# Optimal Operational Strategy for Hybrid Renewable Energy System Using Genetic Algorithms

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*Abstract:* - Off-grid settlements require efficient, reliable and cost-effective renewable energy as alternative to the power supplied by diesel generator. Techno-economic analysis is required to find the optimum renewable energy system in the long run. This paper reviews the application of genetic algorithms in optimization of hybrid system consisting of pico hydro system, solar photovoltaic modules, diesel generator and battery sets. It is intended to maximize the use of renewable system while limiting the use of diesel generator. Daily load demand is assumed constant for derivation of annual load. Power derived from the hybrid should be able to meet the demand. Local weather data is used and analyzed to assess the technical and economic viability of utilizing the hybrid system. Optimization of the system will be based on the component sizing and the operational strategy. Genetic algorithms programming is used to evaluate both conditions in minimizing the total net present cost for optimum configuration. Manufacturer data for the hybrid components is used in calculation of sizing to represent actual power derivation. Several operation strategies will be considered while forming the vectors for optimum strategy. Random selection of sizing and strategy is used to initiate the solution for the problem which will have the lowest total net present cost. Sensitivity analysis is also performed to optimize the system at different conditions.

*Key-Words:* - Genetic algorithms; Operation strategy; Hybrid system; Renewable energy, Optimization

## 1 Introduction

Power supply to off-grid location is usually supplied by generator using diesel or petrol. It is often only available at night and for certain number of hours. Applications of renewable energy at this location are through solar energy via photovoltaic (PV) panels, wind turbines and small hydro turbines. Initially, the system is a single source system. However a single source renewable usually tends to be oversized to accommodate load demand [1]. It leads to high wear and tear, thus increasing operating and life cycle costs. A combination of one or more resources of renewable energy such as solar, wind, hydropower and biomass with other technologies such as batteries and generator, defined as hybrid renewable is a better option [2]. Hybrid system can complement each other and component capacities are better utilized, improve load factors of generators and better exploitation of renewable leads to saving on maintenance and replacement cost. However the hybrid initial capital cost is high thus the needs for long-lasting, reliable and cost-effective system [3]. While designing a hybrid system it is important to look into correct combination of components selection and sizing together with the operation strategy [4].

Kellog *et al.* [5] studied a simple numerical algorithms for unit sizing and cost analysis of a stand-alone wind, solar PV hybrid system. Borrowy and Salameh [6] reported an algorithmss based on energy concept to optimally sized solar PV array in a PV/wind hybrid system. Museli *et al.* [7] has suggested that optimal configuration for hybrid systems should be determined by minimizing the kWh cost. Optimally sizing the components is not enough to get the maximum performance of the hybrid as the problems getting complicated when power supplied by the renewable unable to meet the load demand. The use of battery for storage and power supply and the question of when to start the back-up generator require proper algorithms for operation strategy.

Barley *et al.* [8] has set a guideline about main operation strategies, namely frugal discharge, load-following, state of charge (SOC) set point and the full power strategy. However, the SOC set point procedure is user-defined and it is not optimized. Frugal discharge is based on critical load, where if the net load is higher than the critical load, it is economical to run the generator set. In load-following strategy, batteries are not charged by diesel generator. The diesel operating point is set to match the net load. SOC setpoint Strategy is used to charge batteries at user defined point for the diesel generator to be started. The generator operated at full-power with the excess power is used to charge the batteries without dumping power. Otherwise the generator is set to operate at at maximum point without dumping. Full power strategy is when generator to operate at full power for a minimum time at a low setpoint.

Seeling-Hochmuth [9] had investigated the use of genetic algorithms [10] to solve optimization problem with various constraints. He further suggested an optimization concept combining system sizing and operation control [11]. Koutroulis *et al.* [12] used genetic algorithms to minimize the total system cost based on to load energy requirements. Dufo-Lopez and Bernal-Augustine [13] developed a program based on genetic algorithms, called HOGA, for optimizing the configuration of a PV–diesel system with AC loads and the control strategy. Ashok [14] developed a reliable system operation model based on Hybrid Optimization Model for Electric Renewable (HOMRER) [15] to find an optimal hybrid system among different renewable energy combinations while minimizing the total life cycle cost. Dufo-Lopez and Bernal-Augustine later improved HOGA program to include fuel cell and hydrogen in the hybrid system [16]. Yet the control strategies in HOGA are the same as the ones used in HOMER.

This paper will review a methodology of finding optimum component sizing and operational strategy using genetic algorithms programming. It is focused on maximizing the renewal energy components while trying minimizing the use of generator to provide for the load demand. Several operation strategies will be used in derivation strategy vectors. The objective of the program is to meet the load demand using an optimum operation strategy while maintaining minimum component size, thus minimizing the total operation cost.

## 2 Methodology

The proposed hybrid renewable is consists of a pico hydro turbine, wind turbine and solar photovoltaic (PV) panels. Generator (diesel or petrol-based) with battery and inverter are added as part of back-up and storage system. This proposed system is shown in Fig. 1. The study involves a theoretical load demands as shown in Table 1 and Fig. 2. The load is assumed constant all year. The renewable energy supplied is based on hourly basis as the fluctuation of parameters involved in wind turbine and solar PV.

### 2.1 Mathematical modelling

The following equations, used in the algorithms, are based on equations used by HOMER [15] and Ashok [14] to derive the power supplied by renewable, battery charging and discharging and the calculation of the total net present cost (TNPC).

The hydro power:

$$P_h = \eta_h * \rho_{water} * g * H_{net} * Q \tag{1}$$

The wind power:

$$P_w = \eta_w * \eta_g * 0.5 * \rho_a * C_p * A * V_r^3 \tag{2}$$

The PV power:

$$P_{pv} = \eta_{pv} * N_{pvp} * N_{pvs} * V_{pv} * I_{pv} \tag{3}$$

Total renewable power:

$$P(t) = \sum_{h=1}^{n_h} P_h + \sum_{w=1}^{n_w} P_w + \sum_{s=1}^{n_s} P_s \tag{4}$$

Battery discharging:

$$P_b(t) = P_b(t-1) * (1-\sigma) - [P_{bh}(t)/\eta_{bi} - P_{bl}(t)] \tag{5}$$

Battery charging:

$$P_b(t) = P_b(t-1) * (1-\sigma) + [P_{bh}(t) - P_{bl}(t)/\eta_{bi}] * \eta_{bb} \tag{6}$$

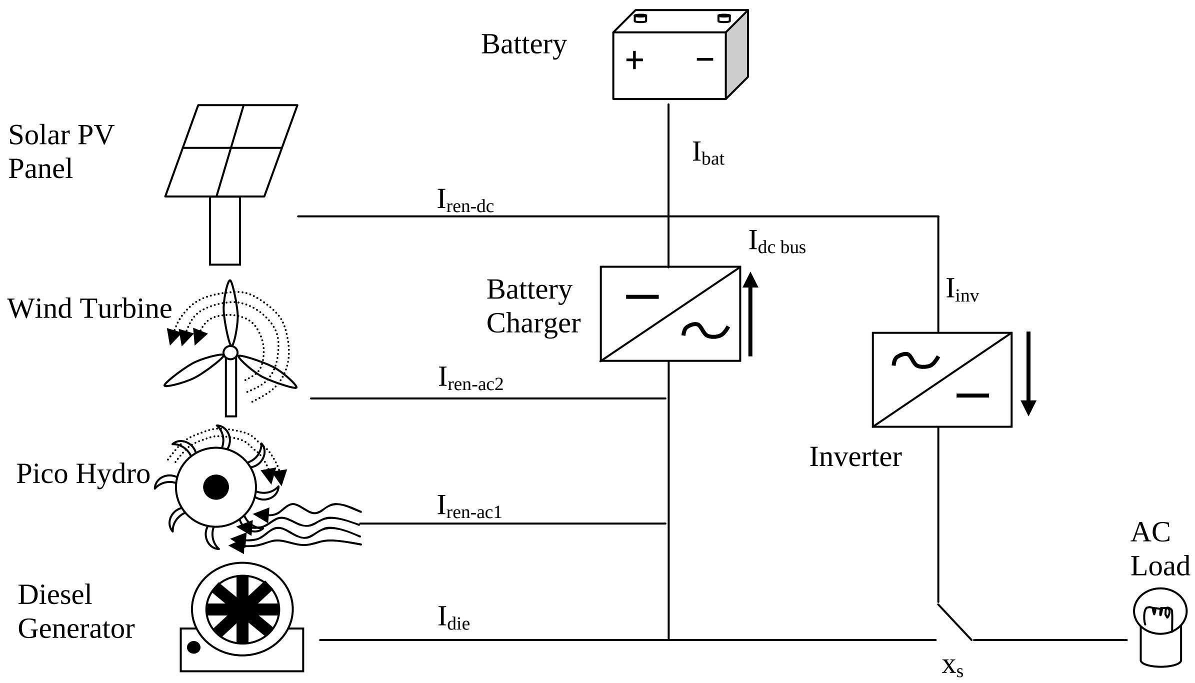


Fig. 1. Renewable Energy Hybrid System

Table 1 Daily load demands

| Time | Load | | | | | |
|---|---|---|---|---|---|---|
| | C Fan | P Light | PC | A Cond | R Light | Total/Hr |
| 12 | | 1000 | | | | 1000 |
| 01 | | 1000 | | | | 1000 |
| 02 | | 1000 | | | | 1000 |
| 03 | | 1000 | | | | 1000 |
| 04 | | 1000 | | | | 1000 |
| 05 | | 1000 | | | | 1000 |
| 06 | | 1000 | | | | 1000 |
| 07 | | | | | | 0 |
| 08 | 100 | | | | 50 | 150 |
| 09 | 100 | | | | 50 | 150 |
| 10 | | | | 750 | 50 | 800 |
| 11 | | | 115 | 750 | 50 | 915 |
| 12 | | | 115 | 750 | 50 | 915 |
| 1 | | | | 750 | 50 | 800 |
| 2 | | | | 750 | 50 | 800 |
| 3 | 100 | | | | 50 | 150 |
| 4 | 100 | | | | 50 | 150 |
| 5 | | | | | | 0 |
| 6 | | | | | | 0 |
| 7 | | | | | | 0 |
| 8 | | 1000 | | | | 1000 |
| 9 | | 1000 | | | | 1000 |
| 10 | | 1000 | | | | 1000 |
| 11 | | 1000 | | | | 1000 |
| Total | 400 | 11000 | 230 | 3750 | 450 | 15830 |

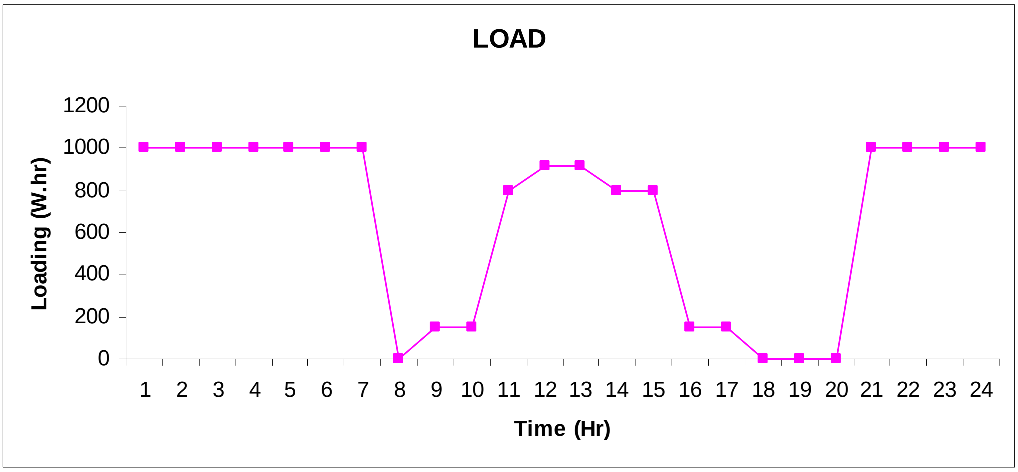


Fig. 2 Daily load demands

The annualized cost of a component includes annualized capital cost, annualized replacement cost, annual O&M cost and annual fuel cost (generator). Operation cost is calculated hourly on daily basis.

$$\sum_{h=1}^{N_h}(C_h + C_{oh} + C_{reph}) + \sum_{w=1}^{N_w}(C_w + C_{ow} + C_{repw}) + \sum_{s=1}^{N_s}(C_s + C_{os} + C_{reps}) + \sum_{g=1}^{N_g}(C_g + C_{og} + C_{repg} + C_{fg}) + \sum_{b=1}^{N_b}(C_b + C_{ob} + C_{repb}) \quad (7)$$

Example for operating cost:

$$C_{op} = \sum_{1}^{365}\{\sum_{1}^{24}[C_{oh}(t)]\} \quad (8)$$

Net present cost (NPC) for each component is derived using:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF} \quad (9)$$

where

$$CRF = \frac{i*(1+i)^N}{(1+i)^N - 1} \quad (10)$$

Annualized capital cost is calculated using:

$$C_{acap} = C_{cap} * CRF_{proj} \quad (11)$$

Replacement cost is formulated based on its salvage value at the end of the project, if any, and the cost of replacement itself.

$$C_{arep} = C_{rep} * f_{rep} * SFF_{comp} - S * SFF_{proj} \quad (12)$$

$$f_{arep} = \begin{cases} CRF_{proj} / CRF_{rep} & R_{rep} > 0 \\ 0 & R_{rep} = 0 \end{cases} \quad (13)$$

$$R_{rep} = R_{comp} * INT\left(\frac{R_{proj}}{R_{comp}}\right) \quad (14)$$

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \quad (15)$$

$$S = C_{rep} * \frac{R_{rem}}{R_{comp}} \quad (16)$$

$$SFF = \frac{i}{(1+i)^N} \quad (17)$$

## 2.2 Genetic Algorithms

Fig. 3 shows the flowchart of genetic algorithms programming. The algorithms first randomly select a set of vector for sizing of the hybrid system. The power derived from these components is compared to the daily load demands. If the power generated by the system able to meet the load demands then TNPC can be calculated.

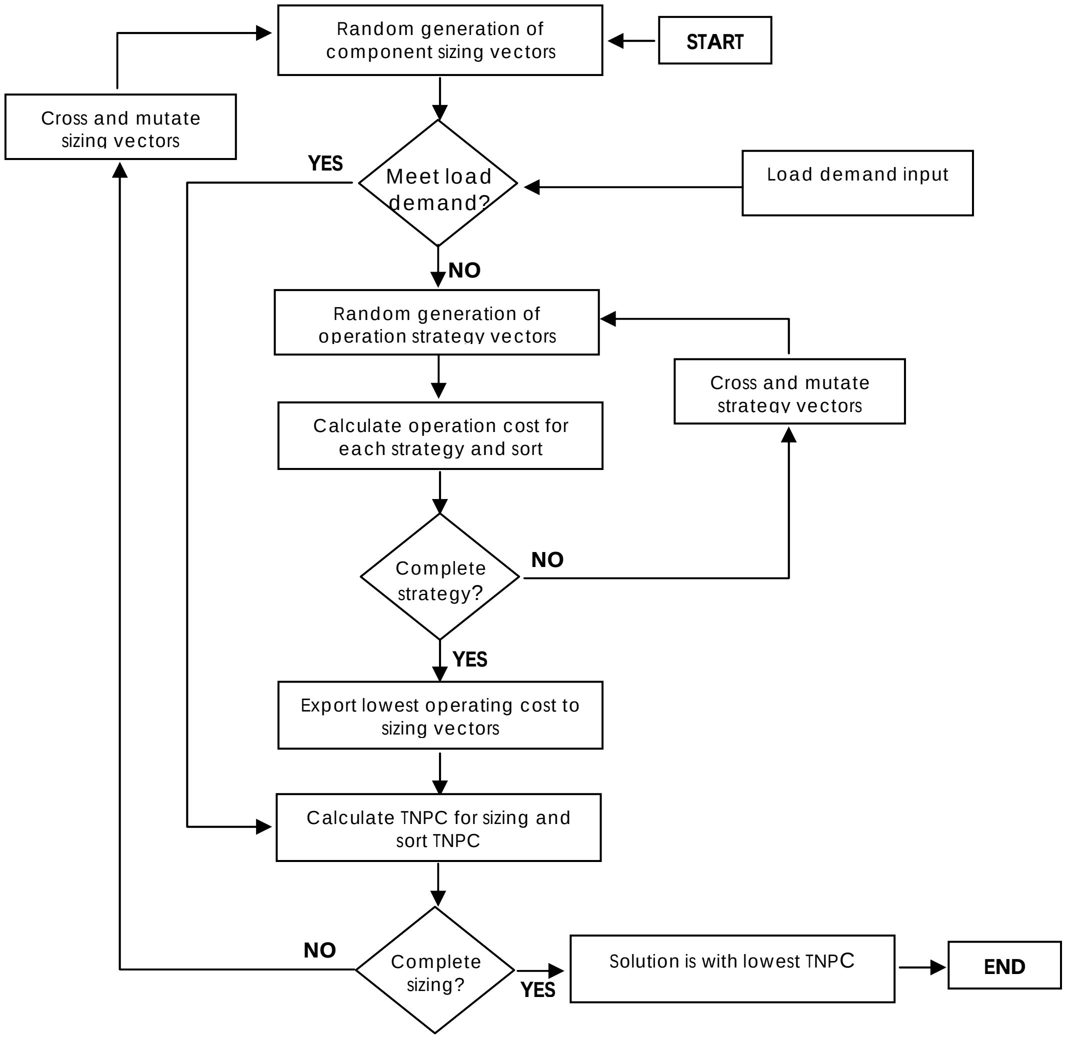


Fig. 3 Flowchart of genetic algorithms

If power derived unable to meet the load demands then the operation strategy takes place. The operation strategy vector is randomly selected. Cost for each strategy is calculated. The lowest operation strategy cost will be added to the sizing for the TNPC for each sizing. Another sizing of component is randomly selected for the next calculation. The solution of the problem will be the one with the lowest cost of TNPC.

Dufo-Lopez and Bernal-Augustin [13] mentioned that for a combination of components and strategies variables of 38 million would require the calculation time of approximately 15 hours to evaluate each combination. By using genetic algorithms only a certain number of combinations are used as in their case only 250000 combinations are evaluated. They have proved that 15 hours of calculation can be reduced to mere 350 seconds based on a computer system which can perform 700 evaluations per second.

## 2.3 Location of Hybrid System

The site of the hybrid system is located in Bandar Baru Bangi, Malaysia at the Universiti Kebangsaan Malaysia campus. The system is set-up at the pond near to the Faculty of Engineering.

### 2.3.1 Pico hydro turbine

The initial capital cost for pico hydro turbine is RM10500 which include some civil works. Its replacement is priced at RM10000. The turbine is estimated to last the project lifetime at 25 years. The water flow rate is assumed to be constant all year at 24 L/s. The turbine has a nominal power of 1 kW and average output of 0.959 kW.

### 2.3.2 Diesel generator

The AC generator has a capacity of 1 kW. Its initial capital cost is RM8500 and its replacement costs RM8000. The operation and maintenance is RM0.10 per hour. The lifetime of the generator is estimated at 15000 operating hours. Diesel is priced at RM1.98 per liter.

#### 2.3.3 Battery and Inverter
The valve regulated lead acid battery is rate at 2 V and has a capacity 500 Ah. Twelve batteries initially cost RM20500. The replacement batteries will cost another RM20000. The operation and maintenance cost add further RM25 to the total cost annually.

#### 2.3.4 Solar PV panels
There are six PV panels with each has a capacity of 75 Watt. The initial cost of the panels is RM11750 and the replacement for each panel is RM1875. The lifetime of the panels will last the project. The monthly average daily solar radiation in Bandar Baru Bangi is between 3000 - 5000 Whr/m$^2$, with the monthly average daily sunshine duration ranging from 4 hr to 8 hr [17] as shown in Table 2. The sunshine hour has been taken from the same duration as that for the global solar radiation. These values are important for sizing of solar energy systems.

Table 2 Average daily global solar radiation and sunshine hours at Bangi

| Month | Solar Radiation | Sunshine Hours |
|---|---|---|
| January | 3657.6 | 4.59 |
| February | 4441.0 | 6.14 |
| March | 4124.7 | 5.13 |
| April | 4464.7 | 6.11 |
| May | 4401.0 | 5.87 |
| June | 4299.7 | 6.09 |
| July | 4656.5 | 6.04 |
| August | 4024.6 | 5.52 |
| September | 3994.3 | 4.77 |
| October | 3943.0 | 4.52 |
| November | 3409.8 | 4.23 |
| December | 3516.5 | 4.82 |

#### 2.3.5 Wind turbine
The wind turbine has a capacity of 0.6kW. Its initial cost is RM20500 and its replacement at RM20000. Annual operation and maintenance cost is RM500. Its hub and anemometer is located at 15 meter height. The turbine is estimated to last the project. The average wind speed for Bandar Baru Bangi is between 1 and 3 m/s as shown in Table 3.

Table 3 Monthly wind speed at Bangi

| Month | Wind Speed (m/s) |
|---|---|
| January | 2.948 |
| February | 2.082 |
| March | 2.287 |
| April | 1.857 |
| May | 1.571 |
| June | 1.687 |
| July | 1.487 |
| August | 2.035 |
| September | 1.533 |
| October | 1.829 |
| November | 1.800 |
| December | 1.938 |

#### 2.3.6 Economics and Constraints
The calculations take into account the annual interest rate at 4% and the project lifetime is 25 years. The operating reserve is as hourly load and set at 10% of the load demands.

### 2.4 Results from HOMER
It is important that the derivation from the genetic algorithms can be compared to other optimization method. Since parts the mathematical modelling is driven by HOMER the results from optimization by the software can be used as comparison and point of reference. Selected data will be used to derive the optimization. This is due to the method of calculation by HOMER would require it to calculate every single combination of components and operation strategy.

## 3 Results & Discussions
The optimization using genetic algorithms derived the following results as shown in Table 4. Pico hydro powered system with battery and inverter have the lowest TNPC at RM63,887 and COE of RM0.708 per kWh. However, the COE of this optimum combination is still three times as much if compared with the current electricity tariff set by government at RM0.236 per kWh. The pico hydro turbine, which is rated at 1 kW, is calculated as having an average output of 0.959 kW.

Table 4 Optimization results for component sizing

| PV (kW) | Wind | Hydro (kW) | Diesel (kW) | Battery | Inverter (kW) | In Cap (RM) | Tot NPC (RM) | COE (RM/kWh) |
|---|---|---|---|---|---|---|---|---|
| | | 1.001 | | 12 | 1 | 51,000 | 63,887 | 0.708 |
| 0.075 | | 1.001 | | 12 | 1 | 53,563 | 66,449 | 0.736 |
| | | 1.001 | 1 | 12 | 1 | 59,500 | 69,461 | 0.770 |
| 0.075 | | 1.001 | 1 | 12 | 1 | 62,063 | 72,023 | 0.798 |
| | | 1.001 | 1 | | | 19,000 | 84,050 | 0.931 |
| | 1 | 1.001 | | 12 | 1 | 71,500 | 92,198 | 1.021 |
| 0.075 | 1 | 1.001 | | 12 | 1 | 74,063 | 94,760 | 1.050 |
| | 1 | 1.001 | 1 | 12 | 1 | 80,000 | 97,772 | 1.083 |
| | 1 | 1.001 | 1 | | 1 | 39,500 | 99,712 | 1.105 |
| 0.075 | 1 | 1.001 | 1 | 12 | 1 | 82,563 | 100,334 | 1.112 |

Table 5 Total annualized cost

| Component | Initial Capital (RM) | Annualized Capital (RM/yr) | Annualized Replacement (RM/yr) | Annual O&M (RM/yr) | Annual Fuel (RM/yr) | Total Annualized (RM/yr) |
|---|---|---|---|---|---|---|
| Hydro | 10500 | 673 | 0 | 0 | 0 | 673 |
| Battery | 20500 | 1312 | 224 | 25 | 0 | 1561 |
| Inverter | 20000 | 1280 | 551 | 25 | 0 | 1856 |
| Total | 51000 | 3265 | 775 | 50 | 0 | 4090 |

Table 6 Optimization results for component sizing with sensitivity: PV panels

| PV Price (RM/kW) | PV (KW) | Hydro (kW) | Battery | Inverter (kW) | In Cap (RM) | Tot NPC (RM) | COE (RM/kWh) |
|---|---|---|---|---|---|---|---|
| 33333 | 0.075 | 1.001 | 12 | 1 | 53,583 | 66,470 | 0.736 |
| 25000 | 0.075 | 1.001 | 12 | 1 | 52,938 | 65,824 | 0.729 |
| 16667 | 0.075 | 1.001 | 12 | 1 | 52,313 | 65,199 | 0.722 |
| 8333 | 0.075 | 1.001 | 12 | 1 | 51,688 | 64,574 | 0.715 |

This factor together with the effect of 10% load reservation and efficiency of the turbine are the reasons why the turbine requires additional support to provide for the peak load at 1 kW. The same can be applied to power provided by diesel generator. The annual pico hydro turbine production is 8405 kWh while the total load served is 5778 kWh. The excess electricity produced is about 33%. The total seemed enough except for its failure to provide the necessary power at peak time which requires the support of battery and inverter.

Table 5 shows the annualized cost of the pico hydro powered components. Pico hydro contributes 17%, battery costs about 38% and inverter the largest at 45% of the total annual cost of RM4090. Pico hydro is assumed to last the lifetime of the project while the battery and inverter needs to be replaced after certain number of hours of discharged. The cost of battery and inverter plays important part in determining the TNPC and COE. Except for three combinations, the system requires battery and inverter as part of the hybrid. High annualized cost of battery (RM1561) and inverter (Rm1856) contributed to high TNPC and COE. This is clearly defined in combination 10 where all components are involved as shown in Fig. 4. The percentage of total annualized cost varies between 54% (combination 10) and 84% (combination 1).

Table 6 shows the optimization of the hybrid system by changing the capital and replacement cost of PV panels as its prices shows a downward trend. Due to rapid technology advances in PV it is assumed that the price of panels will decrease in the future. Several prices of the panels are checked against the COE. Based on the results COE does not decrease as much as predicted. Small decrease of COE is due to the cost incurred by battery and inverter. Tables 7 and 8 show the results of sensitivity of the battery and inverter price and the effect of diesel price changes respectively.

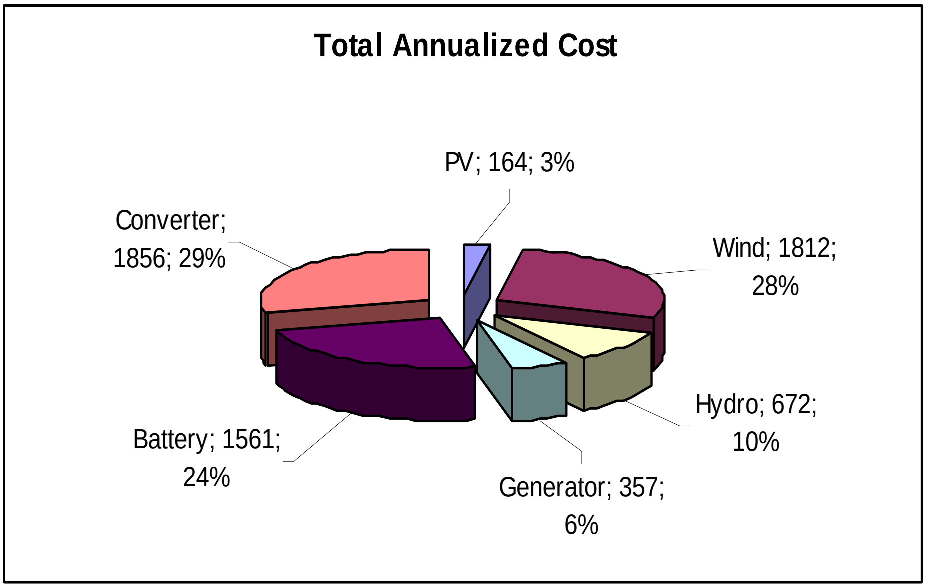


Fig. 4 Total annualized cost

Table 7 Optimization results for component sizing with sensitivity: battery and inverter

| Battery & Inverter Price (RM) | Hydro (kW) | Battery | Inverter (kW) | In Cap (RM) | Tot NPC (RM) | COE (RM/kWh) |
|---|---|---|---|---|---|---|
| 20000 | 1.001 | 12 | 1 | 51,000 | 63,887 | 0.708 |
| 15000 | 1.001 | 12 | 1 | 41,000 | 50,860 | 0.563 |
| 10000 | 1.001 | 12 | 1 | 31,000 | 37,834 | 0.419 |
| 5000 | 1.001 | 12 | 1 | 21,000 | 24,807 | 0.275 |

Table 8 Optimization results for component sizing with sensitivity: diesel generator

| Diesel Price (RM) | Generator (kW) | Battery | Inverter (kW) | In Cap (RM) | Tot NPC (RM) | COE (RM/kWh) |
|---|---|---|---|---|---|---|
| 1.98 | 1 | 12 | 1 | 49,000 | 175,780 | 1.947 |
| 2.40 | 1 | 12 | 1 | 49,000 | 188,528 | 2.089 |
| 2.60 | 1 | 12 | 1 | 49,000 | 194,598 | 2.156 |
| 2.80 | 1 | 12 | 1 | 49,000 | 200,026 | 2.227 |

In combination 1 where both battery and inverter carries as much as 84% of total annualized cost, the reduction of battery and inverter price would have a great effect on TNPC and COE. Reductions of 25%, 50% and 75% of battery and inverter prices would give a reduction of 20%, 40% and 43% of COE.

As global price of oil increase the government of Malaysia has indicated that it can no longer provide the oil subsidy. It is important to note that if the true diesel price is used in the calculation the COE is going up by RM0.14 per kWh. If its price is raised to RM2.80 per liter the COE is increased by 14%. At RM2.80 the pecking order of the combination is also down one spot from fifth to sixth.

If the efficiency of the pico hydro is increased so that the nominal output is at 1.005 kW and operation reserve is set at 0 then the optimum combination is consist of pico hydro only with COE of RM0.116/kWh (Table 9), which is lower than the government tariff. Other combination with pico hydro is somehow misleading as the turbine managed to provide for the load demands on its own. Without the operation reserve diesel generator can also supply the load demand independently but at much higher cost, COE of RM1.561/kWh. The generator used 2083 liter of diesel and operating for 7,300 hours annually. That is almost half of its lifetime operating hours.

Table 9 Optimization with modified parameters

| PV (kW) | Wind | Hydro (kW) | Diesel (kW) | Battery | Inverter (kW) | In Cap (RM) | Tot NPC (RM) | COE (RM/kWh) |
|---|---|---|---|---|---|---|---|---|
| | | 1.048 | | | | 10,500 | 10,500 | 0.116 |
| | | | 1 | | | 8,500 | 140,922 | 1.561 |
| | 1 | | 1 | | | 29,000 | 158,815 | 1.759 |
| 0.075 | | | 1 | | 1 | 31,063 | 172,045 | 1.906 |
| | | | 1 | 12 | 1 | 49,000 | 175,860 | 1.948 |
| 0.075 | | | 1 | 12 | 1 | 51,563 | 176,860 | 1.959 |
| 0.075 | 1 | | 1 | | 1 | 51,563 | 189,317 | 2.097 |
| | 1 | | 1 | 12 | 1 | 69,500 | 194,380 | 2.154 |
| 0.075 | 1 | | 1 | 12 | 1 | 72,063 | 195,481 | 2.166 |

Optimization calculations by HOMER produced the same the results as discussed above. This is due to the mathematical modelling used is similar to the one used by HOMER. The results verify the findings using genetic algorithms. This initial result will lead to the addition of other data for each of the component of the hybrid. At the moment the study is focusing on the confirmation of the results. The time taken in getting the results is identical by both genetic algorithms and HOMER. However, using HOMER will be a problem when calculation of different types of component needs to be calculated simultaneously. First, HOMER needs to calculate every single combination of sizing and operation strategy. Second, the data for each variation of component needs to be entered manually and run separately. As data involved will be large and sensitivity analysis need to be done for selected component it is unlikely HOMER can provide fast and reliable solution of the optimization process.

In all cases involved in previous calculations the operation strategy selected is cycle charging process. Two other operation strategy of load following and setpoint state of charge at 80% are being considered. Since this initial finding lacking input constraints a simple strategy such cycle charging should be enough to guide the selection and distribution of power.

## 4 Conclusion

The preliminary results shows that the algorithms manage to optimize the sizing and the operation strategy for a simple daily load with a set of manufacturer data. The solution will become more interesting when data from other manufacturers are added and daily load are varied to represent actual demands. This will create a meaningful search for the optimum sizing and operation strategy as large data with different pricing and power related parameter for each component.

It is shown that the use of pico hydro in the renewable energy set-up is an important sizing determination. The main advantage is the turbine can operate 24 hours provide enough flowing water into the gathering chamber. Multiple turbines could be used simultaneously to meet higher power demand. They could also be used alternately to provide continuous power while one undergoing servicing. The price of the pico hydro turbine is much less compared to other renewable.

Meanwhile, wind is not consistent at this part of region. The average monthly data could be misinterpreted in the calculation. It is best to derive the optimum combination based on daily data.

Solar energy though aplenty at this location is only available during daytime. In order to provide electricity at night solar panels would require storage system. Adding battery and inverter, however, will add to the cost. In most cases the cost of battery and inverter contribute at least half of the total cost.

The main objective of the exercise is maximizing the power output while minimizing the total cost. In this exercise load demands are met with combination of renewable. However there is plenty of excess energy involved which contributed to the high COE.

Future works include adding constraints such as renewable fraction and maximum generator usage, sensitivity optimization calculations using petrol for generator and varied daily load demands. Another are worth looking to is to find ways of minimizing the excess energy which could leads to reducing the COE.

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*Acronym:*

| **Notation** | **Explanation** |
|---|---|
| $P_w$ | Hydro turbinepower output |
| $\eta_h$ | Efficiency of hydro turbine |
| $\rho_{water}$ | Density of water |
| $g$ | Gravitational acceleration |
| $H_{net}$ | Effective head |
| $Q$ | Flowrate |
| $P_w$ | Wind turbine power output |
| $\eta_w$ | Efficiency of wind turbine |
| $\eta_g$ | Efficiency of generator |
| $\rho_a$ | Density of air |
| $C_p$ | Power coefficient of wind turbine |
| $A$ | Wind turbine swept area |
| $V_r$ | Wind velocity |
| $P_{pv}$ | PV power output |
| $\eta_{pv}$ | Converesion efficiency of PV |
| $N_{pvp}$ | Number of PV panels in parallel |
| $N_{pvs}$ | Number of PV panels in series |
| $V_{pv}$ | Operating Voltage of PV panels |

| Notation | Explanation |
|---|---|
| $I_{pv}$ | Operating Current of PV panels |
| $P_b$ | Battery energy at time interval |
| $P_{bh}$ | Total energy generated by PV array |
| $\sigma$ | Self discharge factor |
| $P_{bl}$ | Load demand at time interval |
| $\eta_{bi}$ | Inverter efficiency |
| $\eta_{bb}$ | Battery charging efficiency |
| $C_{oh}$ | Hydro turbineoperation cost |
| $C_{reph}$ | Hydro turbine replacement cost |
| $C_{ow}$ | Wind turbineoperation cost |
| $C_{repw}$ | Wind turbine replacement cost |
| $C_{os}$ | PV operation cost |
| $C_{reps}$ | PV replacement cost |
| $C_{og}$ | Generator operation cost |
| $C_{repg}$ | Generator replacement cost |
| $C_{fg}$ | Generator fuel cost |
| $C_{ob}$ | Battery operation cost |
| $C_{repb}$ | Battery replacement cost |
| $C_{acap}$ | Annualized capital cost |
| $CRF$ | Capital recovery factor |
| $CRF_{proj}$ | CRF project |
| $CRF_{comp}$ | CRF component |
| $f$ | Factor due to difference of component and project lifetime |
| $S$ | Salvage value |
| $SFF$ | Sinking fund factor |
| $C_{rep}$ | Replacement cost |
| $R_{rep}$ | Replacement years |
| $R_{comp}$ | Component years |
| $R_{rem}$ | Remaining years |
| $C_{npc}$ | Net present cost |
| $C_{ann,tot}$ | Annualized total cost |
| $N$ | Number of years |
| $i$ | Interest rate |