Optimal Design of Wind-PV-Diesel-Battery System using Genetic Algorithm

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Keywords: renewable energy, genetic algorithm, optimal design, diesel generators, CO_2 emission

In many countries, power networks are widely spread for continuous and high quality power supply. However, there still exist many isolated areas, which are not connected to utility grid. Usually, diesel generators (DGs) are utilized to feed power to those areas. Since the fuel price has been increasing in the last decade, the generation cost has also increased. Moreover, the issue of global warming due to the combustion of fossil fuel could increase the temperature of the earth. Hence, applications of renewable energy become popular to be alternative and clean energy. However, the output power generated by the renewable power sources always fluctuates depending on the weather conditions. At present, the capital cost of installing units for renewable energy system is still expensive compared with diesel generators.

In the eastern part of Indonesia, there are many isolated islands, not connected with a common power distribution system. In these places, several diesel generators are utilized to meet the load demand. However, several problems occur such as the extra cost to transport fuel to those islands. In addition, sometimes the transportation system has problems such as it is difficult to support the fuel consumption to the electric power generator continuously.

In order to solve the problem above, the optimal design of Wind-PV-Diesel-Battery hybrid system is proposed in this paper. The system consists of PV panels, wind turbines and batteries as energy storage as shown in Fig. 1. To simplify the simulation, only the total capacity from several diesel generators is to be used for simulation. The diesel generator is connected at AC bus so that it cans directly supplying the load demand without any converter unit.

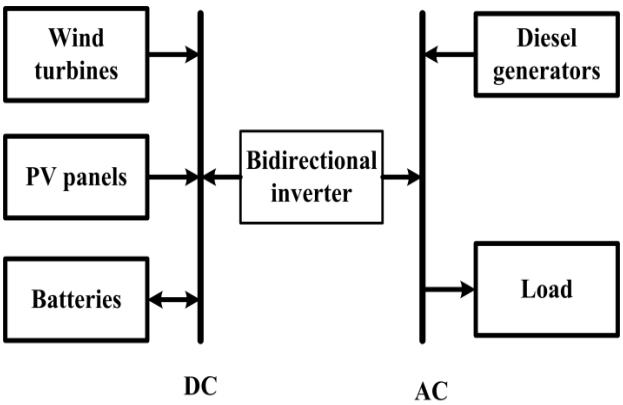

Fig. 1. The system configuration

When the power from renewable energy sources cannot meet the load demand, the strategy will be used to find the economic solution, starting the diesel generator or using the power from battery. This system also uses the dump load that has the function to throw the excess power when the inverter is over regulated or when the renewable energy power is more than the load demand and the batteries are fully charged. Whenever, diesel generator is started the CO_2 emission will be calculated by multiplying the kWh produced by diesel generator with CO_2 emission factor. In this simulation the emmision factor of CO_2 is set to be 0.699 kg/kWh.

The simulation result is shown in Table 1. From simulation results by using genetic algorithm it can be seen that the optimal design of hybrid system in island consist of 44 wind turbines, null of PV panels and 20 batteries storage. The peak power generated from all wind turbines is 44 MW. From Table 1 it can be seen that the annual cost of hybrid Wind-Diesel-Battery is equal to 87.22 million US$. The annual cost of DGs only is 91.14 million US$. Therefore, from economical point of view and environmental aspect the hybrid Wind-Diesel-Battery is suitable to be implemented in East Nusa Tenggara, Indonesia.

Table 1. Comparison with another method

	Hybrid Diesel	**Diesel only**
Peak power of PV panels (W)	120×NULL	-
Peak power of wind turbines (kW)	1,000×44	-
Capacity of batteries (kWh)	5,000×20	-
Diesel generators capacity (MW)	60	60
Interest rate i' (%)	8.25	8.25
Inflation rate f (%)	8.17	8.17
Project lifetime (year)	20	20
SOC minimum of batteries (%)	20	-
Minimum power of diesel generators (%)	40	40
Annual capital cost million (US$)	9.71	-
Annual fuel cost million (US$)	63.82	86.90
Annual O&M million (US$)	4.52	4.24
Annual replacement cost million (US$)	9.17	-
CO_2 emission (Ton/year)	114, 250	200,430
Annual cost of system million (US$)	**87.22**	**91.14**

Paper

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Application of diesel generators to supply the load demand on isolated islands in Indonesia has widely spread. With increases in oil price and the concerns about global warming, the integration of diesel generators with renewable energy systems have become an attractive energy sources for supplying the load demand. This paper performs an optimal design of integrated system involving Wind-PV-Diesel-Battery system for isolated island with CO_2 emission evaluation by using genetic algorithm. The proposed system has been designed for the hybrid power generation in East Nusa Tenggara, Indonesia-latitude 09.30S, longitude 122.0E. From simulation results, the proposed system is able to minimize the total annual cost of the system under study and reduce CO_2 emission generated by diesel generators.

Keywords: renewable energy, genetic algorithm, optimal design, diesel generators, CO_2 emission

1. Introduction

In many countries, power networks are widely spread for continuous and high quality power supply. However, there still exist many isolated areas, which are not connected to utility grid. Usually, diesel generators (DGs) are utilized to feed power to those areas. Since the fuel price has been increasing in the last decade, the generation cost has also increased. Moreover, the issue of global warming due to the combustion of fossil fuel could increase the temperature of the earth. Hence, the application of renewable energy has become popular as an alternative and clean energy. Recently, the alternative energy sources such as wind and solar power are being used to reduce fuel consumption for power generation. However, the output power generated by the renewable power sources always fluctuates depending on the weather conditions. At present, the capital cost of installing units for renewable energy system is still expensive compared with diesel generators. In order to generate the power from renewable energy continuously, there is need for backup systems such battery storage or diesel generators. Therefore, a proper methodology is required in order to build Wind-PV-Diesel-Battery hybrid power system.

In the eastern part of Indonesia, there are many isolated islands, not connected with a common power distribution system. In these places, several diesel generators are utilized to meet the load demand. However, several problems occur such as the extra cost to transport fuel to those islands. In addition, sometimes the transportation system has problems such as it is difficult to support the fuel consumption to the electric power generator continuously. Furthermore, the fuel price always increases by the year so that it is cost effective to use renewable energy sources for the future.

The hybrid Wind-PV-Diesel-Battery system has been studied extensively [(1)–(3)]. However, these references do not calculate the gas emission such as CO_2 produced by diesel generators. Ref. (2) have been introduced an application of artificial neural network on the operation control of the photovoltaic/Battery/Diesel hybrid power generation system. Some of renewable energy software applications like HOMER have been developed in order to model the renewable energy supply with economical consideration. However, this software applications could not solve the optimal configuration of existing diesel generators system with PV and wind turbines already installed [(4)].

Some of the previous studies used monthly average weather conditions such as wind speed and solar insolation for a year. However, it is not suitable and not accurate to design the optimal system due to the intermittent nature of renewable energy sources [(5)]. Hence, by configuring the detail simulation time would obtain the accurate result. Some of the researchers used the iteration techniques to determine the optimal number of renewable energy power sources and the optimal capacity of energy storage devices. These techniques take a lot of computation time and have difficulty in changing the weather data such as insolation and wind speed [(6)–(9)].

This paper proposes a genetic algorithm based-optimal design of Wind-PV-Diesel-Battery hybrid system for isolated island. Genetic Algorithm (GA) is utilized to minimize the objective function in the study system. The case study is taken from East Nusa Tenggara Island in Indonesia. The objective function is to minimize the total annual cost. Where, the annual total cost is the sum of annual capital cost, annual fuel cost of DGs, annual replacement cost and annual

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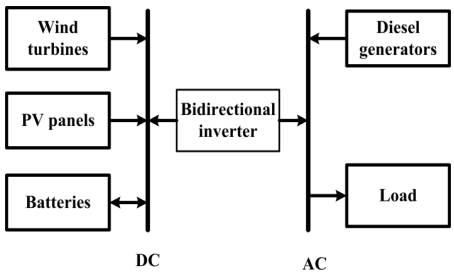

Fig. 1. Configuration of the system

operation & maintenance cost (O&M).

2. Methodology

2.1 Objective Function The objective function is the annual cost of system (ACS) that includes the cost for investment with the discount present values of all future costs throughout the total life time of installation. For this simulation, the lifetimes of units are the same, except the batteries and wind turbines because they need replacement during their lifetime.

The cost of the system could be explained as follows:

(1) Cost for purchasing of PV panels, wind turbines, batteries and inverter.

(2) Cost of replacing units throughout the lifetime of the system.

(3) Cost of operation and maintenance of DGs and units throughout the lifetime of the system.

(4) Cost for consuming fuel for DGs throughout the lifetime.

2.2 Pollutant Emission In this simulation, kg of CO_2 is calculated and obtained due to the combustion of fuel. The CO_2 emission is the main cause of greenhouse effect so that the total amount of CO_2 at the atmosphere must be reduced in order to reduce the global warming. In this simulation the total amount of CO_2 produced by the Wind-PV-Diesel-Battery system throughout one year is calculated and then compared with just operate DGs for this area. The number of CO_2 produced by combustion of diesel engine is calculated by entering the emission factor of CO_2 per kWh electricity produced by the DGs. In this case, the emission factor is set to be 0.699 kg/kWh [(9)(13)].

2.3 System Configuration System consists of PV panels, wind turbines and batteries as energy storage as shown in Fig. 1. To simplify the simulation, only the total capacity from several DGs is to be used for simulation. The DGs are connected at AC bus so that it cans directly supplying the load demand without any converter unit. When the power from renewable energy sources cannot meet the load demand, the strategy will be used to find the economic solution, starting the DGs or using the power from batteries. This system also uses the dump load that has the function to throw the excess power when the inverter is over regulated or when the renewable energy power is more than the load demand and the batteries are fully charged.

2.4 Case Study In this paper, the case study is taken from East Nusa Tenggara, Indonesia-latitude 09.30S, longitude 122.0E. For supplying the load demand, government's electric company installed several units of DGs with total capacity are 60 MW. However, the condition of electricity is not satisfactory. The electricity outage often happens due to maintenance of units or the delayed of delivering the fuel for the DGs. The peak load demand of this island is 47.5 MW and is composed of residential and governmental load. The weekly condition for wind speed and insolation for this island are shown in Fig. 2 and Fig. 3 respectively.

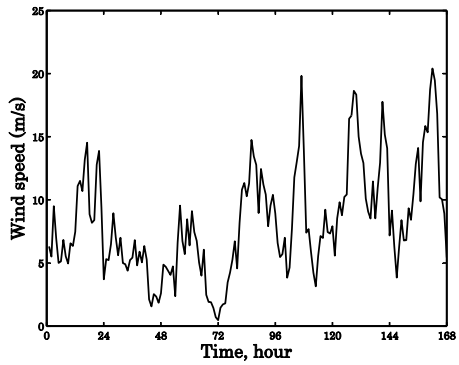

Fig. 2. Weekly wind speed data at East Nusa Tenggara

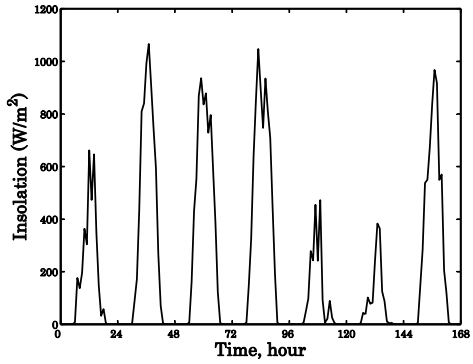

Fig. 3. Weekly insolation data at East Nusa Tenggara

3. Modelling of Renewable Energy Component

3.1 Photovoltaic Model The output power from PV panels is influenced by insolation. Hence, choosing a suitable model for simulation is very essential. In order to simplify the model of PV panel, in this simulation the PV panels are modeled based on the insolation and its efficiency according to the following equation [(1)(5)].

$$P_{PV}(t) = \eta \cdot A_p \cdot N_{PV} \cdot I_{ns}(t) \quad \cdots\cdots (1)$$

Where;

η : Energy conversion efficiency, (%).
A_p : Area of single PV panels, (m^2).
N_{PV} : Number of PV panel
$I_{ns}(t)$: Insolation data, (W/m^2).

3.2 Wind Turbines Model It is very important to select the wind turbine model to simulate the optimal configuration of renewable energy. The appropriate output of wind turbines depends on the wind speed at the location of wind turbines, air density, swept area of rotor and efficiency related to energy conversion from wind energy to electrical energy. Wind turbines curve sometimes is utilized to determine the wind turbines power output. In this simulation, mathematical model of wind turbines is designed to convert hourly wind

speed to be electrical power using following equation [5][7].

$$P_{WT}(t) = \begin{cases} 0, & v(t) < v_c \\ 1/2 \cdot \rho \cdot A \cdot v^3(t) \cdot \eta_w \cdot \eta_c \cdot N_{WT}, & v_c \le v(t) < v_r \\ P_{rated} \cdot N_{WT}, & v_r \le v(t) \le v_f \\ 0, & v(t) > v_f \end{cases} \quad \cdots\cdots (2)$$

Where;

ρ : Air density, (kg/m^3).
A : Swept area of rotor, (m^2).
$v(t)$: Wind speed, (m/s).
η_w : Efficiency of wind turbines (%).
η_c : Efficiency of the AC/DC converter, assumed to be 95%.
v_c : Cut-in speed, (m/s).
v_r : Rated speed, (m/s).
v_f : Furling speed, (m/s).
P_{rated} : Rated power of wind turbines, (kW).
N_{WT} : Number of wind turbines.

3.3 Battery Model The power generated by wind turbines, PV panels and DGs at any time t, can be expressed by the following equation:

$$P_G(t) = P_{WT}(t) + P_{PV}(t) + P_{DG}(t) \cdots\cdots (3)$$

Power from batteries is required whenever the wind turbines, PV panels or DGs power unable to supply the load demand. On the other hand, the power is stored whenever the supply from wind turbines, PV panels or DGs exceeds the load demand. At any hour the state of charge of batteries (SOC) is related to the previous state of charge, the energy production and consumption situation of the system during the time from t-1 to t. Two cases are considered in expressing the energy stored in the batteries for hour t.

Case 1: During charging process, if the total output of wind turbines, PV panels and DGs exceeds the load demand, the available batteries capacity at hour t can be described by the following equation [7].

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1) + (P_G(t) - P_L(t)) \cdots\cdots (4)$$

Case 2: When the load demand is greater than the available generated power, the batteries will be discharged to cover the deficit. Therefore, the available batteries capacity at hour t can be expressed as follow [7]:

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1) - (P_L(t) - P_G(t)) \cdots\cdots (5)$$

Where; SOC(t) is state of charge of batteries at hour t, SOC(t-1) is state of charge of batteries at previous hour. The value of SOC(t) could not be less than the minimum state of charge ($\mathrm{SOC_{min}}$), also while charging operation the value of SOC(t) could not higher than maximum state of charge ($\mathrm{SOC_{max}}$). Where; $\mathrm{SOC_{max}}$ is 1 and $\mathrm{SOC_{min}}$ is determined by depth of discharge (DOD), $\mathrm{SOC_{min}}$ = 1-DOD. In this study, the value of maximum DOD is 80% so that the minimum state of charge is 20%. Mathematically, the constraint of the batteries operation can be expressed as follow [6].

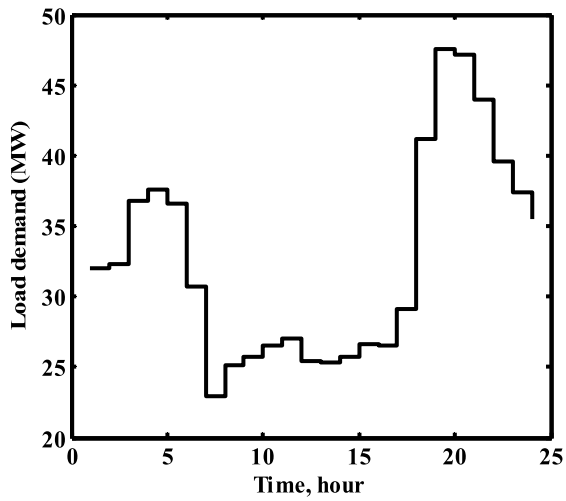

Fig. 4. Daily load profile in East Nusa Tenggara

$$\mathrm{SOC_{min}} \le \mathrm{SOC}(t) \le \mathrm{SOC_{max}} \cdots\cdots (6)$$

3.4 Load Model The power supply from Wind-PV-Battery hybrid system or from the DGs is determined by load demand. The load data used in this simulation based on hourly load data in one day as shown in Fig. 4 then it is repeated for one-year simulation. The peak load demand is in the morning and evening.

3.5 Diesel Generators In this simulation diesel generators are operated to meet the load demand. Hence, in order to calculate operational cost of the DGs, the mathematical model based on Skarstein and Ulhen is required [9].

$$FC = C_f \sum_{t=1}^{8,760} F(t) \cdots\cdots (7)$$

Where;

$F(t)$: Hourly fuel consumption (liter/hour), based on load characteristic of the diesel generators and is calculated as follow [9]–[11].

$$F(t) = (0.246 \times P_{DG}(t) + 0.08415 \times P_R) \cdots\cdots (8)$$

Where;

P_R : Rated power of diesel generators, (kW).
$P_{DG}(t)$: Power generated by diesel generators, (kW).
C_f : Fuel cost per liter, (US$/l).

From equation above, the rated power and the power generation influence the fuel consumption of DGs. Therefore, the DGs should not be operated under its minimum point. Usually, manufacturer of the DGs give the recommendation to set the minimum diesel operation. On the other hand, the maximum efficiency of DGs corresponds to the rated power of the DGs. The operation of DGs has to be operated between the rated powers and specified minimum value [9].

$$P_{DG_{min}} \le P_{DG}(t) \le P_{DG_{max}} \cdots\cdots (9)$$

4. Economic Model Based on ACS Concept

Economical calculation based on the concept of annual cost of system (ACS) is utilized in order to find the best benchmark of system cost analysis in this study. Annual cost of system is composed of annual capital cost (ACC), annual replacement cost (ARC), annual fuel cost of DGs (AFC) and annual operation maintenance cost (AOC). The components to be considered are wind turbines, PV panels, batteries, inverter and diesel generators. ACS can be calculated from following equation [6]:

$$\mathrm{ACS} = \mathrm{ACC}+\mathrm{ARC}+\mathrm{AFC}+\mathrm{AOC} \cdots\cdots (10)$$

4.1 Annual Capital Cost Annual capital cost of each units that does not need replacement during project lifetime such as PV Panels, inverter can be calculated as follows [6]:

$$\mathrm{ACC} = C_{cap} \cdot \mathrm{CRF}(i, Y_{project}) \cdots\cdots (11)$$

Where;

C_{cap} : Capital cost of each component, (US$).
$Y_{project}$: Project lifetime, (year).
CRF : Capital recovery factor, a ratio to calculate the present value of a series of equal annual cash flows. It can be calculated as follows [6]:

$$\mathrm{CRF}(i, Y_{project}) = \frac{i(1+i)^{Y_{project}}}{(1+i)^{Y_{project}} - 1} \cdots\cdots (12)$$

Where;

i : Annual real interest rate. It consists of nominal interest rate and the annual inflation rate. It can be calculated as follows [6]:

$$i = \frac{(i' - f)}{(1+f)} \cdots\cdots (13)$$

Where;

i' : Rate at which we can get a loan, (%).
f : Annual inflation rate, (%).

4.2 Operation Maintenance Cost Maintenance cost of units can be calculated as follows [6].

$$\mathrm{AOC} = \mathrm{AOC}(1) \cdot (1+f)^n \cdots\cdots (14)$$

Where; n is year.

4.3 Annual Replacement Cost Annual replacement cost is the annual cost value for replacing units during the project lifetime. In this study, units that need replacement are batteries and wind turbines. Other units do not require replacement due to their lifetimes are the same as the project lifetime. Economically, annual replacement cost can be calculated from the following equation[6].

$$\mathrm{ARC} = C_{rep} \cdot \mathrm{SFF}(i, Y_{rep}) \cdots\cdots (15)$$

Where;

C_{rep} : Replacement cost of units (batteries, wind turbines), (US$).
Y_{rep} : Lifetime of units (batteries, wind turbines), (year).
SFF : Sinking fund factor, a ratio to calculate the future value of a series of equal annual cash flows. It can be calculated as follow[6]:

$$\mathrm{SFF}(i, Y_{rep}) = \frac{i}{(1+i)^{Y_{rep}} - 1} \cdots\cdots (16)$$

4.4 Annual Fuel Cost of Diesel Generators Annual fuel cost of DGs can be expressed as follows:

$$\mathrm{AFC} = T_{FC} \cdot \mathrm{CRF}(i, Y_{project}) \cdots\cdots (17)$$

Where;

T_{FC} : Total fuel consumption for 20 years, (US$).

5. Operation of Hybrid Wind-PV-Diesel-Battery System

The operation of hybrid system is as shown at Fig. 5. The operation strategy could be explained in detail as follow.

- If load demand (P_L) is lower than total power generated

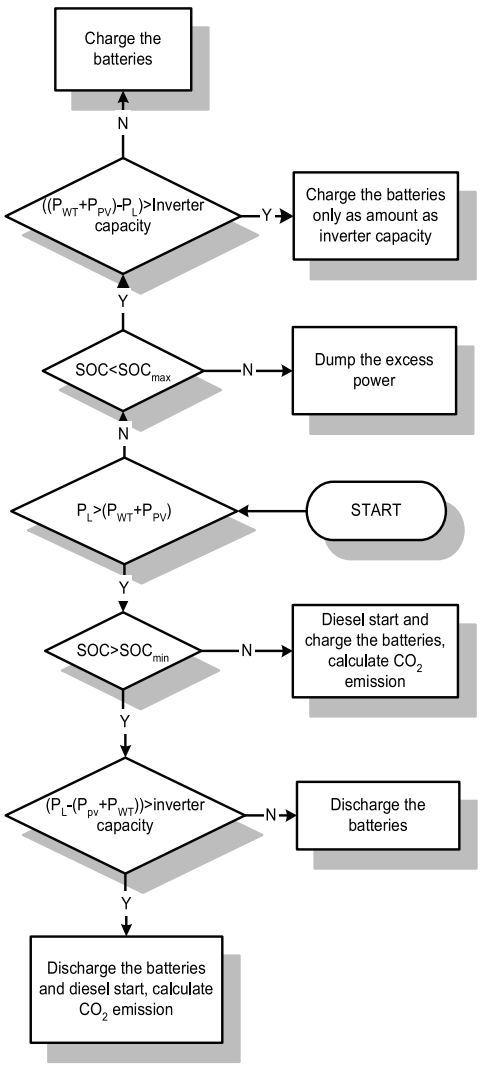

Fig. 5. The operation of hybrid diesel system

from wind turbines (P_{WT}) and PV panels (P_{PV}), then surplus power is use to charge the batteries. If surplus power is higher than inverter capacity, the batteries are charged as amount as inverter capacity and the excess power is dumped.

- If load demand (P_L) is higher than (P_{WT} + P_{PV}) and SOC of batteries is higher than SOC_{min}, then the insufficiency power will be supplied by batteries. Otherwise, if SOC of batteries is equal to SOC_{min}, diesel generators are started to supply the load demand and to charge the batteries.
- However, if insufficiency power is higher than inverter capacity, the batteries are discharged as amount as inverter capacity, then diesel generators are started to meets the load demand.

To calculate the CO_2 emission of DGs, every time whenever DGs started CO_2 emission is calculated correspond with the kWh produced by DGs. From the explanation in the item 2.2, the emission factor for CO_2 is 0.699 kg/kWh [9][13] so that the program will calculate CO_2 emission produced by DGs every hour during 1-year operation.

6. Genetic Algorithm

To determine the optimal configuration, Genetic Algorithm is utilized in this simulation. The concept of GA is different from traditional search and optimization method used in engineering problem. The basic idea of GA is taken from genetic process in biology that used artificially to build search algorithms. This technique is introduced to find the optimal solution based on natural selection. In this proposed method, the optimum configuration includes an optimum number for wind turbines, PV panels and batteries. The flowchart for optimum configuration using GA is shown in Fig. 6. The first step of optimal configuration process is the input of annual data of solar insolation, wind speed and load demand. Numbers of renewable energy components such as wind turbines, PV panels and batteries randomly chosen become the chromosomes of GA. Each chromosome consists of three genes in form of [N_{WT} | N_{PV} | N_{BAT}]. Where;

N_{WT} : Number of wind turbines.
N_{PV} : Number of PV panels.
N_{BAT} : Number of batteries.

After setting initial population, annual simulations are performed to reach the final optimal configuration according to the proposed system. Annual total cost is determined according to optimal configuration. The individual with the lowest cost is chosen as the quasi-optimum solution. The process is repeated to generate the following population until the prespecified convergence is achieved or until the total generation specified at the beginning of simulation is reached. GA will automatically select the best chromosome at every generation. Thus, at the end of generation the chromosome with the lowest cost is obtained. In the simulations Breeder Genetic Algorithm (BGA), one of the techniques of GA is utilized. BGA was originally developed by Heinz Muhlenbein [14]. The model of BGA has artificial selection process like as the performance of human breeders. The BGA selection is a truncation selection. BGA has the rules that the best chromosome at each generation is still used for producing next generation.

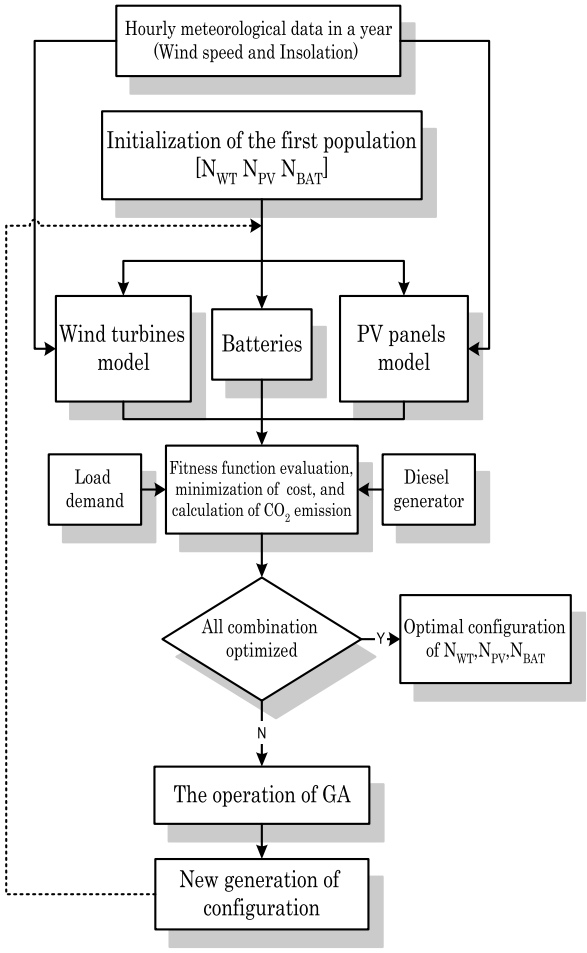

Fig. 6. The scheme of optimization using GA

On the other hand the best elements are guaranteed to be selected and the worst are guaranteed not to be selected.

7. Result and Discussion

7.1 Computational Results An optimum configuration has been performed in this simulation. Meteorological data, load profile and the other factors were taken from isolated island in East Nusa Tenggara, Indonesia. Tables 1, 2 and 3 show the data of renewable energy units. The daily load profiles are represented by power sequences and considered as a constant over time step as shown in Fig. 4. The simulation time is done in one-hour time step until 8,760 hour in one year. The project lifetime in this study is 20 years. Wind turbines and batteries need to be replaced throughout the project lifetime. The inflation rate is 8.17% and interest rate is 8.25% are based on the actual economic condition in Indonesia [18]. The fuel price for DGs is 0.75 US$/l and the O&M cost per hour for DGs is assumed to be 100 US$.

The simulation result is shown in Table 5. From simulation results by using genetic algorithm it can be seen that the optimal design of hybrid system in island consist of 44 wind turbines, null of PV panels and 20 batteries storage. The peak power generated from all wind turbines is 44 MW. From Table 5 it can be seen that the annual cost of hybrid Wind-Diesel-Battery is equal to 87.22 million US$. The annual cost of DGs only is 91.14 million US$. Therefore, from

Table 1. Specification of PV panels

Maximum output power	120 W
Efficiency	16%
Area for single PV panels	1.07 m^2
Capital cost	US$ 1,000
O&M cost	US$ 10
Replacement cost	NULL
Life time	20 years

Table 2. Specification of wind turbines

Maximum output power	1,000 kW
Cut-in speed	3.5 m/s
Furling speed	20 m/s
Rated speed	14 m/s
Swept area of rotor	2,323.09 m^2
Air density	1.225 kg/m^3
Capital cost	US$ 2 million
O&M cost	US$ 800
Replacement cost	US$ 2 million
Life time	10 years

Table 3. Specification of batteries and inverter

Maximum capacity	5,000 kWh
Capital cost of batteries	US$ 400,000
O&M cost	US$ 1,000
Replacement cost	US$ 400,000
Life time	10 years
Inverter capacity	50 MW
Capital cost of inverter	US$ 1.5 million
O&M cost	US$ 500
Replacement cost	NULL
Life time	20 years

Table 4. Parameter of GA

Number of population	20
Truncation probability	0.3
Mutation probability	0.5
Number of generation	100

Table 5. Comparisons with different method

	Hybrid Diesel	**Diesel only**
Peak power of PV panels (W)	120×NULL	-
Peak power of wind turbines (kW)	1,000× 44	-
Capacity of batteries (kWh)	5,000×20	-
Diesel generators capacity (MW)	60	60
Interest rate i' (%)	8.25	8.25
Inflation rate f (%)	8.17	8.17
Project lifetime (year)	20	20
SOC minimum of batteries (%)	20	-
Minimum power of diesel generators (%)	40	40
Annual capital cost million (US$)	9.71	-
Annual fuel cost million (US$)	63.82	86.90
Annual O&M million (US$)	4.52	4.24
Annual replacement cost million (US$)	9.17	-
CO_2 emission (Ton/year)	114, 250	200,430
Annual cost of system million (US$)	**87.22**	**91.14**

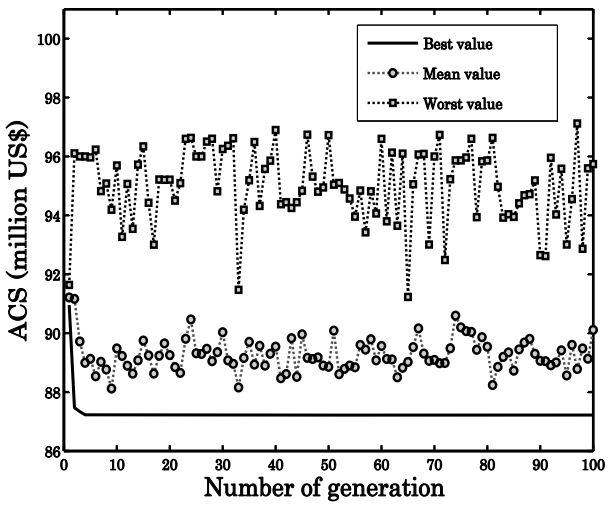

Fig. 7. The performance of GA to find the optimal configuration

economical point of view the hybrid Wind-Diesel-Battery is suitable to be implemented in East Nusa Tenggara, Indonesia. The intensity of wind speed and insolation in this island are quite well. Therefore, the PV panels will consume a large amount of insolation every time. However, the investment cost of PV panels is still very expensive compared with their generated power, hence PV panels are not utilized as power generator.

The proposed configuration also compared with existing system in island that only used DGs. Table 5 shows, the operation of Wind-Diesel-Battery system could decrease the total annual cost of the system. The operation of diesel only consumes a lot of fuel so that the operation cost is expensive. Moreover, the oil prices always increase year by year. Hence, it is cost effective to make combination between renewable energy with DGs. In addition, the operation of only DGs will generate CO_2 emission higher than the proposed system.

7.2 The performance of Genetic Algorithm The parameters of GA can be seen in Table 4. These values are determined by trial and error in order to find the optimal configuration quickly. The performance of GA is shown in Fig. 7. On this figure it can be seen that the mean and the worst values are fluctuating due to the influence of random value caused by truncation and mutation every generation. In BGA, the best value is kept not to be changed by mutation. Every generation, the fitness values are evaluated in order to select the best one. The truncation probability has the function to evaluate the fitness value every chromosome in one population. In this simulation, the value of truncation is 0.3. It means that probability of cromosomes in one generation changed by the best chromosome in previous generation is 0.3. Meanwhile, the mutation probability in this simulation is 0.5. It means that in one generation the probability of chromosomes will be mutated is 0.5. After the number of generation reaches the maximum number of generation, the optimal configuration is obtained. At the end of generation, it can be summarized that the best value is 87.22 million US$, the mean value is 90.11 million US$ and the worst value is 95.74 million US$. The optimal configuration can be obtained by configuration of chromosome [44 0 20].

7.3 Cost of Different Element of the System The total cost of system for different element could be explained from Fig. 8. The O&M cost of DGs and the others components is not really expensive. However, the fuel cost of DGs is expensive so that during the optimal simulation the system attempt to minimize for starting the DGs. The annual capital cost of the system is 9.71million US$. If the government or manufacturer of the renewable energy units give the incentive or subsidy, the total capital cost maybe could

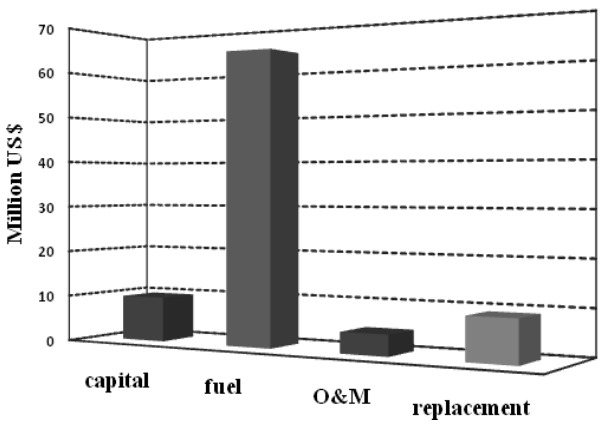

Fig. 8. Cost of different element in million US$

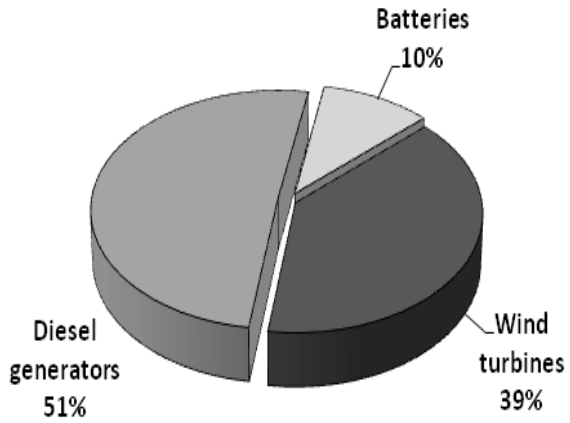

Fig. 9. Annual electricity production each units

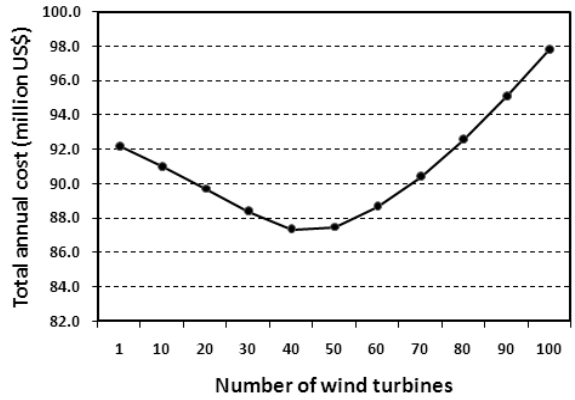

Fig. 10. Comparison of total annual cost under various number of wind turbines

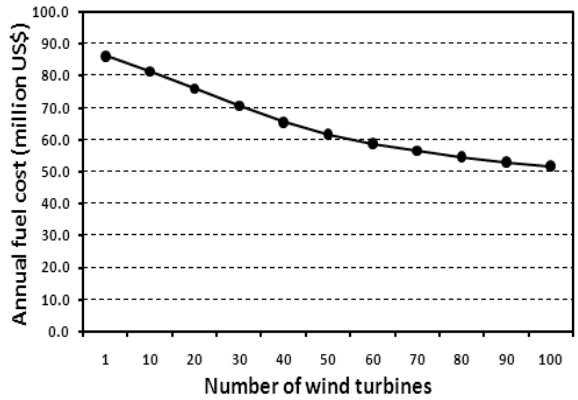

Fig. 11. Comparison of annual fuel cost under various number of wind turbines

Table 6. Influence of minimum SOC of batteries

Minimum SOC of batteries (%)	Diesel fuel cost (Million US$/year)	CO_2 emission (Ton/year)	GWh/year produced by DGs
20	63.82	114,250	163,447
30	63.98	114,880	164,349
40	64.24	115,820	165,693
50	64.50	116,810	167,110

be decreased. The annual replacement cost of batteries and wind turbines is about 9.17 million US$. In this simulation, the strategy of replacement of batteries is not included in the simulation. Hence, during the project life time the batteries will be replaced only one time. In order to make the lifetime of batteries longer, the dispatch strategy based on DOD is required. Actually, the lifetime of batteries is influenced by its operation throughout the project lifetime. For future work, the replacement of batteries would be included into dispatch strategy so that the lifetime of batteries similar with the actual condition.

7.4 The Annual Electricity Production The annual electricity production is shown in Fig. 9. The annual penetration ratio from wind turbines is 39% from the total power production. The insufficient power from wind turbines will be handle with batteries or diesel generators. The annual penetration ratio from batteries and DGs are 10%, 51% respectively. The simple ways, in order to minimize the power generated from DGs, large numbers of wind turbines have to be increased. However, because of the constraint of system operating constraints, technical constraints and economical considerations, increasing large number of wind turbines, will not change the total annual cost. As shown in Fig. 10, increasing the number of wind turbines with fixed number of batteries will make the total cost going down reach the minimum value. However, after reaching the minimal value, the total annual cost is increasing due to the increasing of the number of wind turbines. If the number of wind turbines increases, the capital cost and O&M cost also increase, hence, it is not cost effective to increase the number of wind turbines after reaching the optimal point. Fig. 11 shows the increasing of wind turbines could minimize the operation of DGs. However, reducing of fuel cost of diesel generators has the effect on increasing of capital cost and maintenance cost of wind turbines.

7.5 The Influence of the Minimum SOC of Batteries The manufacturers of batteries usually recommend not to discharge the batteries below its minimum of SOC. Discharging the batteries below its minimum SOC will increase the internal resistance of batteries and make permanently damaged. Further, it will make the batteries lifetime shorter. Hence, in order to prevent the shortage power the DGs have to be started to cover the insufficiency power. However, starting the DGs would affect on increasing of fuel consumption so that the cost for fuel is increased. If the consumption of fuel is increased, the CO_2 emission produced by diesel generators also increased. The value of CO_2 emission corresponds with kWh power generated by DGs. Table 6 shows, increasing of the minimum SOC of batteries would affect on increasing of

both fuel cost of DGs and the CO_2 emission.

8. Conclusion

The optimal design of hybrid Wind-PV-diesel-battery system considering CO_2 emission has been performed in this paper. From results obtained above, the following salient conclusions can be drawn:

(1) Total number of wind turbines is 44 with a capacity of 1,000 kW for one wind turbine. Generated power from the wind turbines supply approximately 39% for load demand.

(2) Total number of batteries is 20 with a total capacity is 20 × 5MWh. Energy from the batteries supply 10% for load demand.

(3) Capacity of diesel generators is 60 MW. Generated power from the diesel generators supply approximately 51% for load demand.

(4) Total annual cost of hybrid Wind-Diesel-Battery to feed load demand is 87.22 million US$. On the other hand, the total annual cost for diesel generator only is 91.14 million US$. Hence, the hybrid proposed system is better from economical point of view and environmental effect.

(5) The hybrid system could be implemented as power generator in East Nusa Tenggara, Indonesia.

(6) Perform necessary preliminary studies before investing and design a hybrid Wind-PV-Diesel-Battery system in East Nusa Tenggara, Indonesia.

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