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Research Article

Performance Analysis of Hybrid PV/Diesel Energy System in Western Region of Saudi Arabia

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The potential implementation of hybrid photovoltaic (PV)/diesel energy system in western region of Saudi Arabia is analyzed in this paper. The solar radiation intensity considered in this study is in the range of 4.15–7.17 kWh/m^2/day. The HOMER software is used to perform the technical and economical analysis of the system. Three different system configurations, namely, stand-alone diesel system, and hybrid PV/diesel system with and without battery storage element, will be evaluated and discussed. The analysis will be addressed to the impact of PV penetration and battery storage on energy production, cost of energy, number of operational hours of diesel generators, fuel savings, and reduction of carbon emission for the given configurations. The simulation results indicate that the energy cost of the hybrid PV/diesel/battery system with 15% PV penetration, battery storage of 186.96 MWh, and energy demand of 32,962 MWh/day is \$0.117/kWh.

1. Introduction

The Kingdom of Saudi Arabia is blessed with abundant energy resources. It has the world's largest oil reserves and the world's fourth largest proven gas reserves. In addition, the Kingdom also has abundant wind and solar renewable energy resources. However, in this country, the use of its renewable energy resources to generate electricity is negligibly small and almost all its electricity is produced from the combustion of fossil fuels [1]. During the last two decades, electrical energy consumption in Saudi Arabia increased significantly due to rapid economic development and the absence of energy conservation measures. It is expected that peak loads will reach 60 GW in 2023 which causes total investment may exceed \$90 billion. Therefore, there is an urgent need to develop energy conservation policies for sustainable development [2].

Remarkable efforts to diversify energy sources and to intensify the deployment of renewable energy options have been increasing around the world. In recent years, a set of renewable energy scenarios for Saudi Arabia has been proposed to examine the prospects of renewable sources from the perspective of major oil producers. The drive towards renewable energy in Saudi Arabia should not be regarded as being a luxury but rather a must, as a sign of good governance, concern for the environment, and prudence in oil-production policy [3, 4].

The first priority in intensifying renewable energy deployment in the 21st century is the combined effects of the depletion of fossil fuels and the awareness of environmental degradation [5]. Therefore, policy makers and researchers are paying more attention to research in this field. For instance, Alnatheer has conducted researches on environmental impacts of electric energy system expansion in Saudi Arabia. It has been concluded that the use of renewable energy and energy efficiency resources gives significant environmental benefits [6, 7]. Apart from local conservation efforts,

the country has an option to reduce domestic diesel consumption and increase its oil exports. By reducing domestic diesel consumption, subsidies can be used to promote the use of renewable energy. This, in turn, contributes to reducing air pollution and greenhouse gas emissions [3, 8].

As one of renewable energy sources, solar energy is a site-dependent, inexhaustible, benign (does not produce emissions that contribute to the greenhouse effect), and potential source of renewable energy that is being developed by a number of countries with high solar radiation as an effort to reduce their dependence on fossil-based nonrenewable fuels [9]. Saudi Arabia, located in the heart of one of the world's most productive solar regions, receives the most potent kind of sunlight [10]. With the average annual solar radiation of 2200 kWh/m^2 in the Arabian Peninsula, applications of solar energy have been growing since 1960 [9, 10]. Now and in the future, exploitation of this important energy resource becomes more imperative for Saudi Arabia [11].

Makkah is the most populous province of Saudi Arabia. It is located in western region of Saudi Arabia and has annual solar radiation of 247.5 W/m^2. There are many factors affecting the electricity demand in this area, such as weather changes, social life activities (work, school, and prayer times), and special events (Ramadan and Hajj) [12]. With the high electricity demand during both day- and nighttime, replacing diesel generators with PV/battery system is not a wise solution. Therefore, very large sizes of PV and battery are needed to meet the electricity demand; otherwise, electricity shortages will occur.

Many researchers have reported that hybrid PV/diesel/battery system is more economically viable than stand-alone diesel system [13–16]. It is not happening in Makkah at the present time. Operation cost for the stand-alone diesel generators is relatively cheap in Makkah because of the low diesel fuel price. However, diesel generators are not environmentally friendly. Although hybrid PV/diesel/battery system is more expensive than the stand-alone diesel, the hybrid system gives other various advantages, such as improved reliability and reduced pollution and emission.

In this paper, a hybrid PV/diesel system is designed to reach its optimum performance to meet load demand in Makkah. Diesel generators are used as a backup for the hybrid system. Minimum sizes of the hybrid system components required to achieve zero unmet electric loads are determined using hybrid optimization model for electric renewable (HOMER) software [17].

2. Solar Irradiance Data

Saudi Arabia is one of the driest and hottest countries in the world. The global solar irradiation in Saudi Arabia is shown in Figure 1. Either the clearness index or the solar irradiation data can be used to represent the solar resource. Based on data from NASA surface meteorology and solar energy (http://eosweb.larc.nasa.gov), the solar irradiation in Makkah (21°26′ North, 39°49′ East) is between 4.15 kWh/m^2/day and 7.17 kWh/m^2/day. The scaled annual average of the solar radiation is estimated to be 5.94 kWh/m^2/day. Figure 2 shows the

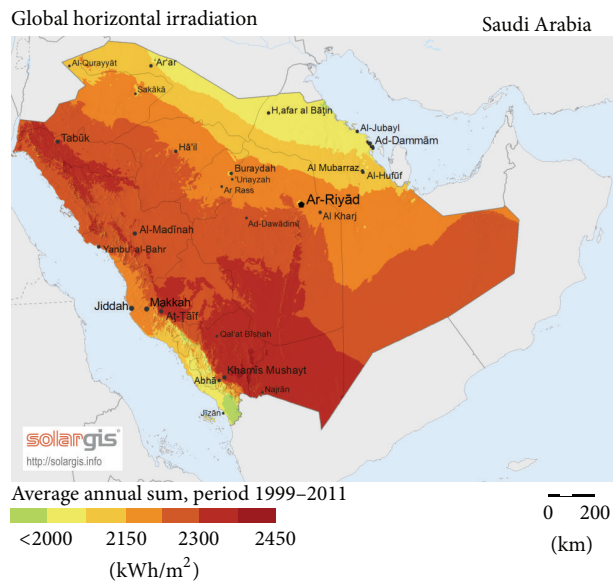

Figure 1: Solar irradiation map in Saudi Arabia.

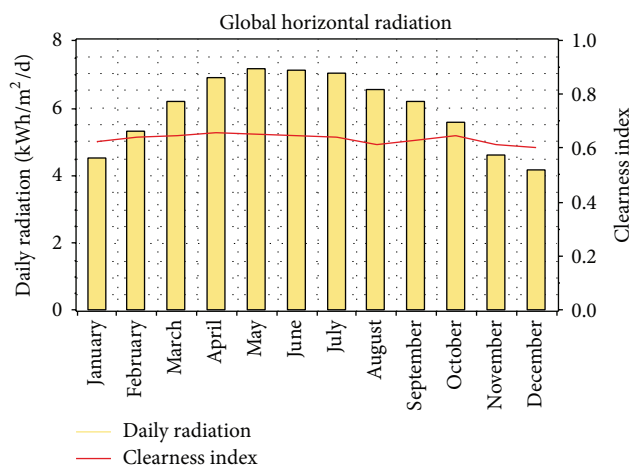

Figure 2: Solar irradiation data.

solar irradiation data; on the right axis is the clearness index of the solar irradiation. It is clearly shown that solar irradiance is high (above the average) in March–September with a peak in June, while solar irradiance is low in January, February, October, November, and December as shown in Figure 3.

3. Design and System Specifications

3.1. Primary Load. The load demand in Makkah varies monthly. Three different reasons for increases in the load demand in Makkah are due to (1) special occasions (Eid al-Fitr, National Day), (2) religious occasions (Hajj, Ramadan, and Umra), and (3) climate conditions. The maximum peak load occurs in the summer season. Sometimes there is an overlapping between the summer season and the Hajj or Ramadan month resulting in a much higher load demand for that period.

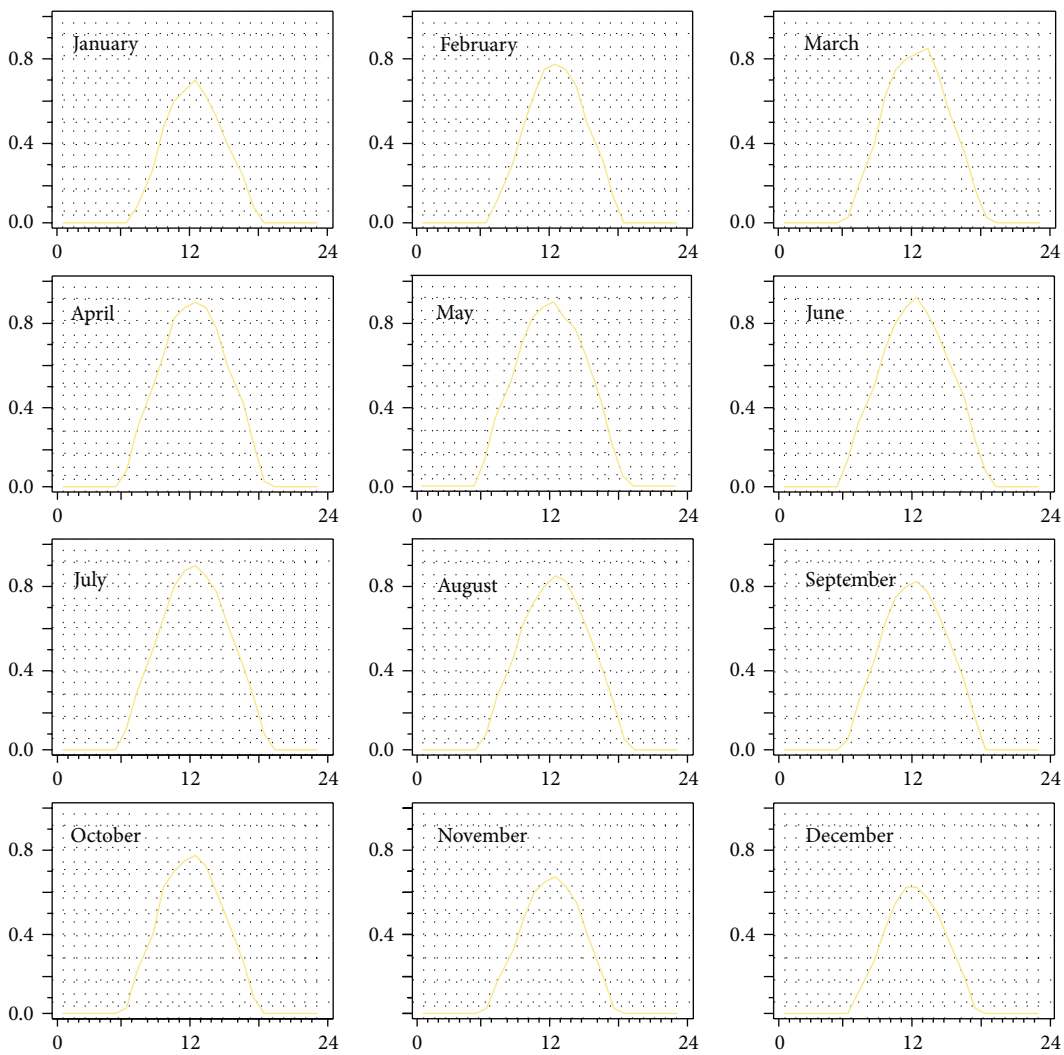

Figure 3: Monthly solar irradiation data.

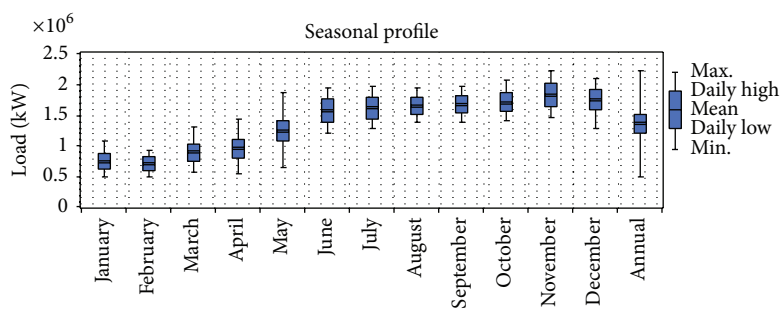

Figure 4: Monthly load profile of Makkah.

Load profile of Makkah is presented in Figure 4. From the load profile, it is shown that peak load in Makkah is 2,213 MW with energy consumption of 32,962 MWh/day. The peak load is about 0.023% or 2 hours during the year.

3.2. Design Specification. In this design, the hybrid PV/diesel/battery system consists of four main system components: (1) PV modules, (2) storage batteries, (3) diesel generators, and (4) inverters. The configuration of the hybrid PV/diesel/battery system is shown in Figure 5.

3.2.1. Diesel Generator (DG). A diesel generator (DG) is characterized by its fuel consumption and efficiency. The fuel characteristic describes the amount of fuel the generator

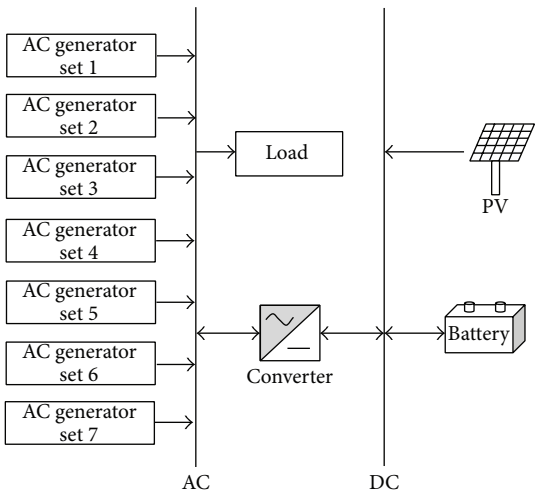

Figure 5: Configuration of hybrid PV/diesel/battery system.

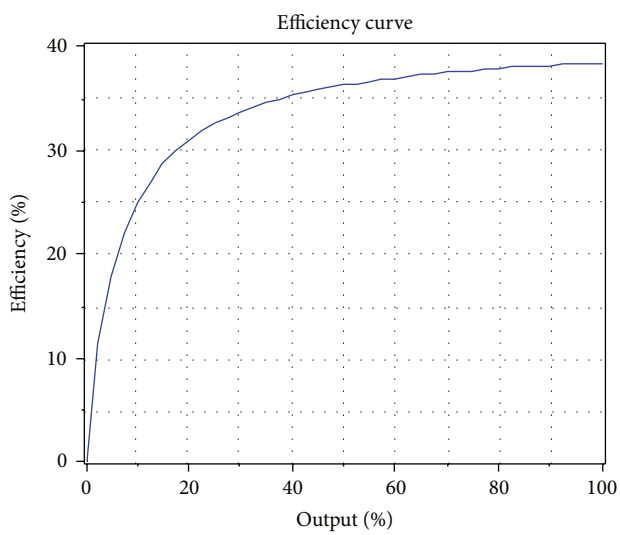

Figure 6: Efficiency curve.

Table 1: Generator groups.

Group	Number of units	Total capacity (MW)
Generator 1	4	320
Generator 2	4	320
Generator 3	4	320
Generator 4	4	320
Generator 5	4	320
Generator 6	4	320
Generator 7	2	160

consumes to produce electricity. The efficiency curve defines electrical energy coming out divided by the chemical energy of fuel going in.

In this design, the DGs have the fuel intercept coefficient of 0.01609 L/kWh and the fuel slope of 0.2486 L/kWh. The efficiency curve of the DGs is shown in Figure 6. The DGs are used as a backup during peak demand periods which cannot be fulfilled by PV and battery. The DGs also support the battery at nighttime when the PV has stopped producing electricity. In order to cover the peak load of 2,213 MW, 80 MW/unit DG is used in the simulation. There are 26 DGs employed in this design to meet the load demand. They are distributed into 7 groups of generators as illustrated in Figure 5. Table 1 presents amount of DGs in each group. The DG cost and technical data are provided in Table 2.

Table 2: DG data.

DG	
Size	80 MW
Lifetime	15000 hr
Min. load ratio	40%
Capital cost	$400/kW
Replacement cost	$350/kW
Operating and maintenance cost	$0.05/hr

Table 3: PV data.

PV system	
Size	1.1–2.2 GW
Lifetime	20 yr
Derating factor	90%
Capital cost	$2500/kW
Replacement cost	$2000/kW
Operating and maintenance cost	$3/yr

3.2.2. Photovoltaic (PV). Solar energy is used as the base-load power source. PV array size is dependent on the load profile, solar radiation, and renewable fraction. The renewable fraction is the fraction of the energy delivered to the load that originated from renewable power sources, and in this case the renewable fraction is related to the PV production.

With the peak load of 2.2 GW, the initial PV size of 2.2 GW is fair enough for the PV/diesel/battery hybrid system. The PV size can be either increased or decreased, according to the amounts of unmet electric load and renewable fraction set in the design. This PV size will be used to cater for the variety of load demand in a year. PV array will only generate electricity at daytime, from 6 a.m. to 6 p.m. The excess generated power will be used to charge the battery. The PV cost and technical data are provided in Table 3.

3.2.3. Inverter. The PV arrays produce direct current (DC) at a voltage that depends on the design and the solar radiation. The DC power then runs to an inverter, which converts it into standard AC voltage. The inverter size is rated based on the selected PV size, in order to maximize the quantity of energy which is harvested from the PV arrays. For 2.2 GW rated output PV, the inverter is rated at 2.2 GW to fully supply the power from the PV. However, it is frequently sized below the PV rated output because the PV does not always produce its full rated power. Smaller size inverter will minimize inverter

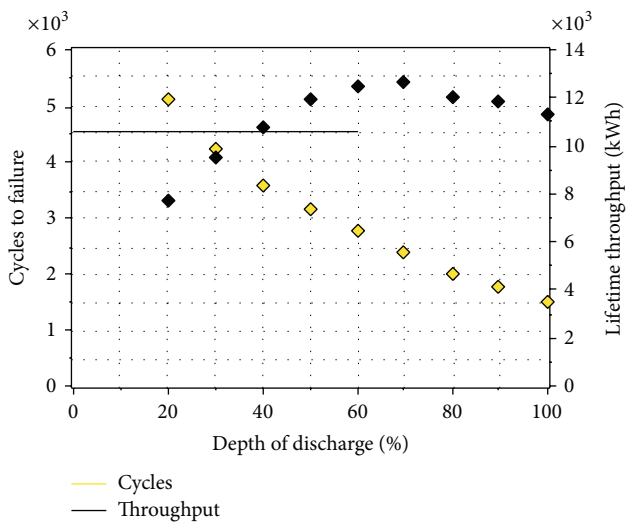

Figure 7: Lifetime curve.

Table 4: Inverter data.

Inverter	
Size	<2.2 GW
Lifetime	10 yr
Efficiency	90%
Capital cost	$400/kW
Replacement cost	$375/kW
Operating and maintenance cost	$20/yr

Table 5: Battery data.

Battery	
Type	Surrette 4KS25P
Lifetime	12 yr
Batteries per string	12
Nominal voltage	4 V (48 V)
Nominal capacity	1900 Ah
Nominal energy capacity of each battery	7.60 kWh
Capital cost	$1200/quantity
Replacement cost	$1200/quantity
Operating and maintenance cost	$60/yr

cost but does not reduce the system performance. A brief summary on the data for inverter is provided in Table 4.

3.2.4. Battery. Battery is used as a storage device which has two operation modes: charging and discharging. Excess electricity from PV or other sources can be stored in the battery. The purpose of the battery is to alleviate the mismatch between the load demand and electricity generation.

State of charge (SOC) indicates the level of battery charge. When the battery is fully charged, the SOC level is 100%. Battery has its specific minimum SOC allowed to operate, and it is usually recommended by the battery manufacturers.

The battery chosen is Surrette 4KS25P. It is a 4-volt deep cycle battery rated at 1,900 Ah at 100 hour rate. The battery's safe operating SOC is between 40% and 100%. Lifetime of the battery is 12 years for operating within the safe region. It will shorten the battery's lifetime if operated below the SOC of 40% or over DOD of 60% as shown in Figure 7. The battery lifetime throughput is 10,569 kWh when operated with minimum SOC of 40% or maximum DOD of 60%. The data for battery is provided in Table 5.

4. Cost of Carbon Emissions

Carbon emissions cause economic costs of damage and resulting climate change. The cost of carbon emissions is calculated by multiplying tons of CO_2 emitted for each type of plant system by an assumed cost per ton for carbon emission. The cost per ton for carbon emissions is not set in Saudi Arabia since there is currently no CO_2 market mechanism. However, emission penalties can be added to analyze the total annual cost of the power system on the assumption that the penalties are $50/t for CO_2, $900/t for SO_2, $2600/t for NO_x, and $2800/t for PM [18, 19].

5. Simulation Results and Discussions

Performance of the stand-alone diesel system, hybrid PV/diesel system without battery, and hybrid PV/diesel system with battery is discussed in this section. Simulations for various configurations are performed by considering the total battery storage sizes of 186.96 MWh for 5 min/autonomy (equivalent to 5 min of average load), while the hourly average load is 1,373.434 MWh/hr.

5.1. Stand-Alone Diesel System. From the simulation results, it can be found that stand-alone diesel system without renewable penetration gives total net present cost (NPC) of $17,335,490,560 and CO_2 emission of 8,460,421,632 kg/yr. This system offers 0% for both the unmet load and excess electricity. This is according to the diesel price of $0.067/L. The cost of energy (COE) for this stand-alone diesel system is $0.102/kWh.

Monthly average electric production and cash flow summary are shown in Figures 8 and 9, respectively.

5.2. Hybrid PV/Diesel System without Battery. To determine the feasibility of hybrid PV/diesel installation, four configuration options will be analyzed:

(1) option 1: PV (1.1 GW) with DGs;
(2) option 2: PV (2.2 GW) with DGs;
(3) option 3: PV (3.3 GW) with DGs;
(4) option 4: PV (4.4 GW) with DGs.

5.2.1. Option 1: PV (1.1 GW) with DGs. From the simulation results, it can be noticed that this system gives total NPC of $20,139,882,496 and CO_2 emission of 7,198,296,576 kg/yr. The COE for this system is $0.119/kWh with PV penetration of 15%.

Monthly average electric production and cash flow summary are illustrated in Figures 10 and 11, respectively.

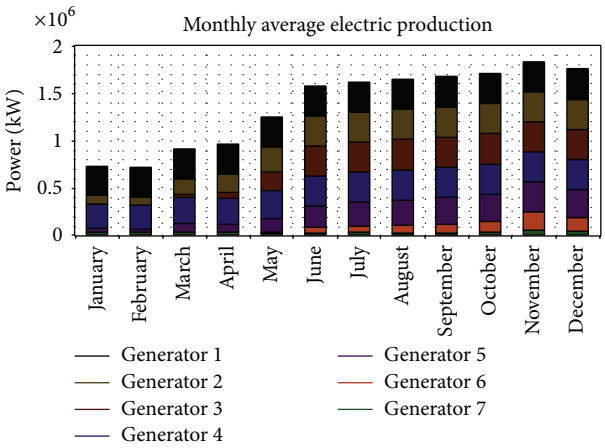

FIGURE 8: DGs monthly average electric production.

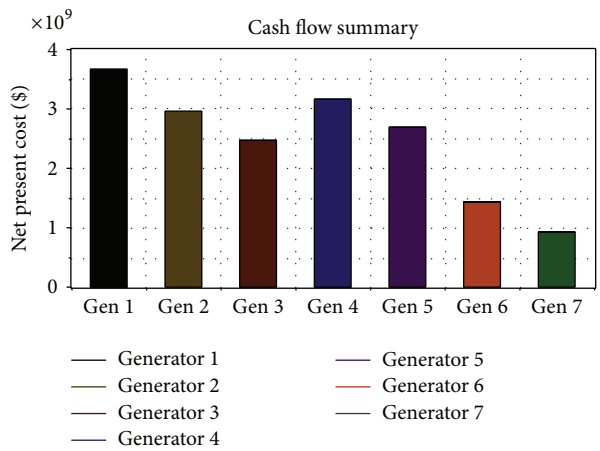

FIGURE 9: DGs cash flow summary.

5.2.2. Option 2: PV (2.2 GW) with DGs. From the simulation results, it can found that this system gives total NPC of \$20,995,399,680 and CO_2 emission of 6,276,211,200 kg/yr. The COE for this system is \$0.124/kWh with PV penetration of 26%.

Monthly average electric production and cash flow summary are shown in Figures 12 and 13, respectively.

5.2.3. Option 3: PV (3.3 GW) with DGs. From the simulation results, it can be seen that this system gives total NPC of \$22,260,590,592 and CO_2 emission of 5,742,476,288 kg/yr. The COE for this system is \$0.131/kWh with PV penetration of 32%.

Monthly average electric production and cash flow summary are illustrated in Figures 14 and 15, respectively.

5.2.4. Option 4: PV (4.4 GW) with DGs. From the simulation results, it can be noticed that this system gives total NPC of \$23,976,376,320 and CO_2 emission of 5,408,787,456 kg/yr. The COE for this system is \$0.141/kWh with PV penetration of 36%.

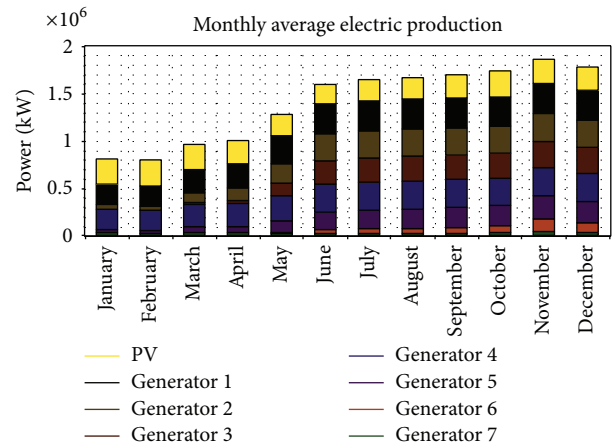

FIGURE 10: Monthly average electric production.

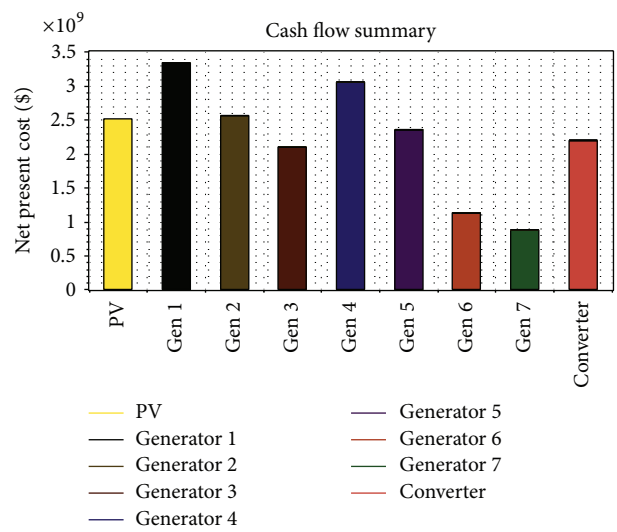

FIGURE 11: Cash flow summary.

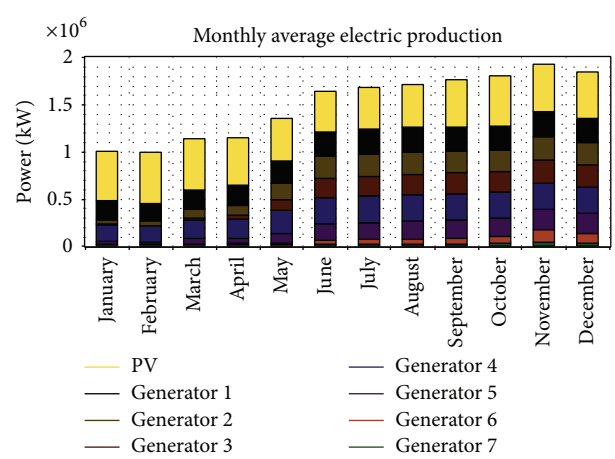

FIGURE 12: Monthly average electric production.

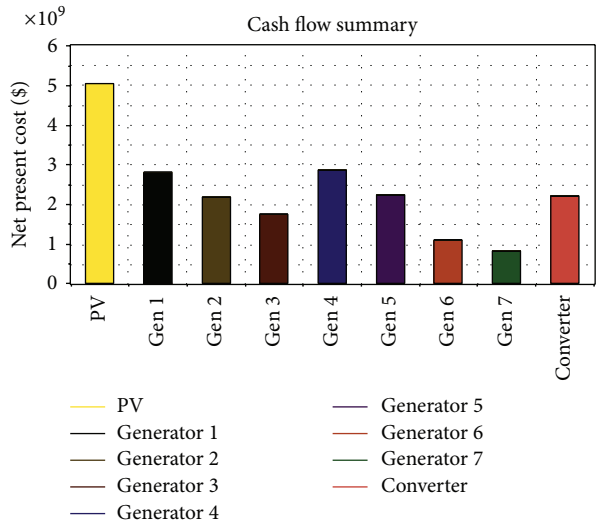

Figure 13: Cash flow summary.

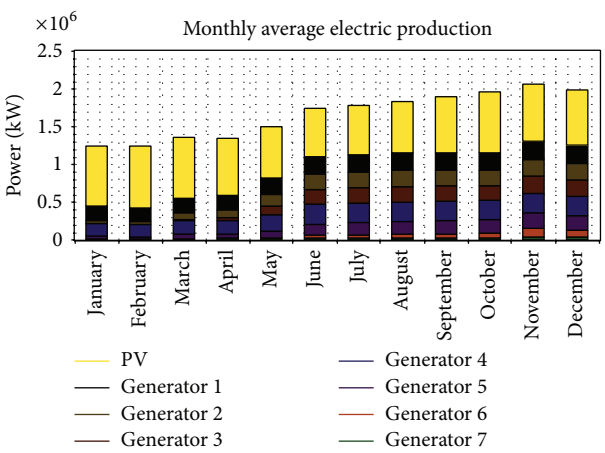

Figure 14: Monthly average electric production.

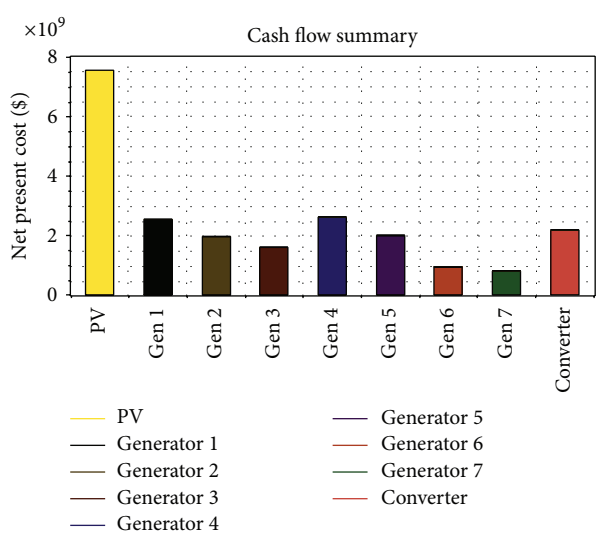

Figure 15: Cash flow summary.

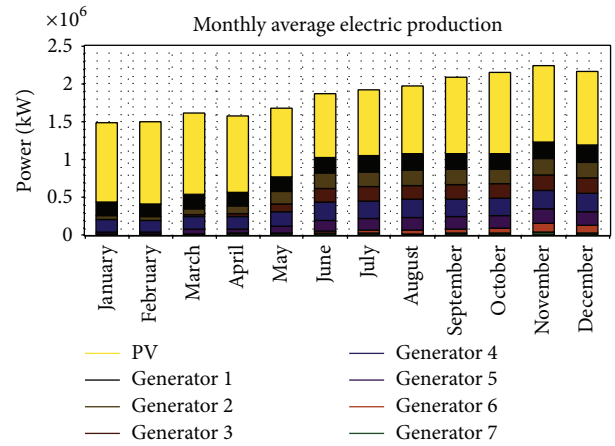

Figure 16: Monthly average electric production.

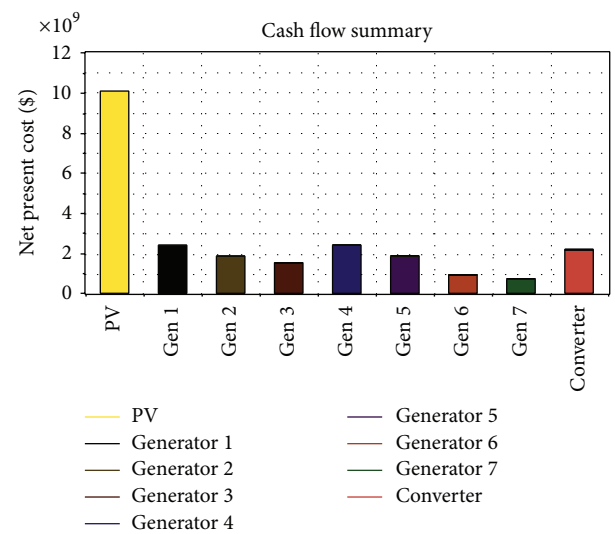

Figure 17: Cash flow summary.

Monthly average electric production and cash flow summary are shown in Figures 16 and 17, respectively.

From the simulation results, it can be found that option 1 is the cheapest and the minimum system requirement to meet all demands. All of them offer the unmet load of 0% as summarized in Table 6.

High PV penetration might result in difficulties in control while maintaining stable voltage and frequency. The level of renewable energy penetration in real application is generally in the range of 11–25%. The utilization of the bigger PV array size will result in a higher value of the total NPC as well as the COE. On the other hand, reducing the PV size will result in higher dependence of DGs and give more CO_2 emission. Therefore, the use of PV array size between 1.1 and 2.2 GW is justified.

5.3. Hybrid PV/Diesel System with Battery. From the simulation results, it can be seen that this system gives total NPC of \$19,849,900,032 and CO_2 emission of 7,176,592,896 kg/yr.

Table 6: Hybrid PV/diesel system without battery performance.

Config.	Unmet load (%)	Excess elect. (%)	NPC ($)	COE ($/kWh)	PV penet.n (%)	CO_2 emissions (kg/yr)
Option 1	0%	0.94	20,139,882,496	0.119	15	7,198,296,576
Option 2	0%	6.09	20,995,399,680	0.124	26	6,276,211,200
Option 3	0%	14.60	22,260,590,592	0.131	32	5,742,476,288
Option 4	0%	23.20	23,976,376,320	0.141	36	5,408,787,456

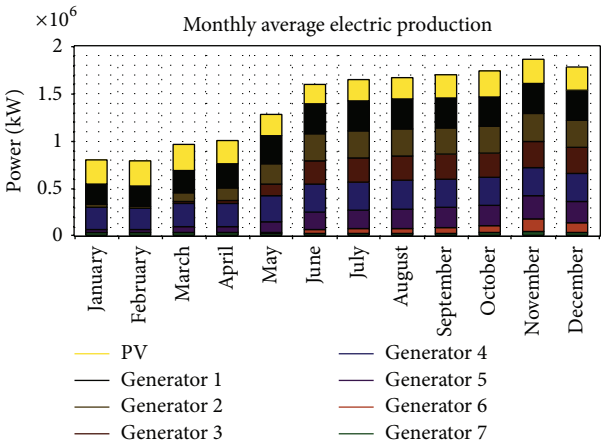

Figure 18: Monthly average electric production.

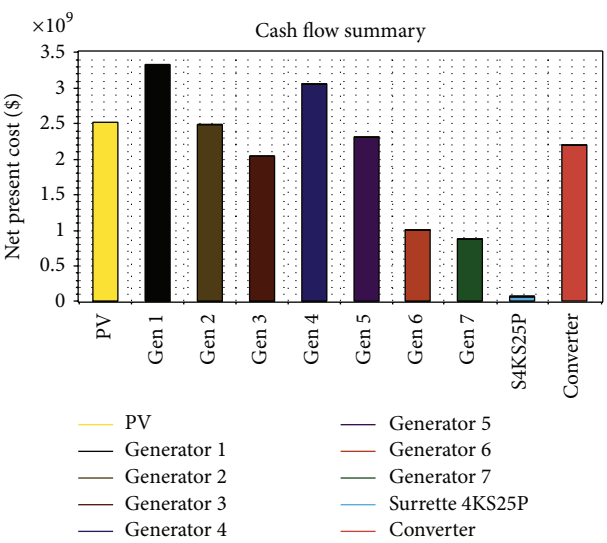

Figure 19: Cash flow summary.

The COE for this system is $0.117/kWh with PV penetration of 15%.

From the previous results, it is shown that PV array size between 1.1 and 2.2 GW offers satisfying options. To determine the feasibility of hybrid PV/diesel with battery installation, two options of configurations are considered:

(1) option 1: PV (1.1 GW) with battery and DGs;

(2) option 2: PV (2.2 GW) with battery and DGs.

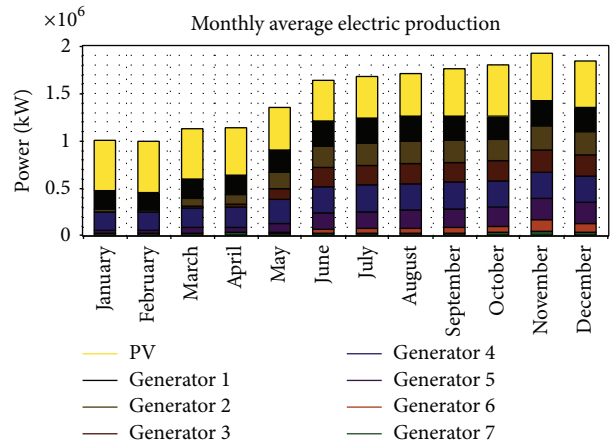

Figure 20: Monthly average electric production.

5.3.1. Option 1: PV (1.1 GW) with Battery and DGs. Monthly average electric production and cash flow summary are illustrated in Figures 18 and 19, respectively.

5.3.2. Option 2: PV (2.2 GW) with Battery and DGs. From the simulation results, it can be found that this system gives total NPC of $20,690,055,168 and CO_2 emission of 6,247,786,496 kg/yr. The COE for this system is $0.122/kWh with the PV penetration of 26%.

Monthly average electric production and cash flow summary are shown in Figures 20 and 21, respectively.

The summaries of hybrid PV/diesel system with battery are presented in Table 7.

5.4. Comparing Designs. The hybrid PV/diesel system using PV array size of 1.1 GW gives 15% renewable penetration. This penetration value makes sense for real-world application. Further, the utilization of PV array size more than 1.1 GW is out of consideration, since it would result in higher values of the total NPC as well as the COE. In addition, higher contribution of renewable energy penetration might give problems related to system instability.

The summaries of the stand-alone diesel system, hybrid PV/diesel system without battery, and hybrid PV/diesel system with battery are presented in Table 8. By using the proposed hybrid PV/diesel system without battery, the total NPC is $20,139,882,496. This system is the most expensive system configuration as can be seen in Table 8. One of the main reasons is that the power generated by PV is not being fully utilized. If there are no storage devices, the excess solar electricity

Table 7: Performance of hybrid PV/diesel system with battery.

Config.	Unmet load (%)	Excess elect. (%)	NPC ($)	COE ($/kWh)	PV penet.n (%)	CO_2 emissions (kg/yr)
Option 1	0%	0.84	19,849,900,032	0.117	15	7,176,592,896
Option 2	0%	5.93	20,690,055,168	0.122	26	6,247,786,496

Table 8: Stand-alone diesel and hybrid PV/diesel with and without battery.

Config.	Unmet load (%)	Excess elect. (%)	NPC ($)	COE ($/kWh)	PV penet.n (%)	CO_2 emissions (kg/yr)
Diesel	0%	0.00	17,335,490,560	0.102	0	8,460,421,632
PV/diesel	0%	0.94	20,139,882,496	0.119	15	7,198,296,576
PV/diesel/battery	0%	0.84	19,849,900,032	0.117	15	7,176,592,896

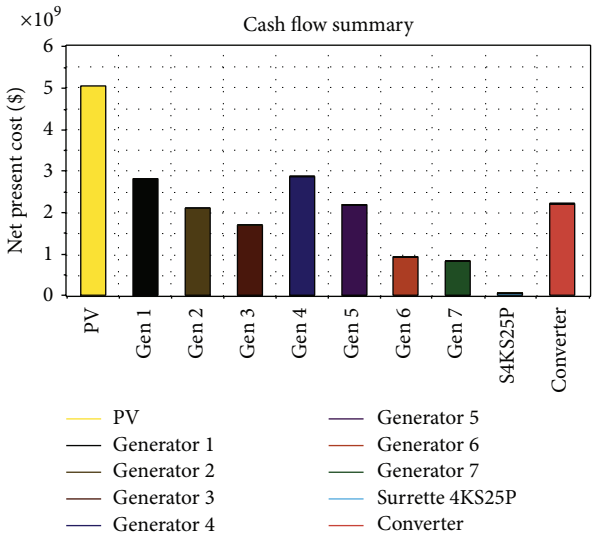

Figure 21: Cash flow summary.

cannot be stored and is considered as losses. When the PV cannot meet the load demand, the DGs will be then operated to cope for the demand. The yearly load has to be provided by DGs if the PV/diesel system does not use battery storages [20].

Although storage devices are typically very expensive, they are very important to ensure that the excess electricity produced from PV can be stored for later use. It would greatly optimize the system and, as a result, the PV/diesel system with battery is less expensive than the PV/diesel system without battery.

The COE of hybrid PV/diesel/battery system (15% PV penetration) with 5-minute battery autonomy is $0.117/kWh (diesel fuel price of $0.067/L). This value is lower than the COE of hybrid PV/diesel system under similar condition which is $0.119/kWh. As reported in some pieces of literature, the COE of PV/diesel system in some countries is in the range of $0.22–0.96/kWh [14, 21–27]. The COE varies depending on diesel fuel prices, PV penetrations, and interest rates.

The present cost of electricity production by diesel power plant in Makkah is about $0.10/kWh. This cost of electricity production matches the simulation result for the stand-alone diesel as shown in Table 8. The average electricity price for residence in Makkah is about $0.0133–0.0693/kWh (1 $ = 3.75 SAR). Residential buildings consume most of electricity in Saudi Arabia and estimated 45–47% of the total electrical energy generated in the country [20, 28]. The difference between cost and price is paid from the government resources which subsidize fuel and electricity prices.

As shown in Table 8, the stand-alone diesel system is cheaper than the hybrid PV/diesel system either with or without battery for application in Makkah. It is because of the cheap subsidized diesel fuel price in Makkah.

By renewable energy penetration of 15% (as in hybrid PV/diesel with battery), the use of diesel fuel can be reduced from 3,212,823,296 L/yr to 2,725,292,544 L/yr. In this case, the country can save 487,530,752 L of diesel fuel per year. From environmental viewpoint, the use of hybrid PV/diesel system will significantly reduce CO_2 emission from 8,460,421,632 kg/yr to 7,176,592,896 kg/yr.

6. Conclusion

The HOMER software has simulated three different system configurations, namely, stand-alone diesel system, hybrid PV/diesel system, and hybrid PV/diesel/battery system, for two options of PV array size, that is, 1.1 GW and 2.2 GW. The hybrid PV/diesel system using PV array size of 1.1 GW gives 15% renewable penetration. This penetration value makes sense for the real-world application. From the simulation, it has been clearly demonstrated that the stand-alone diesel system has the lowest COE but the highest CO_2 gas emission. The use of hybrid PV/diesel system will significantly reduce CO_2 gas emission from environmental point of view. On the other hand, the configuration of hybrid PV/diesel system without battery is the most expensive system. One of the main reasons is that the power generated by PV is not being fully utilized. Since the storage devices are very important to ensure that the excess electricity produced by PV array can be stored for later use, it would greatly optimize the system. As a conclusion, the PV/diesel system with battery is more economical than the PV/diesel system without battery.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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