Genetic Algorithm Based Optimal Sizing of PV-Diesel-Battery System Considering CO2 Emission And Reliability

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GENETIC ALGORITHM BASED OPTIMAL SIZING OF PV-DIESEL-BATTERY SYSTEM CONSIDERING CO\textsubscript{2} EMISSION AND RELIABILITY

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ABSTRACT. The reliability system concern and CO\textsubscript{2} emission reduction are still the main targets of optimization problem in the hybrid generation system components. This paper utilizes Genetic Algorithm (GA) method to determine the optimal capacities of PV system, battery bank and diesel generator (DG) unit according to the minimum cost objective functions that relate to these two factors. In this study, the cost objective function includes the annual capital cost (ACC), annual operation maintenance cost (AOM), annual replacement cost (ARC), annual fuel cost (AFC), annual emission cost (AEC) and annual customer damage cost (ADC). The proposed method has been tested in the hybrid power generation system located in East Nusa Tenggara, Indonesia (latitude 09.30S and longitude 122.0E). To show the effectiveness of this method, three different crystalline Silicon PV module technologies: ASE-300 (mc-Si based EFG), Kyocera KC-120 (mc-Si based wafer) and AstroPower AP-120 (thin-film Si) were used. Simulation results show that the optimum configuration can be achieved using thin-film Si technology of PV modules, battery banks and diesel generator unit with capacities of 139,250x120W, 5x5MWh and 12MW, respectively. This study also reveals the importance of PV and battery systems in the hybrid generation system from economical, reliability and environmental point of views.  
Keywords: PV system, Battery bank, Diesel generator, Genetic algorithm, Optimal size, Cost reduction

1. Introduction. Diesel generator (DG) unit is one of the suitable options for supplying electricity in remote areas due to their compact design and high specific power. The compact design makes it easy to install the unit in non-prepared and small area locations. The high specific power means that the ratio of output power to the weight of unit is considerably high. However, as an independent power source, the DG unit is facing significant problems. The maximum efficiency can only be achieved when the DG unit is operated close to the rated capacity. It is not recommended to operate the diesel unit below its minimum power specified by the manufacturer [1]. This might be problem in remote area application since the load profiles gap during day and night times are very different, depending on daily activities. In East Nusa Tenggara, Indonesia; the remote area case of this study, the daily activities are influenced by cultural and economic behaviors. The other problems of a single DG unit are related to the hard maintenance, fuel supply need and high generation cost [1-3]. To solve this kind of problems, hybrid generation
system combined with utilization of renewable energy sources is one of the promising solutions. In this study, the hybrid combination of PV-battery-diesel systems is the main target, since the location is abundance of sunlight and the community needs to be electrified.

The hybrid generation can offer more significant system improvement than other independent power sources. Combining PV-Diesel system promotes greater reliability for electricity production than a PV-only system or diesel-only system. In this respect, the hybrid power systems have greater flexibility, higher efficiency and lower costs for the same quantity of energy production [4]. The performance of hybrid system is remarkably increased when storage devices are available. The integration of PV-diesel system with battery storage provides a reduction in the operational costs and emitted air pollutants to the atmosphere [5]. However, the invading different types of system and devices to participate in the hybrid form are still remained tasks in the optimization problem. In this reason, the proposed hybrid system should be optimized in terms of type, size and location of devices following certain objective functions.

Several methods can be found in literatures for optimal design of hybrid PV-diesel-battery system [6-8]. In general, they can be categorized into classical and intelligent techniques. In [6], the design and operation control of hybrid system using classical optimization methods was explained. However, the classical optimization methods can only solve certain points in the optimal design problems due to their complex algorithms. The same approach can be found in [7], where the optimization method is started by modeling the diesel generator and then PV and battery sizes in terms of minimum number of storage days and the minimum PV array area. This method is time consuming since the optimization method through a sequential process. On the other hand, the intelligent techniques is one of the promising options for the optimization method since they are simple, fast and are able to solve multi-objective optimization tasks. In [8], an artificial neural network was used to optimize the operation control of PV array-diesel systems. Amongst the intelligent methods, the Genetic Algorithm (GA) is the most popular one to solve the complex problems [9-12]. Reference [13] proposed GA based optimal configuration of power generating systems in isolated islands including renewable energy sources. This method can guarantee the optimum number of solar array panels, wind turbine generators and battery banks. Reference 14 developed GA based C++ to optimize the sizing and operation control of PV-diesel system under worst-case condition. However, all of these methods are sometimes unable to achieve more accurate solutions due to the non-linear and non-convex characteristics of generating units.

This paper presents more comprehensive optimization method for optimal sizing of PV-diesel-battery systems using GA. The effect of CO₂ emission and the reliability of the system are considered during the optimization process. Moreover, the annual damage cost is considered to penalize the system during the electricity shortage in order to satisfy the load demand. Therefore, both cost for CO₂ treatment and penalty cost due to interruption are included in the objective function. Basically, the same approach has already been done using GA to find optimal size of wind-PV-battery system subject to reliability index of loss of power supply possibility (LPSP) [15]. However, this method does not consider the compensation cost due to electricity shortage as well as the CO₂ emission reduction. In other publications, the optimal design of reliable hydrogen based stand alone wind-PV generating system with considering component outage has been proposed [16]. However, the study does not cover the existence of DG unit as back-up power. For these reasons, it is still possible to broaden the research objective by accumulating the drawbacks point in the previous works. In order to do this, the proposed system is constructed including
the algorithm and control strategy using GA. All details about mathematical modeling of PV system, battery bank and DG unit will be provided in the next section.

2. Hybrid System Mathematical Model. The proposed hybrid system configuration in this study is shown in Figure 1. In this model, the renewable energy source by means PV panels, \(P_{pv}\) is utilized to support the power from diesel generators \(P_{DG}\) to supply the load demand \(P_L\). The mathematical modeling of PV system is provided in section 2.1. Since the output power of PV system is intermittent due to sunlight intensity and the necessity to provide constant supply to the load side, a group of battery banks is required as a storage device. The power from battery banks \(P_{BAT}\) is utilized whenever the power from PV panels or diesel generator is unable to supply the load demand. The state operation of battery banks is presented in section 2.2. The power conversion from PV panels and battery system to the load or from diesel generators to the battery system is handled through bidirectional inverter with denoted efficiency of about 95%.

In addition, the power flow inside the model is a time-dependent mechanism and the detailed power flow scenario is explained in section 2.3. The remained parts of section 2 are diesel generator model related to the fuel consumption cost and the economic model based annual cost of the overall system. In this study, it is also important to have the mathematical model on each individual component before proceeding the algorithms. Their mathematical models are explained as follows:

2.1. Photovoltaic system. In this study, the mathematical model of PV system is following the I-V characteristic modeling of Sandia National Laboratory (SNL) [17-20]. This model is effectively used to represent the optimum points of different commercial PV modules. The input variables of this model are only the solar insolation and cell temperature of PV panel. In this model, the important electrical parameters, such as short circuit current \(I_{sc}\), open circuit voltage \(V_{oc}\), current at maximum-power point \(I_{mp}\) and voltage at maximum power point \(V_{mp}\) can be generated from I-V curve [20]. This model is useful in the proposed method since the PV panels are assumed to operate at maximum power points. Therefore, the characterization output of PV module becomes simple because the model only depends on \(I_{mp}\) and \(V_{mp}\) outputs. The mathematical modeling of PV module is described as follows. By assuming the absolute Air Mass \((AM_a)\) function is equal to 1.0 and combining the beam and diffuse components into a single component of insolation. Then, the short-circuit current is calculated based on the following equation:

\[
I_{sc}(t) = I_{sc0} \left( \frac{E(t)}{Eo} \right) \left( 1 + \alpha I_{sc}(T_c(t) - T_o) \right)
\]  

(1)
Other electrical parameters such as maximum power point current ($I_{mp}$), open circuit voltage ($V_{oc}$) and maximum power point voltage ($V_{mp}$) can be generated as follows:

$$V_{oc}(t) = V_{oc0} + N_s \delta(T_e(t))ln(E_e(t)) + \beta_{V_{oc0}} E_e(t)(T_e(t) - T_0)$$  \hspace{1cm} (2)

$$I_{mp}(t) = I_{mp0}(C_o E_e(t) + C_1 E_e(t)^2)(1 + \alpha_{I_{mp}})(T_e(t) - T_0)$$  \hspace{1cm} (3)

$$V_{mp}(t) = V_{mp0} + C_2 N_s \delta(T_e(t))lnE_e(t) + C_3 N_s \delta(T_e(t))ln(E_e(t))^2 + \beta_{V_{mp0}} E_e(t)(T_e(t) - T_0)$$  \hspace{1cm} (4)

The concept of the effective insolation ($E_e$) is utilized due to the fact that the PV panels can not respond to all wavelengths of light contained in the solar spectrum. It can be described as follows:

$$E_e(t) = \frac{I_s(t)}{I_{sc0}(1 + \alpha_{I_{sc}}(T_e(t) - T_0))}$$  \hspace{1cm} (5)

The thermal voltage per cell $\delta(T_e(t))$ in (2) and (3) is given by:

$$\delta(T_e(t)) = \frac{n k(T_e(t) + 275.15)}{q}$$  \hspace{1cm} (6)

The value of temperature inside cells can be calculated using following equation.

$$T_e(t) = T_a(t) + \frac{NCOT - 20^o}{800}E(t)$$  \hspace{1cm} (7)

Finally, total output power from PV panels can be obtained by using following equation.

$$P_{PV}(t) = V_{mp}(t).I_{mp}(t).N_{PV}$$  \hspace{1cm} (8)

where

$E_e$: reference insolation, 1000 W/m$^2$

$V_{oc0}$: V$_{oc}$ at $E_e$=1, $T_e$=$T_0$

$I_{mp0}$: $I_{mp}$ at $E_e$=1, $T_e$=$T_0$

$V_{mp0}$: $V_{mp}$ at $E_e$=1, $T_e$=$T_0$

$\alpha_{I_{mp}}$: normalized temperature coefficient for $I_{mp}$

$\beta_{V_{oc0}}$: temperature coefficient for $V_{mp}$ at 1000 W/m$^2$

$\beta_{V_{mp0}}$: temperature coefficient for $V_{mp}$ at 1000 W/m$^2$

$C_o, C_1$: empirically determined coefficient relating $I_{mp}$ to insolation.

$C_2, C_3$: empirically determined coefficient relating $V_{mp}$ to insolation.

$N_s$: number of cells in series in a cell-string

$\alpha_{I_{sc}}$: normalized temperature coefficient for $I_{sc}$

NCOT: Nominal Cell Operating Temperature ($^o$C)

$T_a$: ambient temperature ($^o$C)

$T_e$: temperature of cells inside module

$T_0$: reference temperature for performance model, 25$^o$C

$n$: empirically determined diode factor for each cell in module.

$k$: Boltzmann’s constant, 1.38066.10$^{-23}$ J/K

$q$: elementary charge, 1.60218.10$^{-19}$ coulomb

$P_{PV}$: photovoltaic output power W

$N_{PV}$: number of PV panel

In this paper, three different Silicon (Si) solar cell technologies are selected to compare the capability of proposed system. The first one is the multi-crystalline (mc-Si) based edge defined film growth (EFG) technology with the brand manufacturer called ASE-300-DGF/17. This module is classified as the world’s most powerful battery charging PV panel with ASE’s crystal clean EFG cell technologies. ASE-300 has low voltage, large-area module and typically used in the systems with charging capabilities are 12, 24 and 48 volt of batteries. The second one is Astropower AP-120 with thin-film Si based technology; which is able to provide optimum battery charging in hot weather or low light.
Table 1. Specification of PV panels based on Sandia National Laboratory (SNL) data (AM1.5; 1000W/m²; 25°C)

<table>
<thead>
<tr>
<th>Material</th>
<th>ASE-300</th>
<th>AP-120</th>
<th>KC-120</th>
</tr>
</thead>
<tbody>
<tr>
<td>mc-Si</td>
<td>2.43</td>
<td>0.98</td>
<td>0.93</td>
</tr>
<tr>
<td>Number of cells in series, N_c</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Number of cells in parallel, N_p</td>
<td>6</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Short circuit voltage at STC, I_{sc}(A)</td>
<td>19.1</td>
<td>7.7</td>
<td>7.45</td>
</tr>
<tr>
<td>Open circuit voltage at STC, V_{oc}(V)</td>
<td>21.1</td>
<td>21</td>
<td>21.5</td>
</tr>
<tr>
<td>Current at maximum power point at STC, I_{mp}(A)</td>
<td>17.4</td>
<td>7.1</td>
<td>7.1</td>
</tr>
<tr>
<td>Voltage at maximum power point at STC, V_{mp}(V)</td>
<td>17.2</td>
<td>16.9</td>
<td>16.9</td>
</tr>
<tr>
<td>Normalized temperature coefficient for short circuit current, (\alpha_{I_{sc}} \text{ °C}^{-1})</td>
<td>0.0009</td>
<td>0.0003</td>
<td>0.0004</td>
</tr>
<tr>
<td>Normalized temperature coefficient for current at maximum power point, (\alpha_{I_{mp}} \text{ °C}^{-1})</td>
<td>0.0004</td>
<td>-0.0005</td>
<td>-0.0006</td>
</tr>
<tr>
<td>Temperature coefficient at 1000 W/m² for open circuit voltage, (\beta_{V_{oc}} (V/°C))</td>
<td>-0.0756</td>
<td>-0.084</td>
<td>-0.089</td>
</tr>
<tr>
<td>Temperature coefficient at 1000 W/m² for voltage at maximum power point, (\beta_{V_{mp}} (V/°C))</td>
<td>-0.0793</td>
<td>-0.084</td>
<td>-0.091</td>
</tr>
<tr>
<td>Diode factor of cell, n</td>
<td>1.288</td>
<td>1.404</td>
<td>1.36</td>
</tr>
<tr>
<td>Empirical coefficient relating between current at maximum power point and insolation, C_0</td>
<td>0.994</td>
<td>0.997</td>
<td>1.01</td>
</tr>
<tr>
<td>Empirical coefficient relating open circuit voltage to insolation, C_1</td>
<td>0.006</td>
<td>0.003</td>
<td>-0.01</td>
</tr>
<tr>
<td>Empirical coefficient relating voltage at maximum power point to insolation, C_2</td>
<td>0.0063</td>
<td>-0.1775</td>
<td>0.0289</td>
</tr>
<tr>
<td>Empirical coefficient relating voltage at maximum power point to insolation, C_3(V^{-1})</td>
<td>-7.6901</td>
<td>-11.0652</td>
<td>-5.9791</td>
</tr>
</tbody>
</table>

Conditions. The last one is Kyocera KC-120 with mc-Si technology based wafer. This module is consisted of 36 cells in series and strongly laminated with glass in an aluminum frame for hardly climate application. The reasons of selecting these module types are the high availability in the PV market with high efficiency performance and competitive price compared than other PV module technologies. All coefficients in (1)-(7) are given in Table 1 for ASE-300, KC-120 and AP-120 PV modules. One of typical I-V and P-V characteristics under constant cell temperature of 50°C of each PV panels based on SNL model can be observed in the Figure 2. Basically, there is no significant differences in characteristic amongst Si based PV module technology. The optimum points is proportionally increased as the insolation level increases. At insolation level reaches 1000W/m², the optimum output power of PV modules are 290W, 115W, 112W, respectively for ASE-300, AP-120 and KC-120; which these values are very close to the rating output. However, as the mismatching losses for AP-120 (thin-film Si technology) is lower than other PV modules, it may contribute much higher power to the total power of hybrid system. The characteristic probably shows a suggestive result that needs to be clearly verified in the proposed method.

2.2. Battery state of charge. The basic principle operation of battery banks is simply explained as follows. The power from battery banks is required whenever the PV or DG power are unable to supply the load demand. On the other hand, the power is stored whenever the supply from PV or DG exceeds the load demand. At each hour, the state of charge of battery banks is related to the previous state of charge [21–23]. The energy production and absorption of the battery system during the time from \(t-1\) to \(t\) is described
Figure 2. The $I-V$ and $P-V$ characteristic of PV panels under different insolation level with $T_c=50^\circ$.

in (9).

$$C_B(t) = C_B(t-1)(1-\sigma) + P_{BAT}(t)$$  \hspace{1cm} (9)

where $C_B(t)$ and $C_B(t-1)$ are the available capacity of battery banks at hour $t$ and at previous hour $(t-1)$, respectively. The term $\sigma$ is the self-discharge rate of the battery banks, in study it is assumed 0.002. Some constraints must be considered under battery banks operation [23]. The value of $C_B(t)$ could not be lower than minimum allowable energy level remained in battery banks ($C_{B_{min}}$), and it could not be higher than maximum allowable energy level ($C_{B_{max}}$) during charging operations. This condition is mathematically expressed in (10).
\[ C_{\text{min}} \leq C_B(t) \leq C_{\text{max}} \]  \hfill (10)

These constraints mean that the battery banks should not be discharged or charged over their limit operating points in order to protect the battery banks against damage and to prolong their lifetime operation [23].

2.3. **Power flow scenario of hybrid system.** The power from PV system through the inverter is hourly measured as follows:

\[ P_{RE}(t) = \eta_{inv} \cdot P_{PV}(t) \]  \hfill (11)

where \( \eta_{inv} \) is the inverter efficiency.

Principles of charging and discharging scenarios are dependent on the state of \( P_{RE}(t) \) and the load power demand at hour \( t \) (\( P_L(t) \)).

(1) If the value of \( P_{RE}(t) > P_L(t) \): The remaining power will be continuously used to charge the battery banks:

\[ P_{BAT}(t) = P_{PV}(t) - (P_L(t)/\eta_{inv}) \]  \hfill (12)

(2) \( P_{RE}(t) < (P_L(t)) \): The remaining power will be supplied from the DG unit or/and the battery banks according to the following dispatch strategy:

(2.1) If the amount of power from battery banks is enough to handle the remaining power, the strategy allows the discharging process of battery banks and turning-off state of DG unit. The power from battery can be determined from the following equation.

\[ P_{BAT}(t) = P_L(t) - P_{RE}(t); \]  \hfill (13)

(2.2) If the battery banks are unable to supply the remained power or the strategy does not allow for the battery banks to discharge, then DG unit is started and the battery banks will be neither charged nor discharged

\[ P_{DC}(t) = P_L(t) - P_{RE}(t); \]  \hfill (14)

(2.3) If the power from DG unit exceeds the load demand then the excess energy will be used to charge the battery banks.

\[ P_{BAT}(t) = (P_{DG_{\text{min}}} - (P_L(t) - P_{RE}(t))) \cdot \eta_{inv} \]  \hfill (15)

(2.4) If the load demand exceeds the DG rated capacity then the DG will run at full capacity and the battery banks will attempt to make up the difference [14],

\[ P_{DG}(t) = P_{R} \]  \hfill (16)

\[ P_{BAT}(t) = \text{Min}[P_{BAT_{\text{max}}}, P_L(t) - (P_{RE}(t) + P_{DG}(t))/\eta_{inv}] \]  \hfill (17)

2.4. **Diesel generator and reduction approach in CO₂ emission.** The fuel consumption of DG unit is related with the rated power and its generated power. Therefore, DG should not be operated under its minimum point. Usually, manufacturers of the DG give the technical specification about their products as well as suggestion for a better operational technique. The fuel cost is calculated for a year as follows [24],

\[ AFC = C_f \sum_{t=1}^{T_{\text{end}}} F(t) \]  \hfill (18)
where $F(t)$ is the hourly fuel consumption (US$/hour), based on load characteristic of the diesel generators $[14,22,24]$. This parameter is calculated as follows.

$$F(t) = (0.246 \times P_{DG}(t) + 0.08415 \times P_n)$$ \hspace{1cm} (19)

where $P_n$ is the rated power of diesel generators in kW, $P_{DG}(t)$ is the power generated by diesel generators in kW and $C_f$ is the fuel cost per liter in US$/l$. In order to reach the maximum efficiency of operation, the unit should be operated within rated power and specified minimum value $[24]$. The optimum operating condition must be in the range of $[14,22,24]$.

$$P_{DG_{min}} \leq P_{DG}(t) \leq P_{DG_{max}}$$ \hspace{1cm} (20)

An environmental concern is one of the main reasons of utilizing hybrid system for power generation. A single unit of DG system even in remote area applications may contribute significant amount of CO$_2$ to atmosphere. It is well known that increasing in CO$_2$ emission will increase the activity of green house gas. Therefore, the gas emission to the atmosphere must be efficiently reduced. In this study, the total amount of CO$_2$ is annually calculated from proposed of hybrid system. This result is then compared to a single operation of DG unit under the same load condition. The amount of CO$_2$ is obtained from combustion process of diesel engine by multiplying the emission function ($E_f$) of CO$_2$ per kWh. In this case, the emission function is set at 0.699 kg/kWh $[1,17]$.

3. Economic Model Based on Annual Cost of System. In this study, the objective function is the annual cost of system (ACS). The ACS model is suitable to find the best benchmark of cost analysis. Annual costs of system covers the annual capital cost (ACC), annual operation maintenance cost (AOM), annual replacement cost (ARC), annual fuel cost of DG (AFC), annual emission cost (AEC) and annual damage cost (ADC). The components to be considered are PV panels, DG, battery banks, inverter $[22]$. ACS is calculated in the following equation:

$$ACS = ACC + AOM + ARC + AFC + AEC + ADC$$ \hspace{1cm} (21)

**Table 2.** Economic parameter considered for system optimization

| Nominal interest rate $i$ (%) $[22]$ | 8.25 |
| Inflation rate $f$ (%) $[22]$ | 8.17 |
| Project Lifetime (years) | 20 |
| PV panel lifetime (years) | 20 |
| Battery banks lifetime (years) | 10 |
| Inverter lifetime (years) | 20 |
| Reliability of PV panels | 0.98 |
| Reliability of inverter | 0.98 |
| Reliability of battery banks | 0.98 |
| Reliability of DG unit | 0.9 |
| Cost of diesel generator (US$/kW) $[28]$ | 600 |
| Cost of PV panel ASE-300 (US$) | 1,830 |
| Cost of PV panel AP-120 (US$) | 630 |
| Cost of PV panel KC-120 (US$) | 685 |
| Cost of battery banks of 5 MWh (US$) $[28]$ | 1,000,000 |
| Cost of inverter (US$/kW) $[28]$ | 138 |
| Fuel cost ($C_f$ US$/l) $[28]$ | 0.75 |
| Emission factor (kg/kWh) $[1,28]$ | 0.699 |
| Emission cost factor (US$/Ton) $[26,28]$ | 30 |
The annual capital cost of each units that does not need replacement during project lifetime such as DG, PV, inverter is calculated as follows:

\[ \text{ACC} = C_{\text{cap}} \cdot \text{CRF}(i, y) \]  

(22)

where \( C_{\text{cap}} \) is the capital cost of each component in US$, \( y \) is the project lifetime in year. CRF is capital recovery factor, a ratio to calculate the present value of a series of equal annual cash flows. This factor is calculated as follows:

\[ \text{CRF} = \frac{i (1 + i)^y}{(1 + i)^y - 1} \]  

(23)

where \( i \) is the annual real interest rate. The annual real interest rate includes the nominal interest and annual inflation rates. This rate is calculated as follows:

\[ i = \frac{(i' - f)}{(1 + f)} \]  

(24)

where \( i' \) is the loan interest and \( f \) is the annual inflation rate. The annual operation and maintenance cost of the system (AOM) as a function of capital cost, reliability of components (\( \lambda \)) and their lifetime can be determine using the following equation [25].

\[ \text{AOM} = C_{\text{cap}}(1 - \lambda)/y \]  

(25)

ARC is the annual cost value for replacing units during the project lifetime. In this study, unit that needs replacement is only battery banks. Other units that do not require replacement due to their lifetimes is the same as the project lifetime. Economically, annual replacement cost is calculated in the following equation [15].

\[ \text{ARC} = C_{\text{rep}} \cdot \text{SFF}(i, y_{\text{rep}}) \]  

(26)

where \( C_{\text{rep}} \) is the replacement cost of battery banks in US$, \( y_{\text{rep}} \) is the lifetime of battery banks in year. In this case the replacement cost of battery banks is similar to its capital cost. SFF is the sinking fund factor, a ratio to calculate the future value of a series of equal annual cash flows. This factor is calculated as follows:

\[ \text{SFF} = \frac{i}{(1 + i)^y - 1} \]  

(27)

AFC of DG unit is estimated based on optimum dispatch of DG system. In this case, the fuel consumption of DG is hourly calculated using equation (19). The AFC may be indicate the CO₂ emission cost. Therefore, this kind of cost component must be reduced in the hybrid system operation in order to minimize the pollutant emission to the atmosphere.

AEC is the annual emission cost to capture the CO₂ emission generated from DG system. The emission cost factor \( (E_{e}) \) CO₂ is around US$30/ton-US$50/ton [26]. From this assumption, the AEC can be expressed using the following equation [27].

\[ \text{AEC} = \sum_{t=1}^{T_{\text{end}}} E_{e} \cdot E_{c} \cdot P_{DG}(t)/1000 \]  

(28)

Finally, to calculate of the expected annual customer damage cost (ADC), the following equation is utilized [28].

\[ \text{ADC} = \frac{TUL_p}{1000} \times [(0.1738 \times (TUL_h)^2) + (0.6083 \times TUL_h) - 0.3001] \]  

(29)
where $TUL_h$ is the total annual unmet load in hour, and $TUL_p$ is the total unmet load in watt. These values can be presented using the following equations.

$$TUL_h = \sum_{t=1}^{T_{end}} LOL_h$$

(30)

$$TUL_p = \sum_{t=1}^{T_{end}} LOL_p$$

(31)

where $LOL_h$ indicates loss of load duration in each hour, the value is 0 if there is no loss of load and 1 if loss of load is occurred. Meanwhile, $LOL_p$ indicates loss of power in each hour. All the economical and the specification data required for the optimization process are listed in Table 2. The economical data is based on the actual condition in hybrid system location. Meanwhile, the lifetime and the reliability coefficient each component are based on the assumption.

![Flowchart of optimization using GA](image-url)
4. Methodology.

4.1. Optimization procedure using GA. The simulation method utilizes genetic algorithm (GA) to determine the optimal sizing of the hybrid system. The concept of GA is different from traditional search and optimization method used to solve the engineering problems. 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. The main objective of the proposed method is to find the optimum configuration number for PV panels, battery banks and capacity of the DG unit. To proceed this study, the annual data of solar insolation and load demand are initially set as the inputs. Then, the numbers of PV panels, battery banks and DG unit are randomly chosen to become the GA chromosomes. Each chromosome consists of three genes in form of \([N_{PV} \mid N_{BAT} \mid P_R]\); where \(N_{PV}\) is the number of PV panels, \(N_{BAT}\) is the number of battery banks and \(P_R\) is the rated capacity of the DG unit.

After setting the initial population, the annual power supply simulation are performed to obtain the annual fuel cost of DG unit and its \(\text{CO}_2\) emission. The simulation of annual power supply are repeated for each chromosome until it reaches the final generation as
defined in the beginning of the simulation process. Each generation of the best chromosome is preserved and compared with the best chromosome obtained from the next generation. The best chromosome in the final generation is considered as the optimum parameter value of the hybrid system. In order to select the chromosomes subjected to the crossover and mutation for processing the next generation population, the roulette wheel method is considered as the selection process. In this simulation, the crossover and mutation probability are assumed as 0.75 and 0.015, respectively. The detailed chart of optimization procedure using GA is provided in Figure 3.

5. Application and Results. GA based matlab m-file code has been developed to determine the optimal sizing of PV-diesel-battery system in East Nusa Tenggara (Indonesia). The daily load profiles are represented by a sequence of powers which is constant over a step time of one hour as shown in Figure 4. In this simulation, the daily load profile is repeated within a year time based simulation. Hence, during one year, there are no differences between the day and the others day. The typical weekly solar insolation in East Nusa Tenggara is shown in Figure 5. For representing the actual meteorological condition, every hour, the insolation levels are fluctuated depend on the actual insolation data in Indonesia. Meanwhile, another data used for the optimization are shown in Table 2. In this simulation, GA parameters consists of 40 populations, and 500 maximum generations. Each chromosome consists of 3 genes which represent the size of PV panels, battery banks and the capacity of diesel generator. The values of crossover and mutation probability are 0.75 and 0.015, respectively. These values are determined by trial and error in order to find the optimal value quickly.

The convergence curves of the GA for 3 different PV panel technologies are depicted in Figure 6. It can be seen that the optimal values can be obtained closed to 300 generations. Hence, 500 iterations can be considered as a fair termination criterion. Table 3 shows the optimization result for the system under study. It can be seen from this table that the optimal size of components obtained from the optimization process for ASE-300 consists of \((47,990 \times 300)W\) of PV panels, \((3 \times 5)MWh\) of battery banks and a DG unit with the capacity of 12 MW. In case of Astropower AP-120, the optimal sizing results in \((139,250 \times 120)W\) of PV panels, \((5 \times 5)MWh\) of battery banks and 12 MW of DG unit. Meanwhile, for Kyocera KC-120 consists of \((123,300 \times 120)W\) of PV panels, \((3 \times 5)MWh\) of battery banks and a DG unit with the capacity is 12 MW. The inverter capacity is also utilized in this system. The inverter size is taken according to the maximum power from battery
banks, PV panels or DG unit. It can be written as follows.

$$\text{Inverter capacity} = \max[C_{B_{\text{max}}}, P_{PV_{\text{max}}}, P_L]$$  \hspace{1cm} (32)

It can be also observed from Table 3 that the size of the inverter is according to the maximum power from PV panel. It means that the maximum power from PV panels is higher than battery banks power or diesel generator capacity. In terms of the ACS values, different results are obtained for three different PV panel technologies, as summarized in Table 3. Basically, introducing a hybrid generating system is able to reduce overall cost system compared with just operates a DG unit-system only. However, the Astropower AP-120 has the minimum ACS value compared to other types of PV panels or to a DG unit-system only. The ACS value obtained from AP-120 is US$20,002,520.53, which represents the cheapest cost of the proposed system. Moreover, the average cost of energy (COE) under the measurement of optimum power through the $I-V$, $P-V$ characteristics is lower than the COE of other PV modules. The important characteristic of AP-120 is the ability to reach the maximum power point close to the rated capacity for a different insolation condition. On the other hand, the ASE-300 and KC-120 fail to reach their maximum power points even they have high standard test condition (STC) output power. The overall COE measurement for all proposed PV modules are provided in Table 4.

The reliability indicator used in this study is based on the unmet load due to the intermittent output of solar power. Simulation results in Table 3 show clearly that all proposed PV panels are able to supply the load demand without any unmet load during simulation time. Under this condition, the value of ADC and the percentage of unmet load as an indicator of unmet power are 0. If this condition is kept maintained, then the proposed hybrid configuration has 100% reliability based on the following equation.

$$\text{Reliability} = \left(1 - \frac{\text{Total Unmet Load}}{\text{Total Annual Load Demand}}\right) \times 100\%$$  \hspace{1cm} (33)

**Figure 7.** Variations in load, PV power, diesel power, and battery energy over the 3 days under the optimal size.
Table 3. Optimization results

<table>
<thead>
<tr>
<th></th>
<th>ASE-300</th>
<th>AP-120</th>
<th>KC-120</th>
<th>Diesel Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum PV power (MW)</td>
<td>14.40</td>
<td>16.71</td>
<td>14.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(47,990×300)</td>
<td>(139,250×120)</td>
<td>(123,300×120)</td>
<td></td>
</tr>
<tr>
<td>Battery banks capacity (MWh)</td>
<td>(3×5MWh)</td>
<td>(5×5MWh)</td>
<td>(3×5MWh)</td>
<td></td>
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<tr>
<td>Diesel generator capacity (MW)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Diesel generator minimum power (%)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
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<tr>
<td>C_{Res} (%)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Reliability (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Inverter capacity (MW)</td>
<td>14.40</td>
<td>16.71</td>
<td>14.80</td>
<td></td>
</tr>
<tr>
<td>Annual overall load energy (MWh/yr)</td>
<td>71,591</td>
<td>71,591</td>
<td>71,591</td>
<td>71,591</td>
</tr>
<tr>
<td>Annual energy deliver by PV (MWh/yr)</td>
<td>22,423.42</td>
<td>25,413.99</td>
<td>22,417.07</td>
<td></td>
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<tr>
<td>Annual energy deliver by DG (MWh/yr)</td>
<td>51,206.41</td>
<td>48,376.55</td>
<td>51,085.39</td>
<td>71,591</td>
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<tr>
<td>Annual energy excess energy (MWh/yr)</td>
<td>924.71</td>
<td>975.86</td>
<td>788.14</td>
<td>0</td>
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<td>Annual unmet load (MWh/yr)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Annual hours of DG operation (hour)</td>
<td>6,066</td>
<td>5,647</td>
<td>6,051</td>
<td>8,760</td>
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<tr>
<td>Annual CO₂ emission generated by DG (Ton/yr)</td>
<td>35,793.28</td>
<td>33,815.21</td>
<td>35,708.69</td>
<td>50,042</td>
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<tr>
<td>ACC (US$)</td>
<td>5,039,346.27</td>
<td>5,151,461.91</td>
<td>4,872,752.66</td>
<td>362,802.14</td>
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<tr>
<td>AOM (US$)</td>
<td>131,808.48</td>
<td>136,033.48</td>
<td>128,502.34</td>
<td>35,999.99</td>
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<tr>
<td>ARC (US$)</td>
<td>299,002.92</td>
<td>498,338.20</td>
<td>299,002.92</td>
<td>0</td>
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<tr>
<td>AFC (US$)</td>
<td>14,041,669.35</td>
<td>13,202,230.51</td>
<td>14,007,980.64</td>
<td>19,843,010.34</td>
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<td>AEC (US$)</td>
<td>1,073,798.60</td>
<td>1,014,456.43</td>
<td>1,071,260.78</td>
<td>1,501,272.91</td>
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<tr>
<td>ADC (US$)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ACS (US$)</td>
<td>20,585,625.62</td>
<td>20,002,520.53</td>
<td>20,379,499.34</td>
<td>21,743,085.38</td>
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Table 4. Power and COE at maximum power point at $T_c = 50^\circ$

<table>
<thead>
<tr>
<th>Insolation (W/m²)</th>
<th>ASE-300 $P_{mp}$ (W)</th>
<th>ASE-300 COE($$/W$$)</th>
<th>AP-120 $P_{mp}$</th>
<th>AP-120 COE($$/W$$)</th>
<th>KC-120 $P_{mp}$</th>
<th>KC-120 COE($$/W$$)</th>
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<tr>
<td>100</td>
<td>23.22</td>
<td>78.80</td>
<td>8.47</td>
<td>74.40</td>
<td>9.09</td>
<td>75.39</td>
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<tr>
<td>200</td>
<td>49.92</td>
<td>36.66</td>
<td>19.04</td>
<td>33.10</td>
<td>19.39</td>
<td>35.33</td>
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<tr>
<td>300</td>
<td>77.10</td>
<td>23.74</td>
<td>29.82</td>
<td>21.12</td>
<td>29.84</td>
<td>22.96</td>
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<tr>
<td>400</td>
<td>104.41</td>
<td>17.55</td>
<td>40.63</td>
<td>15.31</td>
<td>40.32</td>
<td>16.90</td>
</tr>
<tr>
<td>500</td>
<td>131.75</td>
<td>13.89</td>
<td>51.38</td>
<td>12.26</td>
<td>50.77</td>
<td>13.49</td>
</tr>
<tr>
<td>600</td>
<td>159.04</td>
<td>11.51</td>
<td>62.06</td>
<td>10.15</td>
<td>61.19</td>
<td>11.20</td>
</tr>
<tr>
<td>700</td>
<td>186.27</td>
<td>9.82</td>
<td>72.63</td>
<td>8.67</td>
<td>71.55</td>
<td>9.57</td>
</tr>
<tr>
<td>800</td>
<td>213.41</td>
<td>8.58</td>
<td>83.11</td>
<td>7.58</td>
<td>81.85</td>
<td>8.37</td>
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<tr>
<td>900</td>
<td>240.47</td>
<td>7.61</td>
<td>93.49</td>
<td>6.74</td>
<td>92.10</td>
<td>7.44</td>
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<tr>
<td>1000</td>
<td>267.43</td>
<td>6.84</td>
<td>103.77</td>
<td>6.07</td>
<td>102.28</td>
<td>6.70</td>
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<tr>
<td>Average</td>
<td>21.50</td>
<td>19.56</td>
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</table>

Figure 8. Annual energy production each component

5.1. Case study of astropower AP-120. Figure 7 depicts the power flow balance in the proposed system using the Astropower AP-120 PV module, which is considered as the optimal configuration. It can be observed from this figure that DG unit includes the PV system are enough to supply the load demand during 3 days without any unmet loads. With using AP-120 PV and considering the optimum size of other devices in this hybrid system; the DG unit, PV system and battery bank contribute for annual energy production of 62%, 32% and 6%, respectively. This energy proportion is shown in Figure 8. The results imply that a-third of the energy share is obtained from the renewable energy component by means the PV system. Nevertheless, it is difficult to deny that the DG system is still the important backup power for the rural electricity program. Again, the utilization of PV panels and battery bank are satisfied to reduce the operational hours and the portion of power from DG unit, which can be considered as another promising result from this study. As shown in Table 3, the result indicates indirectly that the amount of CO₂ which corresponds with throughput power from DG unit can be minimized from 50,042 Ton/yr to be 33,815.21 Ton/yr. Also, the proposed hybrid system is able to secure the energy supply to the load demand with only operating 12 MW of DG unit. The value of ACS value under this condition is US$ 21,743,085.40. Hence, the overall cost can be cut down about 8%.

Figure 9 shows the relationship between ACC and the reliability as an impact of the rated capacity of DG unit. Increasing the rated capacity of DG unit causes the reliability of the system increases. However, ACC is also raising up despite the reliability has been achieved 100%. It can be noticed here that the reliability of the power system influences the investment cost of the system significantly. In order to obtain high reliability, many power sources or other devices are needed in order to prevent the electricity shortage due
Figure 9. Impact of the rated capacity of diesel generator to the ACC and reliability

Figure 10. Impact of the rated capacity of diesel generator to the AFC and reliability

Figure 11. Sensitivity of the effect of component cost on ACC and ACS

to any component failures. However, the increasing in number or size of generators and components, the investment cost will be considerably high.

The relationship between the fuel cost of DG unit and reliability as an impact of rated capacity of DG unit is shown in Figure 10. The high reliability system can be obtained by
installing sufficient capacity of DG unit. If the capacity of DG unit is small, the maximum power produced by DG is also small. When the electricity shortage occurs due to the stop operation of PV panels and battery banks, the DG unit will be running at full capacity. Based on this reason, the values of AFC and reliability are basically in the same trends. However, after adding higher size of diesel generator, the AFC value will increase and the reliability index will constant. This phenomenon can be simply explained as follows. Increasing size of diesel generator causes the minimum power of diesel generator increases. In fact, the diesel generator must be starting in the range of minimum power and its rated capacity. Therefore, the fuel consumption of diesel always increases whenever its size is increased.

The effect sensitivity of the capital cost components on the ACC and ACS is analyzed and shown in Figure 11. Since the data in this figure as a result of changing the costing function and not from the system design, an increase in 1% of the capital cost of any component will increase the ACC and ACS. The influence of capital cost of PV panels gives the most sensitive impact to the values of ACC and ACS, with sensitivity of ACC=0.86% and ACS=0.23%. The cost sensitivities for the battery banks and inverter are smaller than 0.1%.

6. Future Developments. It is admitted that the proposed method is not perfect to some extents. The method can only suggest the optimum output from each devices based on defined minimum objective functions. Generally speaking, this study is not dealt with very detailed results on each component. For example, the optimum number of PV panel is end up 139,250 of AP-120 PV module. This kind of result is still far from the implementation level because further need the information of the PV array structure; how many modules in series or/and in parallel and what kind of PV configurations as the best option, either series-parallel (SP), bridge-link (BL) and total cross tied (TCT) are highly necessary. And also the capability of the proposed method to handle the partially shaded operation of PV array is necessary to be considered since it is inevitable in the actual operation of PV system. The same output condition is obtained from the number of inverter. This study does not deal with the type configuration of inverter, either central or string based inverter. These kinds of knowledge can be used to proceed the continuous study in the future. More specific study on these topics can be actually performed by simply modify the current algorithm. It means that the method can be adapted for a new task and different target of study without aggressively changing the overall algorithm.

Nevertheless, this method proposes a kind of computational software tools that can be useful for the planning and operation conditions of hybrid generation system. Before designing the hybrid system, it is important to have the information of the overall capacity, the connected devices and the optimum capacities for each device. Also using this tool, different scenarios can be tested through simulation without intervening the running operation of the overall system. In the simple word, the tools will be very helpful for proposing a new hybrid generation system or evaluating the current operation condition.

7. Conclusion. The Genetic Algorithm (GA) method based optimal sizing of hybrid PV-diesel-battery system has been presented in this paper. The optimization method includes the study on three different PV panels technologies; ASE-300 (mc-Si based EFG), Kyocera KC-120 (mc-Si based wafer) and AstroPower AP-120 (thin-film Si). The optimization result indicates that the AP-120 PV module is recommended to be installed in the rural area case; East Nusa Tenggara, Indonesia. This module type basically has lower mismatching losses and lower price than other PV panel technologies. The overall results of this proposed method suggest the optimal sizes of DG unit, PV panels and battery
bank of 12MW, 139,250×120, 5×5MWh, respectively. Under this optimal configuration, the ACS can be reduced to 8%, compared with the annual cost of DG system-only. In addition, the utilization of PV system include the battery storage device can minimize the operational cost of DG unit and reduce the CO₂ emission. The proposed method can be broadly implemented in different cases of the optimization of hybrid PV-diesel-battery system for varieties of load profile and meteorological condition.

REFERENCES


