC Noubarya Farm. The most viable systems are compared and evaluated in alignment with the objectives established by the study. Table 6 presents the outcomes of three categories: (PV/DG/Battery), (PV/WT/DG), and (PV/WT/DG/Battery). Figure 7 presents the application of the developed hybrid renewable energy system to supply power to small-scale Reverse Osmosis desalination System located in NRC Noubarya Farm, Egypt.

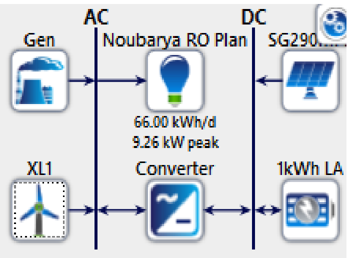

Figure7: proposed system of stand-alone HRES

Table 6: Summary of results

Scen. NO.	**Architecture**						**Cost**	
	PV kW	WT kW	Gen kW	1kWh LA	Conv. kW	NPC $	LCOE $/kWh	RF (%)
1	20		11	24	10	70,563	0.314	76.6
2	40	2	11		9	82,941	0.362	76.2
3	14	5	11	25	9	66,081	0.274	87.1

From above Table it is clear that:

- The scenario 1 ranks the second position between scenarios. This scenario consists of 20 kW of PV module, 10kW of power converter, 24 batteries and 11 kW of diesel generator.
- The scenario 2 ranks the last position between scenarios. This scenario consists of 40 kW of PV module, 2 kW of wind turbine, 9 kW of power converter and 11 kW of diesel generator.
- The scenario 3 ranks the first position between scenarios. This scenario consists of 14 kW of PV module, 5 kW of wind turbine, 9kW of power converter, 25 batteries and 11 kW of diesel generator.

6.1. Comparison analysis between different PV HRES scenarios

The economic aspects of each system are compared in Figure 8, which compares the total project cost (NPC), capital expenses, and maintenance costs (O&M).

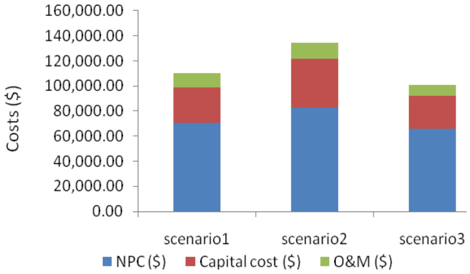

Figure 8: A variety of PV hybrid systems' financial parameters

Figure 9 illustrates the NPC and COE values for the different PV HRES scenario.

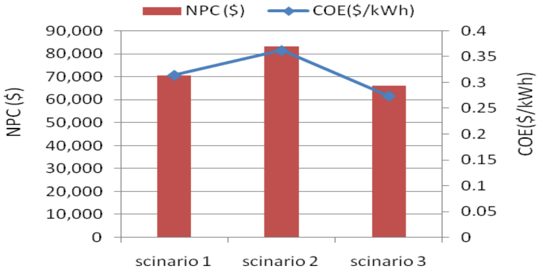

Figure 9: Cost comparison between different PV HRES scenario.

From this figure, it is clear that, NPC and COE of scenario 3 is the optimal NPC and COE over the other scenarios. Scenario 3 has the lowest net present cost is about 66,081$. Also, has the lowest COE about 0.274 $/kWh. On the other had the scenario 2 is the higher NPC about 82,941$ and COE about 0.362$/kWh than other scenarios as shown in Figure 9. Also Figure 10 presents the various PV HRES results for renewable energy fraction (RF) and COE.

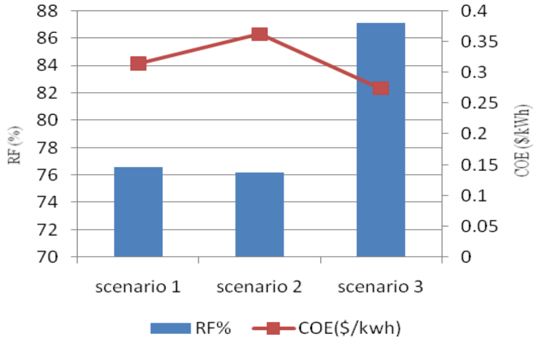

Figure 10: COE and RF for PV HRES scenario

The definitive distinction in the emission levels of deleterious gases and carbon dioxide produced by the proposed systems is illustrated in Table 7. The secinario3 exhibited the minimal quantity of emitted gases relative to all other scenario. Figure 11 provides a comparative analysis of the emissions.

Table 7: Emission for PV hybrid renewable energy systems

Pollutant	Scenario 1	Scenario 2	Scenario 3
Carbon dioxide (kg/y)	5,067	5,954	2,909
Carbon monoxide (kg/y)	31.9	37.5	18.3
Ubarned Hydrocarbon(kg/y)	1.39	1.64	1.2
Sulfur dioxide (kg/y)	12.4	14.6	7.12
Nitrogen oxides (kg/y)	30	35.3	17.2

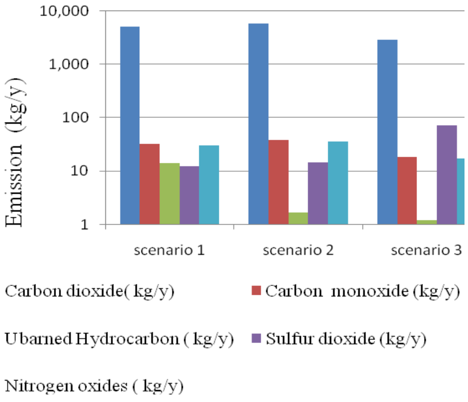

Figure 11: Emission comparison between PV HRES scenarios.

7. Conclusions

This study concerns the NRC farm located in Noubarya, Egyptian remote area outside. The transition to a hybrid renewable energy system is very feasible and advantageous, particularly in such isolated and remote places. This study's objective is to provide a thorough feasibility analysis of several hybrid PV systems for powering a small desalination unit to supply 65m3/day of drinking water. In order to identify the best solution based on lower costs and a reduction in toxic and damaging carbon emissions. The study also uses HOMER software to compare the suggested hybrid system with other alternative systems. Three different scenarios options are considered: PV/DG/Batteries, PV/WT/DG and PV/WT/DG/Batteries. The optimal hybrid renewable system with the lowest expenses and the best returns was determined by using the HOMER Pro tool. Optimal PV hybrid system is scenario 3 which consisting of 14 kW of PV arrays, 5 kW of wind turbine, 11 kW diesel generator, 25 batteries and 9 kW of power converter. When compared to NPC of other setups, it has the lowest NPC. Lastly, the hybrid system (PV/wind/diesel/battery) is less expensive and emits less harmful pollutants.

Conflict of Interest

The authors declare no conflict of interest.

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