Liu Liqun, Liu Chunxia
Taiyuan University of Science & Technology

Techno-economic analysis of off-grid renewable energy power station: A case study

***Abstract**. This paper gives the techno-economic analysis of a wind-PV-diesel system with storage battery backup for an off-grid power station specially located in Dongwangsha, studying data from a particular site in littoral China. The simulation and optimization results indicated the most optimized sizing of hybrid system. Moreover, the sensitivity analysis is discussed at a diesel price of 2$/L and annual average wind speed of 4.41 m/s and interest rate of 6%. The proposed hybrid system is more cost effective and environmental friendly than the diesel only system.*

***Streszczenie.** W artykule przestawiono techniczno-ekonomiczną analizę systemu energetycznego składającego się z urządzeń wiatrowych, fotowoltaicznych i silnikiem Diesla oraz baterii magazynującej na przykładzie sieci w miejscowości Dongwagsha w Chinach. Rezultaty symulacji i optymalizacji pokazały, że system hybrydowy jest znacznie korzystniejszy niż tylko oparty na silniku Diesla. (**Techniczno-ekonomiczna analiza systemu hybrydowego z wykorzystaniem źródeł odnawialnych – na przykładzie Chin**)*

Keywords: enewable energy; Techno-economic analysis; Hybrid power supply system.
Słowa kluczowe: energia odnawialna, analiza ekonomiczna, hybrydowy system energetyczny

Introduction

It is well known that China is the largest developing country and the second largest energy consumption country in the world. The total consumption amount of coal and oil are more than 2.74 and 0.36 billion tons in 2008, respectively, and natural gas is about 80.7 billion m^3 [1]. Abundant energy consumption brought a lot of pollutants and a large amount of emissions. For example, the SO2 emission from 2000 in China is more than 20 million tons, which ranks the first in the world [2]. The CO2 emission is more than 4.5 billion tons, which ranks the second in the world [3]. The total pollution loss accounts for 10% of Chinese Gross Domestic Product [4]. Chinese primary energy supply structure is very inappropriate [5]. Chinese central government and local governments have waked up to the problem to realize the sustainable development of country in future. Renewable Energy Law has been established in February 28, 2005. The development and application of renewable energy has been regarded in order to improve the inappropriate energy structure. The renewable sources in China are abundant, such as wind, solar, and biomass energy, etc. For example, the total amount of wind power in China is more than 3.2 billion kilowatts at 10 meter height, and the amount which can be effectively utilized is about one billion kilowatts. As a conclusion, the prospect of renewable energy in China is beautiful in foresee future.

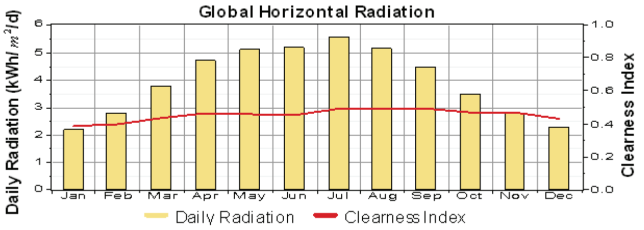
The conventional power grid in China can not supply the total end consumers with enough power. In this period of time, millions of off-grid consumers have to use the diesel generator in order to receive the supply of power. Moreover, some industry equipments located in remote areas which apart from the power grid, such as communication base station, island power system, and radar station, and so on. The generating system uses the renewable sources can afford steady electricity supply. For example, some stand-alone PV power stations have been established in remote areas to improve the power quality of off-grid consumer which have enhanced the standard of living of ordinary people. However, a common drawback is existed in the stand-alone wind energy and solar energy generating power system, and the output electric power is unpredictable which change with the changing of weather, such as insolation, temp, and wind speed, etc. Fortunately, the hybrid wind-solar system can partially overcome the problems which integrate multi-fold resources in a proper combination, and the output quality of power is improved. But the price of wind power generator and PV is costly at present and the initial capital of hybrid only wind-solar system is big. The expensive levelized cost of energy (COE) can not be accepted by the ordinary user. The conventional diesel only power system consumes a lot of diesel and discharge a mass of greenhouse gases. Fossil resource came in increasing price, and the hybrid generating system is suggested to offer steady and reliable and cheap power supply for the off-grid user or the industry equipment as compare with the diesel only generating system. Certainly, the techno-economic analysis of hybrid system is necessary to minimize the initial capital, COE, operating & maintain cost (O&M), net present cost (NPC), diesel consumption and unmet electric rate at suffice for consumer' need.

Many literatures have analyzed the feasibility of renewable resource generating system by using HOMER or Hybrid2 or RETscreen [6-14]. Unfortunately, the renewable power supply system in China did not consider the optimal analysis of components of renewable resources power system at present. The article presents the feasibility analyses of renewable power station to optimal configure and reduce the initial capital and NPC. In order to arouse the regard of designer, an established power station is used to compare with the proposed optimal system. In this context, the present study carries out a techno-economic analysis by using HOMER software of the USA National renewable Energy Laboratory (NREL) and the data of National Aeronautics and Space Administration (NASA) to optimize configure of a hybrid wind-PV-diesel system with storage battery backup for an off-grid power station which located in Dongwangsha, Chongming islands [15-16].

Site and Meteorological data and Electrical load

Dongwangsha located in Chongming island of Shanghai where apart from the national electrical grid. The village gets power through diesel generating power plant in the past. The diesel only system is difficult to ensure the continuous electricity supply during breakdown and scheduled shutdown of diesel units. A hybrid wind-PV-battery power station has been established in the site that is capable of meeting the load. The geographical coordinates of the data established project site were $31^o31'$ N latitude, $121^o57'$ E longitude and 1 meter altitude above mean sea level. The existing meteorological data of wind speeds are measured at 40 meters height according to an established wind speed weather station located in project site, but without accurate data of solar insolation clearness Index, earth skin temperature, relative humidity, and wind speed at 10 meters altitude above the surface of the earth.

The meteorology data from NASA is used to the proposed hybrid system. The monthly average daily total global solar radiation (GSR) ($kW/m^2/d$) and clearness index are shown in Fig.1 (a), and the data is gained via internet by using HOMER based on the latitude and longitude. The scaled annual average value of GSR is $3.95kWh/m^2/d$. The highest values of GSR are gained during the months of May to August with a maximum of $5.559kWh/m^2/d$. The lowest values are gained during the months of December to January with a minimum of $2.183kWh/m^2/d$ .According to solar radiation, Fig.1 (b) shows that the hourly available PV power output throughout the year.



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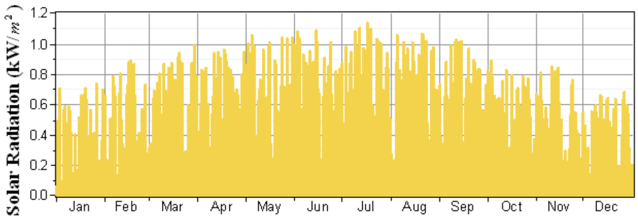
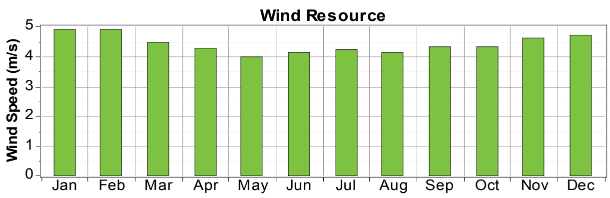


(b)

Fig.1. Meteorological data of solar insolation and available power output at the site

The monthly average daily wind speed (m/s) at the 10 meter above the surface of the earth was collected from NASA as shown in Fig.2 (a), and the scaled annual average value of wind speed is $4.41m/s$. The highest values of wind speed are observed during the months of January to February with a maximum of $4.91m/s$. The lowest values are observed during the months of May with a minimum of $3.97m/s$. The hourly available power output throughout the year according to wind speed is shown in Fig.2 (b). Moreover, the annual average wind speed can not same, and the considered wind speed in this paper are 4, 4.41, and $5m/s$.



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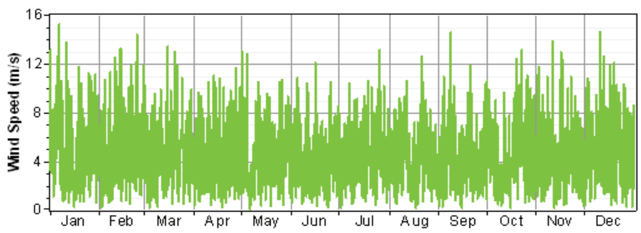
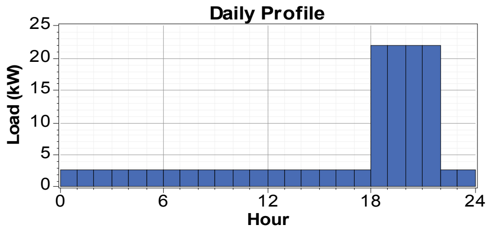


(b)

Fig.2. Meteorological data and available wind speed at the site



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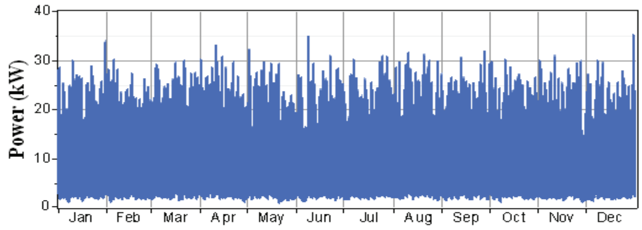

(b)

Fig.3. Variation of Load demands of proposed project.

The hybrid wind-solar only system with one wind turbine of rated power 5kW and PV with rated power 34.3 kW and 990 batteries with rated capacities 100Ah and rated voltage 2V have been established in the Dongwangsha. The initial capital is about 251,397$. The typical hourly electrical consumption data used in this project was measured and described in literature [17]. The average value per day of load was 139kWh, and the maximum hourly power of the load was 35kW, and the daily load factor varied from 0.074 to 0.629. Fig.3 (a) shows the typical hourly load demand. The highest values of electric consumption appeared between 18:00 hours and 22:00 hours with a maximum power of 22 kW , and the lowest value of load demand appeared between 22:00 to 16:00 of the following day with a minimum power of 2.6 kW , and the rated voltage of load is 220V. As shown in Fig.3 (b), the hourly available electric consumption throughout the year is varied with season changing.

Hybrid wind-PV-diesel-battery power station

A hybrid wind-PV-diesel-battery power station is used to discuss the possible optimal configure of power station in Dongwangsha, and the proposed autonomous hybrid system consists of one diesel generator, some PV arrays, some storage batteries, some wind power generators, and a power converter. The hybrid power with battery backup is used to maintain regular supply during the conspicuous bad weather and breakdown and scheduled shutdown of diesel unit. The hybrid power system optimization software HOMER developed by NREL has been used in this proposed power station, which is a computer model to assist in the design of micro power systems and to facilitate the comparison of power generating technologies across a wide range of applications. The physical behavior and life-cycle cost and total cost of installing and operating the system over its life span of a project is described. HOMER allows the modeller to compare with many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the sensitivities [16].

Solar PV modules are connected in series and parallel string in order to produce enough electric power according to the voltage and current demand of load. The initial capital and the replacement cost of PV are 4400$ and 4400$ per kilowatt ($/kW) in China, respectively. The PV sizes are considered to be 0, 10, 15, 20 and 25 kW. Operation and maintenance cost of PV array is 20$/kW per year. PV array were considered as fixed and the slope degree is 31.5. Working lifetime of PV panels are taken as 20 years and don't consider the tracking system. The effect of temp for PV output power is considered in the article. Temp coefficient of power is -0.5%/^{o}C, and nominal operating cell temp is 47 ^{o}C and output power efficiency is 13% at standard test conditions.

The horizontal-axes wind turbine series of Guangdong Shangneng wind power equipment ltd. (GSWPEI) are considered for the proposed power station design. SN-3000WL type wind electric generator is considered for this project via compare with the cost of per watt of other types. The initial capital and the replacement cost of wind turbine are 2100$ and 2000$ per kilowatt, respectively. Five different wind turbines quantities (0, 20, 24, 28 and 32) are taken in the hybrid system. Operation and maintenance cost of wind turbine is considered to be 20$ per year, while the working lifetime of wind turbines and the hub height are taken as 15 years and 15 meters, respectively. The output power of SN-3000WL type wind electric generator during various wind speed can be seen from literature [18].

A battery band is used as a back up system to maintain the electric consumption at bad weather. SN150-12 type battery is considered for the proposed project which is produced by GSWPEI, and the nominal capacity and nominal voltage of each battery are 150 Ah and 12V, respectively. Round trip efficiency and minimum state of charge are taken as 85% and 30%, respectively. The float life, maximum charge rate and maximum charge current are 10 years, 1A/Ah and 18A, respectively. The lifetime throughput and suggested value are 1075 and 2343 kWh. The initial capital and the replacement cost each battery is considered to be 110$ and 100$, respectively. Operation and maintenance cost is 2$ per year. The battery quantities are considered to be 0, 48, 120, 192, 264, and 336.

The initial capital and the replacement cost of diesel generator is taken as 220$/kW and 200$/kW, respectively. The diesel generator sizes are considered to be 0, 15, 20, 30 and 35 kW. Operation and maintenance cost is 0.04$/hr per year. Operating lifetime hours are 15000 hours and minimum load rate is 30%. Furthermore, the carbon monoxide and unburned hydrocarbons and particulate matter and nitrogen oxides of fuel are 6.5, 0.72, and 0.49, and 58 gram per liter (g/L), respectively. And proportion of fuel sulfur converted is 2.2. The current diesel price per liter in China is about 1$. The price of diesel is used for sensitivity analysis and five discrete values (0.5, 0.8, 1, 1.2, and 2 $/L) were considered.

The power converter is needed to maintain power flow between the AC and DC components. The initial capital and the replacement cost of power converter is about 195$ and 195$ per kilowatt, respectively. Six different sizes of power converter (0, 25, 30, 35, 40 and 45 kW) are taken in the model. Operation and maintenance cost is taken as 0$ per year. The lifetime is 15 years. Inverter and the rectifier efficiency is 90% and 85%, respectively.

The annual real interest rate is taken as 6%, and the interest rates are considered to be 4%, 6%, and 8%. The project lifetime is 25 years. Dispatch strategy uses cycle charging. Apply set point state of charge is 80%. Operating reserve includes the percent of load and percent of renewable output, and the hourly load as percent of load is 10%, and solar power output and wind power output is 25% and 50%, respectively.

Optimal results and discussion

According to the above input, there are 202,500 possible system configurations which comprised of 45 sensitivities and 4500 simulations for each sensitivity run. Table.1 displays the values of each optimization variable to simulate all possible system configurations. HP pavilion ze2000 notebook PC, AMD Sempron 2800+ CPU, with 1.59 GHz speed, 768 MB took 1 hour, 31 minutes and 12 second to calculate the possible configurations.

Table.1. Probable of system configurations
Source: Authors' new contribution to this paper.

PV Array (kW)	SN-3000WL (Quantity)	Diesel Generator (kW)	SN150-12 (Quantity)	Converter (kW)
0	0	0	0	0
10	20	15	48	25
15	24	20	120	30
20	28	30	192	35
25	32	35	264	40
			336	45

Table.2 summarizes the optimization results for a wind speed value of 4.41m/s (annual average wind speed at the site), interest rate of 6%, and the diesel price in China, which currently equals 1$/L. The suggested optimal hybrid wind-diesel-battery (WDB) power station consists of 32 wind power turbine with rated power of 3kW, 15kW diesel generator, 336 batteries, and 40 kW sized power converter. The proposed hybrid system was found to have an initial capital of 115,260$ with an annual operating cost of 7,002$, total NPC of 204,775$, COE of 0.316$/kWh, renewable energy fraction of 0.955, the diesel consumption of 1,314 L, and working hours of 282 hours. The suggested system of HOMER decreases initial capital of 136,137$ (251,397$-115,260$) as compare with the established hybrid wind-PV-battery system, and the NPC of suggested system of HOMER is less than the initial capital of hybrid system in literature [17]. The only hybrid wind-PV-battery system is considered for the power station, which can be seen in the third row from Table.2. The system with 10 kW PV, 32 wind turbine with rated power of 3kW, 336 batteries, and 35 kW converter is suggested. The hybrid renewable energy only system increases an initial capital of 39,725$, total NPC of 25,766$, and the COE of 0.039 $/kWh while the operating cost decreases 1,091$ per year to compare with the suggested hybrid WDB system. The renewable fraction is 1. The suggested hybrid renewable energy only system of HOMER decreases an initial capital of 96,412$ (251,397$-154,985$) as compare with the established hybrid wind-PV-battery system in literature [17], and the NPC of suggested system of HOMER is less than the initial capital of hybrid system. The diesel only generating system was found in nine row of Fig.4, which consists of a diesel generator with rated power 35 kW. Which increases an operating cost of 60,796$ per year ($/yr), total NPC of 669,615$, and the COE of 1.032 $/kWh while the initial capital decreases 107,560$ as compare with the suggested hybrid wind-diesel-battery system. The renewable fraction is 0. The diesel consumption increases 50,343L, and the operating hours increases 8478 hours (hrs).

The cash flow summary details of different components for the suggested hybrid WDB system can be seen from Table.3, such as total NPC, initial capital, replacement and operation, fuel and salvage. The suggested hybrid system was able to meet the power requirement of load with 95% wind power and 5% diesel generator power. The AC primary load consumption is 50,709 kWh per year (kWh/yr) and the excess electricity quantity is 23,455 kWh/yr which account for 27.2% of total power production, and unmet electric load quantity is 25.7 kWh/yr which account for 0.1%

of total power production, and the capacity shortage is 32.8 kWh/yr which account for 0.1% of total power production. The monthly average electric production is shown in Fig.4. The wind power can meet the power demand during the months of January to April and June and November to December. The diesel generator is operated in May and July and August and September and October to meet the unmet electric load demand.

Table.2. Probable optimal configurations of system
Source: Authors' new contribution to this paper.

PV (kW)	SN3kW	Gen (kW)	SN150	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen (hrs)
0	32	15	336	40	$115,260	7,002	$204,775	0.316	0.95	1,314	282
10	24	15	336	40	$142,460	6,515	$225,741	0.348	0.96	954	204
10	32	0	336	35	$154,985	5,911	$230,541	0.355	1.00	0	0
20	0	30	120	25	$112,675	18,074	$343,715	0.530	0.39	12,458	1,264
0	0	20	120	25	$22,475	25,181	$344,376	0.531	0.00	20,076	3,044
15	20	35	0	25	$120,575	45,637	$703,966	1.085	0.50	32,981	5,523
0	28	35	0	25	$71,375	53,213	$751,621	1.159	0.47	38,880	6,641
20	0	35	0	25	$100,575	52,885	$776,625	1.197	0.22	39,487	6,518
0	0	35	0	0	$7,700	67,798	$874,390	1.348	0.00	51,657	8,760

Table.3. Cost summary of component
Source: Authors' new contribution to this paper.

Component	Capital($)	Replacement ($)	O&M($)	Fuel ($)	Salvage ($)	Total ($)
SN-3000WL	67,200	26,705	8,181	0	-4,971	97,116
Generator	3,300	0	2,163	16,801	-370	21,893
SN150-12	36,960	31,581	8,590	0	-1,814	75,318
Converter	7,800	3,255	0	0	-606	10,449
System	115,260	61,541	18,935	16,801	-7,761	204,775

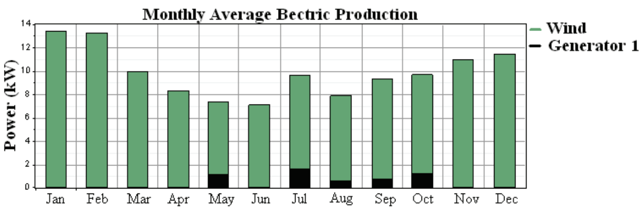

Fig.4. Monthly average electric production of suggested system

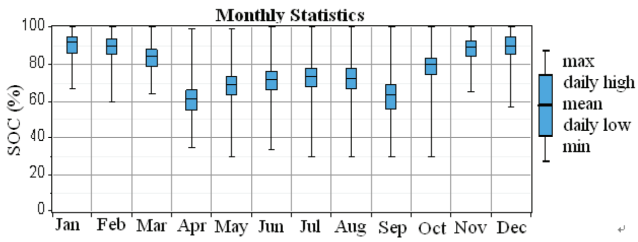

Fig.5. Charge state and monthly storage operating capacity.

The monthly storage operating capacity (SOC) of batteries is shown in Fig.5. The nominal capacity and usable nominal capacity and lifetime throughput are 605 and 423 and 361,200 kWh, respectively. And the autonomy is 73.1 hours (hrs). The battery wear cost and average energy cost are 0.101 and 0.010 $/kWh, respectively. The input energy and output energy and storage depletion and losses and annual throughput are 43,005 and 36,874 and 133 and 5,998 and 39,996 kWh/yr, respectively. The expected life of batteries is 9.03 years. The running characteristic of converter is shown in Table.4. The suggested hybrid wind-diesel-battery power system with 95% wind power could avoid addition of greenhouse gases emissions, such as carbon dioxide, carbon monoxide, unburned hydrocarbons, nitrogen oxides, sulfur dioxide, and particulate matter. The emissions of proposed hybrid system decrease the carbon dioxide of 132,530 (136,031-3,461) kilogram (kg), the carbon monoxide of 327.46 (336-8.54) kg, unburned hydrocarbons of 36.254 (37.2-0.946) kg, particulate matter of 24.656 (25.3-0.644) kg, sulfur dioxide of 266.05 (273-6.95) kg, and nitrogen oxides of 2919.8 (2,996-76.2) kg as compare with the diesel only generating system.

Table.4. Characteristic of converter
Source: Authors' new contribution to this paper.

Quantity	Inverter	Rectifier	Units
Capacity	40.0	40.0	kW
Mean output	5.7	0.3	kW
Minimum output	0.0	0.0	kW
Maximum output	35.2	11.5	kW
Capacity factor	14.2	0.7	%
Hours of operation	8,517	235	hrs/yr
Energy in	55,188	2854	kWh/yr
Energy out	49,669	2,426	kWh/yr
Losses	5,519	428	kWh/yr

Table.5. Probable sensitivity variables
Source: Authors' new contribution to this paper.

Diesel price ($/L)	Average values of annual wind speed (m/s)	Annual real interest rate (%)
0.5	4	4
0.8	4.41	6
1	5	8
1.2		
2		

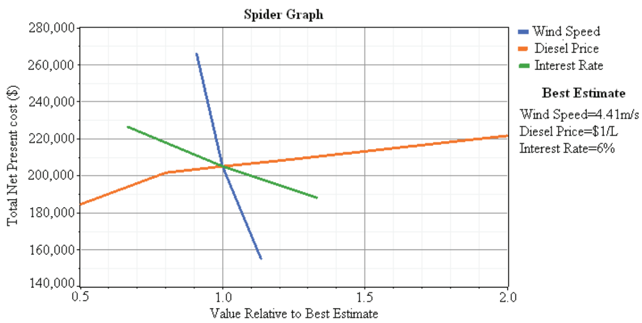

Fig.6. Effect of sensitivities in NPC.

As mention above, there are 45 sensitivity variables which are presented in Table.5. The sensitivity variables will range with the changing of external circumstance, such as meteorological and economical domain. The changing of diesel prices and average values of annual wind speed and different annual real interest rates are considered in this section, which affects the NPC and COE and O&M. For example, the effects of sensitivity variables for NPC are shown in Fig.6. The NPC will increase with the increasing of diesel price and decreasing of annual average wind speed and interest rate. The NPC will decrease with the decreasing of diesel price and increasing of annual average wind speed and interest rate. And the changing of annual average wind speed has the biggest effect for total NPC.

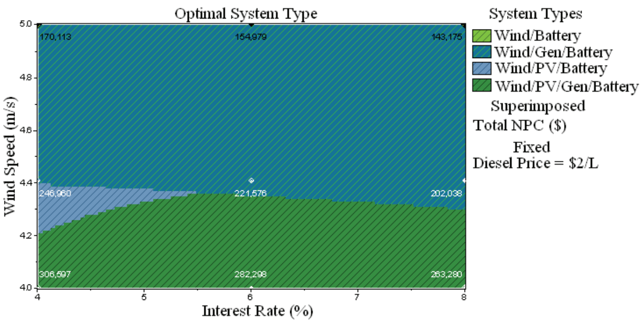

Fig.7. Sensitivity analysis for possible optimal configure.

Fig.7 exhibits the sensitivity analysis results in terms of interest rate and annual average wind speeds for maximum annual capacity shortage of 0%. There are three values for the interest rate and three values for the annual average wind speed were specified. The axes of the graph correspond to these two sensitivity variables. The diamonds in the Figure indicate these sensitivity cases, and the colour of each diamond indicates the optimal system type for that sensitivity case [16]. At the range of annual average wind speed from 4.2 to 4.4 m/s and the interest rate less than 5.5% and the fixed diesel price of 2 $/L, for example, the optimal system type was hybrid wind-PV–battery system. At the annual average wind speed more than 4.4 m/s, the optimal system type was hybrid wind-diesel-battery system. As a conclusion, the design of optimal system must consider the meteorological data of site and external economical condition.

Conclusion

In this article, a hybrid system comprising of wind turbines, PV modules, diesel generator, and storage batteries, is discussed to explore the possibility of utilizing power of the wind and solar to reduce the dependence on fossil fuel for power generation to meet the electric requirement of Dongwangsha located in the seaside of the Chongming islands, Shanghai. The most economical power system consists of 32 wind power turbines with rated power of 3kW, 15kW diesel generator, 336 batteries, and 40kW sized power converter at annual average wind speed of 4.41m/s and diesel price of 1 $/L and interest rate of 6%. The initial capital and total NPC is 115,260$ and 204,775$, respectively. The operating cost is 7,002$ per year and COE is 0.316$/kWh and renewable energy fraction is 0.955 and the diesel consumption is 1,314 L and working hours is 282 hrs. When the power station uses the hybrid renewable energy only system, the economical power system consist of 10kW PV, 32 wind power turbines with rated power of 3kW, 336 batteries, and 35 kW converter. The initial capital and total NPC is 154,985$ and 230,541$, respectively. The operating cost is 5911$ per year and COE is 0.355$/kWh and renewable energy fraction is 1. These suggested systems are more environmental friendly than the conventional diesel only system and the greenhouse gases emission is less than the diesel only system. As a conclusion, the techno-economic analysis is very important to select the optimal configure of hybrid power system.

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***Authors**: Assistant prof. L.Q. Liu, college of electronic and Information engineering, Taiyuan University of Science & Technology, Waliu road 66, Wanbolin district, Taiyuan, China, E-mail: llqd2004@163.com; Assistant prof. C.X. Liu, College of computer science & technology, Taiyuan University of Science & Technology, Waliu road 66, Wanbolin district, Taiyuan, China, E-mail: lcx456@163.com.*