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Optimal Sizing and Techno-Economic analysis of Reverse Osmosis Desalination Systems Based on PV/Wind Green Energy System

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ABSTRACT

This research investigates the techno-economic design optimization of an independent integrated renewable power system integrated with a Reverse Osmosis (RO) desalination plant situated in Alamein, Egypt. The introduced system incorporates photovoltaic, wind turbines (WT), batteries, a power converter, and a upholding diesel generator. HOMER software is employed to conduct simulations, evaluating the optimal system arrangement and component sizing based on the objective of achieving the lower possible cost of energy (COE). The analysis encompasses sensitivity analysis, net present cost (NPC) calculations, and an assessment of pollutant gas emissions. The primary function of the proposed system is to fulfill the demands of the RO plant, which has a daily freshwater production of 250 cubic meters. The results demonstrate that the optimal system configuration, yielding a COE of $0.104/kWh, comprises 200kW of PV panels, one 100kW WT, and a 250kW diesel generator. When compared to alternative system designs, this specific configuration emerges as the most appropriate and best cost solution for the desalination plant's energy requirements.

1. Introduction

The integration of desalination technologies with renewable energy resources presents a highly promising solution to combat freshwater scarcity, particularly in geographically isolated regions [1]. Reverse Osmosis (RO) desalination emerges as the most efficient process when driven by renewable energy, constituting approximately 60% of such implementations, with thermal desalination methods trailing behind [2]. Photovoltaic (PV) systems hold the dominant position as the most deployed renewable energy source for desalination plants, accounting for roughly 45% of installations, followed by solar thermal and wind power options [3]. This convergence of integrated renewable power systems and desalination processes offers a key strategy for the simultaneous conservation of both water and energy resources [4]. The techno-economic optimality of desalination systems powered by renewable energy hinges on several critical factors. These factors encompass the available solar and wind energy potential at the chosen location, the salinity levels of both the input feed water and the produced freshwater, and the overall scale of the desalination plant [5]. Employing a diverse combination of hybrid renewable energy technologies at a specific location can effectively mitigate the challenges arising from the inherent variability and intermittency of these resources [6].

Hypothetical studies and practical investigations into hybrid renewable power sources have consistently demonstrated that integrating multiple renewable technologies offers a more economically viable solution for meeting energy demands compared to relying solely on photovoltaic (PV) or wind turbine systems [7]-[10]. This finding underscores the potential for optimizing the utilization of alternative energy sources in supplying electricity to various loads. Further research exploring the performance of hybrid power systems within the context of Egypt has revealed that the combined deployment of PV and wind turbine technologies yields favorable results throughout the majority of the day-night cycle and across extended periods annually [11]-[14].

Figure 1 illustrates the primary devices of the introduced integrated renewable energy project integrated with a Reverse Osmosis (RO) desalination plant. The system encompasses photovoltaic (PV) panels, WT, batteries for energy storage, a power converter, a diesel generator for backup power, a high-pressure pump (HP) for the RO process, a membrane module for desalination, and a storage tank for the produced freshwater. The primary objectives of this analysis are to determine the optimal sizing of each component to effectively meet the desalination plant's water demand and to ascertain the optimal values for both the COE and the NPC of the system. The project's lifespan is estimated at twenty-five years, with yearly interest rate of 8% factored into the economic calculations.

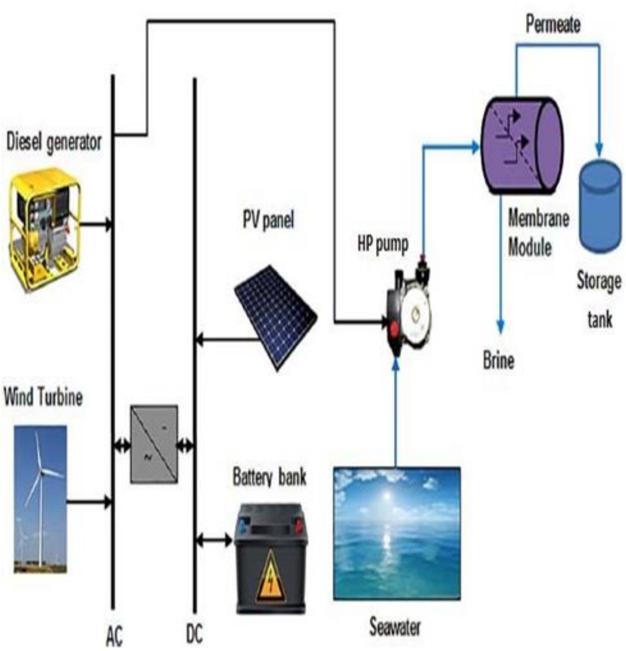

Fig. 1: Main devices of the proposed PV-wind-battery-diesel and RO system.

2. Methodology

2.1. Site Description and Weather Data Inputs

The established RO desalination plant under consideration is situated in Alamein, Egypt, at a latitude of 30°48.3' N and longitude of 28°39.7' W. Table I provides a detailed overview of the plant's technical specifications. The facility requires an average daily energy consumption of approximately 1259.01 kWh to produce 250 cubic meters of desalinated water. Based on measurements obtained from NASA [15], the yearly mean wind speed at the site is recorded at 5.53 m/s. Figure 2 depicts the monthly mean wind speed, ranging from 5.01 to 6.4 m/s. Solar irradiation levels exhibit monthly variations, as illustrated in Figure 3, with values spanning from 2.5 to 7.89 kWh/m^2 and a mean value of 5.29 kWh/m^2. Figure 3 also presents the clearness index for the site, which serves as a crucial parameter in the design of the integrated renewable energy project [16].

Table 1. Technical Nomination of the Reverse Osmosis Plant

Characteristic	**Unit**	**Value**
Capacity	m^3/day	250
Feed pressure	Bar	63
Feed temperature	˚C	25
Feed concentration	ppm	34000
Pressure vessels number	--	4
Membrane number per vessel	--	3
Feed pump consumption	kW	2.5
High pressure pump consumption	kW	71.97
Dosing pump consumption	kW	0.065
Product water pump consumption	kW	1.01 2
Auxiliary loads	kW	2.5 3
Daily operating hours	hr	16

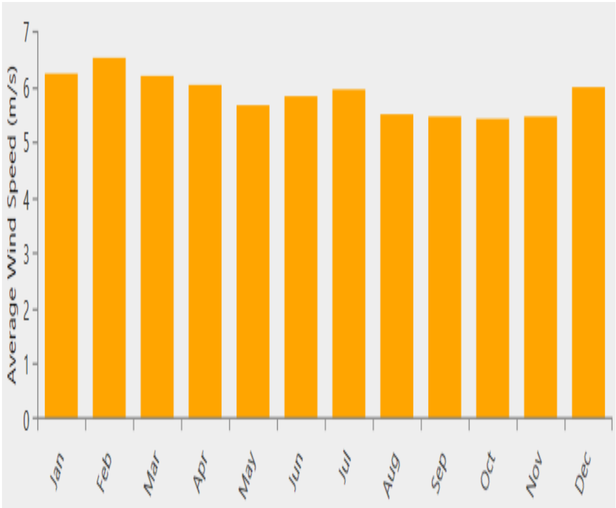

Fig. 2: Monthly mean wind speed in the site [15].

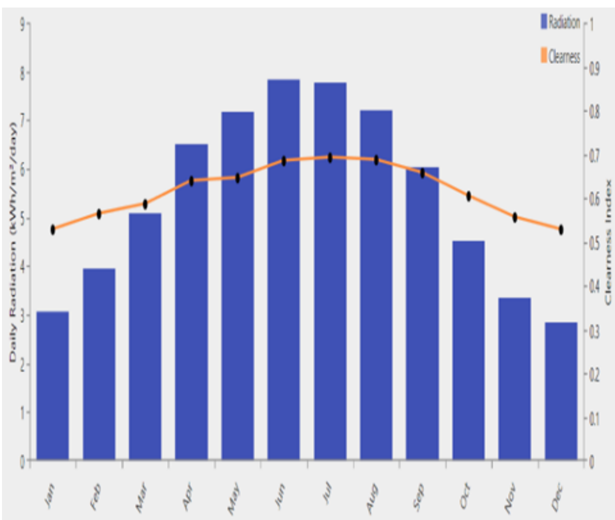

Fig. 3: Monthly mean solar radiation and clearness index in the site [15].

Figure 4 presents a flowchart outlining the primary stages of the simulation analysis conducted for the hybrid renewable energy system. The estimate analysis sequence is executed utilizing equations 1, 2, and 3 while the economic design of the project devices is determined through the application of equations (4) to (7) as detailed in Table 2 [17, 19].

Table 2. The Utlizied Equations for the Design

Quantity	**Equations (No)**
Cost of energy ($/kWh)	$COE = C_{a,\,tot} / E_{a,\,tot}$ (1)
Net present cost ($/year)	$NPC = C_{a,\,tot} / CRF$ (2)
Capital recovery factor	$CRF = i\,(1+i)^n / (1+i)^{n-1}$ (3)
PV array output (kW)	$P_{PV} = P_{rated}\, F_{PV}\, (G/K)$ (4)
Wind turbine power output (kW)	$P_{WT} = (1/2)\, p\, A\, V^3 \eta_w$ (5)
Minimum allowable capacity of battery bank (Ah)	$E_{min} = E_{BN}\,(1 - DOD)$ (6)
Fuel consumption of diesel generator (L/hr)	$F_{DG} = F_0 . P_G + F_1 . P_G$ (7)

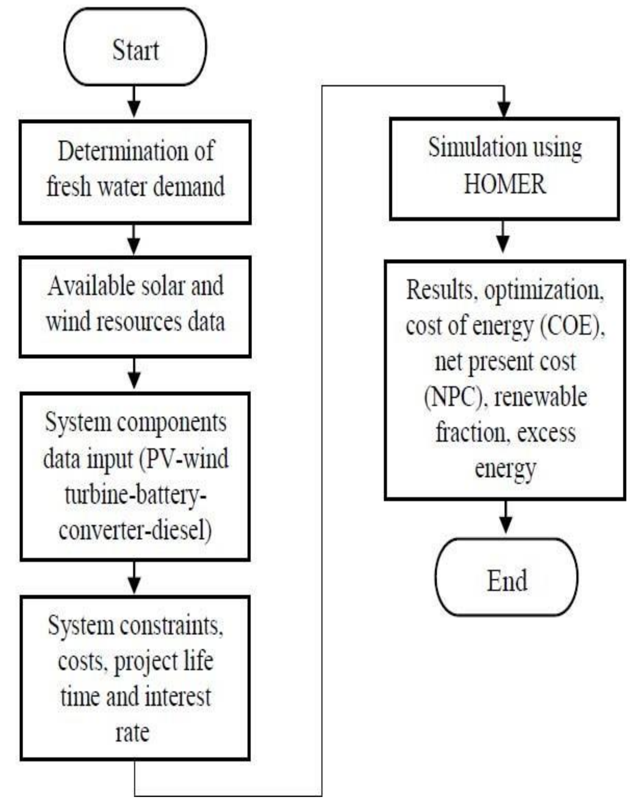

Fig. 4: Main steps for the study analysis.

2.2. Simulation Model

Figure 5 illustrates the proposed integrated system, modeled using HOMER software, which combines a 1259.01 kWh/day RO desalination plant load with a peak demand of 210.51 kW and a hybrid renewable energy source configuration. In this system, the consequence from the WT and diesel generator is connected to the AC bus, while the PV panels and batteries are linked to the DC bus. A bidirectional converter facilitates power flow between the AC and DC sections. The technical specifications and associated estimates of each system component, which are essential for conducting the economic analysis, are presented in Table 3 [20]-[21].

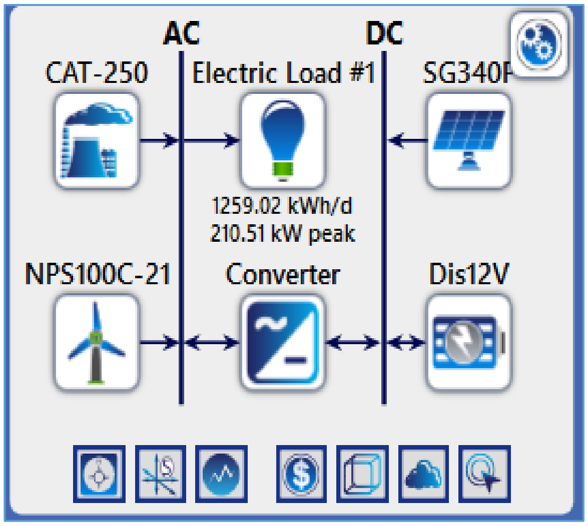

Fig. 5: Schematic diagram of the introduced project.

3. Results and Discussion

Figure 6 presents a summary of the optimization results derived from the input data, showcasing four distinct hybrid system configurations capable of fulfilling the RO plant's energy requirements. The most economically viable option is identified as Case 1, which comprises 200kW of PV panels, one 100kW wind turbine, a 250kW diesel generator, 345 batteries each with a capacity of 3.11 kWh, and a 168kW converter. This configuration boasts the lowest COE at $0.104/kWh and the lowest NPC at $651,029. Furthermore, it achieves a renewable energy fraction of approximately 96.1%, significantly higher than the other systems. The second most economically attractive system, considering both COE and NPC, is the WT/PV/battery configuration presented in Case 2. This scenario incorporates two WT, 200kW of PV panels, 624 batteries, and a 168kW converter. The absence of a diesel generator enables this configuration to achieve a 100% renewable fraction, surpassing Case 1 in terms of renewable energy utilization.

Case 3, consisting of a PV/diesel/battery system with ratings of 200kW, 250kW, and 449 kWh respectively, exhibits higher COE and NPC values compared to the previous cases. Its renewable fraction is also lower, at 57.9%. The least cost-effective project is identified as the PV/WT/generator configuration in scenario 4. This battery less system, comprising 200kW of PV panels, two 100kW wind turbines, and a 250kW generator, results in a COE of $0.393/kWh and an NPC of $2.33 million, both notably high figures. Its renewable fraction is the lowest among the four cases, at only 16.9%. Due to its superior cost-effectiveness, the PV/wind/diesel/battery system (Case 1) is selected for further in-depth analysis, which will be presented in the subsequent sections.

The monthly mean electrical energy output for the optimal system configuration (Case 1) is depicted in Figure 7. This figure illustrates the percentage contribution of each system component to the overall energy generation throughout the year. The PV panels account for approximately 53.5% of the overall power production, while the diesel generator and WT contribute around 2.8% and 43.7%, respectively. Notably, the wind turbines fulfill most of the load's energy demand. The renewable energy fraction for this configuration is confirmed at 96.1%. It is important to highlight that the allowable capacity shortage is set to zero for all cases, ensuring a reliable and uninterrupted energy supply.

Cost Summary

	Base Case	Lowest Cost System
NPC	$2.99M	$615,029
Initial Capital	$133,713	$384,813
O&M	$220,686/yr	$17,808/yr
LCOE	$0.503/kWh	$0.104/kWh

Fig. 6: The Summary of the optimization results.

Table 3. Technical Specifications of the System Devices.

PV Unit (Peimar SG340P)	
Rated Power (kW)	200
Capital cost ($/kW)	640
Operation and maintenance cost ($/year)	10
Lifetime (years)	30
Efficiency (%)	17.5
Derating factor (%)	80
WT	
Rated Power (kW)	100
Capital cost ($/unit)	50000
Operation and maintenance cost ($/year)	5000
Lifetime (years)	20
Replacement cost ($/unit)	50000
Hub height (m)	29
Rotor diameter (m)	20.7
CAT-250kW	
Capital cost ($/kW)	1500
Replacement cost ($/kW)	1500
Operation and maintenance cost ($/kW/hour)	1.5
Lifetime (hours)	15000
Diesel fuel price ($/L)	1.00
Battery (Discover 12VRE-3000TF)	
Nominal voltage (V)	12
Nominal capacity (kWh)	3.11
Maximum capacity (Ah)	43
Capital cost ($/unit)	410
Operation and maintenance cost ($/year)	10
Lifetime (years)	10
Replacement cost ($/unit)	410
Converter	
Capital cost ($/kW)	300
Replacement cost ($/kW)	300
Operation and maintenance cost ($/year)	0

Lifetime (years)	15
Efficiency (%)	95

The amount of excess electricity produced from the hybrid system represents about 23.4% which can be stored in the batteries. The total costs for each component are shown in Fig. 8 including capital, replacement, operating and maintenance (O&M) costs. From the figure batteries, are the highest capital cost of $141.540 while the PV panels have the highest replacement cost which is $128.000, and the wind turbines have the largest O&M cost during the lifetime of the project which is $64.637. It could be seen from the figure also that the diesel generator has the highest total cost due to high fuel cost. Figures from 9 to 11 show the variation of power output of the WT, PV, and diesel generator, respectively during sample days in April. It can be noticed that the energy generated from the PV is more regular than that generated from wind turbines. The diesel generator supplies power to the load when the generated energy from PV and wind is not enough to meet the power demand.

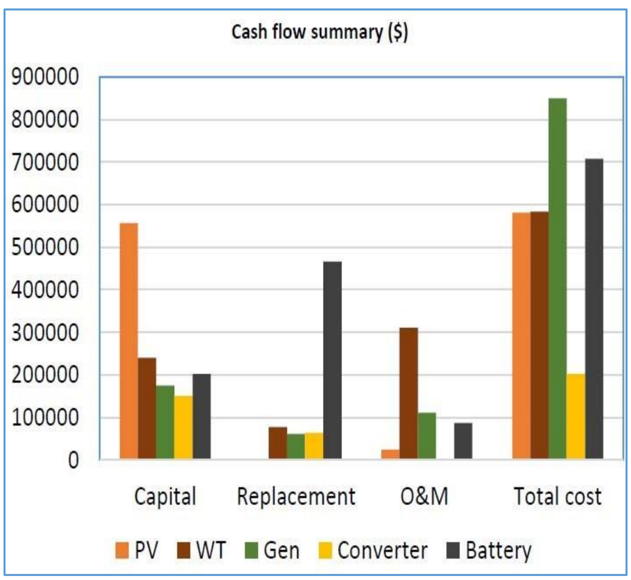

Fig. 7: The optimization results.

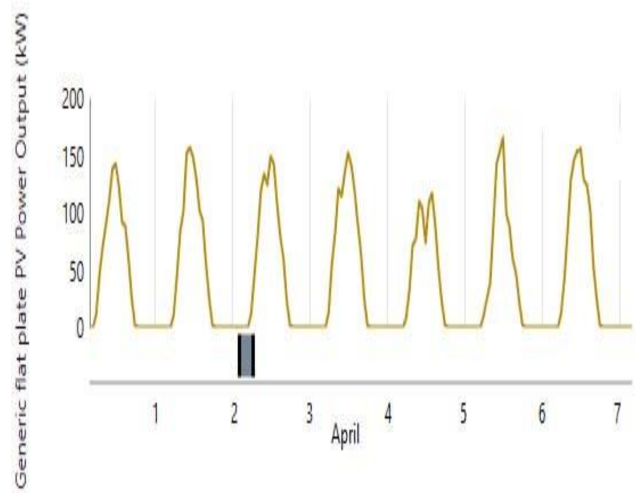

Fig. 8: Variation of PV power output for 7 days of optimum arrangement.

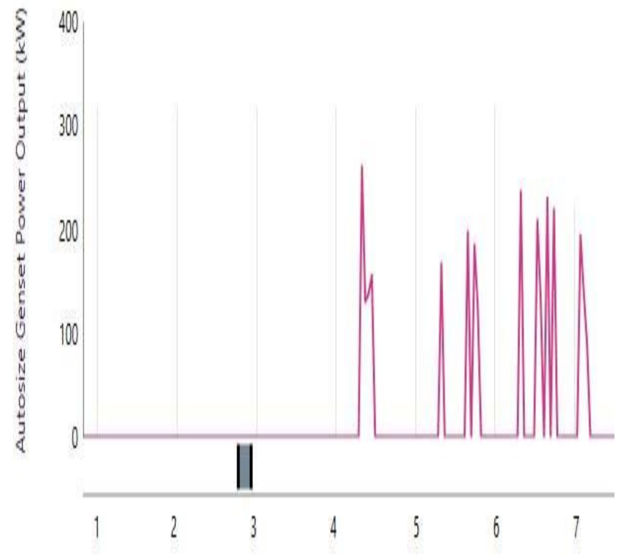

Fig.9: Variation of diesel generator power output for 7 days of optimal arrangement.

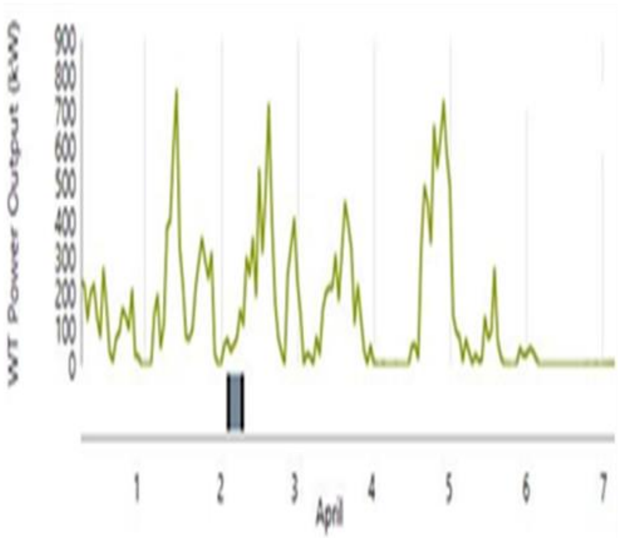

Fig.10: Variation of WT power output for 7 days of optimal arrangement

Table 4. Pollutant Emissions by Diesel Generator of Optimum Configuration

Quantity	**Value**	**Unit**
Carbon Dioxide	17.461	Kg/yr
Carbon Monoxide	18.8	Kg/yr
Unburned Hydrocarbons	0.727	Kg/yr
Particular Matter	0.727	Kg/yr
Sulfur Dioxide	43.4	Kg/yr
Nitrogen Oxides	126	Kg/yr

This paper has undertaken an evaluation of the operational emissions generated by the integrated energy system, specifically focusing on the pollutants emitted by the diesel generator within the optimal system arrangement. It is important to note that emissions associated with the manufacturing and output of the devices themselves are not included in this assessment. Table IV provides a detailed list of the pollutant emissions out by the diesel generator, which operates for approximately 288 hours per year and consumes around 6.61 liters of fuel during that period.

4. Conclusion

This study has conducted a comprehensive analysis of the techno-economic sizing and optimal arrangement for an integrated renewable power project designed to supply a large-scale RO desalination plant with 250 cubic meters capacity per day in Alamein, Egypt. The identified optimal configuration comprises 200kW of PV panels, one 100kW wind turbine, a 250kW diesel generator, 345 batteries each with a capacity of 3.1 kWh, and a 168kW power converter. This specific system configuration achieves the lower COE at $0.104/kWh and the lower NPC at $615,029 compared to alternative configurations. Furthermore, it boasts a renewable energy fraction of 96.1% and generates approximately 23.4% excess energy. The analysis encompassed a detailed cost breakdown for each system component as well as an assessment of the pollutant emissions produced by the diesel generator.

Nomenclature

A	Swept area (m^2)
$C_{a, tot}$	Overall yearly Estimate ($/year)
DOD	Depth of battery discharge (%)
$E_{a, tot}$	Overall energy output (kWh/year)
EBN	Nominal capacity of battery bank
(Ah)F_{PV}	Derating factor (%)
F_0	Fuel curve intercept coefficient
(L/hr/kW)F_1	Fuel curve slope(L/hr/kW)
G	Solar radiation incident on the PV
(kW/m^2)i	Interest rate (%)
K	Creast solar intensity at the equator 1
kW/m^2n	Lifetime (years)
P_{rated}	PV array rated capacity.
(kW)V	Mean wind speed (m/s)
p	Air density (kg/m^3)

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