Ahmed Belhamadia[1*], Muhamad Bin Mansor[2], Mahmoud A Younis[3]

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Optimal Photovoltaic System Sizing of a Hybrid Diesel/PV System

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This paper presents a cost analysis study of a hybrid diesel and Photovoltaic (PV) system in Kuala Terengganu, Malaysia. It first presents the climate conditions of the city followed by the load profile of a 2MVA network; the system was evaluated as a standalone system. Diesel generator rating was considered such that it follows ISO 8528. The maximum size of the PV system was selected such that its penetration would not exceed 25%. Several sizes were considered but the $400kW_p$ system was found to be the most cost efficient. Cost estimation was done using Hybrid Optimization Model for Electric Renewable (HOMER). Based on the simulation results, the climate conditions and the NEC 960, the numbers of the maximum and minimum series modules were suggested as well as the maximum number of the parallel strings.

Keywords: Renewable energy; Solar energy potential; Wind energy potential.

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1. Introduction

One of the most essential utilities that a country must provide is electricity and as the demand on the electricity increases; the generation should increase. It is estimated that the world marketed energy consumption grows by 53 percent from 2008 to 2035 [1]. One of the traditional ways of producing the electrical energy is by burning fossil fuels and their derivatives. As the concern on the carbon dioxide concentration on the atmosphere and the climate change grows, electrical utility companies are facing a great challenge on reducing their carbon dioxide emissions while increasing the electricity generation. This has led to the wide and fast spread of the renewable energy resources adoption by various countries and electrical utilities. Therefore this research examines and studies the economical and operational aspects of a hybrid diesel/PV system in Kuala Terengganu in Malaysia using Hybrid Optimization Model for Electric Renewable (HOMER). HOMER determines the feasibility of a system by evaluating electricity demand vs. electricity generation and compares between options for cost optimization.

2. Characteristics of the region under study

The region between latitudes 15^{o} N and 35^{o} N is the region with the most solar energy, followed by the region between 15^{o} N and the equator [2]. Malaysia is located between 2^{o}N and 7^{o} N, which indicate that it receives an enormous amount of solar energy. However, weather in countries in the equator region is characterized by high humidity and high rainy days which make it difficult to have a full day without clouds covering the skies. A sunshine average of 6 hours a day is estimated by the Meteorology Department [3]. Daily average global solar radiation and temperature data were requested from the Malaysian Meteorological Department for 2011 and 2012 but, they only provided the temperature data since they do not have the solar radiation records. Therefore, solar radiation data were collected from NASA database for the same period. Fig. 1 shows the average temperature and solar radiation.

* Corresponding author: Ahmed Belhamadia, E-mail: a.bel89@yahoo.com
[1] Department of Electrical Engineering, Universiti Tenaga Nasional, Kajang 43000, Selangor, Malaysia.
[2] Department of Electrical Engineering, Universiti Tenaga Nasional, Kajang 43000, Selangor, Malaysia
[3] Sohar University, Faculty of Engineering, Sohar, Oman

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2.1 Load profile

Due to difficulties in obtaining the load profile for a real micro-grid; an assumption has been made. The proposed system is to supply a total load of 2 MVA at a lagging power factor of 0.85. The load profile was assumed and scaled based on the peninsular Malaysia load profile obtained from Tenaga Nasional Berhad (TNB) annual report. Fig. 2 shows the load profile for one day.

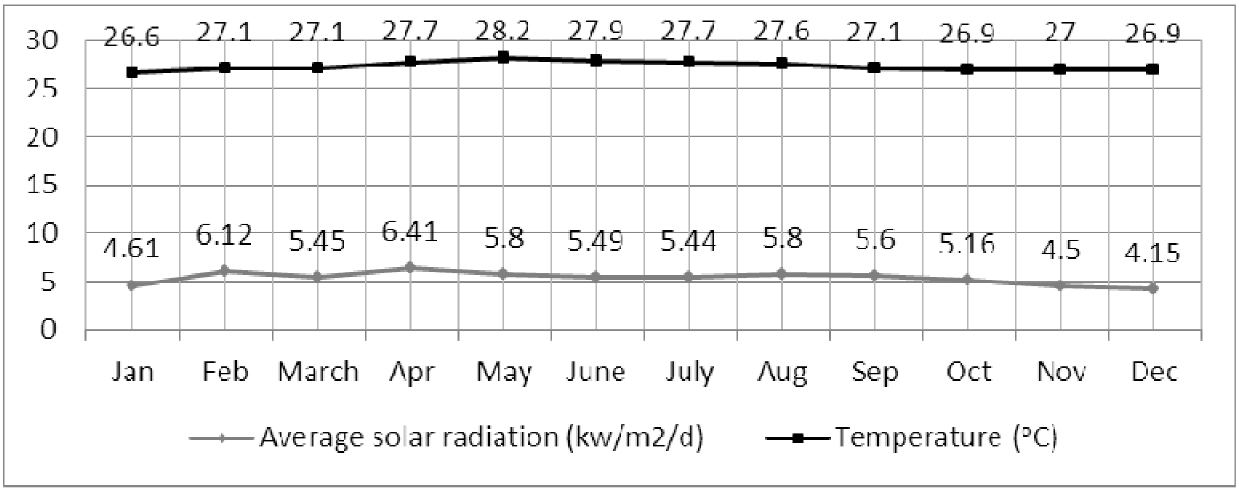

Fig.1. Average solar radiation and temperature of Kuala Terengganu

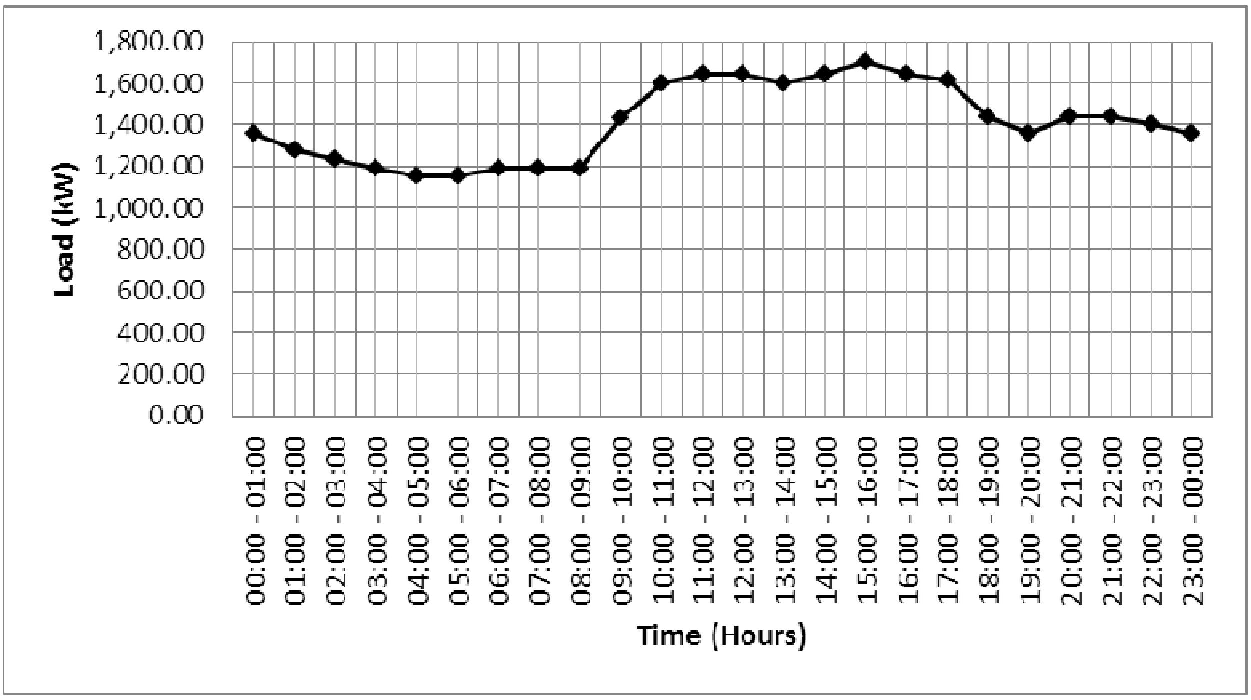

Fig.2. Network Load Profile

3. System Components

3.1 Diesel generator

The network is assumed to be a standalone, and in order to support the load continuously some points were kept in mind especially in sizing the diesel generators. Based on ISO 8528, there are four diesel generator ratings depending on the generator's operating time. These ratings are [4]:

1. Continuous operation rating (COP): the generator runs under constant load for a limitless period of time. This type of rating does not allow for any overload.
2. Prime Power Rating (PRP): the generator can run under variable load for a limitless period of time providing the average daily load is below 70% of the PRP rating. This rating allows for a 10% overload but not to exceed one hour every 12 hours.
3. Limited Time Power (LTP): the generator runs at a constant load for a maximum of 500 hours a year.
4. Emergency supply Power (ESP): the generator runs under variable load for a maximum of 200 hours a year providing the average daily load is below 70% of the ESP rating. No overload is allowed for this rating.

All of the above ratings require periodic inspection and maintenance in order to keep the generators running at their best. However, some other considerations must be taken into account when selecting the size of the diesel generator. Operating temperature, relative humidity, and latitude are major contributors to reconsider the sizing of a diesel generator. Standard reference conditions define the rated power at 25^{o}C, a pressure of 100kPa, and relative humidity of 30%. Most of the time, de-rating the generators appears for latitudes over 1000m and temperature above 40^{o}C. Temperature, latitude, and humidity affect the density of the air entering the engine's combustion chamber, and hence affecting its performance. An important operation aspect of the diesel generators is that they should not be allowed to operate below 30% of their rating; that is due to the mechanical losses in the engine since they are roughly proportional to the speed. As the losses increases the efficiency of the generator decreases and efficiency reduction would be very steep below 30 % of the diesel generator's rating [5].

3.2 PV system:

PV systems convert the incident sunlight into DC electricity. There are several factors that can affect the operation of the PV systems. These factors are the solar radiation and the working temperature. Radiation mainly affects the PV current while temperature affects the operating voltage.
The expected output power from the PV array can be obtained by the following expression [6]:

$$P = P_R \eta \left(\frac{G}{G_{STC}} \right) \left[1 + \gamma \left(T - 25^o \right) \right] \quad (1)$$

Where P_R is the module rated power, η is the de-rating factor which takes into consideration the inefficiencies in the converters, transformers, and the wiring of the PV system. Typical de-rating values can be found in [7]. G is the incident global solar radiation in kW/m^2, G_{STC} (1kW/m^2) is the global radiation at standard test conditions, γ is the module power temperature coefficient ($^oC^{-1}$), and T is the temperature in ^oC.

3.2.1 Design Criteria

There are some standards and regulations regarding the connection of the PV panels, system voltage and current ratings as well as inverters operation. The output of the PV module is affected greatly by the irradiance level and working temperature, and hence the output voltage and current would vary based on these conditions. Inverters usually have a maximum and minimum operating voltage range; therefore the PV system's voltage should be designed such that it would not exceed or drop below the operating range of the inverter. Most utility scale/central inverters are rated at 600-1000 V_{dc}, making the voltage rating of the PV system to be limited to this maximum value. Theoretically, the maximum system voltage is found by summing the open circuit voltage of all modules connected in series. Nevertheless, the open circuit voltage of the system might reach above the limit that the inverter can withstand or even drop below the minimum operating voltage; that if the system design did not consider the temperature effect. NEC 690.7(A) has set a correction factors for determining the maximum voltage of the PV system based on the ambient temperature of the area, these correction factors are listed in Table 1.

Table 1. Voltage correction factors based on the ambient temperature.

Ambient temperature (^0C)	**Correction factor**
25 to 10	1.06
9 to 0	1.10
-1 to -10	1.13
-11 to -20	1.75
-21 to -40	1.25

As the maximum system voltage is of high importance to be determined, the minimum system voltage needs to be calculated; since all inverters have a minimum voltage limit. The minimum system voltage can be calculated by the following expression:

$$V_{min/module} = V_{mp} + [(T_{addition} + T_{max} - T_{STC}) \times T_{coef\_p}] \quad (2)$$

Where $V_{min/module}$ is the minimum voltage obtained per module, V_{mp} is the maximum power point (mpp) voltage of the module, $T_{addition}$ is the due to the fact that the module's temperature is always higher than the ambient temperature by 20-30 ^oC, and 25 ^oC would be a good estimation, T_{coef_p} is the temperature coefficient of power the module, since the variable in interest is the working voltage's temperature coefficient.

After evaluating the minimum module voltage, the following expression is used to determine the minimum number of series modules:

$$\text{Min. number of modules} \geq (\text{min. inverter voltage} \times 1.05)/ V_{min} \quad (3)$$

The 1.05 factor is a safety margin so that the minimum voltage is always above the minimum inverter operating voltage.

Inverter manufacturers always specify the range of operating voltage as well as the maximum current that the inverter can withstand. Based on NEC 690.8 (A), the maximum current of the PV system should be the sum of the parallel modules rated short circuit current multiplied by 125%; that is the current generated by the PV systems can reach values that are higher than the rated short circuit current at solar noon.

4. Simple Economics

Cost optimization is the main concern when starting a new project. One of the methods in evaluating projects and to compare between alternatives is the net present cost (NPC) method. This method considers all the payments that are going to be paid during the project's lifetime and represent it as a single payment if made at the beginning of the project. In order to be able to perform the NPC analysis, knowledge of the interest rate, inflation rate, and the annual payments must be known. Usually to calculate the real interest rate, the value of the annual interest and inflation rates must be evaluated into the following expression [8]:

$$i = (i' - f) / (1+f) \qquad (4)$$

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

To find the net present cost (NPC) of an annual payment series (A) over the project lifetime (N) with a real interest rate (i), the following expression can be applied [9]:

$$NPC = A*[(1+i)^N - 1/i(1+i)^N] \qquad (5)$$

5. Parameters Sizes and Prices:

The system was simulated as an off-grid system, and based on that the following were determined.
Diesel generator: in order to cover the load without any shortage the sizing of the diesel generator was based on the total load of 2MVA or 1.7 MW at a 0.85 pf. Therefore, two 1500 kVA generators were chosen. Each generator operates at 0.8 pf giving a total of 2400 kW assuming a full load efficiency of 90%[1] that would give a 2160 kW. Based on the network average load of 1370 kW, that gives an average operation below 70% of the diesel kW ratings. Since the operation criterion of the diesel generators is to share equally the load; they were considered as one 2160 kW generator in the simulation.
PV system: there was no specific minimum or maximum rating of the PV system, but the selection was based on the penetration level of the PV system. High level of penetration could cause severe fluctuation causing instability to the system. Penetration levels less that 25% are considered to be adequate [10]. Several sizes were considered in the simulation and the one with the minimum NPC was chosen. The sizes considered were 100kW, 200kW, 300kW, and 400kW. Inverters sizes were considered according to the PV system size. Table 2 summarizes the cost of the system components.

Table 2. System's components cost summary.

System Component	Technical Data
Diesel Generator	
Model	Cummins C1500
Initial Cost*	RM 506,592
Size	1500 kVA @ 0.8 pf
Diesel Price	RM 1.8/L
Operation and Maintenance [8]	RM 0.091/h

[1] This is an assumed efficiency; the generator real efficiency might be higher since the efficiency increases with the size of the generator. In [5] a diesel generator rated at 1000kVA has an efficiency of 95% at full load.

Replacement [11]	RM 405,274
Lifetime*	25000 Hours
PV Pannels	
Model	Suntech STP 300-24 Ve
Price/Wp	RM 4.8
Size Considered (kW)	100, 200, 300, 400
Operation and Maintenance [8]	RM 0.76/kW/year
Replacement/Wp [11]	RM 3.84
Lifetime*	25 Years
Inverter	
Price/W [11]	RM 2.169
Replacement/W [11]	RM 1.735
Lifetime [11]	10 Years
*** Estimated**	

6. Results and Discussion:

The generation was optimized for load following, and the minimum operating percentage of the generator was set to 35%. The Malaysian annual interest rate and inflation rate were 3% and 1.6% respectively [12], making the real interest rate based on (4) equal to 1.38%. Based on the different PV sizes considered, system costs[2] are listed in Table 3.

Table 3. Systems Cost Summary.

system	PV Size (kW)	Diesel Gen. Size(kW)	Inverter Size (kW)	Initial Capital (RM)	Operating Cost (RM/yr)	Total NPC (RM)	Cost of Energy (RM/kWh)
1	0	2160	0	1,013,184	5,378,141	114.0 M	0.452
2	100	2160	100	1,710,078	5,327,667	113.7 M	0.452
3	200	2160	200	2,406,973	5,277,192	113.3 M	0.449
4	300	2160	300	3,103,872	5,226,721	112.9 M	0.449
5	400	2160	400	3,800,767	5,176,253	112.6 M	0.446

It is noticeable that the system with the diesel generator only has the lowest initial capital, but considering the NPC it is the most expensive system and that can be regarded to the high operating cost of the diesel generator. As the PV system size increases the initial cost increases as well, but the most important notice is that the total NPC reduces. System 5 is the most cost effective when considering the NPC, making it the most desirable option.

[2] HOMER takes cost inputs in US dollar, all costs were exchanged based on the exchange rate on 18/4/13. 1 US $ = RM 3.0335. Bank Negara Malaysia (Central bank of Malaysia).

Table 4 and 5 provide the electrical characteristics of system 5, and the cost summary respectively.

Table 4. Total electrical characteristics of system 5.

Component	kWh/yr	% of Total Production/Consumption
Electricity production of the PV system	632,991	5
Electricity production of the diesel generator	11,401,694	95
Total electricity consumption	12,003,016	100
Capacity shortage	0	0
Renewable fraction	-	5.01
Max. renewable penetration	-	23.60

Table 5. Cost summary of system 5.

Component	Capital (RM)	Replacement (RM)	O&M (RM)	Fuel (RM)	Salvage (RM)	Total (RM)
PV	1,920,000	0	6,377	0	0	1,926,377
Generator	1,013,183	5,459,687	33,518	102,568,508	-138,097	108,936,799
Inverter	867,571	1,132,831	0	0	-246,357	1,754,045
System	3,800,754	6,592,518	39,895	102,568,508	-384,454	112,617,221

The PV system considered to have a zero salvage value because of the project lifetime which is equal to the PV system lifetime, meanwhile the diesel generator is being replaced each 2.85 years and the inverter is replaced each 10 years which by the end of the project lifetime the generator and the inverter's last replacement would not coincide with the end of the project's lifetime, and hence they were salvaged.

7. Suggested PV system maximum and minimum values

The scope of this study is to determine the cost of the hybrid system, but it is good to have a look at the maximum and minimum system voltage and maximum parallel strings. Form Table I the correction factor in Kuala Terengganu would be 1.06, considering SUNTECH PV module characteristics in Table 6 and a 400kW inverter from POWER ONE in Table7, the system voltage, number of series and parallel modules can be specified.

Table 6. SUNTECH STP300-24/Ve module characteristics.

Parameters at STC	Value
P_{max}	300 W
V_{mp}	36.1 V
I_{mp}	8.32 A
V_{oc}	45.2 V
I_{sc}	8.65 A
Module efficiency	15.5 %
Temperature Coefficient of P_{max}	-0.44 %/°C
Temperature Coefficient of V_{oc}	-0.33 %/°C

Table 7: Aurora 400kW inverter specifications (PVI-400-TL).

Parameters	Value
Rated Power Output	400 kW
Maximum DC Input Voltage	1000 V
MPPT input DC Voltage Range	570-950 V
Maximum DC Input Current	738 A

The number of maximum PV modules to be connected in series would be equal to the maximum DC MPPT voltage of the inverter divided by the open circuit module voltage after including the correction factor, and that would give 19 series modules, meanwhile the minimum number of series modules would be based on (2) and (3) is 17 modules (the maximum temperature in Kuala Terengganu is 34°C). After determining the system voltage system current needs to be determined as well, based on NEC 690.8(A) the string short circuit after the increment of 125% is equal to 10.81A, taking 738A as the maximum current and divide it by 10.81A, would give 68 parallel strings. The total power generated from the PV system would be equal to 387.6 kW_p. Table 8 , summaries the PV system connections.

Table 8. Suggested modules connection

Parameters	Value
Number of series connected modules	19
Number of parallel connected string	68
Maximum power per module	300 W_p
Maximum system power	387.6 kW_p

8. Conclusion

This study considered some design standards and specifications such as ISO 8528 and NEC 690. ISO 8528 define diesel generator rating and loading. A prime power supply diesel generator was considered in this study. The average daily load were not to exceed 70% of the generator's rating and a minimum operating point of 35% of rated was chosen in the simulation, thus preventing too much losses.

HOMER software was used to obtain the most economical option out of several ones. The NPC analysis provides a great way to compare economically between alternatives; since it would present the total cost of the project over its lifetime. This study should give a glimpse of the energy price in general and the energy cost of the PV systems, it is not necessarily that the system will cost exactly as stated in the results a high possibility that it would cost higher than what is stated due to some price approximations and the fixed real interest rate assumed throughout the project lifetime.

Temperature plays a major role in the output voltage of the PV system. Temperatures below the STC's temperature would cause the open circuit voltage to rise and that will impose a limit on the maximum number of the series connected modules. On the other hand, high operating temperature would raise the number of the minimum series connected modules. Sort circuit current of the string should be multiplied by 125% as per NEC 690.8(A) and the maximum strings current is limited to the current handling capability of the inverter.

Acknowledgement

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