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Optimization Assessment of Off-Grid Hybrid Distributed Generation System for Remote Sub-Village-Sized

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Abstract *- This paper presents an optimization assessment of several technologies for remote sub-village-sized off-grid hybrid distributed generation system in the rural areas. Three system configurations considered in this study are combinations of PV-battery, wind turbine, and diesel generator. The optimization is conducted under simulation subject to minimization of economic parameters such as system cost and cost of energy with considers CO_2 emission reduction coming from greater renewable generation fraction provided system's optimum sizing. The least cost of energy and total system cost are given by the optimum sizing of generator-PV-battery-wind turbine at the highest annual average wind speed.*

Keywords*: Off-grid, hybrid distributed generation, CO_2 emission, optimization, rural electrification*

1. INTRODUCTION

Rural electrification is recently becoming high concern in Indonesia. Small scale rural based economic activities which have been proven withstand to the economic crisis need to be further developed and boosted by the available and durable electricity service. Disadvantages in economic considerations as well as low potential in electricity consumption are hindered the grid extension, thus causing many areas isolated from the utility's grid. Utilization of hybrid off-grid power generation system is a promising way to overcome such condition as reported by several studies [1-4]. Application of hybrid renewable power generation system for a typical rural household-sized was presented in the previous study [5], for which the cost of energy in USD/kWh generated by the optimum system is 0.817-0.894, which is considerably still high. In this paper, electricity service is enhanced to a sub-village-sized. Hybrid systems options consists of diesel generator as non-renewable power sources, PV-battery, and wind turbine are assessed to determine system's optimum sizing and improve system reliability as well as economic viability compared to that achieved in the application for a household-sized.

2. METHODOLOGY

In this study, optimization assessment on electricity supply provision is conducted using HOMER (Hybrid Optimization Model for Electric Renewable) software developed by the US National Renewable Energy Laboratory [6]. Sizing procedure performed by HOMER highly depends on the accuracy of the resources data. Methodology for overall assessment is comprised of: load profile determination, renewable energy data gathering, system configurations options, and system modeling consists of both technical and economic parameters, constraints, and sensitivity.

2.1. Load profile

A rural household structure particularly in the remote area is simple thus it generally consumes light electricity for lighting and entertaining only. A hypothetical load profile for a sub-village used in this simulation is based on 50 households [7]. Typical installed equipments and daily energy requirement for each household is shown in Table 1.

Table 1. Typical electric equipments installed in the rural household [5]

Equipment	Power (W)	Daily usage (hour)	Energy (Wh/day)
Lamps			
• Terrace	10	10	100
• Room	30	6	180
• Kitchen	10	3	30
• Toilet	10	1	10
• Tape/radio	30	4	120
TV/VCR	70	3	210
Total			650

The coincident factor is considered equal to 1 where each individual load hit their peak at the same time in order to accommodate possible system's maximum peak load. Hence, approximate typical load profile for entire 50 households is given in Figure 1.

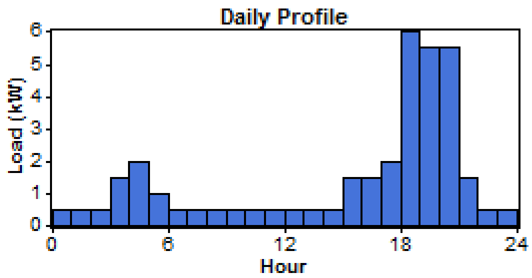

Fig. 1: Typical daily load profile

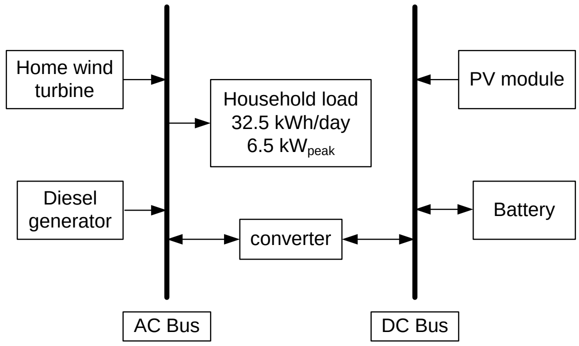

Fig 2: System configuration in complete option

2.2. Renewable energy data

The availability of renewable energy resources at the selected site is an important factor to develop the hybrid system. In this study, Baa region in Rote Ndao district of East Nusa Tenggara is selected as the simulation site. Geographically located on 10°50' South latitude and 123°0' East longitude, the area provides typical condition necessary for installing PV-wind turbine technology since solar and wind energy is sufficiently available. The weather data are gathering from NASA since there is no measurement available from the nearest meteorology office. The average annual weather condition in terms of daily solar radiation, wind speed, and clearness index is presented in Table 2.

Table 2. Weather condition in Baa, Rote Ndao district

Month	Daily radiation ($kWh/m^2/day$)	Clearness index	Wind speed (m/s)*
January	5.87	0.532	4.91
February	5.73	0.524	5.13
March	6.25	0.598	3.82
April	6.35	0.667	4.03
May	5.93	0.695	5.00
June	5.52	0.690	5.47
July	5.76	0.701	5.00
August	6.53	0.721	4.19
September	7.21	0.718	3.25
October	7.54	0.704	2.72
November	7.25	0.661	2.82
December	6.41	0.582	3.98

*)Wind speed is measured on 10 meters high and as an average of 10 years satellite measurement.

2.3. System configuration options

The hybrid power generation system is connected to the household load having a total energy requirement of 32.5 kWh/day with 6 kW peak load demand. Considering 5% standard deviation in the sequence of daily averages gives the peak load to be 6.5 kW. A complete configuration containing full technology option considered for hybrid system is shown in Figure 2.

Three possible hybrid system configurations to be assessed are: 1) Generator-PV-battery; 2) Generator-wind turbine-battery; and 3) Generator-PV-battery-wind turbine. It is focused on maximizing the renewable energy contribution while trying minimizing the use of generator to supply load demand. The presence of generator in all alternatives configurations is necessary as the supply reliability should be maintained satisfactory. In addition, modification is made compared to previous study in terms of the load is supplied with AC voltage and wind turbine is placed to generate AC voltage.

2.4. System modeling

The following equations used in the algorithm are based on equations as used in [1], [5], [7]. System modeling is represented mathematically as follows:

- PV module

The power output generated by ignoring the effect of temperature on the PV array is calculated as:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) \tag{1}$$

As cost reference for PV module, the initial cost of a $135W_{peak}$ PV module is taken USD 530 with a replacement cost of USD 480. PV system is assumed to be installed without tracking capability. The de-rating factor is accounted for 85%. The ground reflectance of solar radiation is 20% and the lifetime expectancy of the solar PV module is 25 years. Various sizes up to 4 kW is considered in the model.

- Wind turbine

Maximum power output that can be generated by a wind turbine is calculated as:

$$P = \frac{1}{2} \rho A V^3 C_{PMax} \tag{2}$$

There are up to 3 wind turbine considered in the simulation, each is rated at 1.8 kW and working at

220 V AC. Its nominal capacity per month is 400 kWh at the wind speed of 5.5 m/s with the starting speed of 3.5 m/s. The initial cost is taken USD 4,000 and the replacement cost is USD 3000. Meanwhile, annual operation and maintenance cost is neglected. The hub is located at 10 m height. The lifetime is assumed for 15 years. Variation of wind speed considered in the simulation are 3.5, 4, 5, and 5.5 m/s considering wind speed variation at the selected site. It is then applied as the sensitivity variable by which the optimum component sizing and the associated costs will be affected. The power curve of selected wind turbine is shown in Figure 3.

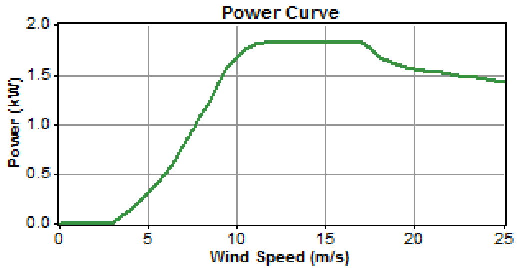

Fig 3: Power curve of a 1.8 kW wind turbine

- Diesel generator

The total annual electricity production of the generator is based on the specific fuel consumption and given by:

$$E_{gen} = \frac{F_{tot}}{F_{spec}} \tag{3}$$

The generator's cost of energy can be divided into two parts. The first part is the cost per hour of simply running the generator without producing any electricity, calculated as:

$$C_{gen,\,fixed} = C_{OM,\,fixed} + \frac{C_{rep,\,gen}}{R_{gen}} + F_0 Y_{gen} C_{fuel,\,eff} \tag{4}$$

The second part is additional cost per kilowatt-hour of producing electricity, given by:

$$C_{gen,\,mar} = F_1 C_{fuel,\,eff} \tag{5}$$

The initial cost of diesel generator is USD 240 per kW with a replacement cost of USD 200 and hourly maintenance cost of USD 0.04. The generator is estimated to operate up to 15,000 hours with a minimum load ratio of 30%. Fuel curve intercept is taken 0.05liter/hr/kW_{rated} and fuel curve slope is 0.33liter/hr/kW_{output} [8]. Fuel used for the generator is priced at USD 0.8 per liter. The amount of CO_2 is taken 2.6 kg/liter. Up to 6 kW generator size is considered in the model.

- Battery

The maximum charging and discharging power are calculated as follows:

$$P = \frac{kQ_1 e^{-k\Delta t} + Qkc(1-e^{-k\Delta t})}{(1-e^{-k\Delta t}) + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{6}$$

$$P = \frac{-kcQ_{max} + kQ_1 e^{-k\Delta t} + Qkc(1-e^{-k\Delta t})}{1e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{7}$$

The battery is rated at a nominal voltage of 12 V DC with nominal capacity of 200 Ah, 2.4 kWh. The battery's state of charge is 40% and the lifetime throughput is 917 kWh. Initial cost of a battery is USD 480 and the replacement cost is USD 380 with operating and maintenance cost of USD 4 per year. Up to 6 batteries are considered in the simulation.

- Converter

The initial capital cost of a converter is taken USD 730 per kW with a replacement cost of US$ 730. The expected lifetime of the converter is 25 years in which the efficiency of the inverter is 90% and the rectifier 85%. 3 kW, 5 kW, and 7 kW size converters are considered in the model.

- System economic

The overall economics evaluation of the system is achieved by involving several indicators into consideration including initial cost (USD), total operating cost (USD/year), total net present cost (USD), and cost of energy (USD/kWh). The total net present cost is used to represent the life cycle cost of a system and is given by:

$$C_{NPC} = \frac{C_{ann,\,tot}}{CRF(i, R_{proj})} \tag{8}$$

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{9}$$

All prices are assumed escalate at the same rate over the project lifetime. In this study, the real annual interest rate is considered as 8% using adjusted-inflation approach and project lifetime is taken on 25 years. System fixed capital cost is approximated to be USD 2,000 for entire system life cycle. Salvage value is assumed linear depreciation of components and is given by:

$$S = C_{rep} \frac{R_{comp} - (R_{proj} - R_{rep})}{R_{comp}} \quad (10)$$

The cost of energy is defined as the average cost per kWh of useful electrical energy produced by the system as:

$$COE = \frac{C_{ann,tot}}{E_{DC} + E_{AC}} \quad (11)$$

System constraints include maximum annual capacity shortage which is set 0%, meaning there is no capacity shortage for the entire total annual load.

3. RESULTS AND DISCUSSIONS

The aim of the simulation is to identify a configuration among a set of systems that meets the desired system reliability requirements with the lowest electricity unit cost. Electric demand in the hour is compared to the energy that the system can supply in that hour and the flow of energy to and from each component of the system is calculated to determine whether it can meet the electric demand under the specified conditions, and estimates the cost of installing and operating the system over the lifetime of the project. Prior conducting main simulations using three hybrid system configurations involving diesel generator, preliminary investigation is started with a simulation over a hybrid system consists of renewable resources only, meaning there is no generator to be placed in the hybrid system. Applying this system under the maximum capacity shortage constraint, would generate optimum sizing as given in Table 3. For load supplied with DC load, the proposed wind turbine is the same with that proposed in earlier study, i.e. DC wind turbine [5]. Economic implication of applying such system is presented in Table 4.

Table 3. Optimum hybrid system sizing without generator

Wind speed (m/s)	PV (kW)	Wind Turbine (pcs)	Battery (pcs)	Converter (kW)
Load is supplied with DC voltage				
3.5	9	-	51	-
4	8	5	55	-
5	6.5	12	53	-
5.5	6	14	50	-
Load is supplied with AC voltage				
3.5	7	3	57	7
4	6.5	3	52	7
5	5.5	5	32	7
5.5	5	4	35	7

Table 4. Economic of optimum system without generator

Wind speed (m/s)	IC (USD)	OC (USD/yr)	TNPC (USD)	COE (USD/kWh)
Load is supplied with DC voltage				
3.5	61,813	3,679	101,085	0.799
4	63,307	3,522	100,902	0.797
5	61,359	3,183	95,337	0.753
5.5	59,356	3,025	91,646	0.724
Load is supplied with AC voltage				
3.5	73,951	3,641	112,814	0.892
4	69,589	3,389	105,768	0.836
5	64,063	2,678	92,650	0.732
5.5	59,540	2,471	85,916	0.679

Note: IC = Initial Cost, OC = Operating Cost, TNPC = Total Net Present Cost, COE = Cost of Energy

From Table 3 and Table 4, optimum hybrid systems without generator supplied with AC voltage is composed from relatively large size of PV, battery, and wind turbine. This is necessary to supply the required load and to meet the imposed constraint of 0% capacity shortage for the whole year. Therefore, a large land should be allocated with respect to plants sitting. Moreover, the hybrid systems are considered highly uneconomical since the IC, TNPC, and COE obtained for AC voltage are USD 59,540, USD 85,916/year, and USD 0.679/kWh, respectively, which are not much difference with the result obtained from earlier study for single household as in [5], i.e. COE was in the range of USD 0.817-0.894/kWh. Moreover, larger component size and worst economic indicator are resulted by the optimum hybrid systems supplied with DC voltage.

Three hybrid system options which include the presence of diesel generator as mentioned earlier in Section 2.3 are simulated as well. Optimum components sizing are presented in Table 5. The economic indicators for each option are subsequently given in Table 6.

Table 5. Optimum hybrid systems sizing with generator

Wind speed (m/s)	PV (kW)	WT (pcs)	Batt (pcs)	Conv (kW)	Gen (kW)	% RE
Option 1: Hybrid Gen-PV-battery-wind turbine						
3.5	1	1	3	3	5	0.26
4	1	2	3	3	5	0.43
5	0.5	2	3	3	5	0.53
5.5	0.5	2	3	3	5	0.60
Option 2: Hybrid Gen-wind turbine-battery						
3.5	-	2	5	3	5	0.22
4	-	2	5	3	5	0.31
5	-	3	4	3	5	0.62
5.5	-	3	4	3	5	0.69
Option 3: Hybrid Gen-PV-battery						
-	1	-	3	3	5	0.15

Note: PV = photovoltaic, WT = wind turbine, Batt = battery, Conv = converter, Gen = diesel generator, % RE = portion of total energy produced from renewable energy resources.

Table 6. Economic of hybrid systems sizing with generator

Wind speed (m/s)	IC (USD)	OC (USD/yr)	TNPC (USD)	COE (USD/kWh)
Option 1: Hybrid Gen-PV-battery-wind turbine				
3.5	14,756	4,889	66,946	0.529
4	18,756	4,287	64,520	0.510
5	16,793	3,808	57,444	0.454
5.5	16,793	3,505	54,213	0.428
Option 2: Hybrid Gen-wind turbine-battery				
3.5	15,790	5,418	73,630	0.581
4	15,790	4,957	68,710	0.543
5	19,310	3,726	59,082	0.467
5.5	19,310	3,358	55,152	0.436
Option 3: Hybrid Gen-PV-battery				
-	10,756	5,328	67,632	0.534

Several implications could be observed from the results presented in Table 5 and Table 6. The renewable energy fraction becomes increasingly large along with the increasing wind speed. The renewable energy fraction has reached above 50% when the wind speed has reached 5 m/s, for both option 1 and option 2. This means the optimum hybrid configurations are capable to contribute significant amount of energy originating from renewable power sources. In case of wind turbine is not taken as consideration as it is simulated in option 3, the optimum hybrid configuration is composed of 1 kW PV, 3 kW converter, 5 kW diesel generator, and 3 batteries 12 V 200 Ah, which is the simplest hybrid configuration among others. However, the renewable energy fraction is found the lowest for 15% only. In terms of economic indicator, option 1 is likely the most cost efficient configuration since the COE and TNPC are 0.428/kWh and USD 54,213, respectively. COE and TNPC are found the lowest for option 1 compared to option 2 particularly with respect to the highest wind speed as well as against option 3.

In terms of environmental impact, annual CO_2 emission from three hybrid configurations as seen on Table 7 can be estimated by multiplying the fuel consumed by diesel generator with CO_2 emission coefficient for diesel oil, which is taken 2.6 kg/liter. Hence, CO_2 emission and mitigation is presented in Table 7.

Table 7. Annual CO_2 emission for hybrid configurations

Wind speed (m/s)	Diesel oil (liter/year)	CO_2 emission (kg/year)
Option 1: Hybrid Gen-PV-battery-wind turbine		
3.5	4,011	10,562
4	3,428	9,027
5	3,017	7,944
5.5	2,766	7,284
Option 2: Hybrid Gen-wind turbine-battery		
3.5	4,267	11,236
4	3,895	10,258
5	2,810	7,400
5.5	2,521	6,638
Option 3: Hybrid Gen-PV-battery		
-	4,468	11,766

From Table 7, CO_2 emission from option 1 and option 2 are more or less in level. On contrary, CO_2 emission obtained from option 3 is considered high since its renewable energy fraction is found only 15%. Thus, it is clear that lower CO_2 emission could be obtained from greater renewable energy fraction which is taken place along with increasing annual average wind speed. As consequences, the generator operational hours will be reduced, affecting on lessen fuel consumption. Variations of monthly electricity production with respect to the annual average wind speed are shown in Figure 4 to Figure 7.

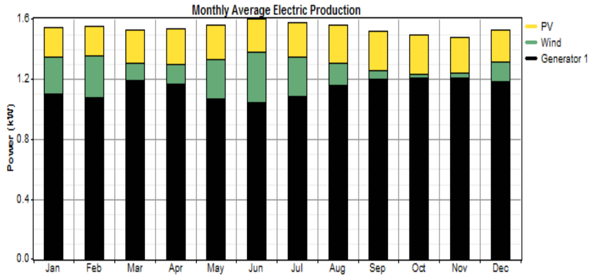

Fig 4: Monthly average of electricity production for annual average wind speed 3.5 m/s

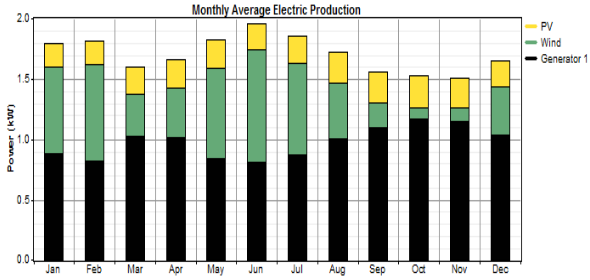

Fig 5: Monthly average of electricity production for annual average wind speed 4 m/s

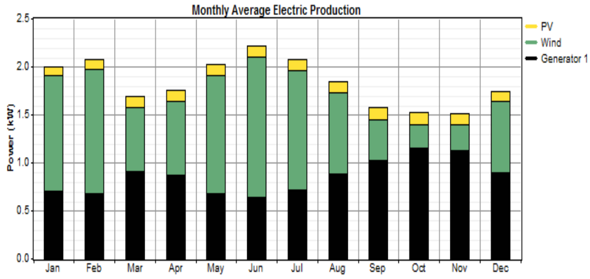

Fig 6: Monthly average of electricity production for annual average wind speed 5 m/s

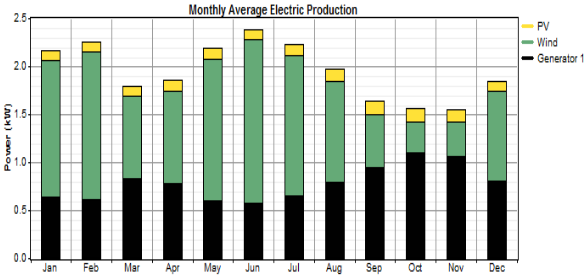

Fig 7: Monthly average of electricity production for annual average wind speed 5.5 m/s

Finding in Figure 4 to Figure 7 is inconformity to the wind speed potential as presented in Table 2. Electricity generation originating wind turbine may be reached its maximum output during two early months and then followed by several months in the mid year. In the range of 3.5 to 5.5 m/s of wind speed, the generator's contribution could be significantly fall off 34%, or reduced from 74% to just 40%

4. CONCLUSIONS

In this paper, effects of adding generator into hybrid off-grid generation system for sub-village-sized are analyzed through simulations. The main findings include technical and economical aspects, for which adding diesel generator resulted in lower cost of energy and thus total cost of system over the economic evaluation period. It has shown that environmental impact in terms of CO_2 emission could be reduced by increasing renewable energy fraction. The study also reveals that wind turbine holds the larger share in producing electricity provided the optimum hybrid component sizing over an increase wind speed. In this regard, PV contribution to increase renewable energy fraction is still possible. Thus, strategies to increase power produced by PV arrays may interesting to be explored in the future research.

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Acronym:

Notation	Explanation
Y_{PV}	the power output under standard test condition (kW)
f_{PV}	the PV de-rating factor
G_T	the solar radiation incident on the PV array in the current time step (kW/m^2)
$G_{T,STC}$	PV cell temperature under standard test conditions (25 °C)
ρ	air density (kg/m^3)
A	the swept area (m^2)
V	wind velocity (m/s)
C_{PMax}	theoretical maximum power efficiency (0.59)
F_{tot}	total annual generator fuel consumption (liter/year)
F_{spec}	the average amount of fuel consumed by generator (liter/kWh)
$C_{OM,gen}$	the operation and maintenance cost (USD/hour)
$C_{rep,gen}$	the replacement cost of generator (USD)
R_{gen}	generator lifetime (hour)
F_0	the fuel curve intercept coefficient (liter/kWh)
Y_{gen}	the capacity of generator (kW),
$C_{fuel,eff}$	the effective price of fuel (USD/liter)
F_1	the fuel curve slope (liter/kWh)
$C_{fuel,eff}$	the effective price of fuel (USD/liter)
Q_1	the available energy (kWh) in the battery at the beginning of the time step
Q	the total amount of energy (kWh) in the battery at the beginning of the time step
c	the battery capacity ratio

k	the battery rate constant (hour^{-1})
Δt	the length of the time step (hour)
$Q_{\max}$	the total capacity of the battery bank (kWh)
$C_{ann,tot}$	total annualized cost (USD/year)
CRF	the capital recovery factor
i	Interest rate (%)
R_{proj}	project life time (year)
N	number of years
C_{rep}	replacement cost (USD)
R_{comp}	component lifetime (year)
R_{rep}	replacement cost duration (year)
E_{DC}	DC primary load served (kWh/year)
E_{AC}	AC primary load served (kWh/year)