SIZING OPTIMIZATION AND OPERATIONAL STRATEGY OF HRES (PV-WT) USING DIFFERENTIAL EVOLUTION ALGORITHM

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***Abstract* - The instability of energy resources and corresponding cost of the system are the main two problems for designing the hybrid solar-wind power generation systems. The configuration of the system must have a high reliability on the power supply availability but with a minimum cost. The purpose of this paper is to find the most optimum or balanced configuration between technical reliability and total annual cost for the PV module number, the wind turbine number, and the battery number. The appropriate strategy of load management is needed by adjusting the potential energy resource to the load power demand. Loss of Power Supply Probability (LPSP) is a method to determine the ratio of power generation unavailability by the system configuration which used as technical analysis. Annualized Cost of System (ACS) is a method to determine the total annualized cost of the project lifetime which used as economic analysis. The result from the simulation showed that the Differential Evolution (DE) algorithm can be an alternative method to find the best configuration with a low number of LPSP and ACS. Since DE has a better efficacy and faster time to find global optimum than other algorithms.**

Keywords - LPSP, ACS, Differential Evolution.

I. INTRODUCTION

Nowadays, renewable energy is considered as an alternative energy to replace fossil fuel which starts to rareness. But, the main problem of renewable energy is the availability of the energy really depends on the weather condition that can intermittently change every time.

A system uses only one type of energy resource disposed to has not maximum result to fulfill the load demand. It leads to over-sizing components (unnecessary components) and life-cycle cost [1-4]. Therefore, by combining two or more resource of renewable energy can complement the drawbacks in each individual energy source.

Due to intermittent sunlight intensity and wind speed, the generated energy in each time has a big influence on the system reliability toward the power supply availability. Therefore, a proper power management strategy is needed to determine the size of the components. The reliability level of hybrid renewable energy system can be known with LPSP method. LPSP is a method to determine the ratio of power supply unavailability that is produced by system configuration. LPSP is used as a technical analysis.

Besides a technical analysis, economic analysis is an aspect that is important as well as technical analysis. An economic analysis is used to understand how much cost the configuration system has. ACS becomes an economical analysis method in this paper.

Finding the most optimum system configuration consider both a technical aspect and economical aspect, an optimization method or optimization algorithm is needed in search of the global optimum e.g. genetic algorithm (GA), particle swarm optimization (PSO) algorithm and differential evolution (DE) Algorithm [5-14].

In [5-6] [8], which used genetic algorithms to size optimal PV/Wind/batteries hybrid systems by minimizing LPSP and the ACS. The studied showed genetic algorithms made possible to calculate the number of the components of the optimal configuration which ensure a cover of the load with an acceptance of an LPSP. However, to create the program of GA is not easy. PSO is easy to code but weak in search of global optimum [6-7]. Meanwhile, DE has a high efficacy and be able to find global optimum faster than other algorithms [7-14].

Based on the background above, the propose this paper determine the best configuration system in hybrid renewable energy generation (PV-wind turbine) with optimal LPSP and ACS using DE algorithm.

II. METHODOLOGY

A. Hybrid Component Design

Hybrid renewable energy system consists of PV panel, wind turbine, battery, inverter, battery charge controller and others. The schematic diagram of the system in this paper is shown in Fig. 1.

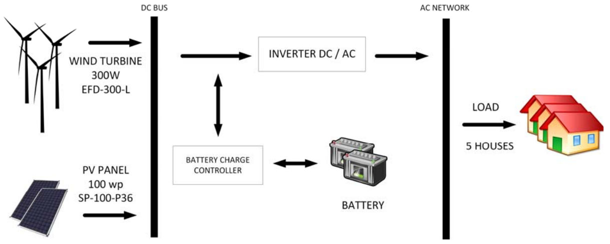

Fig. 1. Schematic Diagram of Hybrid Renewable Energy System

1) PV Array

The power supplied by the panels can be calculated as a function of the solar radiation by using the following formula [4][7]:

$$P_{pv} = P_{N-pv} \times npv \times \frac{G}{G_{ref}} \times \left[1 + K_t\left(T_c - T_{ref}\right)\right] \quad (1)$$

Where, $P_{N\text{-}pv}$ is rated power under reference condition, in this paper uses a 100 wp PV panel, *npv* is PV module number, G is solar irradiation (W/m^2), G_{ref} is solar irradiation under reference condition (1000 W/m^2), T_{ref} is cell temperature under reference condition (25 ^{o}C), K_t is the temperature coefficient of the maximum power (-3.7 x 10-3 (1/^{o}C)). The cell temperature T_c can be calculated as the equation below.

$$T_c = T_{amb} + (0.0256 \times G) \quad (2)$$

where T_{amb} is ambient temperature.

2) Wind Turbine

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The energy that is caught by the blades can be calculated as the equation below [15]:

$$P = \frac{1}{2} . \rho . A . v^3 . Cp \qquad (3)$$

where ρ is air density (kg/m^3), A is intercepting area of the rotor blades (m^2), v is wind speed (m/s), dan Cp is power coefficient of a wind turbine. The theoretical maximum value of the power coefficient is 0,593, also known as Betz's coefficient. But, in the reality, the value of power coefficient is between 0,35-0,45 [15].

Cut-in speed (v_C) is the lowest wind speed (v_R) where the turbine starts to rotate and produces an energy. *Cut-out speed* is the highest wind speed. *Rated output speed* is wind speed between *cut-in speed* and *cut-out speed* where the power output reaches the maximum power and is called *rated power output*. The power output in terms of wind speed can be estimated using the equation below [15]:

$$P_w(v) = \begin{cases} \frac{v^k - v_C{}^k}{v_R{}^k - v_C{}^k} . P_R & v_C \leq v \leq v_R \\ P_R & v_R \leq v \leq v_F \\ 0 & v \leq v_c \text{ dan } v \geq v_F \end{cases} \qquad (4)$$

Where P_R is *rated power* and k is Weibull shape factor. The total of P_w will be multiplied by the number of the wind turbine (*nwt*).

3) Battery

Batteries have a big role in the off-grid hybrid renewable energy system and also have a big share of initial cost [15]. Batteries are used as backup storage when the produced energy is larger than the energy from the load demand.

The storage capacity of the battery (C_B (Ah)) can be calculated according to the following relation [7][16]:

$$C_B = \frac{E_L \times A_D}{V_B \times (DOD)_{max} \times \eta_{inv} \times \eta_B} \qquad (5)$$

where E_L is daily load (Wh). The autonomous days (A_D) is the number of days that the battery will be capable to supply the load if the renewable sources are bad [4][7]. V_B is battery voltage (Volt), DOD$_{max}$ is the maximum depth of discharge, η_{inv} is inverter efficiency dan η_B is battery efficiency.

4) Inverter

The Inverter is one of the important components in the hybrid renewable energy system. An Inverter can convert DC current from PV and wind turbine to become AC current which is needed for the load demand.

An inverter must be able to capable of handling the AC load when it reaches a maximum point. Thus, designing the capacity of the inverter can be assumed 20% higher than maximum AC load from the entire load demand [4].

5) Battery Charge Controller (BCC)

Battery Charge Controller acts as the interface between batteries and individual generator and DC bus. BCC protects the batteries both from overcharging and deep discharging. BCC shall switch off the load when the batteries reach the certain state of discharge. BCC shall switch off the batteries from the DC bus when it is fully charged.

Determining the capacity of BCC according to the battery voltage and the output power from the wind turbine and PV panel. The capacity of BCC is 20% larger than the output power from the wind turbine and PV panel.

B. Meteorological Data

The area which is chosen by this paper at the Third Campus of University of Muhammadiyah Malang (UMM) lies on the geographical coordinates of 7°55'14.8" S and 112°35'55.4" E. The solar irradiation and wind speed data are gotten from NASA Surface Meteorology and Sun Energy, that is https://eosweb.larc.nasa.gov. The solar irradiation data is shown in fig.2 and the wind speed data is shown in fig. 2.

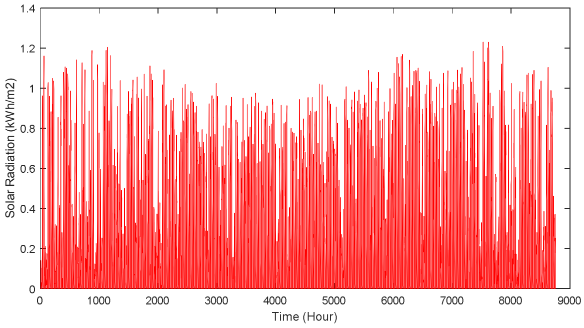

Fig. 2. Solar Irradiation Data during One Year

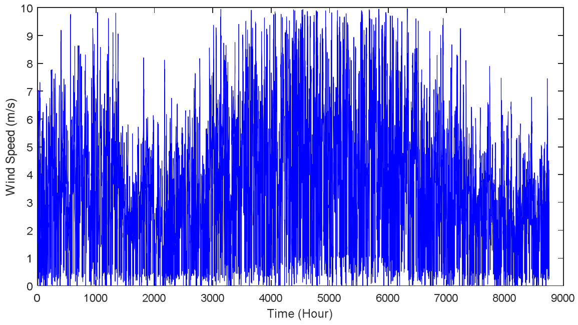

Fig. 3. Wind Speed Data during One Year

The ambient temperature data in that area will be assumed. The highest temperature occurs in the middle of the day and the lowest temperature occurs in the middle of the night. T_{amb} will be assumed constantly during a year. The daily T_{amb} is shown in Fig. 4.

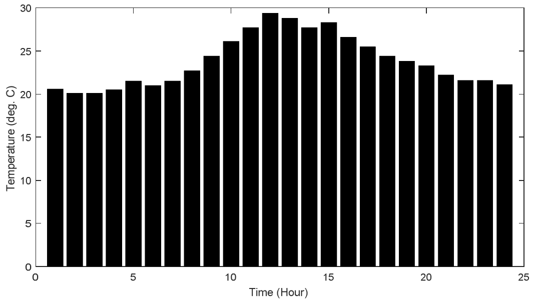

Fig. 4. Daily Ambient Temperature

C. Load Profile

The number and capacity of batteries depending on the load profile. Moreover, the maximum load and the characteristic of consumers affect the reliability of the system such as the sizing of the components and the electricity price [7].

The load profile which is used in this research is rural load characteristic. The average user of electricity is assumed 2 kWh per day, which is sufficient for the basic load household. The number of houses is assumed to be 5. The load profile of the rural area in hourly is shown in Fig. 5.

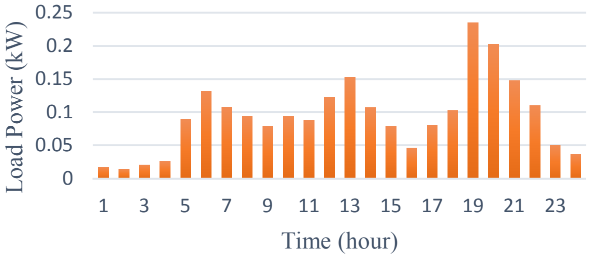

Fig. 5. Load Profile of Rural Area

D. Power Management Strategy

The Uncertainty of renewable energy source makes the power management strategy to become very complex, especially when the source of energy must match the time distributions of load demand. Because of limited renewable energy resource from generated power, the generator's capacity cannot directly increase to match the increasing demand. Therefore, having a power management strategy is very important in the hybrid renewable energy system. The following conditions will be considered to create power management strategy [4][7]:

- Condition 1
  The excess of generated energy from a renewable source which has already fulfilled the load is used to charge the battery.
- Condition 2
  The renewable source is not enough to provide energy for the load. The energy which is stored in the batteries is used to supply (discharging) the load.
- Condition 3
  The renewable source fails to provide energy for the load and the stored energy from the battery is also depleted. In this condition occurs a blackout.

The flowchart from several conditions is shown in Fig. 6.

E. Optimization Criterion

1) Power Reliability Analysis based on LPSP Concept

LPSP is a probability of insufficient power supply when the hybrid generation system and the stored energy from batteries are unable to fulfill the load demand. If LPSP is 0 means that the load will be fully satisfied. On the contrary, if LPSP is 1 means that the load will never be satisfied. The Objective function of LPSP time-0 to time-T can be described as the equation follow [5]:

$$LPSP = \frac{\sum_{t=0}^{T} Power\ failure\ time}{T} = \frac{\sum_{t=0}^{T} \mathrm{Time}(P_{available}(t) < P_{needed}(t))}{T} \quad (6)$$

where T is the total hour. *Power failure time* or blackout time is defined as the time when both the hybrid generation system and the energy from batteries are unable to fulfill the load demand. The power which is needed by the load can be described by the following equation:

$$P_{needed}(t) = \frac{P_{AC\,load}(t)}{\eta_{inverter}} \quad (7)$$

and the power available from the hybrid system can be described by the following equation:

$$P_{available}(t) = P_{pv}(t) + P_{wt}(t) + E_b(t) - E_{bmin} \quad (8)$$

where $P_{pv}(t)$ is the power produced by PV panels time-t. $P_{wt}(t)$ is the power produced by wind turbines time-t. $E_b(t)$ is the stored energy from batteries time-t. E_{bmin} is the minimum energy stored in the batteries.

2) Economic Analysis based on ACS Concept

The economic analysis in this research uses the concept of (ACS). The annualized cost of the system consists of *annualized capital cost* (C_{acap}), *annualized replacement cost* (C_{arep}) and *annualized maintenance cost* (C_{amain}). Table 1, shows the data cost information and lifetime from the component used by the system. ACS can be described by the following equation [5]:

$$ACS = C_{acap} + C_{arep} + C_{amain} \quad (9)$$

a) Annualized capital cost (C_{acap})

C_{acap} consists of the cost of each component and the installation cost. It is calculated using the equation:

$$C_{acap} = C_{cap} \,.\, CRF(i, Y_{proj}) \quad (10)$$

where C_{cap} is the initial capital cost for each component, US Dollar. Y_{proj} is the lifetime of the component, year. CRF is the capital recovery factor. The Equation of CRF is calculated by:

$$CRF(i, Y_{proj}) = \frac{i\,.\,(1+i)^{Y_{proch}}}{(1+i)^{Y_{proch}} - 1} \quad (11)$$

where i is the annual real interest rate. Can be described by the following expression below:

$$i = \frac{i' - f}{1+f} \quad (12)$$

where i' is the nominal interest rate and f is the annual inflation rate.

b) Annualized Replacement Cost

Annualized replacement cost is the annualized value for all replacement cost of the hybrid system during the project lifetime. In this study, the battery is the only component which must be replaced periodically during the lifetime of the project.

$$C_{arep} = C_{rep} \,.\, SFF(i, Y_{rep}) \quad (13)$$

where C_{rep} is the replacement cost (battery), US Dollar. Y_{rep} is the lifetime of the component, year. *SFF* is sinking fund factor. *SFF* can be described by the following equation:

$$SFF(i, Y_{rep}) = \frac{i}{(1+i)^{Y_{rep}} - 1} \quad (14)$$

c) Maintenance Cost

Maintenance cost of the hybrid system is gradually increased in every year because of inflation. Thus, the maintenance cost is given as the equation below:

$$C_{amain}(n) = C_{amain}(1).(1+f)^n \quad (15)$$

where $C_{amain}(n)$ is the maintenance cost for the year-n.

TABLE I. THE SYSTEM COMPONENTS' COST AND LIFETIME

Component	Initial Capital Cost	Replacement Cost	Maintenance Cost (1st year)	Lifetime (Year)	Interest Rate *i'* (%)	Inflation Rate *f* (%)
PV Panel	1000 US$/kW	-	10 US$/kW	20	12	4
Wind Turbine	1000 US$/kW	-	30 US$/kW	20		
Battery	1500 US$/kAh	1500 US$/kAh	50 US$/kW	4		
Inverter	300 US$/kW	-	10 US$/kW	20		
BCC	250 US$/kW	-	7,5 US$/kW	20		

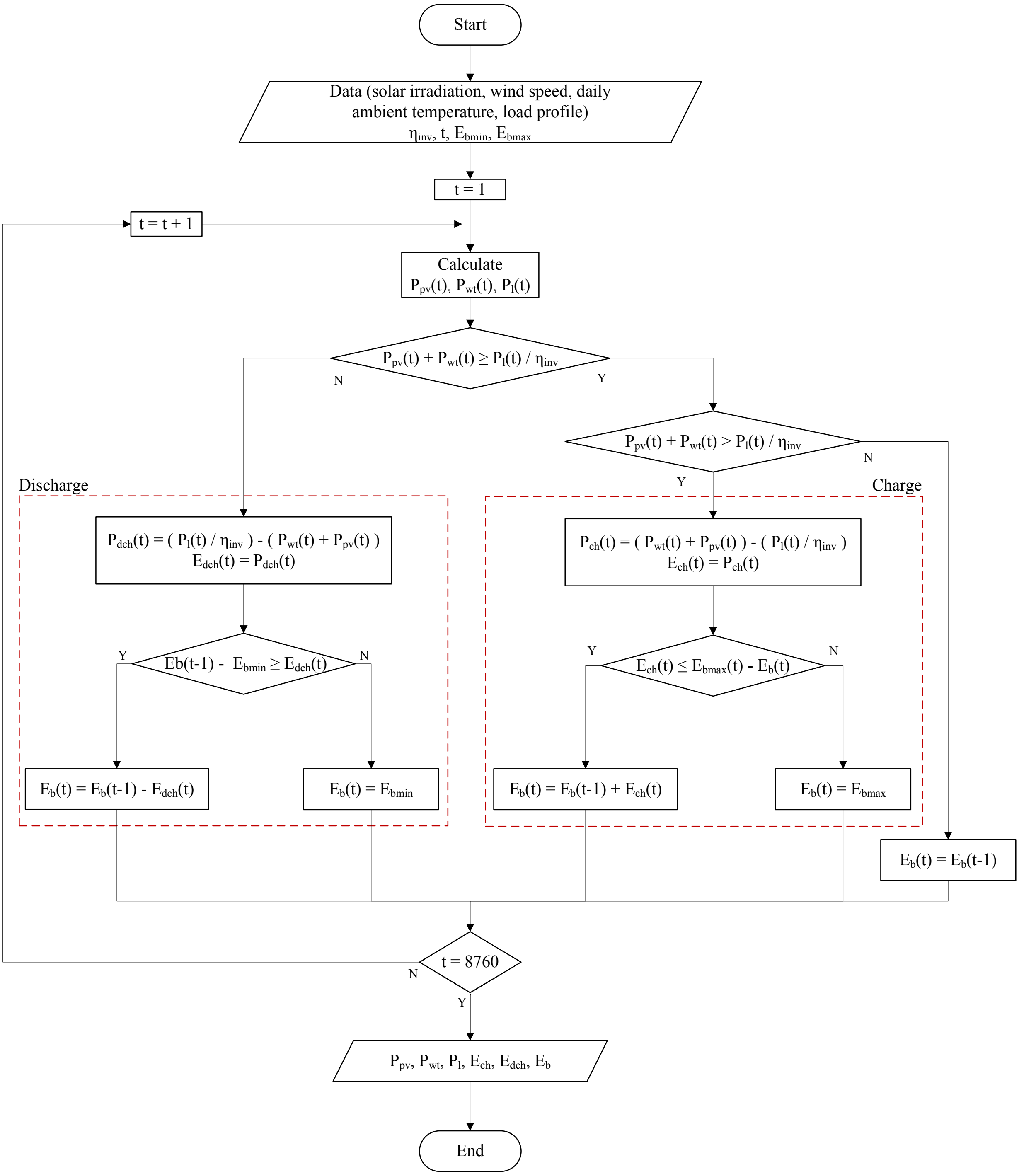

Fig. 6. Flowchart of Power Management Strategy

F. Multi-Objective Optimization

Optimization of the hybrid renewable energy system is categorized as a multi-objective problem. Linear scalarization is one of the most popular approaches because of its simplicity. This method converts the multi-objective problem into a single objective problem. The fitness function can be calculated as [7]:

$$fitness = min\left\{\sum_{i=1}^{k} w_i \frac{f_i(x)}{f_i^{\max}}\right\}, w_i \geq 0 \; \& \; \sum_{i=1}^{k} w_i = 1 \tag{16}$$

where x is the decision variable vector, w_i is the weight of importance of each objective, k is the number of objectives, f is the objective function and $f_i^{\max}$ is the upper bound of i-th objective function.

In this studied, LPSP and ACS are equally important criterions to find the optimum system configuration. Thus, the weight (w_i) for both objectives is 0.5 [7].

G. Optimization using DE Algorithm

DE algorithm was invented by Rainer Storn and Kenneth Price in 1995 [9][10]. This algorithm is categorized as an evolutionary algorithm [14]. Evolutionary algorithm mimics the evolution theory from Darwin where each of the individuals in the population evolves from one generation to the next generation. This mimic process is analogized by the process such as mutation, crossover, selection.

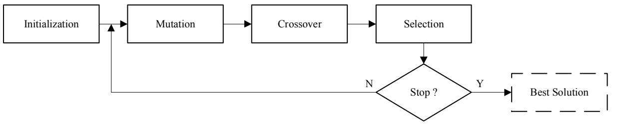

Fig. 7. Block Diagram of DE Algorithm

1) Initialization

The first process in initialization is determining the lower bound U_L and the upper bound U_B in every parameter with initial vector D-dimensions. Next, generate the number randomly in every j from i vector in g-generation or iteration. The initialization process can be calculated as [13][18].

$$X_{j,i,0} = rand_{i,j}\,[0,1].(U_{Bj} - U_{Lj}) + U_{Lj} \tag{17}$$

with $i = \{1,2,3,...,NP\}$ and $j = \{1,2,3,...,D\}$. NP is the number of population. D is the number population in every pupulation. The vector's result from initialization process above is called parent vector.

2) Mutation

Biologically, "mutation" means characteristic's changed of a chromosome. In the context of evolutionary computing paradigm, mutation is also seen as a change of information with a random element. The parent vector will be combined with a mutant vector. A mutant vector $V_{i,g}$ is expressed by the following equation [9][13].

$$V_{i,g} = X_{r1,g} + F.(X_{r2,g} - X_{r3,g}) \tag{18}$$

where $i, r1, r2, r3 \in \{1,2,3,...NP\}$ are random indexes, integer, and different. F is a scale factor that impacts the difference vector $(X_{r2,g} - X_{r3,g})$.

3) Crossover

The purpose of crossover or recombination is to increase the diversity of the population. Recombination creates a trial vector or offspring vector $U_{i,g}$. It is calculated as[17]:

$$U_{i,g} = (U_{1i,g}, U_{2i,g}, ..., U_{ni,g}) \tag{19}$$

where:

$$U_{i,g} = \begin{cases} V_{j,i,g} & if(rand_j(0,1) \leq CR \\ & or\; j = j_{rand} \\ X_{ji,g} & others \\ & j = 1,2,\ldots,n \end{cases} \tag{20}$$

where $rand_j$ (0,1) is the uniform random number with an interval of |0,1| and newly formed in every j. j_{rand} is an integer random number starts from 1 to D and newly formed in every i. CR is a crossover rate.

4) Selection

Selection process chooses the best vector among a parent vector $X_{i,g}$ and the offspring vector $U_{i,g}$ according to their fitness value. For example, if we have a minimization problem the selected vector can be calculated as [9][17]:

$$X_{i,g+1} = \begin{cases} U_{i,g} & if\; f(U_{i,g}) \leq f(X_{i,g}) \\ X_{i,g} & others \end{cases} \tag{21}$$

A vector which has a smaller fitness value will survive and will become a new parent vector in the next generation $X_{i,g+1}$.

DE algorithm is a simulation tool to help in search of the process from various configurations in the hybrid renewable energy system based on LPSP and ACS. DE algorithm will select a configuration which has a lowest-balanced number of LPSP and ACS. However, there is some minor modification for determining the evaluation value that configurations. The value of LPSP is much smaller than ACS. This case makes LPSP has a small effect on the evaluation value. Thus, ACS will be modified into the cost of electricity (US$/kWh). The DE's parameters in this study are shown in Table 2 below. The flowchart of sizing optimization using DE algorithm is shown on Fig.8.

TABLE II. DE'S PARAMETERS

Number of Populations *NP*	10
Dimentions *D*	3
Mutation Scale *F*	0,7
Crossover Rate *CR*	0,7
Max. Iterations	50

In this study, there are four different types of mutation's strategy, those are [13-14]:

- DE/rand/1
  $\mathrm{V}i, = Xr0, + F\,(Xr1, - Xr2,)$
- DE/current-to-rest/1
  $\mathrm{V}i, = Xi, + (Xbest, - Xi,) + Fi\,(Xr1, - Xr2,)$
- DE/best/1
  $\mathrm{V}i, = Xbest, + F\,(Xr1, - Xr2,)$
- DE/best/2
  $\mathrm{V}i, = Xbest, + Fi\,(Xr1, - Xr2, + Xr3, - Xr4,)$

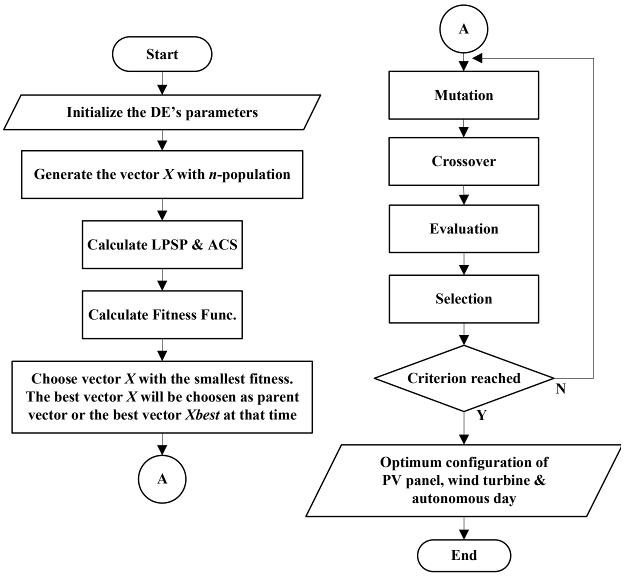

Fig. 8. *Flowchart of Sizing Optimization using DE Algorithm*

III. RESULT

A. The Result of the Entire System

There are two types of simulations do in this study. First, optimization based on one objective only (LPSP and ACS). Second, optimization using DE algorithm. The results are tabulated in Table 3 below:

TABLE III. THE RESULT OF ENTIRE SIMULATIONS

Configuration	PV Panels	Wind Turbine	*Autonomous Day*
Based on LPSP Only	28	7	2
Based on ACS Only	4	10	0
DE Algorithm	22	2	1

Then, all of the configurations are reevaluated to understand how many hours of the blackout will probably occur and how much money is needed to build the configuration. On Table 3, configuration based on LPSP only is considered as Configuration I, configuration based on ACS only is considered as Configuration II and configuration from DE algorithm is considered as Configuration III.

TABLE IV. THE RESULT OF REEVALUATION

Configuration	Blackout Time (Hour/Year)	Total Annualized Cost (US$)
Configuration I	8	1,962.23
Configuration II	4454	725.23
Configuration III	269	1,240.41

From the table above, Configuration I has the fewest blackout time during a year, but it needs a big amount of annualized cost to build the configuration. This configuration is ineffective from the perspective of the economy. Because there is a big possibility of unnecessary operational and lifecycle costs. Meanwhile, Configuration II has a smallest annualized cost. However, the blackout time is exceedingly big. This configuration is not good in term of power supply reliability.

The final decision towards the configurations above, Combination III is the most balanced configuration in terms of power supply reliability as well as economic's perspective. By choosing the Configuration III, it only needs to increase 71% of the annualized cost from Configuration II and the blackout time can be reduced up to 94%. Rather than increasing the annualized cost by 170% just to reduce the blackout time become 99% by choosing the Configuration I.

B. Performance Test from The Algorithm's Result

From Explanation above, the most optimum configuration is the Configuration III or the algorithm's outcome. This configuration has 22 PV panels, 2 wind turbines and 1 autonomous day. Fig. 9 shows a circle diagram of power contribution produced by each component. As can be seen, PV energy is the biggest power contributor for the hybrid system. It means that the solar energy has a big potential amount of energy in the area. Followed by the battery and the least is wind energy. Meanwhile, Fig. 10 shows the contribution of each of the component's initial cost.

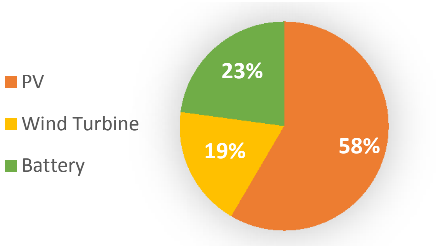

Fig. 9. The Components' Contribution Power

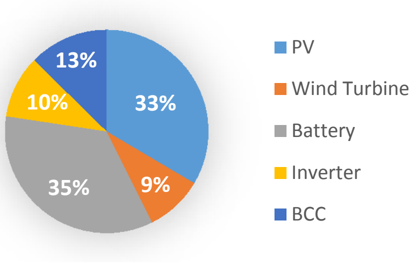

Fig. 10. The Initial Cost Contribution

TABLE V. THE RESULT OF ENTIRE PERFORMANCE TEST OF SYSTEM CONFIGURATION

PV Panel		**Inverter**	
Numbers	22	Initial Cost	655 US$
Initial Cost	2,200 US$	Capacity	2.1818 kW
Produced Energy	4045.597 kWh	**BCC**	
Wind Turbine		Initial Cost	830 US$
Numbers	2	Capacity	3.324 kW
Initial Cost	600 US$	**Annualized Cost**	
Produced Energy	1295.153 kWh	Initial	653.8 US$
Battery		Replacement	334.4 US$
Capacity	1522,3 Ah	Maintenance	252.2 US$
Initial Cost	2,283.5 US$	**Blackout Time**	269 Hours
Used Energy	1581.064 kWh		

C. Comparison

In this study, the performance's result from the DE algorithm is compared with the PSO. The number of populations is ten and the number of iterations is 50 for both algorithms. The results are tabulated in Table 6 below.

TABLE VI. THE COMPARISON'S RESULT BETWEEN DE AND PSO

Algorithm	**Best Configuration (npv nwt ad)**	**Evaluation Value**	**Time (Second)**
DE	22 2 1	0.3707	25.52
PSO	20 3 1	0.3744	25.70

From the table above, DE finishes the simulation slightly faster than PSO with 0.18 second of difference. The DE's evaluation value is also smaller.

Meanwhile, Fig. 11 and. Fig. 13 are shown the convergence graphic of DE and PSO, respectively. DE reaches the convergence point before 15th iterations, while PSO reaches more than 15th iteration. It can be concluded that DE has a better way to find the global optimum than PSO due to DE has a more efficient code. Thus, DE can become an alternative method to find the best configuration for a hybrid renewable energy system.

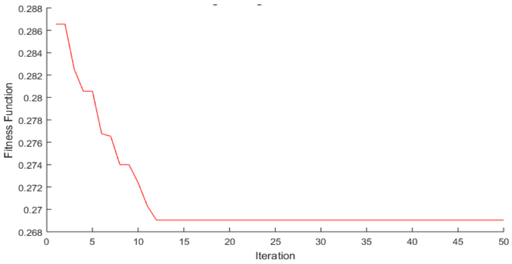

Fig. 11. The DE Convergence Graphic

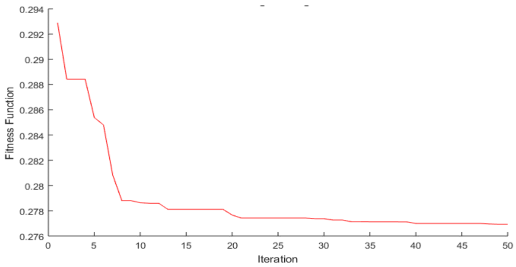

Fig. 12. The PSO Convergence Graphic

IV. CONCLUSION

The result of this study shows that sizing optimization in a hybrid renewable energy system with only one aspect or one objective leads to unbalanced between power supply reliability and lifecycle cost. Therefore with the use of DE algorithm, the sizing optimization can reach a power supply reliability well with a minimum cost. The performance of DE algorithm in sizing optimization is also better than other algorithms, especially PSO. DE can finish the simulation slightly faster and better in search of global optimum than PSO. Thus, DE can be an alternative method to find the best configuration for a hybrid renewable energy system.

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