High-Efficient and Low Cost Hybrid Renewable Energy Systems Configuration for Mina Region

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تشكيل أنظمة الطاقة المتجددة بكفاءة عالية وتكلفة منخفضة لمنطقة منى

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ملخص البحث (Abstract):

تقع منى في منطقة مكة المكرمة ، المملكة العربية السعودية حيث توجد ١٠٠٠٠٠ خيمة مكيفة لتوفير الإقامة المريحة للحجاج. وقد تبين من المسح الأدبي أنه خلال موسم الحج ٢٠١٨ كان الطلب على الكهرباء في اليوم حوالي ٢٨٥ ميجاوات، ٧٠٪ من تلك الكهرباء كانت تستخدم في تكييف والتبريد. تم تزويد هذه الطاقة بالكامل من محطات الطاقة التقليدية التي تعمل بالوقود الأحفوري (النفط والغاز الطبيعي). إن الاعتماد المستمر على الوقود الأحفوري الذي يمثلا مصدر أساسي للطاقة قد يستنفد سريعا ، و قد يسبب التلوث البيئي ، وله أثار سلبي للغاية على صحة الإنسان والاقتصاد الوطني. لذلك ، قد يكون استخدام مزيج من مصادر الطاقة المتجددة المختلفة المسماة بنظام الطاقة المتجددة المختلط (HRES) حلاً لهذه المشكلة. في هذا الصدد ، تعرض هذه الورقة تنفيذ منهجية جديدة باستخدام برنامج (HOMER) الشهير للتوصل إلى تصميم مرن للشبكة HRES. وقد تم إختيار منطقة منى في المملكة العربية السعودية لإجراء تقييم تقني-اقتصادي مفصل ، وتحليلات للأداء التشغيلي ، وتقييم الجوانب البيئية المتعلقة بالنظام المذكور لكل من الأنظمة المتصلة بالشبكة. تم النظر في أنظمة مختلفة من الخلايا الكهروضوئية (PV)، ومولدات الديزل ، وبطاريات التخزين في هذا العمل لمعرفة أي مجموعة تناسب المنطقة بتكلفة منخفضة وأثر بيئي أقل. كما تم إجراء تحليل الحساسية لتمثيل آثار تغيير المعايير الرئيسية ، مثل: الوقود ، PV ، أسعار البطاريات ، إعادة البيع ، شراء الطاقة والحمل المطلوب بالنسبة لأداء النظام. تظهر النتائج بأن الأفضلية تتجه نحو استخدام مصادر الطاقة المتجددة التي بدورها تعتبر أقل تكلفة. يعتبر نظام PV / Diesel / Battery الهجين الأفضل تقنيا بالمقارنة مع جميع السيناريوهات الأخرى لكل من التوصيلات الخارجية والشبكة ، بالاضافة الى تمتعها بالأداء الاقتصادي والبيئي الجيد ، مما يؤدي إلى زيادة استدامة النظام.

الكلمات الدالة: الكهروضوئية (PV)، مولدات الديزل ، بطاريات التخزين ، نظام الطاقة المتجددة الهجين

In this paper, the implementation of a novel approach using Hybrid Optimization of Multiple Electric Renewables (HOMER) software to come up with a flexible design of a hybrid renewable energy sources (HRES) is presented. Mina region of Makkah, Saudi Arabia has been considered to conduct detailed techno-economic assessments, analyses of operational performance, and the evaluation of environmental aspects relating to the aforementioned system for both off-grid and grid connected modes. Different combination of photovoltaic (PV), diesel generators, and storage batteries has been considered in this work to see which combination fits the city with low cost of energy and less environmental effect. A sensitivity analysis was also conducted to represent the effects of changing main parameters, such as; fuel, sell-back, power purchase and load demand on the system performance. The results show more trends towards using renewable energy sources in energy which has the lowest net present cost (NPC) and the cost of energy (COE). Hybrid PV/Diesel/Battery system is seen to be the best technical performance compared to all other scenarios for both off-grid and on-grid connections, while also reporting good economic and environmental performance, which result in increased system sustainability.

Keywords: Grid connection; HOMER; Hybrid RE system.

1. Introduction:

The Kingdom of Saudi Arabia is privileged with ample energy resources. Though the Kingdom has bounteous wind and solar renewable energy resources, almost all its electricity is produced from the fossil fuels by overlooking the use of renewable energy resources to generate electricity [1]. Electrical energy consumption in Saudi Arabia has increased remarkably during the last two decades. It is expected that peak loads will reach 60GW in 2023, which may cause the total investment to exceed $90 billion [2]. Therefore, the need to develop energy conservation policies for sustainable development has become essential in Saudi Arabia.

A set of renewable energy frameworks for Saudi Arabia has been proposed in recent years to inspect the prospects of renewable sources by taking account the combined consequences of the awareness of environmental deterioration and the alleviation of fossil fuels and [3-5]. Solar energy being one of the potential renewable energy sources, is an inexhaustible, site dependent, eco-friendly, which is initiated by a number of countries with high solar radiation as an effort to lessen their reliance on fossil-based nonrenewable fuels [6]. Saudi Arabia receives the most effective kind of sunlight for existing in the heart of one of the world's most productive solar regions [7]. Applications of solar energy have been evolving since 1960 with the average annual solar radiation of 2200 kWh/m2 in the Arabian Peninsula [6, 7]. Now and in the future, for Saudi Arabia exploitation of this important energy resource becomes more indispensable [8].

Mina is located in Makkah Province of Saudi Arabia where to provide accommodations to visiting pilgrims 100,000 air-conditioned tents are installed. It has annual solar radiation of 247.5W/m2 and is located in western region of Saudi Arabia. In this area, there are many factors influencing the electricity demand, such as weather changes, social life activities (work, school, and prayer times), and special events (Ramadan and Hajj) [9, 10]. Replacing diesel generators (DG) with small/medium size or standalone PV/battery system is not a wise solution with the high electricity demand during both day and night time. Therefore, to reduce the electricity shortages PV and battery should be integrated with DG to form HRES. Since it is more economically viable than stand-alone diesel system [10]. However, this is not happening at the present time in Mina due to the low diesel fuel price compared to high operation cost of HRES. HRES gives various advantages, such as improved reliability and reduced pollution and emission, although the system is expensive than the stand-alone diesel system. In addition, according to 2030 vision of Saudi Arabia government, to reserve their oil and gas resources they want to diversify their power generation system from fossil fuel to renewable energy based system [10].

In this regard, by taking into account 50,000 tents located in Mina region of Makkah, Saudi Arabia a detailed framework of a flexible HRES design has been proposed in this paper which includes all associated operational performance parameters in both off-grid and on-grid connections. Furthermore, to design and analyze a flexible HRES performance, it demonstrates a comprehensive approach using HOMER software.

2. Methodology:

Successful evaluation of any renewable energy project requires appropriate criteria to be applied on the selected area to ensure that the operational behavior of different scenarios can be analyzed in an accurate manner. The following analysis frameworks are used in the current work.

2.1 Specification of the selected site

The work examines Mina region of Makkah Province which is located western part ((21°26′ North, 39°49′ East) of Saudi Arabia where 100,000 air-conditioned tents are built to provide accommodations for visiting pilgrims. It has been observed that the energy demand in this region is completely fulfilled by the nation grid and 70% of the total electricity has been used on air conditioning and cooling.

Figure 1 shows the monthly load profile of 50,000 tents located in Mina, Makkah, Saudi Arabia. It is observed for the selected tents the peak load in Mina is 410 kW with energy consumption of 35,462 kWh/day.

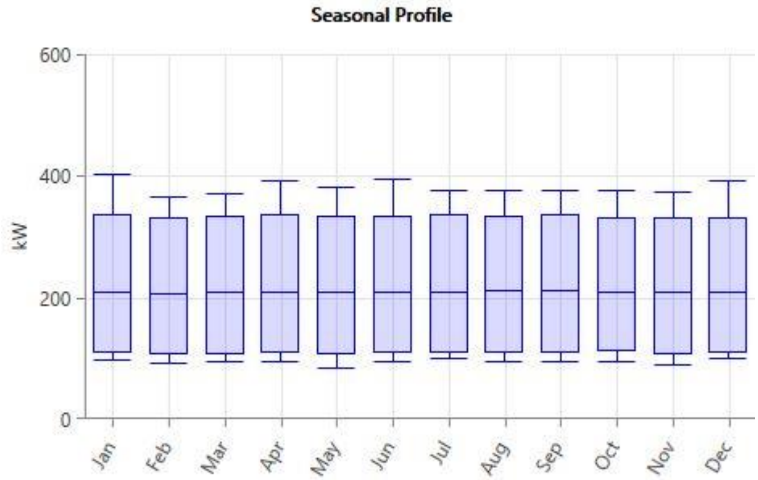

Fig. 1. The daily load profile of Mina

2.2 Solar resource and temperature

In this framework, HOMER software uses the monthly average global horizontal solar radiation and ambient temperature as input parameters.

- The solar radiation and clearance index data for the Mina region of Makkah, Saudi Arabia (21°26′ North, 39°49′ East) are presented in Figure 2. These data are obtained from the NASA website. The, maximum solar radiation (7.17 kWh/m^2/day) is recorded in May, and the minimum solar radiation (4.15 kWh/m^2/day) is recorded in December.

- The monthly average ambient temperature for the chosen area is illustrated in Figure 3. The summer season shows the highest ambient temperature, at 38.15 °C in July, and the lowest ambient temperature, at 30.05 °C in January.

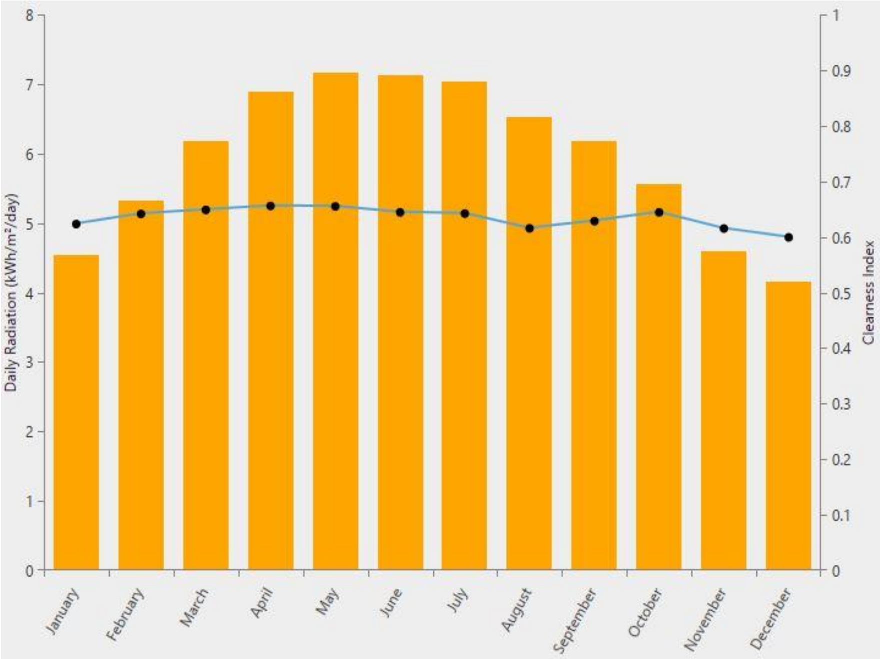

Fig. 2. Monthly average solar global radiation and clearance index of Mina

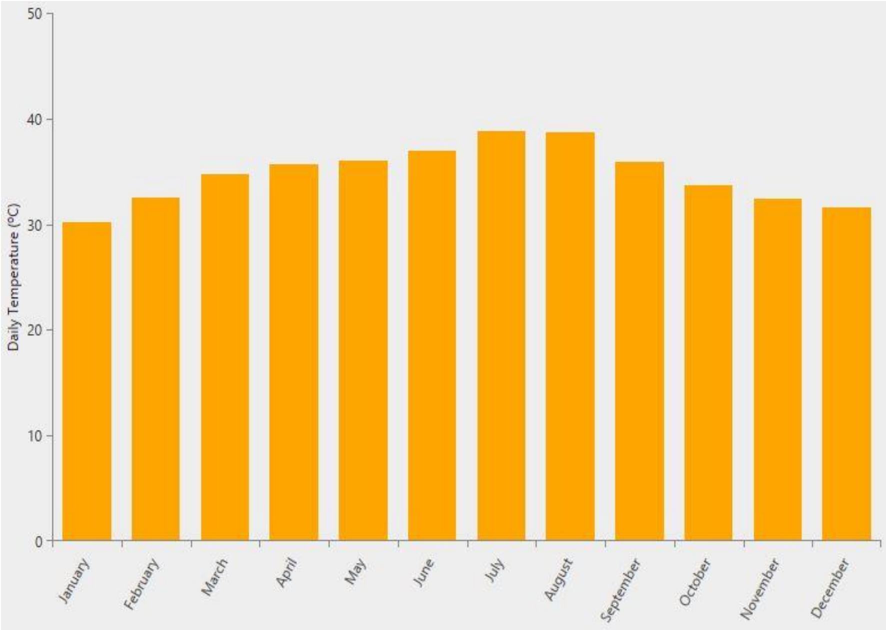

Fig. 3. Monthly average temperature of Mina

2.3 System components

In this research, the proposed HRES consists of four components, i.e., the PV system, diesel generator, converter, and batteries. The techno-economic input parameters for all components in the HRER are explained in detail in Table 1; note that the technical parameters and costs of the components were obtained from different references [11, 12]. A schematic diagram of the proposed HRES is illustrated in Figure 4.

Table 1. Input parameters and costs of different components

Description	Specification
PV system	
Tracking system	Fixed
Rated capacity	400 kW
Nominal operating cell temperature	-0.5% / °C
Temperature Coefficient	47 °C
Efficiency at standard test condition	13%
Derating factor	80
Capital cost	$ 2500/kW
Operating and maintenance cost	$ 3/kW/year
Cost of replacement	$ 2000/kW
Lifetime	20 years
Diesel generator	
Cost of capital	$ 400/kW
Cost of operating and maintenance	$ 0.05/kW/hr
Cost of replacement	$ 400/kW
Lifetime	15000 hr
Batteries	
Model	Lead Acid
Nominal capacity	1900 Ah (7.6 kWh)
Nominal voltage	2 V
Capital cost	$ 1200
Operating and maintenance cost	$ 30 /year
Replacement cost	$ 1200
Lifetime	12 years
Converter	
Efficiency	90% for inverter, 85% for rectifier
Cost of capital	$ 400/kW
Cost of operating and maintenance	$ 20/year
Cost of replacement	$ 375/kW
Lifetime	10 years

2.4 Economic model

The optimum combination of the HRES components are obtained on the basis of the NPC, which is the sum of all costs and revenues that take place throughout the lifetime of a project. To calculate the total NPC of a system, the following equation is used [13-15]:

$$NPC = \frac{C_{ann,tot}}{CRF(i, T_p)} \qquad (1)$$

where $C_{ann,tot}$ is the total annualized cost ($/year), i is the annual real interest rate (%), T_P is the project lifetime (year), and CRF is the capital recovery factor [16].

COE is the average cost per kWh of producing electricity, given by [16]:

$$COE = \frac{C_{tot}}{E_{served}} \qquad (2)$$

where E_{served} is the total electrical load served (kWh/year).

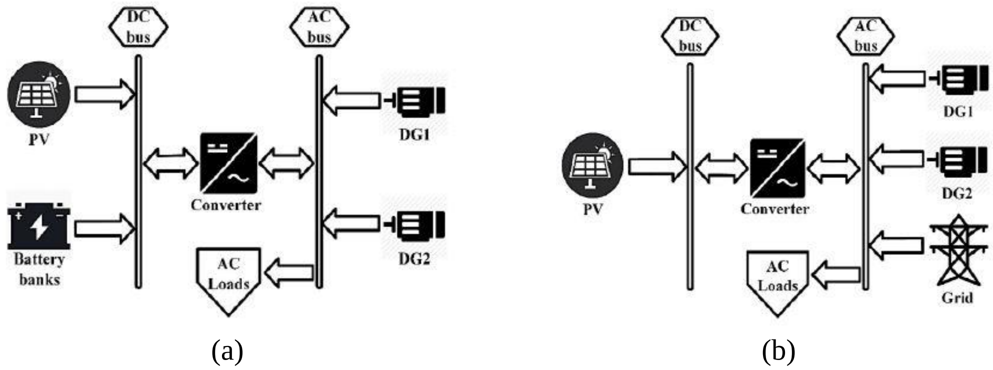

Fig. 4. Schematic diagram of HRES (a) Off-grid, and (b) On-grid

2.5 Control strategy

The two main control methods of the hybrid PV/diesel/battery system are the Load Following (LF) and Cycle Charging (CC) dispatch strategies. In this study, LF strategy has been used to design and analyze the data collected. Because LF uses diesel generators to supply loads only when renewable energy sources are unavailable. The LF strategy is more trend to generate lower amount of CO_2 emissions. LF seems to be the optimal strategy, as it helps reducing the excess energy and total NPC [17].

3. Results and Discussions

With each containing different technical and economic configurations, several scenarios were carried out in this paper. Initially to find the optimum solution, the system is tested over the off-grid connection. Then, the investigation of the technical, economic, and environmental performance of the proposed system has been taken place. Also, the impact of changing fuel prices and load demand on the optimal design has been analyzed for off-grid connection during the sensitivity analysis. Similarly during on-grid connection, the optimum design of proposed HRES is also investigated, which includes the effects of grid inclusion on the system's component combination and operational performance. Furthermore, by changing important variables at the on-grid connection, the optimum design is examined during sensitivity analysis. The simulation has been carried out in HOMER platform. The simulation results show different combinations of the optimal scenarios including different COE, and NPC values.

3.1 Off-grid HRES

In this stage, no grid connection has been considered. A standalone system including DG, batteries, converters, and PV are proposed without any technical disruption to meet the load demand is depicted in Figure 4 (a). In this scenario, to generate adequate power, the system is designed to depend on PV generated power, where DGs are used as a backup when the PV and/or battery are unable to meet load requirements.

As the best configuration in terms of COE and NPC, the specific step sizes are summarized in table 2, which have been selected by HOMER. Two DGs with capacities of 100 kW and 60kW are included in the optimum system where the best options for converter, PV, and batteries are found 150 kW, 250 kWp, and 330 kWh respectively. The total NPC of the system is found $2452919.0 for the optimum HRES, while the COE is 0.238 $/kWh. In addition, the total salvage and operating costs of optimum HRES has been calculated by HOMER are $101889.0 and $18109.0, respectively. In table 3, the total produced harmful gas emissions are shown, where CO_2 forms the majority of the produced harmful emissions which is 270789.0 kg/Yr. While, emission of carbon monoxide, unburned hydrocarbons, particular matters are found null.

Table 2. Part of the various arrays of component's arrangements

System	PV (kWp)	DG1 (kW)	DG2 (kW)	Battery (kWh)	Converter (kW)	COE ($/kWh)	NPC ($)
System 1	250	100	60	330	150	0.238	2.45 M
System 2	300	100	50	330	150	0.239	2.50 M
System 3	300	140	30	330	150	0.239	2.50 M
System 4	350	110	40	330	150	0.241	2.57 M
System 5	350	100	50	330	150	0.241	2.57 M
System 6	400	100	30	330	200	0.244	2.65 M

Table 3. Generated harmful gas emissions by HRES

Emissions	Kg/Yr
Carbone dioxide	270789.0
Carbone monoxide	0
Unburned hydrocarbons	0
Particular matters	0
Sulfur dioxide	1174.50
Nitrogen oxide	574.24

3.1.1 Sensitivity analysis

To examine the system behavior, sensitivity analysis is performed by varying DG fuel price. The result of the sensitivity analysis by changing the diesel price from the current price (0.7 $/L) is shown in Figure 5 (a), to more than (1.15 $/L) in Figure 5 (b), along with increasing the average load demand (+2.5% per year) with respect to monthly average solar radiation. The results exhibit that the optimum HRES is flexibly performs during increasing load growth, average solar radiation and diesel price variations.

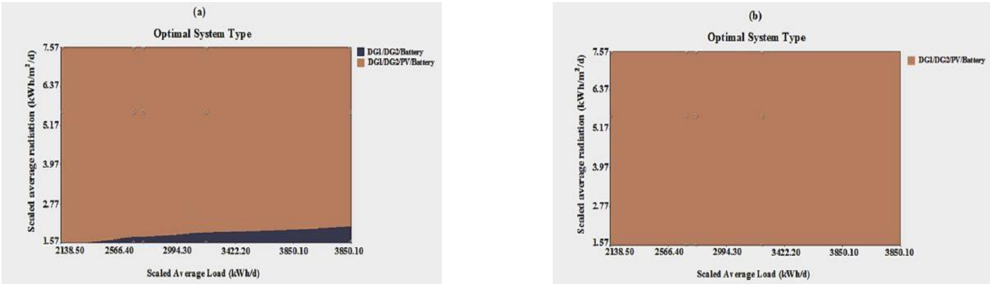

Fig. 5. Sensitivity analysis of off-grid HRES for average loads v/s average solar radiation at (a) 0.7 $/L and (b) 1.15 $/L.

3.2 On-grid HRES

The optimal design assigned to a grid connection is discussed in this section. Therefore, to include this addition without making any change to the system configuration, the system should be flexible as shown in Figure 4 (b). Power purchases and sell-back prices are the two key parameters which have direct influence on grid-connected HRES. It is assumed that due to the non-availability of data from the selected site, the power purchase price has been considered higher than the nearest location with a grid connection due to the far distance of the proposed site. For this study, the sell-back price has been chosen higher than the power purchase prices as well as the off-grid system's COE. Alike off-grid HRES for grid connected HRES also the best optimum configuration has been consisted of PV, DG1, DG2, converter and grid which is shown in table 4. The total NPC and COE for the optimum design has been observed $ 172367.0 and 0.167 $/kWh respectively.

Table 4. Part of the various arrays of component's arrangements

System	PV (kWp)	DG1 (kW)	DG2 (kW)	Converter (kW)	COE ($/kWh)	NPC ($)
System 1	250	100	60	150	0.167	1.72 M
System 2	300	100	50	150	0.169	1.78 M
System 3	300	140	30	150	0.170	1.78 M
System 4	350	110	40	150	0.174	1.86 M
System 5	350	100	50	150	0.174	1.86 M
System 6	400	100	30	200	0.180	1.95 M

3.2.1 Sensitivity analysis

Comprising all changes to the on-grid system's operation, this section performs an extensive sensitivity analysis. The power purchase, load demand, fuel prices, and sell-back are included in the applied changes. The effects of changing the load demand against power purchase and sell-back prices are shown by Figure 6. It is seen that the system tends to depend more on the DG2/PV/Grid choice if the value of the sell-back price is lower than the COE of the off-grid system (0.238 $/kWh) and power purchase price, while the load keeps increasing. However, in addition to the power purchase, increasing the sell-back price to exceed the COE of the off-grid system will cause the system tends to depend more on the optimum design (DG1/DG2/PV/Grid) configuration.

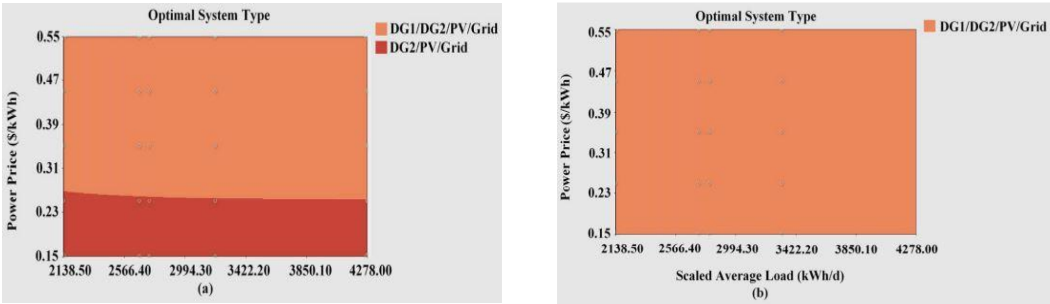

Fig. 6. Sensitivity analysis of on-grid HRES for power price v/s average loads at different sell-back prices in ($/kWh) (a) 0.15 and (b) 0.45 and above

3.2.2 Environmental impact

In this work, the study of environmental impact of each system is also carried out. Table 5 shows the result of CO_2 emissions for different sellback prices and power purchase. The dependency on the grid to meet the load demand can be decreased by higher power purchase prices and increasing the usage of the hybrid system which includes DGs and renewable energy components. Due to the usage of DGs during renewable energy sources unavailability, larger amount of the CO_2 emissions has been found in the optimum design of HRES.

Table 5. CO_2 Emissions vs different power purchase and sell-back prices

Sellback Price ($/kWh)	Power Purchase ($/kWh)	CO_2 Emissions (kg/Yr)
0.15	0.45	294630
0.25	0.40	347000
0.30	0.35	475000
0.35	0.30	512000
0.40	0.25	530000
0.45	0.15	550000

4. Conclusions

To meet the load demand of Mina region of Makkah, Saudi Arabia, the optimum hybrid renewable energy system was designed in this paper. HOMER software has been used to perform several scenarios for off-grid and on grid connections. The optimal system was found including, two DGs of 100 kW and 60 kW, PV modules of 300 kWp, battery banks of 330 kWh, and a 150 kW converter for both the cases. The sensitivity analysis proved that the COE normally falls within a range of (0.167-0.244 $/kWh), while the NPC of (172367.0-225374.0 $) for both off and on grid systems. The system emits a range of (270289.0-481652.0 kg/Yr) of CO2 emissions, in both off and on grids systems. Based on the work it can be said that the obtained optimal HRES shows effective performance by satisfying corresponding economic and environmental concerns compared to other hybrid system configurations for both off and on grid connection modes.

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