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Optimization and Feasibility Analysis of PV/Wind/ Battery Hybrid Energy Conversion

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Abstract**—**In this paper, the optimum design for renewable energy system powered an aquaculture pond was determined. Hybrid Optimization Model for Electric Renewable (HOMER) software program, which is developed by U.S National Renewable Energy Laboratory (NREL), is used for analyzing the feasibility of the stand alone and hybrid system in this study. HOMER program determines whether renewable energy resources satisfy hourly electric demand or not. The program calculates energy balance for every 8760 hours in a year to simulate operation of the system. This optimization compares the demand for the electrical energy for each hour of the year with the energy supplied by the system for that hour and calculates the relevant energy flow for each component in the model. The essential principle is to minimize the total system cost while HOMER ensures control of the system. Moreover the feasibility analysis of the energy system is also studied. Wind speed, solar irradiance, interest rate and capacity shortage are the parameters which are taken into consideration. The simulation results indicate that the hybrid system is the best choice in this study, yielding lower net present cost. Thus, it provides higher system performance than PV or wind stand alone systems.

Keywords**—**Wind stand-alone system, Photovoltaic stand-alone system, Hybrid system, Optimum system sizing, feasibility, Cost analysis.

I. Introduction

ALTERNATIVE energy sources such as solar and wind energies, has attracted many researchers and communities throughout the world since the ‘‘energy crisis” of the 1973[1]. In addition, the increasing energy demand, high energy prices, as well as increasing concerns over environmental, health and climate changed implications of energy related activities are increasing concerns on alternative energy studies in communities [2]-[6]. The high costs of electricity may be due to centralized energy systems which operate mostly on fossil fuels and require large investments for establishing transmission and distribution grids that can penetrate remote regions [6]. Furthermore, the fossil fuel combustion results in the emission of obnoxious gases rising concerns about the climate change and other health hazards [7]. To allow a real penetration of the huge dispersed naturally renewable resources (wind, sun, etc.) intermittent and more or less easily predictable, optimal sizing of hybrid renewable power generation systems prove to be essential [8]. This paper presents the optimal sizing of electrical system. The electrical system has three different configuration which are PV stand alone, wind stand alone and PV wind hybrid system. The optimization technique is carried out using HOMER software.

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II. Electrical Load Profile

Load profile study and determination is the first step for design of any electric power system. Nature of operation of loads and behavior of consumers are the parameters that determine the load profile. This study based on supply electricity for an aquaculture farm and a house near the pond required for operators. The load consists of the main components required for a small house, freezer for the pond operation, pumps and valves required for solar thermal water heating system. The daily load power variation in summer and winter is presented in Fig. 1.

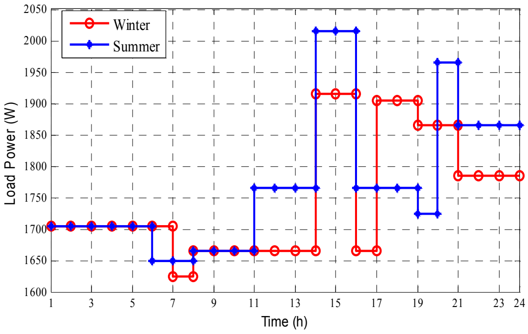

Fig. 1 Load profile variation over the year

III. Metrological Data

To get optimum design of electrical system, it is important to collect meteorological data (solar irradiance, wind speed and air temperature) for the site under consideration. The used data are practical data [9]. Table I shows the monthly average values of global solar radiation, air temperature, wind speed and relative humidity over the site under consideration. It is clear that, Mersa Matruh has high solar irradiance and wind speed over the year so it is suitable for system design.

IV. Site Characteristics

The chosen zone is a rural area near the Mediterranean Sea in Mersa Matruh to be near the water source. This site has high solar irradiance, low air temperature and high wind speed over the year which is suitable for the system operation. The latitude and longitude of the town under consideration is 31^{o} 33' and 27^{o} 22' respectively [9].

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V. System Component Specifications

The specification data of the wind turbine and PV modules used in this evaluation are provided in Tables II and III, respectively. Lead acid battery is selected for this study. The complete parameters of the battery are shown in Table IV. The capital costs listed in the above tables include all installation. The annual maintenance costs for the wind turbines and PV panels. In the current study an annual maintenance cost of 2% of capital cost is used for the wind turbine.

TABLE I
METEOROLOGICAL DATA IN MERSA MATRUH

Mon	Irrad ($Kwh/m^2/d$)	Air Temp (°C)	R.H (%)	Wind speed (m/S)
Jan.	4.31	13.2	66	6.06
Feb	5.23	13.7	65	6.06
March	5.65	15.3	63	6.29
April	6.33	17.4	61	5.7
May	6.30	20.05	64	4.88
June	6.35	23.25	68	5.38
July	6.42	24.75	73	5.19
Aug	6.43	25.4	73	4.72
Sept	6.23	24.15	68	4.41
Oct	5.28	21.9	67	4.26
Nov	4.47	18.3	68	4.77
Dec	3.96	14.8	66	5.85
Annual mean	5.58	19.3	67	5.29

TABLE II
WIND TURBINE PARAMETERS [10]

Rated power output	3 KW
Rated speed	10.5 m/s
Start up speed	3.4 m/s
Survival wind speed	55 m/s
Rotor Diameter	4.5 m
Air density (kg/m^3)	1.225
Total capital cost ($)	9000
Annual maintenance cost ($)	240
Replacement cost($)	7500
Life time (yrs)	15

TABLE III
PV MODULE PARAMETERS [11]

Maximum power (W)	125
Voltage (V)	12
Area (m^2)	1.0177
Total capital cost/kW ($)	5000
Replacement cost ($)	0
Annual maintenance cost ($)	0
Life time (yrs)	25

TABLE IV
BATTERY PARAMETERS [12]

Voltage (V)	24
Capacity (Ah)	500
Roundtrip efficiency (%)	86
Minimum charge (%)	30
Capital cost ($)	1800
Annual maintenance cost ($)	120
Replacement cost ($)	1800
Lifetime (yrs)	5

VI. The Optimization Results

A. PV Standalone Results

The monthly average electrical production of PV is given by Fig. 2. It is clear that, PV has generated high electric power all over the year as this location has high solar irradiance. The battery state of charge is shown in Fig. 3. The battery keeps at high state of charge, 100% as a maximum value and 30% as a minimum value. The economic results of the PV stand alone system are shown in Table V. It is clear from these table and figure that, the PV followed by the battery has a significant impact in the systems costs. It can be observed that the load could be met right through the day with excess energy. The battery state of charge varies between 35% and 100%.

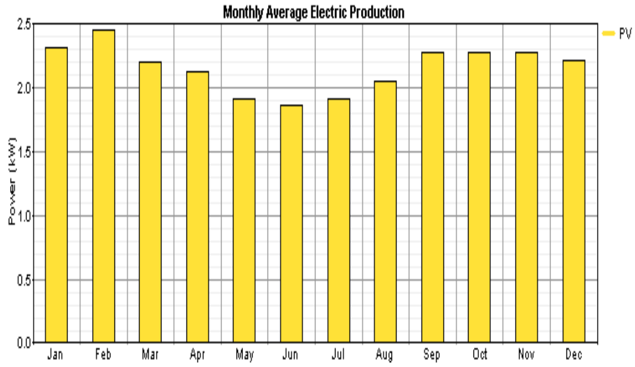

Fig. 2 Monthly average energy generation of PV standalone system

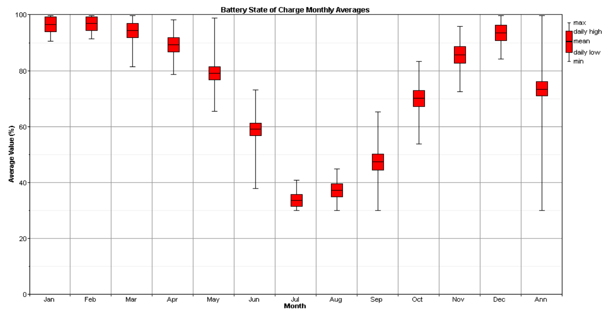

Fig. 3 Monthly battery state of charge

B. Wind Standalone Results

Fig. 4 represents the monthly electrical production for the wind stand alone system. The electrical power production in winter is higher than that in summer due to high wind speed in these months. The battery state of charge is adopted in Fig. 5. The state of charge keeps at 100% most time over the year. The economic results of the wind stand alone system are summarized in Table VI. It is clear from these table and figure that, the wind followed by the battery has a significant impact in the systems costs. The battery state of charge varies between 98% and 100%.

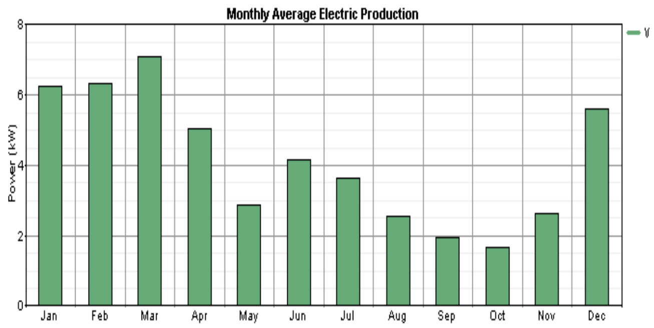

Fig. 4 Monthly average energy generation of wind standalone system

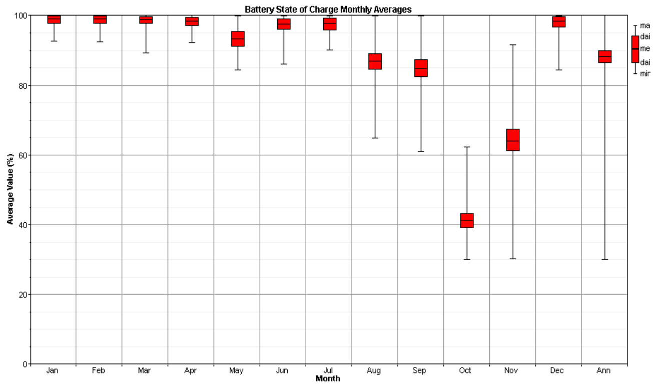

Fig. 5 Monthly battery state of charge

C. PV-Wind Hybrid System Simulation Results

The monthly output power of PV array is shown in Fig. 6. It is clear that, the generation power from PV array is high due to the high solar resources that already exist in the site under consideration. Fig. 7 shows the output power of wind turbine over the year. State of charge variation of lead acid battery bank over the year is depicted in Fig. 8. it is shown that, the battery state of charge has a high value over the year, it takes value in range of 55% as minimum value and 100% as a maximum value, this means that, the load has been fed from the renewable energy sources over the year except for the day which has low solar irradiance and low wind speed.

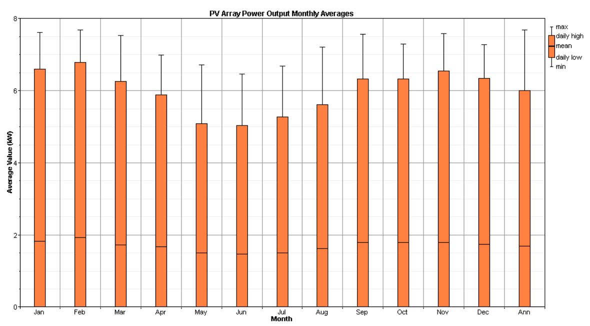

Fig. 6 Monthly output power of PV array

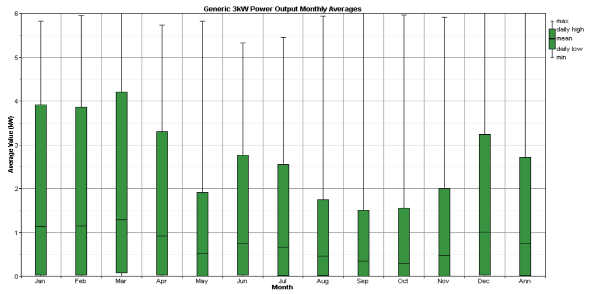

Fig. 7 Monthly output power of wind generator

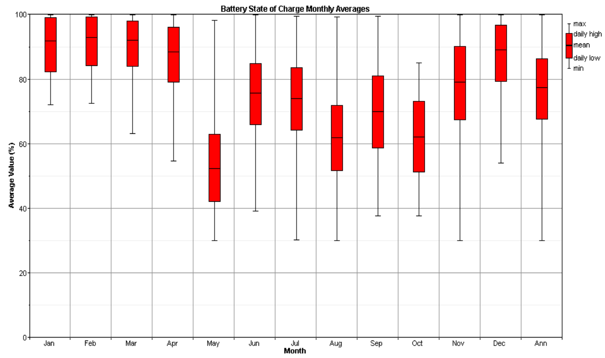

Fig. 8 Monthly battery state of charge

Homer combines the costs along with the salvage and any other costs/revenues for each component to find the component's annual cost. It is combined the annual costs of each component to find the total system cost. Table VII gives the system cost of each component. For the hybrid PV wind power system, 69 % of the electricity demand was produced from solar panels, with 14855 kWh/yr, while 31 % of the energy requirement was supplied from WT, with 6593 kWh/yr. Monthly average electric production of the entire system is shown in Fig. 9. It is shown that, the wind power is high during the year except for the summer months which has low wind speed in these periods. The battery has high state of charge over the year and approximately equal 100%.

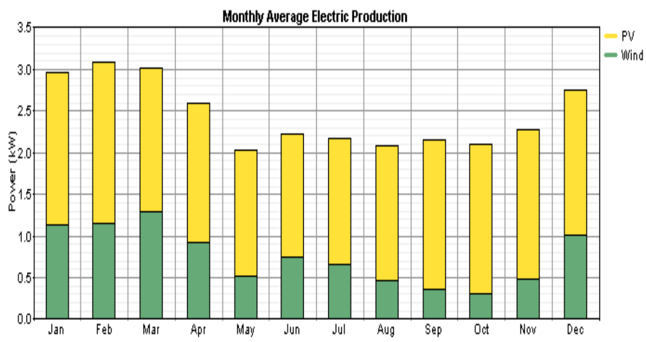

Fig. 9 Monthly average energy generation of hybrid system

VII. Comparison between Different Configurations

Table VIII Summarize the optimal results of the three different configurations of power systems. The results show that PV-Wind hybrid system has the optimum design for this case and at these available environmental conditions in this site. The hybrid system gives the minimum cost and levelized cost of energy at 0.517 $/kWh. However wind stand alone gives the highest cost due to medium wind speed available in this site and gives levelized cost of energy at 1.183 $/kWh. PV stand alone has total system cost in between hybrid system and wind stand alone system and its levelized cost of energy at 0.553 $/kWh, this value has a small difference than PV-Wind hybrid system due to high solar irradiance. From this analysis, the PV-Wind hybrid system is the best configuration can be applied in this area.

VIII. Sensitivity Analysis

After run the optimization techniques it is important to see the environmental condition and economical parameters variation effects on the system sizing. Four parameters are considered which are solar irradiance, wind speed as an environmental condition, interest rate as economical parameters, and finally maximum allowable capacity shortage. Table IX shows the different parameters variation on the of PV stand alone system sizing. There are 74066 solutions were simulated, among them there are 66132 were feasible and 7934 were infeasible due to capacity shortage constraints. The program takes 0:35:28 hours. As the solar irradiance increase the PV sizing and the battery sizing decrease due to the high power generated from PV with solar irradiance increment. Varying interest rate affects mainly on total system cost. The capacity shortage percent affects mainly on system sizing and the cost, also decrease as system sizing decease. It is remarked from the results:

- For the site condition the optimum design is given in the first row. At interest rate 8.25% and 1% maximum allowable capacity shortage, the total system cost is 87692 at system sizing (10.5 kW PV and 10 batteries).
- As solar irradiance increase to 7 kWh/m²/d as average value, the system cost become 57534 $ at system sizing 9 kW PV and 2 batteries.
- As capacity shortage increase to 5% it affects on battery number mainly and so the system cost. At 9 kWh/m²/d and interest rate 8.25 the system cost become 497680 $ at size of 8.5kW PV and 1 battery. At the same condition except for capacity shortage 1 % the system cost become 54721 $ at size of 9 kW PV and 2 batteries. The wind stand alone system sensitivity analysis is summarized in Table X. There are 126237 solutions were simulated among them there are 113148 were feasible and 13089 were infeasible due to capacity shortage constraints. The program takes 0:57:41 hours. These remarks can be concluded as follows, as summarized in Table X.
- As wind speed varying from 5.29 to 7 m/s the system sizing change from 11wind turbines and 12 batteries to 5 turbine and 3 batteries. The effect on system cost change from 189586 $ to 79771 $. If wind speed increase to 10 m/s the system cost change to 36193 $ and the sizing change to 2 wind turbines and 2 batteries. It is clear that, the wind speed variation affect the mainly on system cost, the total cost decease by 19% when wind speed varying from 5.29 to 10 m/s.
- Capacity shortage variation affect on the number of battery and so affect system cost. As capacity shortage varying from 0 to 5, the system sizing change from 11wind turbines and 15 batteries to 11wind turbine and 12 batteries. The system cost vary from 200708 $ to 156718 $.
- The effect of interest rate variation is mainly on total system cost. At the same condition the system cost varying from 216325 $ to 169813 $ as the interest rate changes from 5 to 12%.

Table XI shows the feasibility analysis of PV wind hybrid system. Solar irradiance, wind speed, interest rate and finally maximum allowable capacity shortage have been an important effect on system sizing and cost. There are 1026156 solutions were simulated among them there are 680160 were feasible and 345996 were infeasible due to capacity shortage constraints. The program takes 7:28:49 hours. As already mentioned the main points of the present analysis can be summarized as follows:-

1- Wind speed variation affects the wind turbine numbers. As wind speed increase the number of wind turbine increase as clear in Table XI when wind speed change from 5 to 10 m/s the system sizing change from 8.25 KW PV, 2 wind turbines and 2 batteries to 2 wind turbines and 2 batteries and the total cost become 41712 $ rather than 82962 $.
2- Capacity shortage affects the system sizing and cost. As capacity shortage vary from 0% to 5% the system cost varying from 91458 $ to 67317 $ wind turbines change from 2 turbines to 0 turbine while the sizing of PV change from 8.75 KW PV to 10.5 KW PV, and battery changes from 3 to 2 at the same environmental condition and interest rate.
3- As solar irradiance change from 5.28 to 9 kWh/m²/d the system cost varying from 82962 $ to 58820 $ and the system sizing change from 8.25 KW PV, 2 wind turbines and 2 batteries to 10 KW PV, 0 wind turbines and 1 battery.
4- Interest rate variation also affects system cost only because it is an economical parameter used to calculate the cost.

TABLE V
COST ANALYSIS OF PV STAND ALONE SYSTEM

Component	Initial Capital ($)	Annualized Capital ($/yr)	Annualized Replacement ($/yr)	Annual O&M ($/yr)	Total Annualized ($/yr)
PV Array	52,500	5,024	0	0	5,024
Battery	18,000	1,722	175	1,200	3,097
Converter	1,600	153	37	80	270
Totals	72,100	6,899	212	1,280	8,391

TABLE VI
COST ANALYSIS OF WIND STAND ALONE SYSTEM

Component	Initial Capital ($)	Annualized Capital ($/yr)	Annualized Replacement ($/yr)	Annual O&M ($/yr)	Total Annualized ($/yr)
Wind	99,000	9,473	2,041	2,640	14,154
Battery	21,600	2,067	210	1,440	3,717
Converter	1,600	153	37	80	270
Totals	122,200	11,693	2,288	4,160	18,141

TABLE VII
COST ANALYSIS OF PV WIND HYBRID SYSTEM

Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
PV	41,250	0	0	0	41,250
Wind	18,000	4,567	5,016	-689	26,895
Battery	3,600	5885	2,508	0	11,993
Inverter	1,600	457	836	-69	2,824
System	64,450	10909	8361	-758	82,962

TABLE VIII
OPTIMAL SIZING RESULTS

System type	PV KW	Wind T No.	No. of batteries	Total cost ($)	Levelized cost of energy ($/kWh)
PV stand alone	10.5	—	10	87692	0.553
Wind stand alone	—	11	12	189586	1.183
PV-wind hybrid system	8.25	2	2	82962	0.517

TABLE IX
SENSITIVITY ANALYSIS OF PV STAND ALONE SYSTEM

Solar ($kWh/m^2/d$)	**Interest Rate (%)**	**Max. Cap. Shortage (%)**	**PV (kW)**	**Battery No.**	**Converter (kW)**	**Initial capital ($)**	**Operating cost ($/yr)**	**Total NPC ($)**	**COE ($/kWh)**
5.28	8.3	1.0	10.5	10	2	72,100	1,492	87,692	0.553
5.28	8.3	5.0	10.0	2	2	5,200	422	59,608	0.391
5.28	8.3	0.0	10.5	15	2	81,100	2,179	103,875	0.648
5.28	5.0	1.0	10.5	10	2	72,100	1,519	93,512	0.437
5.28	5.0	5.0	10.0	2	2	55,200	433	61,296	0.298
5.28	5.0	0.0	10.5	15	2	81,100	2,218	12,367	0.520
5.28	12.0	1.0	10.5	10	2	2,100	1,448	83,456	0.701
5.28	12.0	5.0	10.0	2	2	5,200	404	58,369	0.510
5.28	12.0	0.0	10.5	15	2	81,100	2,116	97,698	0.813
7.00	8.3	1.0	9.0	3	2	52,000	530	57,534	0.363
7.00	8.3	5.0	8.5	1	2	45,900	370	49,768	0.323
7.00	8.3	0.0	9.8	3	2	56,000	530	61,534	0.384
7.00	5.0	1.0	9.0	3	2	52,000	540	59,614	0.279
7.00	5.0	5.0	8.5	1	2	45,900	380	51,262	0.247
7.00	5.0	0.0	9.8	3	2	56,000	540	63,614	0.294
7.00	12.0	1.0	9.0	3	2	52,000	512	56,017	0.471
7.00	12.0	5.0	8.5	1	2	45,900	353	48,671	0.421
7.00	12.0	0.0	9.8	3	2	56,000	512	60,017	0.499
9.00	8.3	1.0	9.0	2	2	50,200	433	54,721	0.343
9.00	8.3	5.0	8.5	1	2	45,900	371	49,780	0.320
9.00	8.3	0.0	9.2	3	2	53,000	530	58,534	0.365
9.00	5.0	1.0	9.0	2	2	50,200	444	56,459	0.262
9.00	5.0	5.0	8.5	1	2	45,900	382	51,279	0.244
9.00	5.0	0.0	9.8	2	2	54,200	444	60,464	0.280
9.00	12.0	1.0	9.0	2	2	50,200	414	53,445	0.446
9.00	12.0	5.0	8.5	1	2	45,900	354	48,680	0.417
9.00	12.0	0.0	9.2	3	2	53,000	512	57,017	0.474

TABLE X
SENSITIVITY ANALYSIS OF WIND STAND ALONE SYSTEM

Wind speed (m/s)	Interest Rate (%)	Max. Cap. Shortage (%)	Wind T. No.	Battery No.	Converter (kW)	Initial capital ($)	Operating cost ($/yr)	Total NPC ($)	COE ($/kWh)
5.29	8.3	0.0	11	15	3	128,400	6,919	200,708	1.245
5.29	8.3	1.0	11	12	2	122,200	6,448	189,586	1.183
5.29	8.3	5	10	6	2	102,400	5,198	156,718	1.004
5.29	5	0.0	11	15	3	128,400	7,158	229,288	1.054
5.29	5	1.0	11	12	2	122,200	6,678	216,325	1.001
5.29	5	5	10	6	2	102,400	5,396	178,447	0.848
5.29	12.0	0.0	11	15	3	128,400	6,527	179,594	1.484
5.29	12.0	1.0	11	12	2	122,200	6,071	169,813	1.412
5.29	12.0	5	10	6	2	102,400	4,873	140,617	1.201
10	8.3	0.0	2	2	2	23,200	1,243	36,192	0.224
10	8.3	1.0	2	2	2	23,200	1,243	36,192	0.224
10	8.3	5	2	1	2	21,400	1,106	32,955	0.207
10	5	0.0	2	2	2	23,200	1,288	41,347	0.190
10	5	1.0	2	2	2	23,200	1,288	41,347	0.190
10	5	5	2	1	2	21,400	1,148	37,576	0.175
10	12.0	0.0	2	2	2	23,200	1,170	32,380	0.267
10	12.0	1.0	2	2	2	23,200	1,170	32,380	0.267
10	12.0	5.0	2	1	2	21,400	1,037	29,531	0.247
7	8.3	0.0	5	4	2	53,800	2,795	83,008	0.514
7	8.3	1.0	5	3	2	52,000	2,657	79,771	0.496
7	8.3	5.0	4	2	2	41,200	2,094	63,087	0.403
7	5	0.0	5	4	2	53,800	2,898	94,645	0.435
7	5	1.0	5	3	2	52,000	2,758	90,874	0.419
7	12	5.0	4	2	2	41,200	2,175	71,851	0.340
7	12	0.0	5	4	2	53,800	2,626	74,393	0.614
7	12	1.0	5	3	2	52,000	2,492	71,545	0.592
7	12	5.0	4	2	2	41,200	1,962	56,591	0.482

TABLE XI
SENSITIVITY ANALYSIS OF PV WIND HYBRID SYSTEM

Solar (kWh/m²/d)	Wind speed (m/s)	Interest Rate (%)	Max. Cap. Shortage (%)	PV (kW)	Wind T. No.	Battery No.	Converter (kW)	Initial capital ($)	Operating cost ($/yr)	Total NPC ($)	COE ($/kWh)
5.28	5.290	8.3	1.0	8.25	2	2	2	64,450	1,771	82,962	0.517
5.28	5.290	8.3	0.0	8.75	2	3	2	68,750	2,173	91,458	0.567
5.28	5.290	8.3	5.0	10.5	—	2	2	57,700	920	67,317	0.431
5.28	5.290	5.0	1.0	8.25	2	2	2	64,450	1,824	90,157	0.417
5.28	5.290	5.0	0.0	8.75	2	3	2	68,750	2,232	00,208	0.461
5.28	5.290	5.0	5.0	10.5	—	2	2	57,700	937	70,903	0.337
5.28	5.290	10.0	1.0	8.25	2	2	2	64,450	1,732	80,174	0.575
5.28	5.290	10.0	0.0	8.75	2	3	2	68,750	2,129	88,074	0.628
5.28	5.290	10.0	5.0	10.5	—	2	2	57,700	908	65,938	0.486
5.28	10.00	8.3	1.0	—	2	2	2	23,200	1,771	41,712	0.259
5.28	10.00	8.3	0.0	—	2	2	2	23,200	1,771	41,712	0.259
5.28	10.00	8.3	5.0	—	2	1	2	21,400	1,370	35,715	0.224
5.28	10.00	5.0	1.0	—	2	2	2	23,200	1,824	48,907	0.225
5.28	10.00	5.0	0.0	—	2	2	2	23,200	1,824	48,907	0.225
5.28	10.00	5.0	5.0	—	2	1	2	21,400	1,416	41,356	0.192
5.28	10.00	10.0	1.0	—	2	2	2	23,200	1,732	38,924	0.278
5.28	10.00	10.0	0.0	—	2	2	2	23,200	1,732	38,924	0.278
5.28	10.00	10.0	5.0	—	2	1	2	21,400	1,336	33,525	0.242
9.00	5.290	8.3	1.0	10.0	—	1	2	53,400	519	58,820	0.368
9.00	5.290	8.3	0.0	9.75	—	2	2	53,950	920	63,567	0.394
9.00	5.290	8.3	5.0	8.75	—	1	2	47,150	519	52,570	0.333
9.00	5.290	5.0	1.0	10.0	—	1	2	53,400	529	60,852	0.283
9.00	5.290	5.0	0.0	9.75	—	2	2	53,950	937	67,153	0.309
9.00	5.290	5.0	5.0	8.75	—	1	2	47,150	529	54,602	0.256
9.00	5.290	10.0	1.0	10.0	—	1	2	53,400	511	58,038	0.418
9.00	5.290	10.0	0.0	9.75	—	2	2	53,950	908	62,188	0.444
9.00	5.290	10.0	5.0	8.75	—	1	2	47,150	511	51,788	0.378
9.00	10.00	8.3	1.0	—	2	2	2	23,200	1,771	41,712	0.259
9.00	10.00	8.3	0.0	—	2	2	2	23,200	1,771	41,712	0.259
9.00	10.00	8.3	5.0	—	2	1	2	21,400	1,370	35,715	0.224
9.00	10.00	5.0	1.0	—	2	2	2	23,200	1,824	48,907	0.225
9.00	10.00	5.0	0.0	—	2	2	2	23,200	1,824	48,907	0.225
9.00	10.00	5.0	5.0	—	2	1	2	1,400	1,416	41,356	0.192
9.00	10.00	10.0	1.0	—	2	2	2	23,200	1,732	38,924	0.278
9.00	10.00	10.0	0.0	—	2	2	2	3,200	1,732	38,924	0.278
9.00	10.00	10.0	5.0	—	2	1	2	1,400	1,336	33,525	0.242

Fig. 10 shows the Levelized cost of energy variation with solar irradiance and wind speed variation. As solar irradiance and wind speed increase the levelized cost of energy decrease due to the high power generated from PV modules and wind turbines. With constant values of solar irradiance, as wind speed increase the levelized cost decrease in an obvious way. On the other hands when wind speed has a constant value, as solar irradiance increase the levelized cost of energy decrease but not in the same manner of wind variation; this is because of the high installation cost of PV.

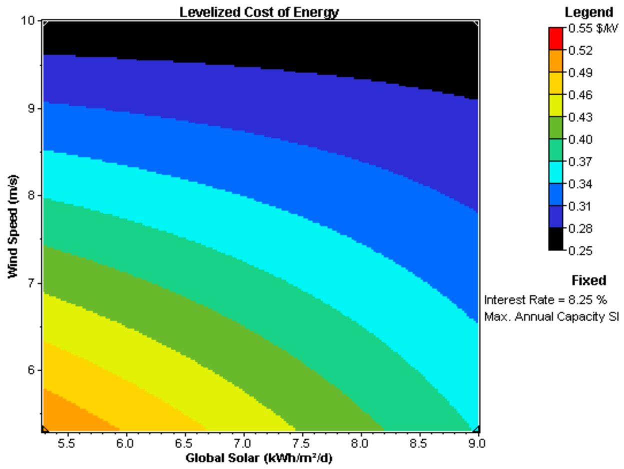

Fig. 10 Levelized cost of energy variation with solar irradiance and wind speed variation

IX. Conclusion

For several years, a growing interest in renewable energy resources has been observed. The hybrid system utilization is becoming popular due to increasing energy costs and decreasing prices of turbines and photovoltaic panels. However, prior to construction of a renewable generation station, it is necessary to determine the optimum number of PV panels and wind turbines for minimal cost during continuity of generated energy to meet the desired consumption. The HOMER program was used to simulate the system operation and calculate technical economic parameters for each configuration. The program requires input values such as technology options, component costs and reconciliation of resources, and arranges applicable combinations by net cost for different system configurations, using all these facts/information. This paper presented the optimal design of an energy system powered an aquaculture pond. The electrical system components are PV array, wind turbines and lead acid batteries. A comparative study between three different configurations (PV-battery stand alone, wind-battery stand alone and PV-wind-battery hybrid system) is carried out to choose the optimum design of renewable energy system suitable for the selected location. The hybrid energy system has the optimal performance over the other two systems. The sensitivity analysis is carried out in order to use the same system in any other location or at different conditions.

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