The techno-economic and environmental aspects of a hybrid PV-diesel-battery power system for remote farm houses

Article *in* International Journal of Global Warming · January 2009

DOI: 10.1504/IJGW.2009.027101

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Abstract: In this study, the solar radiation data of Balikesir in Turkey are analysed to assess the techno-economic viability and environmental performance of a hybrid photovoltaic (PV)-diesel-battery power system to meet the load requirements of a typical remote farm house. The average daily solar global radiation values range from 1.55 to 7.38 kWh/m^2. The NREL's HOMER software is used to carry out a comprehensive techno-economic analysis. Several technical aspects of the system are studied through the Cost of Energy (CoE), the operational hours of diesel generators, the unmet load, excess electricity generation, percentage of fuel savings, *etc*. The PV-diesel-battery simulation results indicate that for a hybrid system with a PV system of 20 kWp and a diesel system of 15 kW (with a battery storage capacity of 5.7 h), PV penetration is calculated to be 36%. The CoE for this kind of hybrid system is found to be 1.245 US$/kWh. Simulations based on an actual system operational in Cagis, Turkey, are performed for three cases (diesel-only system, PV-diesel system and PV-diesel-battery system) for a one-year period. In the simulations, it is obtained that a diesel-only system produces 63 900 kWh of electricity and 69.7 tonnes of CO_2, 13.0 kg of PM and 1.53 tonnes of NOx emissions per year as a result of diesel fuel usage. Using PV-diesel and PV-diesel-battery systems helps reduce CO_2 emissions to 61.0 and 42.0 tonnes, for PM, to 11.4 and 7.83 kg and for Nox, to 1.34 and 0.92 tonnes, respectively. The diesel-only system is more economical if the fuel price is below 2 US$/L. If the fuel price goes above this, PV-diesel and PV-diesel-battery systems become more cost-effective. Also, the environmental impact improvement factor, developed as a new parameter for renewable energy systems, is found as 0.127 and 0.399 for CO_2, 0.123 and 0.397 for PM and 0.124 and 0.398 for NOx for both PV-diesel systems and PV-diesel-battery systems, respectively.

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or "PV-Diesel-Battery"?

or "PV-Diesel"?

"NOx" or "Nox" or "NO$_x$"?

Keywords: stand-alone photovoltaic; hybrid energy system; diesel generator; solar energy.

Reference to this paper should be made as follows: Akyuz, E., Oktay, Z. and Dincer, I. (xxxx) 'The techno-economic and environmental aspects of a hybrid PV-diesel-battery power system for remote farm houses', *Int. J. Global Warming*, Vol. X, No. Y, pp.000–000.

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Please provide Biographical notes (maximum of 100 words for each author). Thank you.

1 Introduction

Concerns over global warming as a potential result of greenhouse gas emissions (mainly CO_2 emissions) caused by fossil-fuel based energy sources have motivated many to do research on cleaner and greener energy options, *e.g.*, photovoltaic (PV) systems for various applications. The hybrid, renewable-based energy systems for power production have recently received much attention as compared to the conventional, hydrocarbon fuel-based systems. Apart from the mobility of the system, it also has a longer life cycle (Gupta *et al*., 2007).

In general, it becomes a hybrid electric power system when two or more different sources of electricity are connected to a common grid and operate hand in hand to supply the desired load. The sources of electric power in this kind of hybrid system may be a diesel generator, a battery bank or a PV array. A hybrid energy system may or may not be connected to the grid. Baring (1998) outlines the foundations of hybrid power systems architecture and design. He presents hybrid systems as an optimum approach for stand-alone power supply systems for certain remote area applications where the load demand and the available renewable energy resources are in-line with the basic requirements a hybrid system needs to be functional. In addition, several more researchers (*e.g.*, Alsema, 1998; Alsema *et al*., 1998; Keoleian and Lewis, 1997) have discussed the energy requirements for the production of PV solar energy conversion systems and their energy pay-back-time. Wichert *et al*. (2001) present an evaluation of the technical and economic characteristics of hybrid power systems, and outlines the expected future directions for the development of hybrids. Hybrid systems are currently in a more favourable position when the cost of diesel fuel for transportation and environmental impact are incorporated in the analysis.

For off-grid power supplies, a diesel generator system is most attractive because of its low capital, while their operation and maintenance costs are high. But their high engine emissions remain a great environmental concern (Nayar *et al*., 1989; Bakirtzis and Gavanidou, 1992). In some cases, diesel generator may not be cost effective due to higher fuel cost in remote areas. For systems employing totally clean renewable energy, a higher capital cost becomes an important barrier. However, one can produce green power by adding different renewable energy sources to diesel generator and battery, which is called a hybrid system. This kind of system can compromise investment cost, diesel fuel usage cost and also operation and maintenance costs. Many hybrid systems have been studied and optimised through some cost-based analyses, based on system Life Cycle Cost (LCC) and energy cost (*e.g.*, Diaf *et al.*, 2007; Khan and Iqbal, 2005). Studying cost and environmental impacts of such hybrid PV-diesel generator systems over other systems is of great importance to diminish global warming issues as a result of greenhouse gas emissions.

Optimisation of such hybrid energy systems is quite site specific and depends upon the resources available and the load demand. The aim of this study is to identify the most economic and appropriate power supply system for a selected remote rural area, namely Cagis-Balikesir, by comparing the simulations of three different systems (*e.g.*, diesel only system, PV-diesel system, and PV-diesel-battery system) regarding their annual electrical energy consumption. These systems are compared with respect to their electricity production, cost and environmental impact analyses. In this study we also aim to develop a new parameter, so-called: environmental impact improvement factor for such renewable energy-based systems and study how this parameter changes for the three cases considered.

or "PV-Diesel"?

or Diesel"?

or "PV-Diesel-Battery"?

2 Methodology

2.1 Simulated hybrid energy system

A hybrid energy system has an integrated structure, consisting of two or more energy systems with an energy storage system, power conditioning equipment and a controller, and appears to be the most appropriate energy production option for isolated communities such as remote areas. There are generally two accepted hybrid energy system configurations, namely:

1 systems based mainly on diesel generators with renewable energy used for reducing fuel consumption

2 systems relying on the renewable energy source with a diesel generator used as a back-up supply for extended periods of low renewable energy input or high load demand (Haque *et al.*, 2006).

In this study, three systems, namely (1) diesel only, (2) PV-diesel, (3) PV-diesel-battery systems are considered and simulated by Hybrid Optimisation Model for Electric Renewable (HOMER) software[1] to assess their techno-economic viability and relevant aspects. The HOMER software developed by the US-National Renewable Energy Laboratory (NREL) for micro-power optimisation studies, is used to find out the best energy efficient renewable based hybrid system options. It contains a number of energy component models and evaluates suitable technology options based on cost and availability of resources. The layouts of the simulated hybrid PV-diesel-battery and PV-diesel system used in this study are shown in Figures 1(a–b), respectively. The operation of the system is as follows: in normal operation, PV energy feeds the load demand. The excess energy from PV charged the battery until full capacity of the storage system is reached. The main purpose of introducing battery storage is to import or export energy depending upon the situation. The diesel system is used when PV energy fails to satisfy the load or the battery storage is depleted. In the system without battery storage or "PV-diesel"?

when PV energy fails to satisfy the load, the diesel generator is used more frequently. Due to use of these PV-Diesel systems, the cost of fuel becomes higher. In diesel only system, load requirements entirely is met by diesel generator.

Figure 1 (a) Simulation scheme for PV-diesel-battery system (see online version for colours)

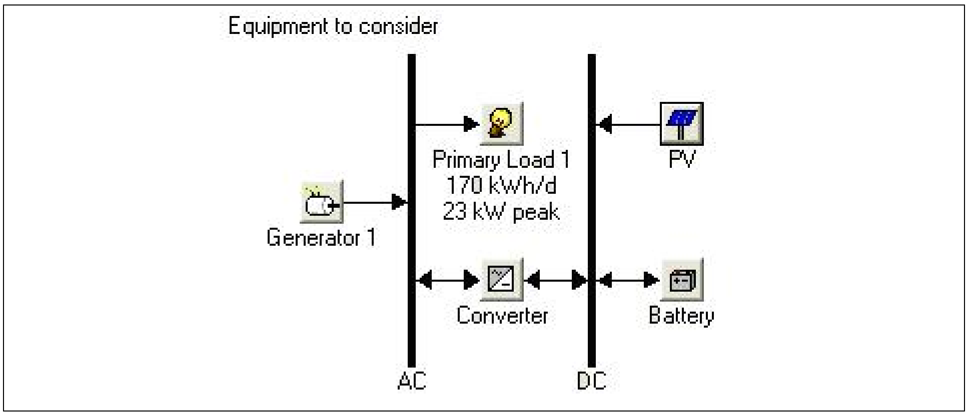
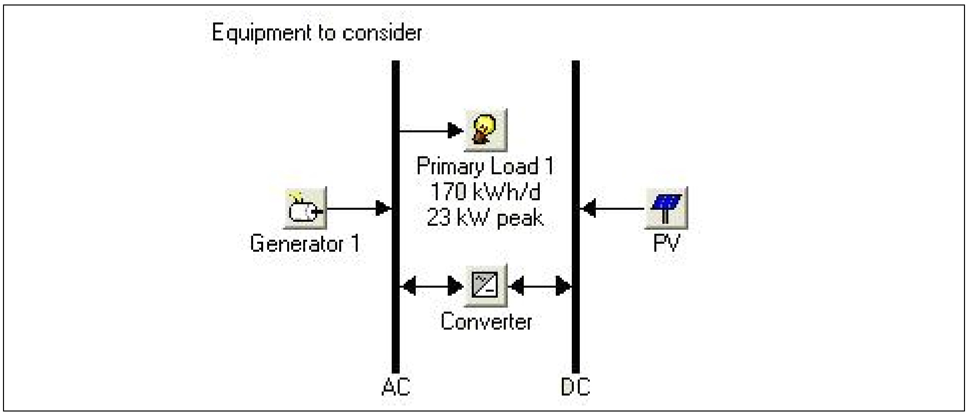


Figure 1 (b) Simulation scheme for PV-diesel system with no battery option (see online version for colours)



Due to intermittent nature of solar energy, it does not match 24-h time basis of load demand. Fort the system considered here, a battery option is required for night times. Use of diesel system with PV-battery reduces battery storage requirement. Hybrid combination of PV-diesel-battery system represents an economically acceptable compromise between the high capital cost of PV autonomous system and high Operating and Maintenance (O&M) cost and fuel cost of generators (Iqbal, 2003). The technical data and economic assumptions of PV, diesel generator unit, DC-AC inverter and batteries are presented in Table 1.

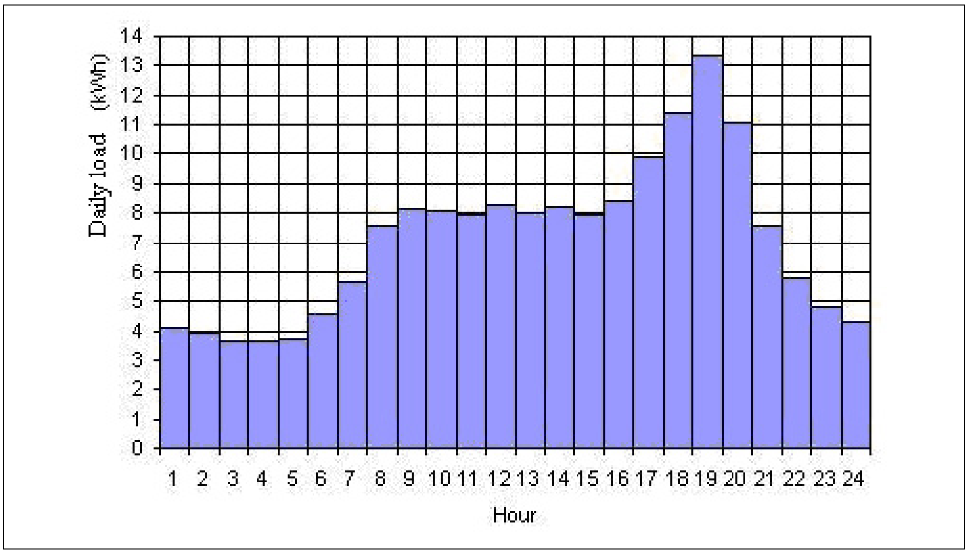
Table 1 Technical and cost data considered for hybrid energy systems in the analysis

System	*Values*	*System*	*Values*
PV		*Diesel generator unit*	
Rated power of PV	20 kW	Rated power of diesel unit	15 kW
Capital cost	US$150,000	Capital cost	US$7500
Life time	25 years	Operation and maintenance cost	US$0.15 per hour
Operation and maintenance cost	US$0 per year	*Batteries*	
Tilt angle PV modules	Lat: 39°30' N (Cagis)	Type of batteries vision	6FM200D
Rated power of PV	20 kWp	Nominal voltage (V)	12 V
Number of Panel (N)	16	Nominal capacity	200 Ah
P_{mp} (W)	125 W	Quantity	17
I_{mp} (A)	17.6	State of Charge (SOC)	40%
V_{oc} (V)	22.1	Capital cost	US$11 900
I_{sc} (A)	7.54	Operation and maintenance cost	US$50 per year
A_{sc} (m^2)	1.018	Dispatch/Operating strategy	Multiple diesel load following
NOTC (C°)	47 ± 2	Total energy capacity of battery	40.8 kWh

2.2 Location description

As mentioned earlier, the design of a hybrid energy system is site specific and it depends upon the resources available and the load profile. The simulations of the present study have been applied to design a stand-alone hybrid power system in order to generate energy for an ordinary farm house in Cagis which is located in the 20 km south-east in Cagis, Balikesir (39°30' N–28°1' E). The farmhouse is considered to have an average energy consumption of about 170 kWh per day, with a peak demand of 23 kW and average 7.08 kW. Usually the energy consumption is higher in the evening hours. The daily load demand is given in Figure 2.

Figure 2 The daily load profile for the Cagis farm house (see online version for colours)

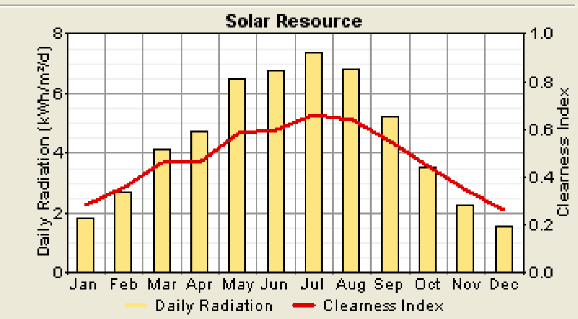


In the simulations, the actual data on the hourly global solar irradiations on a tilted plane (39°) for 2003 were collected from Balikesir Airport and used for calculations. The monthly solar irradiation data, presented in Figure 3 for the region, are collected from Turkish State Meteorology Service. Solar irradiation level is higher in the summer months. The monthly solar global radiation values, between December and July, range from 1.55 to 7.38 kWh per m^2. The annual average daily solar global radiation level is found as 4.48 kWh per m^2. The clearness index is also seen from the latitude information of the site under investigation.

Figure 3 The monthly global solar irradiation data and clearness index of Balikesir (see online version for colours)

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.287	1.820
February	0.362	2.720
March	0.461	4.150
April	0.461	4.760
May	0.585	6.480
June	0.598	6.780
July	0.660	7.380
August	0.644	6.800
September	0.552	5.210
October	0.448	3.550
November	0.347	2.280
December	0.260	1.550
Average:	0.500	4.468



Scaled data for simulation

Scaled annual average (kWh/m²/d) 4.468 {..}

Plot... Export...

2.3 Cost analysis

A cost-based economic analysis of the system is conducted using Energy Payback Time (EPBT) values. In order to calculate the EPBT for the PV array, it is essential to know the energy required in the construction of the PV array (embodied energy). Knapp *et al*. (Knapp and Jester, 2000) describe a method to calculate the embodied energy of a PV array. Embodied energy of a PV system and EPBT is given by Wies *et al*. (2005):

$$\text{kWh}_{\text{emb}} = 5600\ \text{kW}_{\text{pv}} = 112\,000\ \text{kWh} \tag{1}$$

$$\text{EPBT} = \frac{\text{kWh}_{\text{emb}}}{E_{pv}} = \frac{112\,000}{25\,992} = 4.309\ \textit{year}. \tag{2}$$

LCC analysis is a tool used to compare the ultimate delivered costs of technologies with different cost structures. Rather than comparing only the initial capital costs or operating costs, LCC analysis seeks to calculate the cost of delivering a service over the life of the project. The final cost per kWh is estimated independent of the technology used to deliver the electricity. The Levelised Energy Cost (LEC) can be explained with Total Present Value (TPV), Annual Load (AL), as follows (Lazou and Papatsoris, 2000):

$$\text{TPV} = \text{Initial cost} + \Sigma\,\text{O\&M} + \Sigma\,\text{Replacement} + \Sigma\,\text{Fuel cost} \tag{3}$$

$$LEC = \frac{TPV * CRF}{AL}, \tag{4}$$

where CRF is the Capital Recovery Factor and defined as:

$$CRF = \frac{(1+R)^N * R}{(1+R)^N - 1}. \tag{5}$$

Here, R is the net discount rate and N is the economic evaluation period in a year.

2.4 Environmental impact assessment

Please provide reference details.

Human effect to global warming is widely accepted in the scientific community (US Greenhouse Gas Inventory Program, 2002). Use of renewable energy sources reduces combustion of fossil fuels and consequent CO_2 emissions, which is principal cause of global warming (Shaahid and Elhadidy, 2007). Approximately 37% of CO_2 emissions are from electricity and heat production; therefore, power plant equipment manufacturers have the technical challenge of reducing CO_2 emissions without sacrificing efficiency and cost of electricity.

Here in this section we introduce a new parameter (so-called: environmental impact improvement factor) for renewable energy systems which we define as the ratio of the emissions reduction because of the use of renewable energy-based system to the emissions discharged to environment from the base-case system as follows:

$$EIIF = \frac{(BCE - PSE)}{BCE} \tag{6}$$

where BCE is Base-Case Emissions (here, it is diesel system which is case 1) and PSE is the proposed system emission (PV-diesel and PV-diesel-battery as cases 2 and 3).

3 Results and discussion

The farmhouse is considered to have an average energy consumption of about 170 kWh per day, with a peak demand of 23 kW and average 7.08 kW. The daily load demand changes with various hours. Energy consumption is higher in the evening hours. Hourly solar irradiation data for the region are collected from Turkish State Meteorology Service. Solar irradiation level is higher in the summer months. The annual average daily solar global radiation level is found to be 4.48 kWh/m^2, using the programme. The HOMER simulation results for each system are presented in Table 2.

Table 2 Simulation results for each system studied

Parameters	*Diesel-only system*	*PV –Diesel system*	*PV–Diesel-Battery system*
System NPC (US$)	591,657	715,243	605,799
Initial capital (US$)	8,500	183,500	195,400
Cost of energy (US$/kWh)	1.223	1.478	1.245
Fuel consumed (L/yr)	26 487	23 180	15 972
Total cost of fuel ($)	394,702	345,428	238,016
CO_2 emitted (tonnes)	69.7	61	42
PM emitted (kg)	13	11.4	7.83
NO_x emitted (tonnes)	1.53	1.34	0.92
System load (kWh/yr)	61 686	61 697	62 048
Total Energy (PV-Gen)	63 900	77 996	71 784
20 kW PV (kWh)	0	25 992	25 992
15 kW Generator (kWh)	63 900	52 003	45 792

Application of LCC method for Diesel-only, PV-Diesel and PV-Diesel-Battery system for Cagis farm house location yielded Table 2 for diesel price US$1.9/L. The LEC is for diesel price US$1.9/L defined as shown in Table 3.

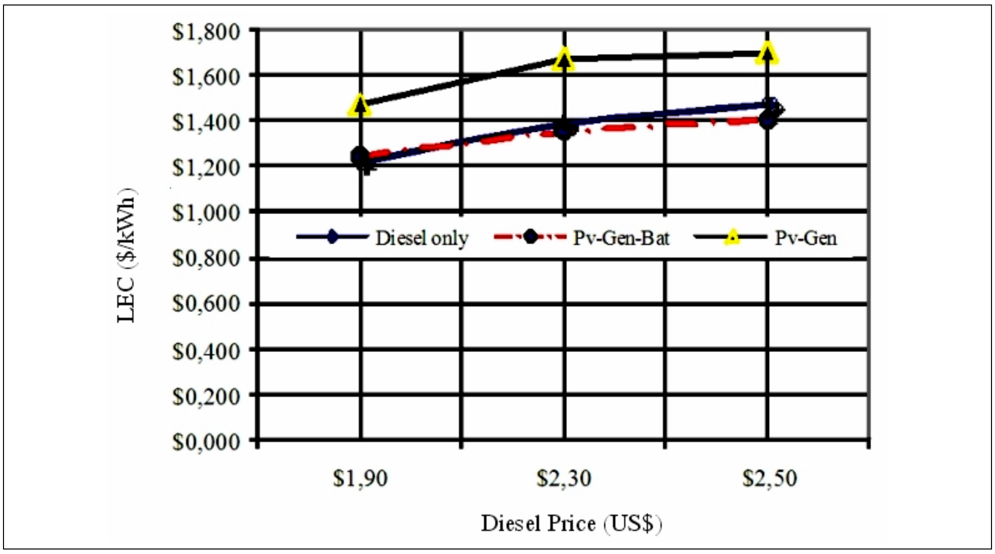
or “diesel”; “PV-diesel”; “PV-diesel-battery”?

Table 3 Comparison for levelised energy cost for diesel price 1.9 US$/L

System	*Capital (US$)*	*Replacement (US$)*	*O&M (US$)*	*Fuel (US$)*	*Total (US$)*	*AL (kWh)*	*LEC (US$/kWh)*
Diesel only	8,500	26,164	162,431	394,702	591,657	61,686	1.223
PV-Diesel	183,500	29,517	157,543	345,428	715,243	61,697	1.478
PV-Diesel-Battery	195,400	98,735	74,639	238,016	605,798	62,048	1.245

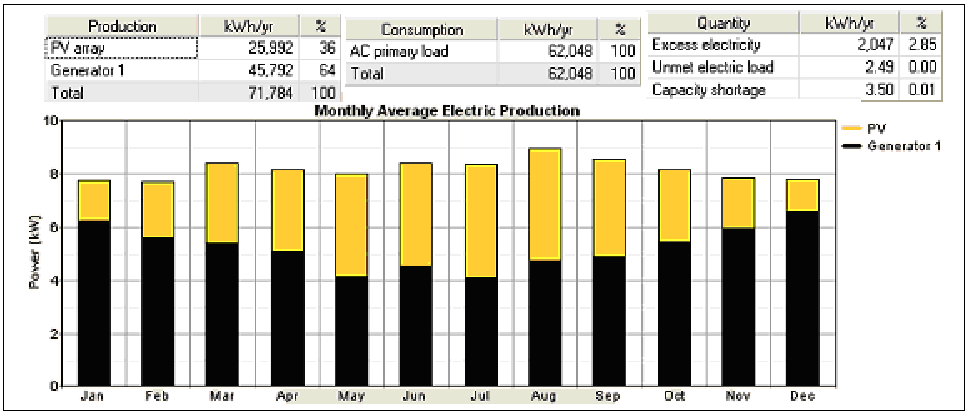
The LEC was calculated for each system for varying diesel fuel price by sensitivity analysis. Diesel fuel costs of US$/L 1.9, 2.3 and 2.5, respectively, considered as a sensitivity variable. In Figure 4, three conditions were presented. As it shown in the figure, the increase in the fuel price leads to increase in the total fuel cost of each system. PV-Diesel-Battery systems depend on diesel fuel price less than the other systems. It is clear that PV-Diesel-Battery system is more economic for diesel fuel price over US$2/L. While diesel only system is more economic if the fuel price is below US$2/L, PV-Diesel-Battery system become more economic than diesel only system when the price of diesel cost exceed US$2/L.

Figure 4 Variation of levelised energy cost for varying diesel fuel price (see online version for colours)



The PV-diesel-battery system simulation results of monthly electricity generation are presented in Figure 5. During the summer months, energy generated by PV is higher due to the global irradiation data in region and diesel electric generation is lower as compared to other months. While 36% of electricity is generated by PV array, the rest is produced by diesel generator. Unmet electric load is found as 0% and excess electricity is generated 2.85%.

Figure 5 Monthly electricity generation PV-Diesel-Battery system (see online version for colours)



These ratings are calculated for Diesel-only and PV-Diesel system from Tables 2 and 4. For diesel – only system simulation, 100% of electric is generated by diesel generator, unmet electric load is 0.59% and generated excess electricity is 3.44%. For PV-Diesel system, 33.33% of electric is generated by PV array and 66.67% is generated by diesel generator. The unmet load is found as 0.6% while the generated excess electricity is 19.20%. The effect of battery usage in hybrid system is very important for excess electricity, COE and carbon emissions. The excess energy is calculated as 5.57 h battery capacity of average load of 40.8 kWh.

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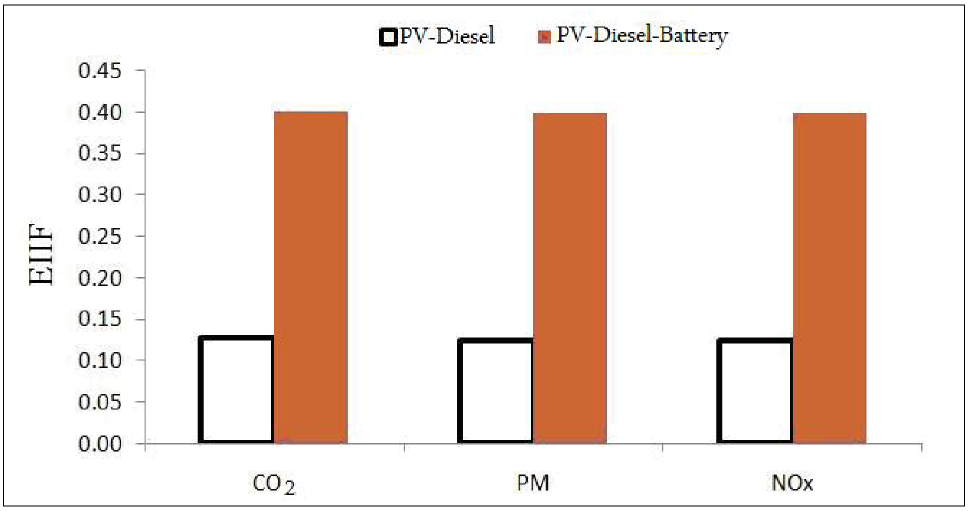
Table 4 Comparison for three systems considered for excess, unmet electric load and capacity shortage

	Diesel only		*PV-Diesel*		*PV-Diesel-Battery*	
Excess electricity (kWh/yr)	2215	3.44%	14 982	19.20%	2047	2.85%
Unmet electric load (kWh/yr)	364	0.59%	353	0.6%	249	0.00%
Capacity shortage (kWh/yr)	544	0.88%	529	0.9%	350	0.01%

The diesel-only electricity generation mainly depends on fuel. Therefore amount of fuel usage and its negative environmental effect is high. As it is shown in Table 2, diesel only system produced 63 900 kWh electric energy and 69.7 tonnes of CO_2, 13.0 kg of PM, 1.53 tonnes of NO_x emission in one year time as a result of diesel fuel usage. Replacing the diesel only system with 20 kW PV array, reduced greenhouse gas emission of CO_2 to 61 tonnes, PM to 11.4 kg, NO_x to 1.34 tonnes. PV-Diesel-Battery system will reduce emission of CO_2 to 42 tonnes and NO_x to 0.92 tonnes in one year time period.

We have also developed a new parameter, namely environmental impact improvement factor for renewable energy systems as given in Equation (6). An application of this parameter is conducted, to the PV-diesel and PV-diesel-battery system assessments. This parameter is calculated for PV-diesel and PV-diesel-battery system for comparison purposes and hence, graphically presented in Figure 6.

Figure 6 The Environmental Impact Improvement Factor (EIIF) values for PV-Diesel and PV-Diesel-Battery systems for CO_2, PM and NOx



As shown in Figure 6, we can summarise that the Environmental Impact Improvement Factor (EIIF) for PV-diesel system is found as 0.127, 0.123 and 0.124 for CO_2, PM and NOx, respectively, while for PV-diesel-battery system it takes values as 0.399, 0.397, 0.398 for CO_2, PM and NOx, respectively. In fact, the EIIF essentially represents the percentage of total load met by renewable energy, depending on the cost of fuel used. When the fuel type remains same, renewable energy utilisation ratio becomes equal to its EIIF. For example, reducing CO_2 by 40% means that 40% of total energy is to be provided by renewable energy. Adding a battery will help reduce it further by about 27.5%.

4 Conclusions

The results of this study show that for a given hybrid configuration, the operational hours of diesel generators decrease with increase in PV capacity. Integrating PV array into diesel only power system not only reduces operating cost but also the greenhouse gases and particulate matter emitted to the atmosphere. PV-diesel-battery hybrid system simulation is also examined and as due to use of battery there is substantial saving in the fuel consumption and reduction in drastic amount of greenhouse gases emission into atmosphere by the diesel generator. For PV-Diesel-Battery simulation results indicate that the PV penetration is 36% diesel generator fuel consumption is 15 972 litres (For diesel only fuel consumption is 26 487 litre). The cost of generating energy (COE, US$/kWh) for PV-Diesel and PV-Diesel-Battery systems have been found to be US$1.478/kWh and US$1.245/kWh, respectively (with the assumption of having diesel fuel price as US$1.9/L). In this paper we have also present a new parameter as environmental impact improvement factor. This parameter appears to be key indicators to show how much the system is apparently sustainable for environment for PV-diesel-battery systems. Environmental impact improvement factor can be also used to evaluation another renewable energy source. Thus, all renewable energy sources are to be possible for comparison each other.

For diesel – only system simulation, 100% of electric is generated by diesel generator, unmet electric load is 0.59% and generated excess electricity is 3.44%. For PV-Diesel system, 33.33% of electric is generated by PV array and 66.67% is generated by diesel generator. Unmet load is found as 0.6% and generated excess electricity is 19.20%. During the summer months, energy generated by PV is higher due to the global irradiation data in region and diesel electric generation is lower as compared to other months. While 36% of electricity is generated by PV array, the rest is produced by diesel generator. Unmet electric load is found as 0% and excess electricity is generated 2.85%.

At present, renewable energy based hybrid energy systems not cost-competitive against conventional fossil fuel based stand-alone or grid interfaced power sources. As result of need for cleaner energy sources, improvements in alternative energy technologies and increase in fuel price it is expected that it will be widespread use of various alternative energy source in the future.

As a future study, it is planned to conduct some experiments to compare with the simulation results. In order to reduce the greenhouse gases emission and have system work reliable wind turbine will also integrated to the hybrid system. Integration of a hybrid energy system with hydrogen storage, which will use system excess energy, will improve the system performance. Such results are expected to guide designers, engineers and policy makers for better implementation of renewable energy systems.

Acknowledgements

The authors acknowledge the support provided by Balikesir University in Turkey, and the Natural Sciences and Engineering Research Council in Canada.

Nomenclature

P_{mp}	Maximum power (W)
V_{mp}	Maximum voltage (V)
I_{mp}	Maximum current (A)
V_{oc}	Open-circuit voltage (V)
I_{sc}	Short-circuit current (A)
A_{sc}	Array surface area (m^2)
NOTC	Normal Operating Cell Temperature (C°)

Abbreviations

LEC	Levelised Energy Cost (US$)
NPC	Net Present Cost (US$)
TPV	Total Present Value (US$)
AL	Annual Load (kWh)
COE	Cost of Energy (US$/kWh)
O&M	Operation and Maintenance (US$)
EPBT	Energy Payback Time (year)
CRF	Capital Recovery Factor
R	Net discount rate
N	Economic evaluation period (year)

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Note

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