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Research Article

Technoeconomic and Carbon Emission Analysis for a Grid-Connected Photovoltaic System in Malacca

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A 1 MW grid-connected PV system is studied and analyzed in this project using the National Renewable Energy Laboratory's HOMER simulation software. The economic feasibility of the system in a small industry area of Malacca, Rembia in Malaysia, is investigated. The aim of the proposed PV system is to reduce the grid energy consumption and promote the use of renewable energy. In this paper, the emphasis is placed on the reduction of greenhouse gases emission. HOMER is capable of performing simulation on renewable energy systems as well as system optimization, in which, the optimization is based on the available usage data and the renewable energy data, such as solar irradiance and temperature. In addition, HOMER can perform sensitivity analysis according to different assumptions of uncertainty factors to determine its impact on the studied system and also the per unit energy cost. Finally, the most suitable or the best configuration system can be identified based on the requirements and constraints.

1. Introduction

Over the decades, most of the power generation consumes nonrenewable resources particularly fossil fuel, coal, and natural gas [1]. These conventional ways of power generation are not environment friendly while also exhibiting significant sustainability problem [2]. Due to rising demands, prices of nonrenewable energies will continue to soar in the coming decades [3, 4]. Solar energy emerged as a prospective reliable energy supply in recent years. Solar technology has evolved to achieve power generation of high efficiency (up to 20%) at a cost of only roughly 2 Malaysian Ringgit (RM) per watt [5].

Utility providers in Malaysia are using mixed generation to provide the power supply needed by domestics, commercials, and industries. The generation fuel mix is a combination of 62.6% gas, 20.9% coal, 9.5% hydro, and 7% from other forms of fuel in Malaysia [6, 7]. PV generation method is still new in Malaysia but very potent due to favorable geographical location and solar irradiance index [8].

A grid-connected PV system generates electricity from sun light and the electricity is converted into grid-compliant AC by inverter [9, 10]. The process of PV electrical generation itself is totally pollution-free but the manufacturing and system setup of PV modules will impose some environmental cost [11]. An increase in portion of Renewable Energy (RE) contribution in the National Power Generation is also beneficial to both economics and politics; reducing the nation dependency on fossil energy will lessen the fossil economic effects to the nation [12].

Most of the solar power generation systems in Malaysia are building integrated PV (BIPV) implemented under Malaysia Building Integrated Photovoltaic project [13, 14]. Ministry of Energy, Green Technology and Water has a mission and action plan to increase RE contribution in the national power generation mix for the next 40 years as shown in the Table 1 [15].

2. Project Background

This project chose Malacca as the prospective location of the 1 MW grid-connected solar PV system because of the availability of the solar component resources in the near future [20]. Sunpower Malaysia Manufacturing PTE. LTD. will readily supply the PV system components to the system development. Besides, Malacca state government is allocating

Table 1: National renewable energy policy and action plan, 2010 [15].

Year ending	Cum. total RE (MW)	Share of RE capacity	Annual generation (GWh)	RE Mix	Annual CO_2 avoidance (tone)
2011	219	1%	1,230	1%	848,493
2015	985	6%	5,385	5%	3,715,415
2020	2,080	11%	1,1246	9%	7,759,474
2030	4,000	17%	1,7232	12%	11,889,887
2050	21,370	73%	44,208	24%	30,503,589

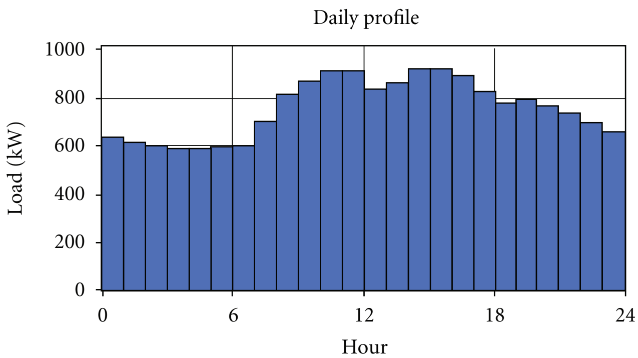

Figure 1: The daily load profile of the small industrial area in Rembia-Krubong, Malacca.

7,246.43 hectare of Rembia, Malacca as the first solar valley in Malaysia, concentrating on investment of renewable energy components manufacturing industries [6]. The state government is promoting more industrial investment in green technology through its 10-year development plan. Industrial development in the area is expected to increase the power supply demand, and in the long run, it is wiser to seek alternative energy to support the area [6, 21]. PV system will impose one-time environment cost compared to conventional fossil generation which will continuously release greenhouse gases, not to mention its generation cost will fluctuate as oil price rise and fall. In fact, PV system helps to reduce the release of greenhouse gases despite the increase of energy demand because the only fuel for PV comes from the sun, and it is free.

In this project, the economic feasibility of 1 MW PV system for a small industrial area in Rembia-Krubong, Malacca is examined by using the HOMER simulation software. Several optimizations depending on the few sensitivity factors will be simulated and the best optimized system will be proposed as the feasible system.

3. Input Data Information

3.1. Load Profile of the Area. The small industrial area is estimated to accommodate 40 small factories with total peak load of 915 kW. With added consideration for demand variation of 2% for day to day and hour to hour, the peak load is estimated to be 982 kW. Figure 1 shows the daily load profile of the interest area [22]. The load demand starts to peak after 9 am. The load does not drop too much at any time of the day. Further looking at the variations over the months of a year at Figure 2, the load is higher for the middle 2 quarters of the year, which is from April to September, because most factories are in maximum operation during this period [3, 23, 24].

3.2. Energy Resource. Malaysia is blessed with abundant solar radiation. The solar irradiance data is based on the interest area geographical coordinate [22], latitude North 2°2′, longitude East 102°15′ [25]. The average daily radiation for the whole year is 4.947 kWh/m^2/d. The solar irradiance maintains a stable trend throughout the whole year, which makes the area perfect for PV energy generation [26]. Figure 3 shows the irradiance data and clearness index generated by HOMER software. The data generated by HOMER was similar to the irradiation data provided by the Malaysian Meteorological Department [27].

3.3. Grid Utility. Malaysia Grid is 50 Hz AC at typical voltage of 240 V for single phase and 415 V for 3-phase system. The Grid utility in Malaysia is managed by a sole distributor, Tenaga Nasional Berhad (TNB). For grid-connected PV-generated electricity, TNB pays for the generated power using the "Net-Metering" concept, whereas the rate TNB pays for the PV-generated electricity is the same as Feed-in Tariff (FiT) charged to regular consumers [28].

For grid-connected system in this project, there will be no physical energy storage element, but it will utilize the grid utility as the virtual energy storage where the system distributes the extra generated electricity and consumers are compensated in term of reduced electricity charge [29].

4. Simulation Software

A computer approach is employed in this simulation project. The simulation compares the cost of two energy supply systems. The first case is grid standalone without the PV system installed. The result is compared to the second case, a system with PV system installed. HOMER will perform the simulation, optimization, and sensitivity analyses of several system configurations. Simulation will determine the technical feasibility of the system and optimization of the system will be performed based on different system configurations to determine which of them will be the most suitable system. In the system configuration, the different sizes of PV and inverters are considered. The sensitivity analysis will show the effects of uncertainties on the system performance [30]. Figure 4 shows the HOMER simulation design flow chart.

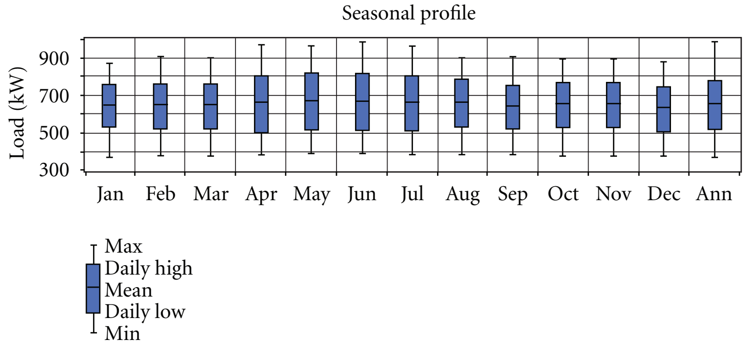

FIGURE 2: Seasonal load profile of the small industrial area in Rembia-Krubong, Malacca.

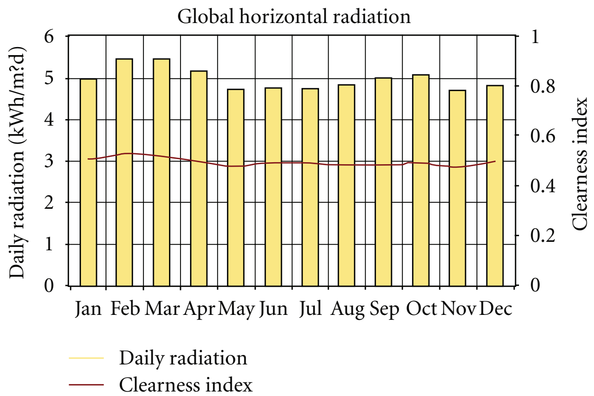

FIGURE 3: Daily radiation of Rembia-Krubong, Malacca.

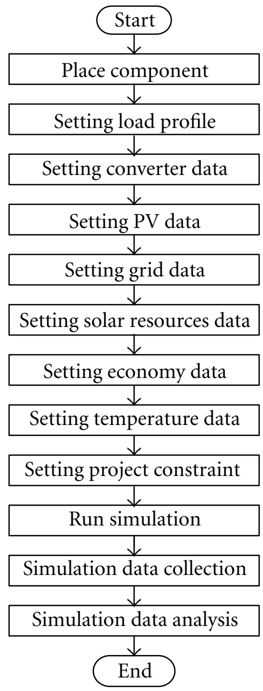

FIGURE 4: HOMER simulation design flow chart for 1 MW grid-connected PV system.

5. System Design Specification

There are 4 main components of the system, namely, PV modules, DC monitoring system, inverter central, and public grid. A grid-connected system usually does not employ any storage component. The extra generated energy is normally sold to the utility. Hence, in this project, the storage element is eliminated. The system design is as illustrated in Figure 5, generated by HOMER software. The DC and AC lines are connected via the inverter (converter). Several inverters will be working in parallel to power up the 1 MW systems. The DC source from the PV generation will be converted into AC power and fed into the grid system using the inverters. All the monitoring tasks will be done by the inverter central. Thus, high-performance inverter is crucial in this project design.

5.1. Photovoltaic Modules. PV modules available in the market can be grouped into two major types according to their technology, that is, crystalline silicon and thin film. In this project, our focus is on crystalline PV modules because the system is expected to be a solar farm. Both types of polycrystalline and monocrystalline modules are taken into consideration for the analysis. Monocrystalline modules have slightly higher efficiency than polycrystalline modules. Table 2 shows the PV modules used in the system analysis.

The PV modules are connected in series to obtain a voltage of 500–600 V, and several strings of the series are paralleled to obtain adequate current for the power of 250 kW or 500 kW according to the inverter system used. Table 3 shows the number of PV modules used in each configuration options. The area occupied for each configuration is also shown for comparison. The estimated initial capital cost of 6144 unit 165 W modules is RM 3,126,783, 4480 unit 225 W modules is RM 3,939,840, and 3200 unit 315 W modules is RM 393,984. Additional 8 units of Sunny String Monitors SSM24-11 is used as DC side safety monitoring of the PV module system to increase the system security. SSM24-11 continuously measure and monitor the individual string currents and any malfunction will be detected and analyzed by the Sunny Central Control.

The maintenance cost for the PV modules is assumed to be negligible since Malaysia is located near to the equator with heavy rainfall all year along. Thus, PV modules do not require regular cleaning cost. The operation and maintenance cost is estimated as 0.5% of the installation

Table 2: PV modules used in the system analysis [16–18].

PV module	BP3165	SunPower 225	SunPower 315
Type	Polycrystalline	Monocrystalline	Monocrystalline
Rated power	165 W	225 W	315 W
Efficiency	13.1%	18.1%	19.3%
V_{mpp}	35.2 V	41.0 V	54.7 V
I_{mpp}	4.7 A	5.49 A	5.76 A
Temperature coefficient	−0.5%/K	−0.38%/K	−0.38%/K

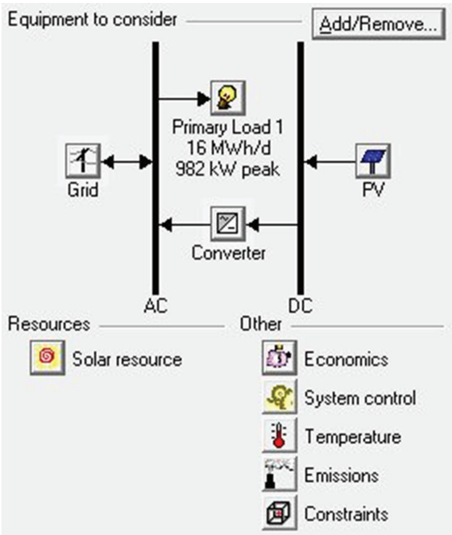

Figure 5: System configuration of a grid-connected PV in HOMER.

Table 3: Number of PV modules used and the total area consumption [16–18].

PV module	BP3165	SunPower 225	SunPower 315
Quantity	6144	4480	3200
PV module dimension	1.25847 m^2	1.244082 m^2	1.672554 m^2
Total modules area	7732 m^2	5574 m^2	5352 m^2

cost of PV system. Replacement cost for mounting structure and the cable connections of modules is also considered. The replacement cost over the 25 years is assumed to be as small as 0.05% of the capital since PV manufacturers normally provide warranty of at least 80% performance for 25 years for their PV modules. The total cost for PV modules is as tabulated in Table 4. The PV capital includes the cost of DC safety monitoring units and installation cost.

5.2. Grid-Connected Inverter. This project considers two different implementations of inverter for comparison. The first case as shown in Figure 6, uses 4 units of Sunny Central 250 U (250 kW) to get a total output of 1 MW whilst the second case uses 2 units of Sunny Central 500 U (500 kW). The inverters generate similar output characteristic, that is, 400–480 V three-phase AC at frequency of 50 or 60 Hz. The output voltage is set to 415 V at 50 Hz for grid compatibility in Malaysia. The output from the inverters has a power factor of more than 0.99 which ensures the power quality of the system.

Table 4 shows the total cost for the different types of inverters. The capital cost is inclusive of price of inverters and installation cost. Replacement cost of the inverter is the same as the capital, whilst the operation and maintenance cost is assumed to be 50% of the installation cost of the inverter system. The inverters' life cycle is 20 years, thus, there will be one-time replacement in the projected period of 25 years.

Table 4: System components capital/replacement cost, operation, and maintenance cost, and life time [16–19].

Description	Data
PV modules	
BP3165	165 W
Capital	RM 3126783/MW
Replacement cost	RM 1564/MW
O&M	RM 625.36/year
Life time	25 years
SunPower 225	225 W
Capital	RM 3939840/MW
Replacement cost	RM 1970/MW
O&M	RM 788/year
Life time	25 years
SunPower 315	315 W
Capital	RM 3939840/MW
Replacement cost	RM 1970/MW
O&M	RM 788/year
Life time	25 years
Inverter	
Sunny Central 250U	250 kW
Capital	RM 448920/MW
Replacement cost	RM 448920/MW
O&M	RM 1496.4/year
Life time	20 years
Sunny Central 500U	500 kW
Capital	RM 421200/MW
Replacement cost	RM 421200/MW
O&M	RM 1404/year
Life time	20 years

Table 5: Homer optimization results for grid standalone and PV-integrated systems.

PV panel and inverter	PV derating factor (%)	Inverter life (yr)	PV (kW)	Converter (kW)	Grid (kW)	Initial capital (RM)	Operating cost (RM/yr)	Total NPC (RM)	COE (RM/kWh)	Net grid purchases (RM/kWh)	Renewable fraction (%)	Capacity shortage	Emission (kg/yr) Carbon dioxide	Emission (kg/yr) Sulfur dioxide	Emission (kg/yr) Nitrogen oxides
Inverter = 250 KW × 4															
PV = 165 W	90	20	1000	1000	16000000	3,575,703	413,995	8,667,948	0.121	4,316,632	0.26	0			
PV = 225 W	90	20	1000	1000	16000000	4,388,760	414,266	9,684,464	0.132	4,316,632	0.26	0	2728111	11828	5784
PV = 315 W	90	20	1000	1000	16000000	4,388,760	414,266	9,684,464	0.132	4,316,632	0.26	0			
Inverter = 500 KW × 2															
PV = 165 W	90	20	1000	1000	16000000	3,547,983	413,713	8,836,623	0.120	4,316,632	0.26	0			
PV = 225 W	90	20	1000	1000	16000000	4,361,040	413,876	9,651,764	0.131	4,316,632	0.26	0	2728111	11828	5784
PV = 315 W	90	20	1000	1000	16000000	4,361,040	413,876	9,651,764	0.131	4,316,632	0.26	0			
Grid	—	—	—	—	16000000	RM0	542,896	6,940,033	0.095	5,744,363	0	0	3630438	15740	7697

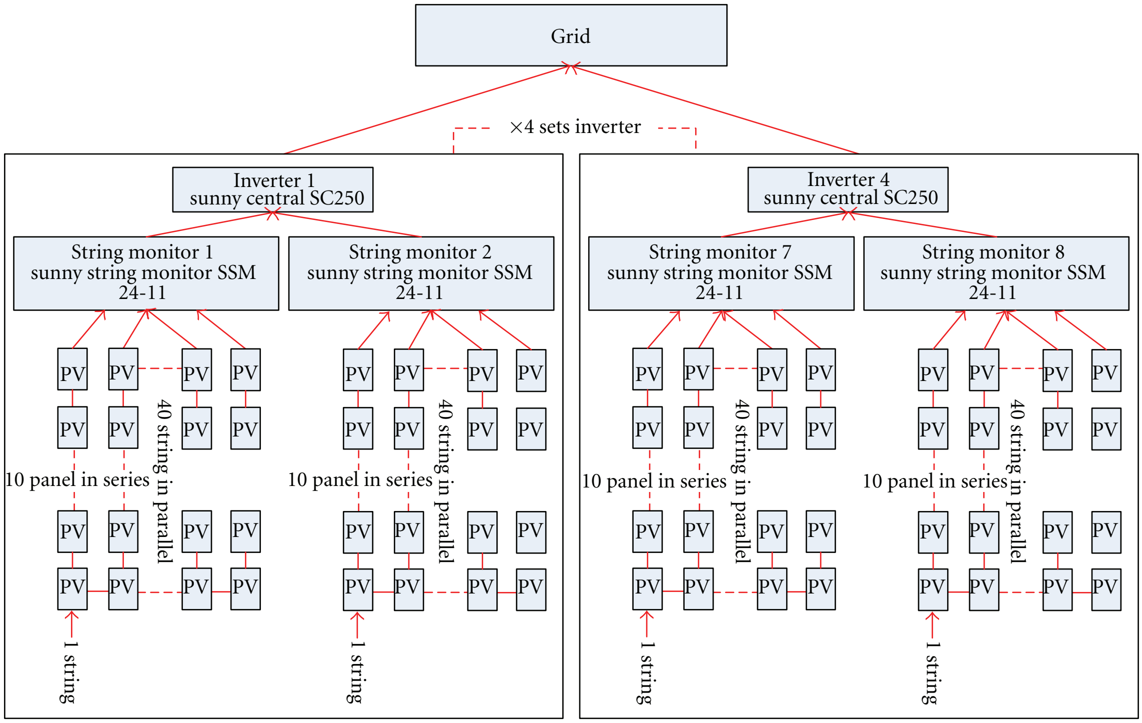

FIGURE 6: Arrangement of PV modules (315 W Sunpower Monocrystalline PV panel) with 4 × 250 kW Sunny inverter central.

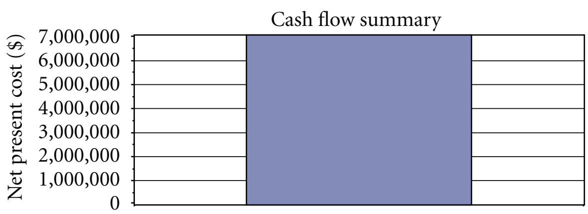

FIGURE 7: The initial capital cost of grid standalone system.

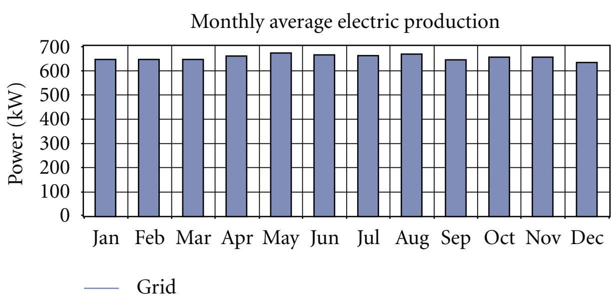

FIGURE 8: Yearly average of electric production for the grid.

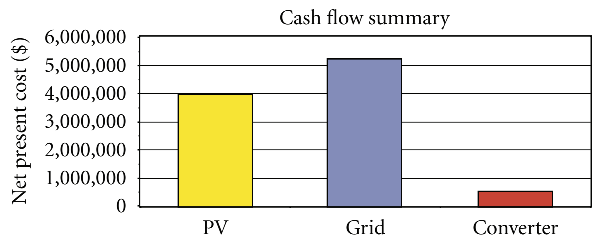

FIGURE 9: Cash flow summary for grid-connected PV system (4 × 250 kW inverter and 3200 × 315 W PV panel).

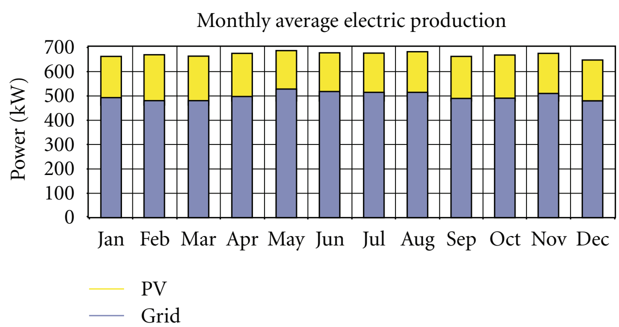

FIGURE 10: Yearly average electric production of grid-connected PV system.

6. Result and Discussion

The simulation was done based on a 25-year projection with annual interest rate of 6%. Simulation results for different configurations of PV modules and inverters were generated by HOMER. Different optimization approaches are done by the HOMER for comparison. In this project, two inverters with different power capacities (250 kW and 500 kW) and three types of PV modules with different output powers (165 W, 225 W, and 315 W) were taken into consideration to output different configurations and optimizations of the

Table 6: Pollutant emission of a grid standalone system and a grid-connected PV system.

Pollutant	Emissions (kg/yr)	
	Grid standalone	Grid-connected PV
Carbon dioxide	3,630,438	2,728,111
Carbon monoxide	0	0
Unburned hydrocarbons	0	0
Particulate matter	0	0
Sulfur dioxide	15,740	11,828
Nitrogen oxides	7,697	5,784
Total emissions	3,653,875	2,745,723

system. Simulation, optimization, and sensitivity analyses for various configurations were done by HOMER.

Table 5 shows some of the optimizations result. The optimized system configuration recommended by HOMER is using the combination of 165 W PV modules with two 500 kW inverters. The net present cost of this optimization is RM 8,836,623 and the cost of generated RE is 12 cents per kilowatt hours. This optimization configuration is rejected because of the flexibility and energy sustainability issue of the system. Although the setup cost of this inverter system might be slightly lower, the system cannot yield maximum utilization of the solar energy in case where either of the inverters failed, which will cause the 50% of the energy from the available PV modules to be wasted. This is compared to 4-inverter system, the system lose only 25% of energy if there is one failed inverter. Therefore, we specially chose system with 4-inverter configuration.

The ratio of output power to area consumption for the PV modules is considered in the project since the minimum area is preferred. Table 3 shows the total number of PV modules required for the 3 types of module and its estimated area consumption in this project.

6.1. Grid Standalone (without Renewable Energy Fraction). From Table 5, the system with the lowest net present cost (NPC) is the grid standalone system without any solar energy generation which is RM 6,940,033. This configuration is also the cheapest energy supply system. From Table 5, the consumer is paying the least cost of energy (COE) at RM 0.095 per kWh. The overall energy is purchased from the grid alone. Thus, the monthly average electrical production (Figure 8) of the grid is identical to seasonal load profile of Figure 2. The capital for this system is zero since there will be no installation of system components required, as shown in Figure 7. The operating cost of this system is the highest which is RM 542,896 because all the energy is purchased from the grid. Although this is the cheapest solution currently available in the market, the operation cost of this grid standalone system is subjected to the changes in the world fossil fuel prices. Simulation of this grid standalone system without RE energy generation is compared to the grid-connected PV system.

6.2. Grid-Connected PV Systems. Several configurations of the grid-connected system will be analyzed. Table 5 shows several selected optimizations of different system configurations from HOMER software. This project selected the system configuration with 4 × 250 kW inverter and PV module of 315 W as the most suitable system as highlighted in Table 5.

Although the NPC of the system is higher, RM 9,684,464, the system has advantages over others in terms of the inverter system failure analysis as mentioned previously, and the area occupied for the PV panels is also the least, as shown in Table 3. The operating cost of this system, RM 413,876, is cheaper compared to grid standalone system since less energy is purchased from the grid. The COE for this system is RM 0.132 which is higher compared to grid standalone system due to the high capital on setup of the system. The net grid purchase is reduced by the PV penetration of 26% for the energy supply. Renewable fraction of 0.26 seems to be a reasonable load sharing between the grid and the PV panels.

Figure 9 shows the cash flow summary of the system. Even though the NPC of the grid is reduced, the overall NPC of the system is increased due to addition of NPC from the PV. This includes the capital cost and operating and maintaining (O&M) cost of the PV in the overall system. Figure 10 shows that a total of 1,499,717 kWh/year of solar energy is generated to support the load, hence reduced the grid purchase to 4,370,732 kWh/year, compared to purchase of 5,744,363 KWh/year in grid standalone system. Also it is noticed that 99% of the system energy is for supporting the load demand and only 1% is sold back to grid.

6.3. Green House Gasses Emission. Energy from the grid is mostly generated with fossil fuel which emits greenhouse gasses [31, 32]. This means that purchasing of the grid energy contributes to emission of the greenhouse gasses. Table 6 compares the emissions generated by each system. The PV grid-connected system observes a significant reduction of emission to 908,152 kg/yr.

7. Conclusion

HOMER simulation has demonstrated that the grid-connected PV system in the long run is beneficial although the NPC of the system is higher compared to grid standalone supply. Large PV energy system may protect industrial expenses from expected fluctuations in fossil fuel prices in years to come. The maintenances cost of PV system itself is not high; hence it is a one-time investment that has higher return rate in the long run. Application of green RE is advisable to save the world from the global warming and potential energy crisis, since solar energy is renewable, free, and abundant. Also, the cost of using solar energy is showing promising, decreasing trend in recent years; it is indeed a viable solution for consumers, industrial, or domestic alike.

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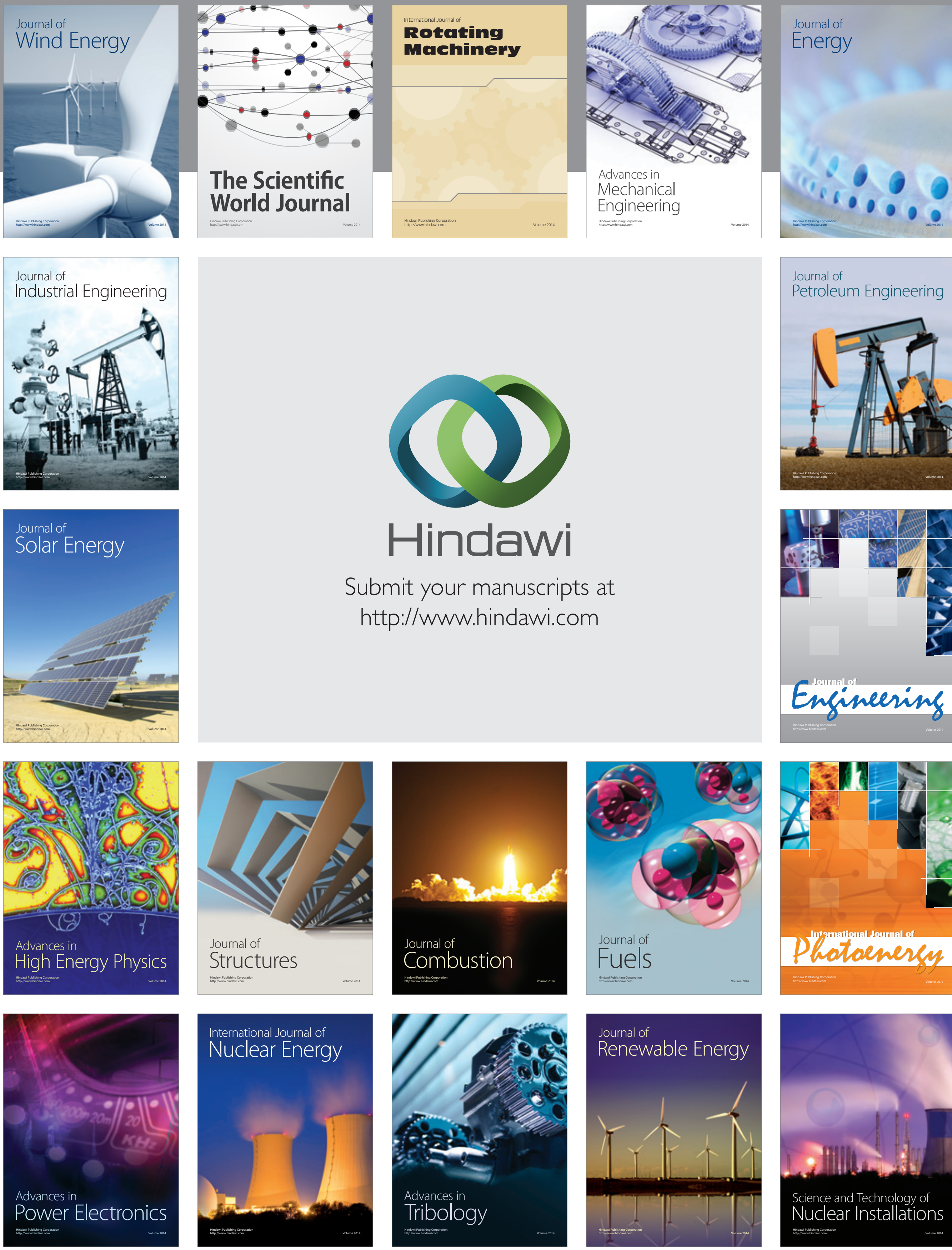
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