

Modelling flood reservoir integrated with pumped hydropower storage for electricity production using HOMER

Aishah Safi¹*, Shahrani Anuar¹, Daing Mohd Nafiz¹, Firdaus Basrawi¹, Mohd Nazani¹, and Ahmmad Shukrie¹

¹ Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia.

Abstract. This paper presented the potential of flood reservoir integrated with pumped hydropower storage for electricity production in Pekan, Malaysia. Based on the procedure in Technical Release 55 (TR-55), the volume of the reservoir to attenuate flood was 5.2 million³. The volume estimated will be the size of the lower reservoir of proposed PHS and act as flood water catchment during flood seasons. The system proposed an integration of PHS with wind turbines and connect it to the grid. The Hybrid Optimization Model for Electric Renewable (HOMER) software was used to model system for electricity production. The software has simulated 200 different configurations of systems which included the diesel-only system and hybrid wind/diesel system. The standalone diesel system could produce about 25,041,824 kWh of electricity per year and emits 30,030,457 kg/year of pollutants into the atmosphere. Meanwhile, the hybrid wind/diesel could produce 25,668,980 kWh/year of electricity and emits 29,293,174 kg/year of total pollutants into the air. Although, the standalone diesel has the lowest cost of energy among all configurations which is RM0.852/kWh, but it releases the most amount of carbon dioxide. The high emission of this gasses can have many environmental effects in a long term.

1 Introduction

In the early construction of reservoirs and dams, most of them were built for a single purpose only such as for water supply or irrigation, but now there is growing number of multipurpose dams especially in developing countries. This is because the population can receive both domestic and economic benefits with only single investment for dam construction. Among various objectives of reservoir operations, hydropower production is very significant to fulfill the increasing power demand of various sectors and as well for flood control. Based on the report published by World Register of Dams, 17 % of reservoirs construction are for hydropower production and 10 % is for flood mitigation [1].

* Corresponding author: aishahsafi203@gmail.com

There are few types of hydropower technologies that produce electricity from the gravitational force of moving water. Among the type of hydropower is pumped hydropower storage (PHS). The electric energy is stored in the form of hydraulic potential energy by spinning of turbines backward, which causes the turbines to pump water from a lower reservoir to an upper reservoir. The pumping water to a high elevation usually conducted during off-peak periods such as when the price of electricity is cheap or the demand is low. During the peak period of electricity demand, water from the upper reservoir is released back into the lower reservoir which causes the turbines to spin forward and activating generators to produce electricity [2]. Hence, those water reservoirs are capable of storing in huge amounts of electrical energy and as well for a long duration of time.

In 2014, according to the International Energy Agency (IEA), the total installed large scale energy storage currently operating around the world is at least 140 GW and 99 % of the capacity coming from PHS [3]. Along with the capability to store large quantities of energy, well-established technologies of hydropower production have turned PHS to be a great alternative energy storage device for most renewable energy which has inflexibility of power production. Intermittent renewable energy sources such as the wind, solar radiation, tides or stream flow usually depend on diurnal and seasonal patterns to generate electricity [4]. PHS recovering and exploit the excess energy from intermittent energy by pumping water from the lower reservoir and refill the upper reservoir [5]. Thus, integrating PHS with the intermittent energy sources can increase the reliability and flexibility of the hybrid system and at the same time enabling the system to operate at optimum efficiency [6].

Meanwhile, in flood management, reservoirs can be effectively used for flood mitigation by holding water and regulating the stream discharge during major flood events. The water level in the reservoir will be kept low prior to a monsoon or heavy rain event which will create more storage to capture excess discharge water. Then, the water captured in the reservoir will be released at a desired rate to prevent flooding at the downstream [7].

The main objective of this paper is to model flood reservoirs integrated with wind pumped hydro storage for electricity production. The reservoirs of PHS will act as flood water catchment to temporarily store the flood water and slowly release it after the river return to the normal water level. Estimation of storage volume to attenuate flood in the study area was calculated based on results from Hydrological Modelling System (HEC-HMS) software, and the Hybrid Optimization Model for Electric Renewables (HOMER) software was used to model the proposed PHS.

This paper has four sections. The first section briefly explained the functions of water reservoirs. The second section discussed the method to estimate the volume of the reservoir for flood mitigation and also the steps to model pumped hydropower system in HOMER software. The next section presents the calculated volume of the reservoir, outputs of system simulated in HOMER software, analysis of the results and the final section contain the conclusions.

2 Methodology

2.1 Estimation of reservoir volume for flood attenuation

Technical Release 55 (TR-55) contains simple procedures to calculate the storage volume requires for floodwater reservoirs. The volume of flood reservoir can be estimated by knowing the runoff volume, peak inflow, and peak outflow. Figure 1 shows the relationship

between the peak inflow and peak outflow to the storage volume of reservoir and volume of runoff.

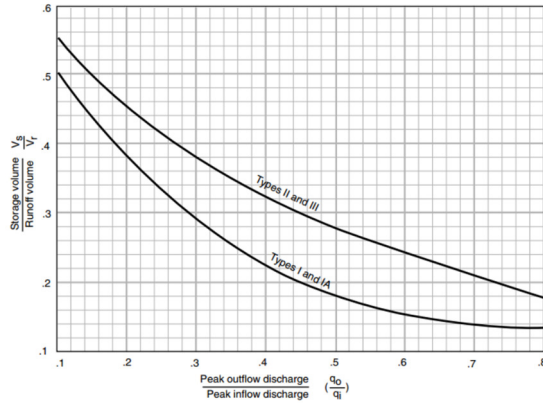


Fig. 1. Approximate detention basin routing for rainfall types I, IA, II, and III.

The runoff in Kuala Pahang (the last point in Pekan town before water discharge into the South China Sea) with 75.1 km² area size was computed using initial and constant-rate loss model in HEC-HMS to be 0.242 m and the peak inflow discharge was 429.8 m³/s. The runoff volume was estimated by using following equation:

$$V_R = Q \times A \tag{1}$$

$V_R = \text{Runoff volume (m}^3\text{)}$

$Q = \text{Runoff (m)}$

$A = \text{Area (m}^2\text{)}$

The volume of flood water reservoirs was estimated by using following equation:

$$V_s = V_R \times \left(\text{ratio of } \frac{Q_o}{Q_i} \text{ from graph in Fig.1} \right) \tag{2}$$

$V_s = \text{Required volume off flood storage}$

$Q_o = \text{Peak out flow (m}^3\text{/s)}$

$Q_i = \text{Peak in flow (m}^3\text{/s)}$

2.2 Modelling pumped storage hydropower modelling in HOMER

Canales and Beluco had explained the method for modelling of PHS with a few modifications in HOMER [4]. This software was developed by National Renewable Energy Laboratory (NREL) for the optimization of hybrid systems on a micro and small scale and can be freely accessed in its Legacy version [8]. In HOMER, a battery was created as equivalent to electrical storage mechanism of PHS with particular capacity and roundup efficiency. The connection between the battery created and PHS was explained further in next sub-section.

2.2.1 Battery representing the reservoir

The battery is capable of storing excess energy and supply when there is a demand which has the similar capability of PHS reservoirs. The properties of battery modelled in HOMER was

assumed to remain the same during its lifespan. Based on explanation by Canales and Beluco [4], the total stored energy in the volume of reservoir can be described by the following equation:

$$E_s = \frac{9.81 \times \eta_{hyd} \times H \times Vol}{3600} \quad (3)$$

where

E_s = Total stored energy (kWh)

H = Gross head (m)

η_{hyd} = Efficiency in turbine mode (%)

Vol = Volume of reservoir (m^3)

The discharge current of the battery with a fixed voltage and capacity is considered independent, and the stored energy can be expressed by the following equation:

$$E_s = \frac{V \times C_B}{1000} \quad (4)$$

where

E_s = Stored energy (kWh)

V = Voltage (V)

C_B = Capacity ($A \cdot h$)

The power produced by the battery is corresponding to the value of current when the voltage is assumed to be constant and can be calculated by the following equation:

$$P_{bat} = \frac{V \times I}{100} \quad (5)$$

where

P_{bat} = Power (kW)

V = Voltage (V)

I = Capacity ($A \cdot h$)

According to Canales and Beluco, there are three steps to model PHS in HOMER. The first step is to determine a reference voltage of the equivalent of the battery and calculate the capacity of the equivalent battery which proportional to the reservoir volume. The battery also must be set on DC bu. This important to ensure that inputs and outputs of the battery will represent the flow rate of water being stored or leaving the PHS reservoir. The second step is to create an equivalent battery with selected reference voltage and capacity decided earlier. The round trip efficiency should be set at 100% and 0 % for the minimum state of charge. The value of maximum charge current need to proportional to the time required to fill the reservoir. The third step is to include the converter component, which will represent the various options for hydropower plant capacity. This component can be used to control the conversion efficiency in either pump or turbine modes.

2.2.2 Description of input parameters

The simulation of proposed system in HOMER software requires some input parameters to calculate the optimization results of configuration systems. The input parameters are load demand, wind resource input, the flow rate of stream discharge and the costs per unit for each component.

1. Load demand

The load demand shown in Figure 2, was based on the hourly power consumption of all households in Kuala Pahang, Pekan. The base load of 339.9 kW occurred through the day and a peak load of 9,064.0 kW takes placed at night. The daily energy load demand is 2,526 kW.

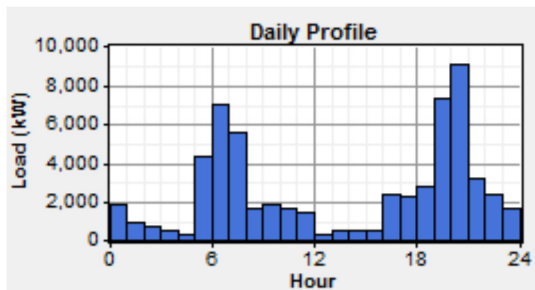


Fig. 2. Hourly load profile.

2. Wind resource

Figure 3 shows the wind resource over one-year period. The daily average of wind speed measured at the anemometer height of 10 m above ground was 2.0 m/s.

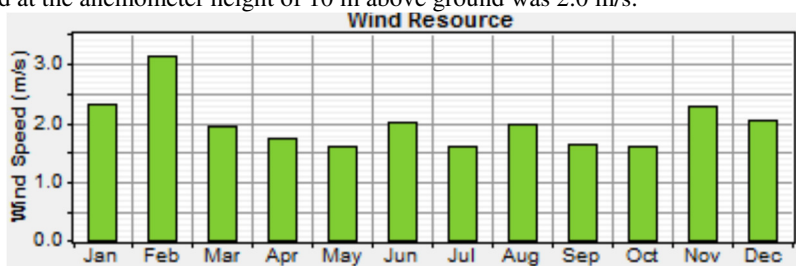


Fig. 3. Wind resource profile.

3. Economic and technical specification

Table 1 shows the details on the economic and technical specification for each component of the proposed hybrid energy system.

Table 1. Economic and technical specification of each component.

Description	Specification
1. Storage battery (reservoirs)	
Capital cost	\$1.25 mil or RM 5 mil
Replacement cost	\$1.25 million or RM 5 million
Operating and maintenance cost	\$2505 or RM 10 000
Lifetime	25 years
2. Wind turbine	
Model	Enercon, E-48
Capital cost	\$1.75 mil or RM 6.9 mil
Replacement cost	\$ 1.75 mil or RM 6.9 mil
Operating and maintenance cost	\$ 2000 or RM 7984
Lifetime	25 years
3. Inverter	
Model	Solectria PVI-80kW-480V
Rated power	80 kW
Capital cost	\$655/kW or RM 2654.7/kW

Replacement cost	\$655/kW or RM 2654.7/kW
Operating and maintenance cost	\$10/year or RM 39.9/year
Lifetime	15 years
4. Generator	
Model	Cummis Generator
Rated power	80 kW
Capital cost	\$225 or RM 898.2
Replacement cost	\$180 or RM 718.6
Operating and maintenance cost	\$0.03/hr or RM 0.12/hr
Lifetime	15,000 operating hours

The costs of all components were converted to Ringgit Malaysia as the costs simulated in HOMER software was based on US Dollar. Based on the trade currency of July 2016, 1 US Dollar is equivalent to RM 4.03.

3 Results and discussion

3.1 Volume of reservoir for flood water catchment

The volume of runoff calculated was 18.2 million³ and the volume of the reservoir to attenuate flood event was 5.2 million³. The calculated reservoir volume will be the size of the lower reservoir of proposed PHS. This lower reservoir will act as flood water catchment during flood seasons. The principle operation of proposed PHS system in Figure 4, was design based on explanation in “Optimal operation and hydro storage sizing of a wind–hydro power plant” [9].

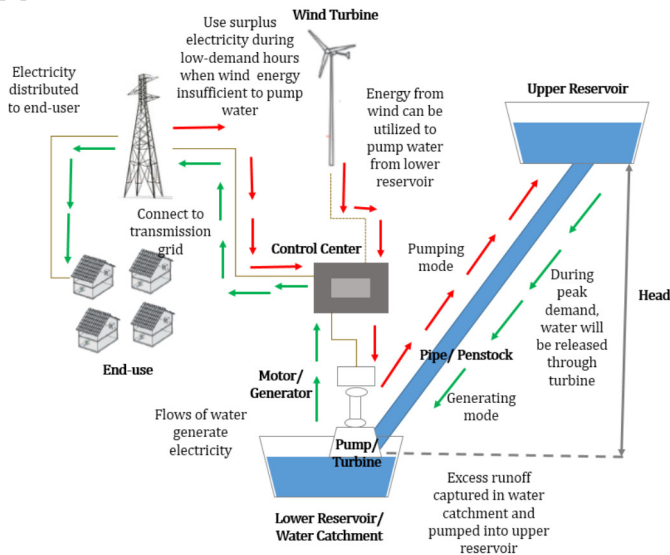


Fig. 4. Proposed system layout [10].

The system proposed an integration of PHS with wind turbines and connect it to the grid. During low demand of electricity or when there is an excess of energy produced by the wind turbine, water will be pump from the lower reservoir to the upper reservoir. When there is high demand for electricity, the pumped water in the upper reservoir will be released through

the turbines and driving generators to produce enough electricity. The storage space of the lower reservoir is kept low for a huge discharge of excess runoff during extreme hydrological events or flood seasons. The lower reservoir which acts as flood water catchment only needs to temporarily store the excess runoff water and can slowly release if after river water return to normal level.

3.2 Simulation of proposed pumped hydro storage in HOMER

The outputs from the simulation in HOMER software by using the methods previously explained are presented and discussed in this section. Figure 5 shows the configuration of proposed system as designed in HOMER. The simulated peak demand of primary load is 16 MW and the total energy consumption is 61 MWh/day.

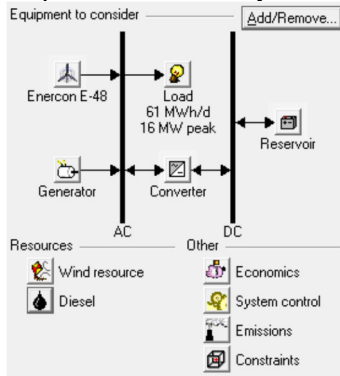


Fig. 5. Schematic diagram of the system.

The simulation was conducted by comparing the optimal configuration of stand-alone diesel system and optimal configuration of hybrid wind/diesel with battery storage element (flood reservoir). In Figure 6, after optimization was performed, the cheapest system among all studied configuration is standalone diesel system with total net present cost (NPC) of RM 241 million based on the diesel price of RM 1.60/L and the levelized cost of energy (COE) for this system is \$0.213/kWh or RM 0.852/kWh. The electricity generation of standalone diesel generator could produce is 25,041,824 kWh/year with 9.3% of excess electricity as shown in Figure 7.

Sensitivity Results		Optimization Results									
Double click on a system below for simulation results.											
Icon	E-48 Label (kW)	Reservoir	Conv. (kW)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Ren. Frac.	Diesel (L)	Label (\$/yr)	
	12...	1	80...	\$ 11,583,750	5,372,603	\$ 80,263,648	0.284	0.00	13,418...	6,478	
	14...	1	800...	\$ 5,694,375	5,922,311	\$ 81,401,384	0.288	0.00	15,250...	6,487	
	16...	1	800...	\$ 5,051,550	6,424,795	\$ 87,181,992	0.308	0.00	16,601...	6,408	
	16...	1	8000...	\$ 5,110,500	6,558,748	\$ 88,953,304	0.314	0.00	16,948...	6,476	
	14...	1	80...	\$ 11,589,375	6,075,514	\$ 89,254,832	0.316	0.00	15,250...	6,487	
	16...	1	800...	\$ 5,700,000	6,584,075	\$ 89,866,576	0.318	0.00	16,974...	6,460	
	18...	1	800...	\$ 5,057,175	7,126,126	\$ 96,152,976	0.340	0.00	18,429...	6,408	
	18...	1	8000...	\$ 5,116,125	7,161,252	\$ 96,650,952	0.342	0.00	18,518...	6,374	
	16...	1	80...	\$ 11,595,000	6,737,278	\$ 97,720,024	0.345	0.00	16,974...	6,460	
	18...	1	800...	\$ 5,705,625	7,275,910	\$ 98,716,176	0.349	0.00	18,778...	6,449	
	14...	1	80...	\$ 39,375	7,727,116	\$ 98,817,848	0.349	0.00	20,167...	8,759	
	14...	1	80	\$ 5,040,030	7,778,033	\$ 104,469,4...	0.369	0.00	20,134...	8,758	
	20...	1	800	\$ 5,062,800	7,834,079	\$ 105,208,6...	0.372	0.00	20,275...	6,408	
	20...	1	8000	\$ 5,121,750	7,839,457	\$ 105,336,3...	0.372	0.00	20,286...	6,354	
	18...	1	80...	\$ 11,600,625	7,429,113	\$ 106,969,6...	0.377	0.00	18,778...	6,449	
	20...	1	80...	\$ 5,711,250	7,985,359	\$ 107,790,9...	0.381	0.00	20,627...	6,451	
	20	8000	1	8000	\$ 39,592,000	5,528,738	\$ 110,267,8...	0.390	0.05	10,831...	7,440
	20	8000	1	80...	\$ 40,181,500	5,537,792	\$ 110,973,0...	0.392	0.05	10,815...	7,400
	16...	1	80...	\$ 45,000	8,683,820	\$ 111,053,3...	0.393	0.00	22,631...	8,759	
	20	10...	1	8000	\$ 39,597,624	5,917,585	\$ 115,244,2...	0.407	0.05	11,845...	6,712
	20	10...	1	80...	\$ 40,187,124	5,880,903	\$ 115,364,8...	0.408	0.05	11,709...	6,596
	20...	1	80...	\$ 11,606,250	8,138,561	\$ 115,644,3...	0.409	0.00	20,627...	6,451	
	16...	1	80	\$ 5,045,655	8,736,131	\$ 116,722,7...	0.413	0.00	22,631...	8,758	
	20	8000	1	80...	\$ 46,076,500	5,690,994	\$ 118,826,5...	0.420	0.05	10,815...	7,400
	20	12...	1	8000	\$ 39,603,248	6,465,930	\$ 122,259,5...	0.432	0.05	13,273...	6,484
	20	12...	1	80...	\$ 40,192,752	6,463,455	\$ 122,817,4...	0.434	0.05	13,228...	6,411
	20	10...	1	80...	\$ 46,082,124	6,034,107	\$ 123,218,2...	0.436	0.05	11,709...	6,596

Fig. 6. Homer optimization results.

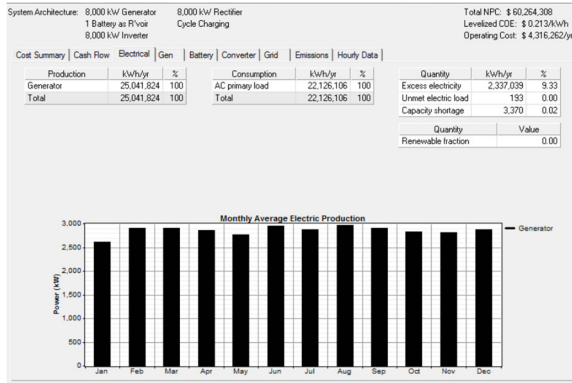


Fig. 7. Summary of standalone diesel generator configuration.

Figure 8 shows the participating of wind turbines in the hybrid system delivers 1,387,405 kWh/year or 5 % of electricity production when operating in the hybrid configuration.

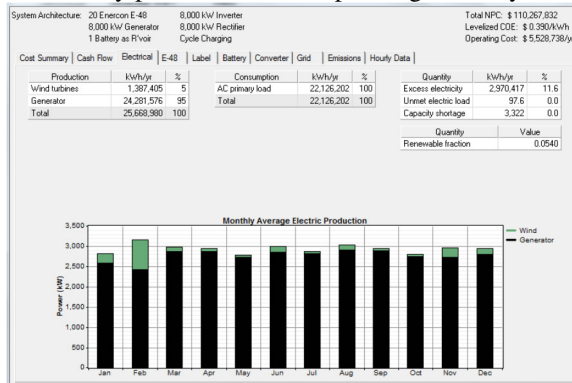


Fig. 8. Summary of hybrid wind/diesel with storage configuration.

Based on the simulation results, 20 unit of wind turbines with 8000 kW of the generator is the best configuration of the hybrid system. The system could produce 25,668,980 kWh/year of electricity which 24,281,576 kWh/year come from the diesel generator and 1,387,405 kWh/year delivers from the wind turbines. The cost of energy (COE) of this hybrid system from the HOMER simulation is \$0.390/kWh or equivalent to RM 1.56/kWh. According to Ministry of Energy, Green Technology and Water, the average electric tariff rate is 38.53 sen/kWh or \$ 0.09/kWh [11]. As can be seen, the COE calculated by HOMER is much higher than average rate of the electric tariff in Malaysia. High rates of calculated COE maybe due to the increase costs in operation and maintenance. In addition, the rise of annual inflation rate which directly increase the rate of annual interest also can increase the cost [12]. The value of COE also could be reduced by using a more uniform wind profile and a more precise lifetime of each component [13].

Meanwhile, the Total Net Present Cost (NPC) is \$110 267 832 or RM 441 071 328 and the operating cost is \$5 528 738/year or RM 22 114 952/year. The economic costs of hybrid system were analyzed so that cost of energy produced from the proposed system could be afforded by residents in that area. The initial capital cost of the system is \$39 592 000 or RM 158 368 000, at 6 % interest rate, the total initial cost of the system is \$41 967 520 or RM 167 870 080. At tariff rate RM 0.24/kWh, the annual revenue of the system is RM 6 067 578.2, so the payback period or the number of years required recovering the cost of the investment and cost benefit analysis is 27.6 years.

Based on the results, the portion of wind turbines in electricity production is a little bit small due to the low wind resources in the study area. Actually, the PHS plant could be an interesting alternative for flood mitigation and electricity production by considering few other factors such as site selection and the component of the system. The reservoir of PHS not only can be used to capture and store flood water but also can be a complementary energy storage system for wind energy. Thus, the participation of this intermittent resource in the market can be improved by integrating with PHS.

As shown Figure 9, the total pollutants emitted by standalone diesel system is 30,030,457 kg/year. On the other hand, Figure 10 show the total polluted emissions produced by hybrid wind/diesel with battery (water reservoir) system which is 29,293,174 kg/year.

Pollutant	Emissions (kg/yr)
Carbon dioxide	29,242,052
Carbon monoxide	72,180
Unburned hydrocarbons	7,995
Particulate matter	5,441
Sulfur dioxide	58,723
Nitrogen oxides	644,066

Fig. 9. Pollutants emitted by standalone diesel system.

Pollutant	Emissions (kg/yr)
Carbon dioxide	28,524,124
Carbon monoxide	70,408
Unburned hydrocarbons	7,799
Particulate matter	5,308
Sulfur dioxide	57,281
Nitrogen oxides	628,254

Fig. 10. Pollutants emitted by hybrid wind/diesel with storage system.

The introduction of wind turbines into the system has reduced the emission of carbon dioxide (CO₂) to a considerable amount. The burning of fossil fuels such as diesel is unavoidably producing CO₂ and huge emission of this gaseous are the main cause of global warming. Although the participation of wind energy into the system is low but eventually it can cut down the amount of CO₂ into the atmosphere. In the future, for more effective CO₂ reduction, solar Photovoltaic (PV) can be combined with the wind energy to ensure a continuous supply of power to the load.

4 Conclusion

This paper presented the study on the utilization of pumped hydropower storage reservoir for flood mitigation and electricity production. An area in Pekan was the basis of this study. The reservoir not only can be used to captured and stored flood water but also can be an interesting alternative as a complementary energy storage system to deal with the intermittency of renewable sources. The standalone diesel system produces the lowest value of the cost of energy compared to the hybrid wind/diesel configuration, but it releases more amount of pollutants emission into the atmosphere.

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