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A Comparative Assessment of Economic Viability of Off-Grid Generation Power Systems

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ABSTRACT

In this paper, a comparative study of economic viability between different off-grid power generation (OGPG) systems for an industrial plant is carried out using HOMER software. Three OGPG systems are proposed to find out the optimum OGPG system which is capable to feed the load with minimum cost. These systems include: (i) Off-grid diesel generator (OGDG) system, (ii) Off-grid PV (OGPV) system, and (iii) Off-grid PV-diesel hybrid (OGPVDH) system. The optimum economical design was chosen based on two performance indicators, namely the minimum cost of energy (COE) and net present cost (NPC). The economical performance indicators have shown that a PV renewable system combined with battery storage and diesel generator (DG) is the most competitive solution.

Key words: Renewable energy, HOMER, sensitivity analysis, net present cost, cost of energy, optimization.

1.INTRODUCTION

Today, the world has become a warmer place because of energy and a place where all its components of water, air and rocks can be used in all kinds of sciences. In fact, by exploiting the different kinds of technologies, energy becomes the convertible currency to any form. As global population grows, the persistent need for more and more energy is exacerbated [1]. Recently, the world suffers from the energy problem. In fact, 41% of the electrical power is generated using coal, 5% oil, 21% Gas, 13% nuclear, 16% hydro, and 4% of the power produced by renewable methods [2]. The problem of energy can be obviously seen in Jordan. Indeed, Jordan faces some critical troubles and challenges associated with this issue. However, the problem starting with a real challenge in securing its energy demand due to the fact that there are no indigenous energy resources and high dependency on imported energy. Besides, Jordan like many countries suffers from the instability of worldwide fuel prices. Not only this, but also, due to population growth and enhanced life style, the demand on energy is significantly increasing. This will pose new challenges which lead to a huge deficit and consumption of most of the foreign currency. Jordan is one of the countries of the world that is rich of renewable energy resources. Many studies consider that Jordan has many suitable locations for building solar energy stations as the solar irradiance in Jordan reaches up to 5.5kWh/m^2 as indicated in the solar map of Jordan in Figure 1 [3]-[6].

2. RESEARCH METHODOLGY

The approach is started with collecting the site's load data. After these data have been analyzed, the peak load was estimated as well as the annual load energy from the load profile. Next, the desired load is computed. Considering the compelling nature of the previous steps and the efficiency of the DG, the proposed study has suggested determining the corresponding size of the PV system to deliver the peak load [7]-[15]. It is important, however, to mention that HOMER software can estimate the *NPC* of any power generating system. Consequently, an estimation of the *NPC* of the three OGPG systems is utilized.

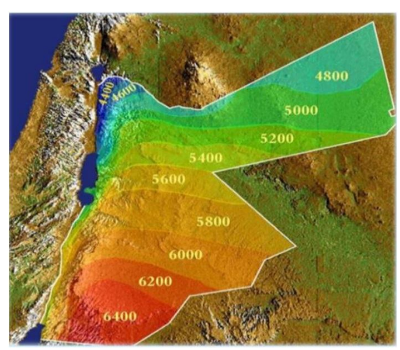

Figure 1: Solar Map of Jordan

3. ECONOMICAL ANALYSIS OF THE SYSTEM

3.1 PV System Analysis

There are main factors affect the *NPC* of a solar PV system; the initial capital cost (*ICC*) which is given by the sum of costs of every PV system part, i.e. PV array and miscellaneous (electric cables, outhouse, etc.). These investments depend on the peak power rating of the PV array [16], the value of operation and maintenance costs for PV system (OM_{PV}), and the costs of replacing the current battery (R_{PV}). Equation 1 is used to calculate the *NPC* [16].

$$NPC = ICC + OM_{PV} + R_{PV} - S \quad (1)$$

where *S* is the salvage cost which is the value remaining in a component of the power system at the end of the project lifetime. The salvage cost is given by (2) [16]:

$$S = C_{rep} \frac{R_{rem}}{R_{comp}} \quad (2)$$

where C_{rep} is the replacement cost of the component, R_{rem} is the remaining life of the component, and R_{comp} is the lifetime of the component. The HOMER uses *NPC* value to estimate the total annualized cost (*TAC*) which is the annualized value of the total *NPC* and calculates the *TAC* using (3) [16]:

$$TAC = CRF \times NPC \quad (3)$$

where *CRF* is the capital recovery factor which is a ratio used to calculate the present value of an annuity. The *CRF* is obtained using (4) [16]:

$$CRF = \frac{i \times (1+i)^N}{(1+i)^N - 1} \quad (4)$$

where *i* is the real discount rate and *N* is the number of the years. The real discount rate *i* is calculated using (5) [16]:

$$i = \frac{i' - f}{1 + f} \quad (5)$$

where *i'* is nominal discount rate and f is the inflation rate.

There are several determinates that should be taken into account when deciding the OM_{PV} such as: taxes, insurance, maintenance, recurring costs, etc. It is generally specified as a percentage (say *m*) of the *ICC*. All operating costs are escalated at a rate of *f* and discounted at a rate *i'* [8].

$$OM_{PV} = m \times ICC \quad (6)$$

The battery replacement cost (R_{PV}) denotes how many times the battery is replaced (*v times*) over the system lifetime; this factor is given as [8]:

$$R_{PV} = v \times C_{b0} \quad (7)$$

where C_{b0} is the battery cost.

The HOMER software uses the *TAC* to calculate the *COE* which is given by [16]:

$$COE = \frac{TAC}{E_{served}} \quad (8)$$

where E_{served} is the total amounts of primary load that the system serves per year.

3.2 Analysis of the Diesel Generator

It is necessary to take into account that the size of generator set should meet the maximum power demand. It is also important to consider the fuel consumption, where the fuel consumption is given by the following equation [8]:

$$Fuel\ consumption = AOH \times FCR \times 365 \quad (9)$$

where *AOH* (h/day) denotes the average operating hours per day of the generator and *FCR* denotes the fuel consumption rate. The previous studies approved that the *ICC* of the DG increases continuously over the size range. The average load factor of the most diesel plants comes in a rate within 12-25% [9]-[11]. In the OGPG system, it is considered that the DG factor is 25%. The following limitations are taken into account when designing the proposed system; (i) Oil and filter change; this operation includes several components: air inspection and fuel filters, fuel systems, starter battery and system connections. (ii) Decarburization; this operation refers to changing air and fuel filters, cleaning the head of cylinder, nozzles, gaskets, etc. (iii) Engine overhaul; this operation can be performed when needed considering the replacement of generator engines and replacement of system batteries, etc. The total *NPC* of the DG (NPC_{DG}) is the sum of ICC of the DG (ICC_{DG}), *NPC* of fuel (NPC_{fuel}), *NPC* of maintenance cost (NPC_{main}) and *NPC* of replacement cost (NPC_{rep}) as given in (10) [16]:

$$NPC_{DG} = ICC_{DG} + NPC_{fuel} + NPC_{main} + NPC_{rep} \quad (10)$$

4. SIMULATION RESULTS

4.1 Cost and Lifetime of System Components

Table 1 show the cost and lifetime data for each component of the OGPG system. These data has been introduced to HOMER software.

Table 1: Data of the OGPG system

System Description	Value
1. Load	
Load Annual consumption	520 kW 2.3 GW
2. PV	
Capital Cost	756 $/kW
Life Time	25 years
Operation and Maintenance	15 $/kW/year
3. Diesel Generator	
Minimum load generators %	25% of rated power
Capital Cost	100 $/kW
Replacement cost	100 $/kW
Operation and Maintenance Cost	0.274 $/kW
Life time	90,000 hours
Fuel Price	0.85 $/L
4. Converter	
Capital Cost	144.28 $/kW
Replacement cost	144.28 $/kW
Operation and Maintenance Cost	0
Lifetime	25 years
5. Battery	
Capital Cost	616 $/unit
Replacement cost	616 $/unit
Operation and Maintenance Cost	0
Lifetime	15 years

4.2 Description of the Load

The OGPG system, located in Ramtha city, is intended to feed an industrial plant with a total load of 520 kW and a corresponding energy of 2.3 GWh/year. The load consumption is considered a fixed daily load over 12 working hours. The daily load profile of the load is shown in Figure 2 where the daily working hours extend from 07:00 am till 07:00 pm. Moreover, the considered lifetime of the project is 25 years.

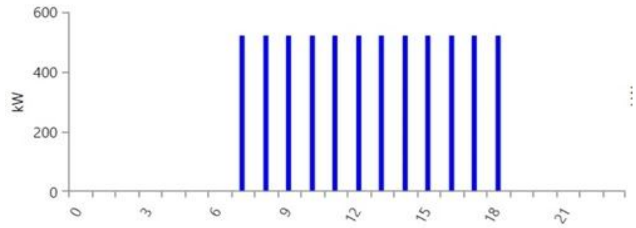

Figure 2: Daily load profile

The seasonal profile of the annual load is depicted in Figure 3. It an be seen that the annual maximum load is 939.1 kW which occurs in August and the corresponding average load is 272.1 kW. The hourly load profile of August is shown in Figure 4.

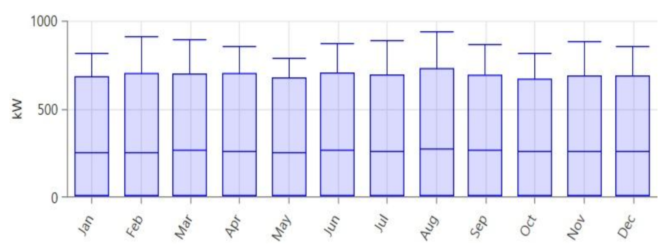

Figure 3: Seasonal load profile

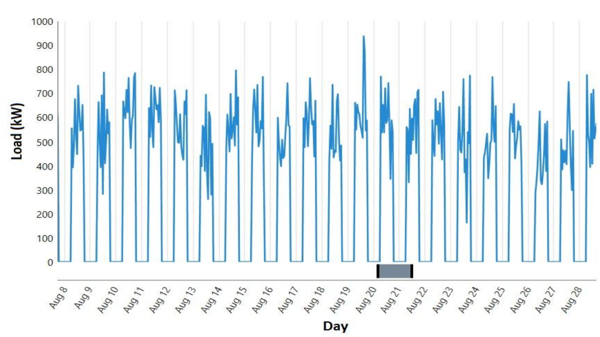

Figure 4: Hourly load profile August

In Ramtha city, the solar radiation varies from 2.51 kWh/m^2/day in December to 7.79 kWh/m^2/day in June. The monthly variation of the radiation and clearness in Ramtha city is shown in Figure 5.

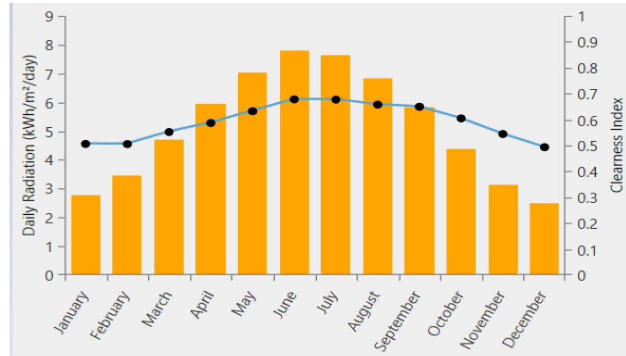

Figure 5: Annual variation of solar radiation in Ramtha city

4.3 Economical Results

A Comparative study of economic viability between different off-grid power systems for long term construction project in Jordan is carried out using HOMER software. Three OGPG systems are tested to find out the optimum OGPG system which is capable to feed the load adequately with minimum cost. These systems are (i) OGDG system, (ii) OGPV system, and (iii) OGPVDH system. The *NPC* of each OGPG system is compared to the *NPC* of the Grid-Only system in order to estimate the payback period for each OGPG system. The *NPC* of the Grid-Only system at the end of project lifetime is estimated to be $6.82 M.

The schematic diagram of the OGDG system is shown in Figure 6. The rated power of the generator is 1 MW and the minimum load ratio of the generator is set at 25%. The optimization results are obtained from HOMER simulation, Table 2 shows the optimization results of the OGDG system. The simulation results show that the *COE* is $0.233 /kWh and the *NPC* at the end of the project is $12.1 M. It is obvious that the system does not have a payback period due to high *NPC*.

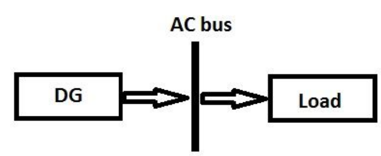

Figure 6: OGDG System

Table 2: Economical results of the OGDG system

Rated Power (MW)	COE ($/kWh)	ICC ($)	NOC ($)
1.00	0.233	115,000	12 M
Replacement ($)	**Salvage ($)**	**NPC ($)**	**Payback period**
85,657	64,885	12.1 M	null

A schematic diagram of the OGPV system is shown in Figure 7. The system consists of a load, a PV system, a storage bank, and a controller. The optimal HOMER results of the OGPV system is illustrated in Table 3. The results shows that the *COE* is $0.104 /kWh, the *NPC* is $2.68 M and the payback period of the OGPV system is around 17 years.

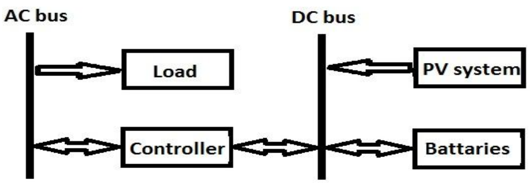

Figure 7: OGPV system

Table 3: Optimal economical results of the OGPV system

COE ($/kWh)	ICC ($)	NOC ($)	Replacement ($)
0.104	1. 78 M	395,370	731,730
Salvage ($)	**NPC ($)**	**Payback Period (Years)**	
226,209	2.68 M	17	

A schematic diagram of the OGPVDH system is shown in Figure 8. The system consists of a load, a DG, a PV system, a storage bank, and a controller. Table 4 shows the optimal economical results of the OGPVDH system. It was found that the *COE* is $0.0745 /kWh and the *NPC* is $1.92 M. Likewise, the proposed OGPVDH system has a payback period of 10 years.

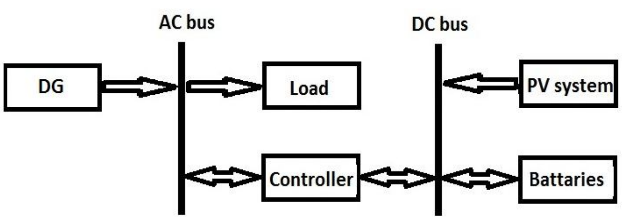

Figure 8: OGPVDH system

Table 4: Optimal economical results of the OGPVDH system

COE ($/KWh)	ICC ($)	NOC ($)	Replacement ($)
0.0745	1.01	770,993	207,965
Salvage ($)	**NPC ($)**	**Payback Period (Years)**	
64,290	1.93 M	10	

4.4 Production Results

The annual production results of the three proposed OGPG systems are presented in Table 5.

Table 5: Production results of the proposed OGPG systems

System	OGDG	OGPV	OGPVDH
PV array output (GWh/year)	0.00	1.99	1.43
Batteries output (GWh/year)	0.00	0.30	0.29
DG output (GWh/year)	2.3	0.00	0.08
Batteries autonomy (h/year)	0.0	60.1	17.1

The proposed OGDG system is designed to meet the entire demand using DGs only. Accordingly, the consumed energy is found to be around 2.3 GWh/year. Power production during working hours of the plant is depicted in Figure 9.

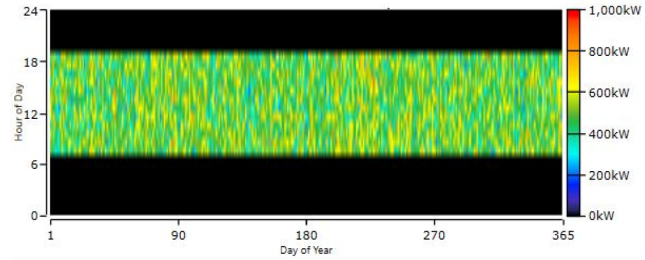

Figure 9: Annual power production of the DG

As for the OGPV system, the PV system is designed aiming to meet the entire demand. The corresponding energy produced is 1.99 GWh/year. Figure 10 shows the produced energy by the PV arrays during the working hours.

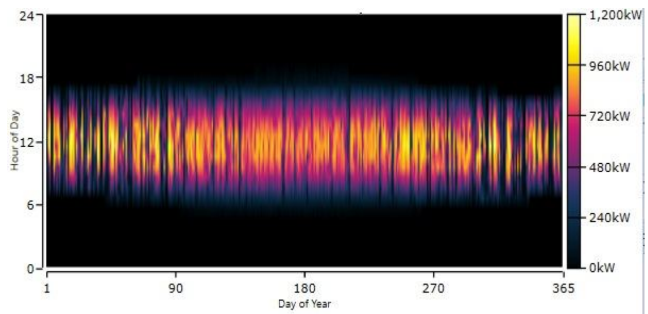

Figure 10: Annual power production of the OGPV system

Figure 11 shows the state of charge of the storage system. The nominal capacity of the storage system is 8,681 kWh.

The PV arrays charge the battery during the day time. However, early in the morning and lately in the evening, the storage bank provides the load with its needs of electricity. The annual throughput is 304,423kWh/year and the autonomy is 60.1 hours. The hours of operation of the controller are 4,378 hr/year.

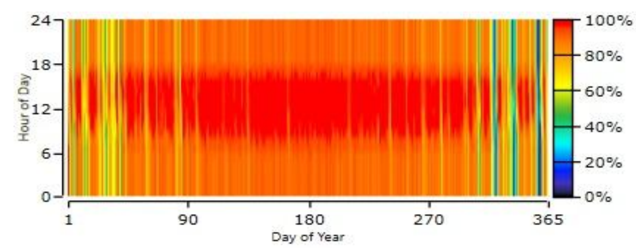

Figure 11: Annual battery state of charge of the OGPV system

Figure 12 shows the output of the inverter which has a capacity of 573 kW.

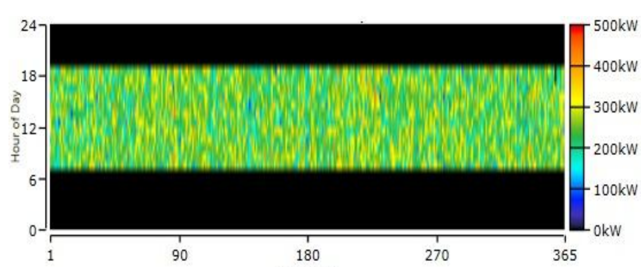

Figure 12: Annual controller output power of the OGPV system

Likewise, for the proposed OGPVDH system, the PV modules are designed to meet the demand and are capable of producing annually an amount of energy of 1.43 GWh. The annual power production of the PV modules during working hours is shown in Figure 13.

The state of charge of the storage system is shown Figure 14. The nominal capacity of the storage system is 2,467 kWh. The annual throughput is 290,294 kWh/year and the autonomy is 17.1 hours.

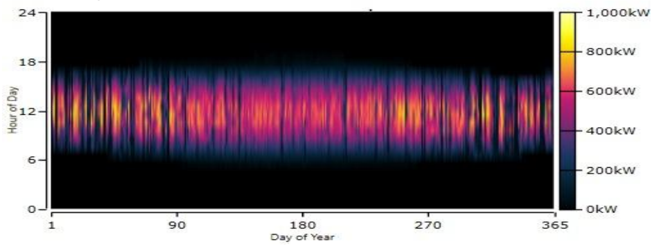

Figure 13: Annual power production of the OGPVDH system

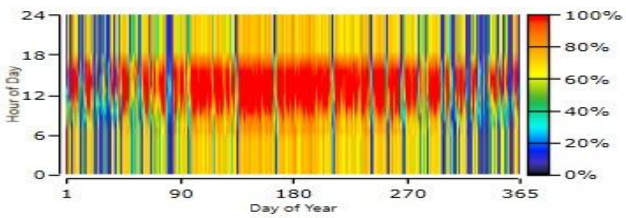

Figure 14: Annual battery state of charge of the OGPVDH system

The annual controller output of the OGPVDH system is shown in Figure 15. The operational hours of the controller is 4,310 hr/year. As for the inverter rating, |its capacity is 287 kW and it can produce a maximum power output of 260 kW. In the proposed OGPVDH system, the working hours of the DG is around 448 hrs/year and the number of starts is 130 starts/year. The corresponding energy produced by the DG is around 80,125 kWh/year. the annual power production of the OGPVDH system is depicted in Figure 16. The DG covers the load when battery reaches the minimum level and the PV array does not produce energy.

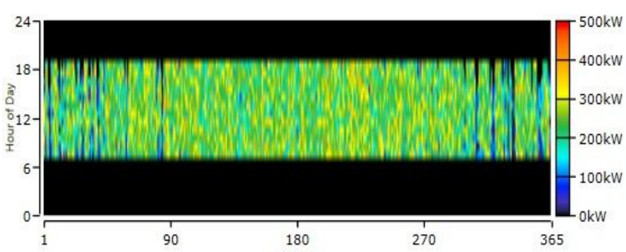

Figure 15: Annual controller output power of the OGPVDH system

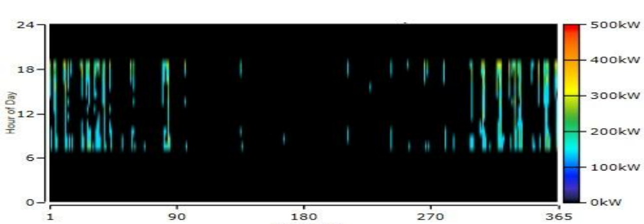

Figure 16: Annual power production of the OGPVDH system

4.5 Emissions

Table 6 shows the amount of Carbon dioxide (CO_2) emissions of the three proposed power systems. Table 6 reveals that the amount of emissions of the OGPVDH system is around 66,235 kg/year which is 95.91% less as compared to the emission if the OGDG system which emits around 1,618,821 kg/year.

Table 6: Amount of Carbon dioxide emissions

System	OGDG	OGPV	OGPVDH
Amount (kg/year)	1,618,821	0	66,235

5. DISCUSSION

In this work, the techno-economic performance of the proposed OGPG systems has been evaluated using HOMER software. The input data that was introduced to the HOMER software for optimizing the system includes load profile, PV data, system component specifications and costs. System simulation is carried out over one year of operation. The performance of the proposed systems was evaluated in terms of several performance indicators.

5.1 OGDG System VS OGPV System

Simulation results of HOMER software show that the operation of OGPV system is more economical than the OGDG system. In this regard, it was found that the NPC of the OGPV system is almost $2.68 M, whereas the NPC for the OGDG system is almost $12.1 M. Therefore, it can be noticed that the OGPV system has 77.85% saving when compared to that of the OGDG system. The simulation results of the OGDG system are presented in Table 7.

Table 7: Optimization results of the OGDG system

Rated Power	COE ($/kWh)	NPC ($)	Production (GW/year)	ICC ($)
1 MW	0.233	12.1 M	2.3	115,000
Hours (h)	**Operating Cost ($/year)**		**Fuel (L/year)**	**Fuel Cost ($/year)**
4380	528,654		617,346	524,744

Similarly, simulation results of the OGDG system show that the operational hours of the DG is 4380 hours but for OGPV system the operational hours of the DG is zero. Hence, it can be noticed that, with 100% PV penetration, the operational hours of the DG are reduces by 100% as compared to the OGDG system. Table 6 shows that the amount of CO_2 emissions of the OGDG system is almost 1,618,821 kg/year. On the other hand, for the OGPV system, the CO_2 emissions are zero. This indicates that the percentage of CO_2 emissions with 100% PV penetration reduces by 100% as compared to OGDG system. Therefore, the main advantage of the renewable energy source is that it provides cleaner energy because it is less pollutant and less contributor to greenhouse effect and global warming. Table 7 shows that the annual diesel fuel consumption of the OGDG system is 61,346 L/year while the OGPV system has no fuel consumption at all. The percentage of fuel savings using OGPV system is 100% as compared to the OGDG system.

5.2 OGPVDH System VS OGDG System

In this paper, the OGPVDH system has been studied considering the public grid is off. The OGPVDH includes a DG coupled with an energy management system (EMS) to supply the load profile demand. In the OGPVDH system, a PV with maximum capacity of 836 kW and one DG with maximum capacity of 580 KW are used to cover the load. The spinning reserve has been set to 10% to avoid rapid changes in load. In similar manner, the techno-economic performance of the OGPVDH system of Figure 8 was evaluated using HOMER. Table 8 shows as the PV penetration level increases the fuel consumption of the DG decreases accordingly.

Table 8: Renewable penetration VS fuel consumption

Percentage Renewable Penetration	Total Fuel (L/year)	DG Working Hours (h/year)
96.4	12,649	233
94.3	20,147	358
93.0	25,067	448
92.1	28,361	508
90.3	34,430	616
89.0	39,490	717

In the case of OGDG system, the operational hours of the DG is 4380 hours/year. However, for the OGPVDH system with 93% PV penetration, the operational hours of the DG is 448 hours. This means that the operational hours of the DG are reduce by 89.77% as compared to OGDG system. The simulation results show that the annual diesel fuel consumption of the OGPVDH system is less than the OGDG system. It can also be observed that when comparing the fuel consumption of the OGPVDH system with that of the OGDG system, the OGPVDH system results in 95.7% fuel saving. Moreover, Simulation results show that the amount of CO2 emissions for the OGDG system are almost 1,542,252 kg/year. However, for the OGPVDH system, the CO2 emissions are 66,235 kg/year (Table 6). This indicates that the percentage of CO_2 emissions of the OGPVDH system have been reduced by 95.7% as well.

5.3 Summary of Economical Results

The *COE* and the *NPC* are the dominant parameters for any power generation system. Table 9 shows the *CO*E and *NPC* for the three proposed OGPG systems.

Table 9: The optimization results of economics

Power System	COE ($)	NPC ($M)
OGDG	0.230	11.4
OGPV	0.104	2.68
OGPVDH	0.0745	1.93

Examining Table 9, one can find that the OGPVDH system is the most economical hybrid energy system that suits the industrial plant under study.

6. SENSITIVITY ANALYSIS

A challenge that often confronts the micro-power system designer is uncertainty in key variables. Sensitivity analysis can help the designer understand the effects of uncertainty and make good design decisions despite uncertainty. HOMER user can perform a sensitivity analysis with any number of sensitivity variables. Each combination of sensitivity variable values defines a distinct sensitivity case.

6.1 Uncertainty of Fuel Prices

The analysis of the OGPG systems is done at fuel price of $0.85/L. In reality, the fuel price changes every month in Jordan which performs an uncertainty of the results. A random set of the fuel prices is selected as following: $0.40/L, $0.85/L, $1.00/L, and $1.20/L. Table 10 shows the sensitivity results of fuel price change.

Table 10: The optimization results of economics

Fuel Price ($/L)	OGDG System		OGPVDH system	
	COE ($/kWh)	NPC ($M)	COE ($/kWh)	NPC ($M)
0.400	0.111	5.76	0.0609	1.57
0.850	0.233	12.1	0.0745	1.93
1.000	0.274	14.2	0.0773	2.00
1.200	0.328	17	0.0807	2.09

The *COE* is clearly affected by the fuel price. Both of the *COE* and the *NPC* increase when the fuel price increases. It can be seen in Table 10 that the OGPVDH system is more economical than the OGDG system at all prices of fuel and the uncertainty is disappeared.

6.2 Uncertainty of Battery Lifetime

For the OGPVDH system, a random set of battery lifetime is selected as the follows: 3.5 years, 7.5 years, 15 years, 20 years, 22.5 years, and 25 years. Table 11 shows the sensitivity results of battery lifetime change. It can be observed that both of the *COE* and the *NPC* are clearly affected by the fuel price; where both of the economic indicators decrease when the battery lifetime increases.

Table 11: Battery lifetime effect-OGPVDH system

Battery Lifetime (year)	COE ($/kWh)	NPC ($M)
3.5	0.100	2.58
7.5	0.0844	2.18
15	0.0745	1.93
20	0.0707	1.83
25	0.0678	1.75

7. CONCLUSION

An optimal design of a 520 kW OGPVDH system for a factory in Ramtha has been investigated in this paper. Electricity is supplied by sets of 285 Wp monocrystalline PV modules, off-grid inverters which convert DC power from PV modules to AC power and feed in directly to the load through the AC bus. In case of non-sunshine hours, power is supplied by the banks of batteries, which are connected to the AC bus through bi-directional inverters. The environmental and economic impacts of this solar power system were examined. Based on the *COE* and the *NPC*, the optimal design of the OGPVDH system has been compared with OGDG and OGPV systems. It was found that the OGPVDH system is the most optimal economical system. The *COE* and the *NPC* are $0.0745 /kWh and $7.92 M, respectively.

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