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Distributed Generation to Reduce Carbon Dioxide Emissions: A Case Study for Residential Sector in Oman

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Abstract: The paper presents a case study in Oman to reduce the CO_2 emission by diesel-photovoltaic based distributed power system feeding to a house located in remote area. Model of a hybrid power system comprising of a photovoltaic module, along with a diesel generator and essential auxiliary devices is proposed. The actual average solar radiation and residential load data, collected from the meteorological department and local utility office are used in this case study. The simulation results carried out using HOMER software indicate that the proposed hybrid system is attractive to reduce CO_2 emission by 38% when compared to the diesel system alone, and by 2.67 % compared to the main interconnected system. The study also includes operational and per unit energy cost estimates. It is seen that the diesel-photovoltaic hybrid system is attractive in terms of operational costs, which is lower by 29.44% compared to the diesel system; while per unit energy cost is 12.08% lower. It may be noted that the cost estimates arrived at for main interconnected system are better in terms of per unit energy cost, which is lower by 8.43 % compared to the proposed hybrid system, while it is not attractive in terms of CO_2 emissions.

Keywords: Carbon emission, Distributed generation, Greenhouse gases, Hybrid power system, PV-module, Residential load, Solar energy.

1. INTRODUCTION

As on February 2009, 183 countries in the world have signed and ratified the Kyoto Protocol to the United Nations Framework Convention on Climate change (UNFCC) with the goal of achieving stabilization of greenhouse gas concentrations. The Oman, as a member of UNFCC has agreed on January 2005 to contribute to combating global warming with the rest of the world.

The Gulf Cooperation Council (GCC) states i.e. Kuwait, Saudi Arabia, Qatar, Bahrain, United Arab Emirates and Oman are dependent on fossil fuel (the main cause of carbon emissions); and their economies are reliant on the oil, gas and petrochemical based industries. According to World Resources Institute [1], Saudi Arabia and United Arab Emirates are among the world's top 50 carbon emitters. Due to rapid growth and diversify of economy, electricity demand in the Oman is accelerating. To meet the future electricity demand, the government has recently announced to invest around US Dollar ($) 7.75 billion to upgrade and construct the conventional diesel, gas and coal based power plants. This action will persist to enhance the emission of Greenhouse Gases (GHG). To diminish the ill effects of climate-sensitivities and to combat global warming problem, reduction of CO_2 and other pollutants are inevitable.

The Kyoto Protocol provides various mechanisms like joint implementation, clean development mechanism and international emission trading that enable countries to acquire GHG reduction credits. The evaluation and deployment of carbon credit is a key component to mitigate the growth in concentration of GHG. Prabhakant and Tiwari [2] have carried out an analysis to determine the carbon credits earned using standalone solar PV system which is encouraging and cost effective than conventional power generation. The other viable option to curb the carbon emission is substantial use of renewable energy along with the conventional resources.

The paper presents a case study to reduce the GHG by proposing a Diesel-Photovoltaic Hybrid System (D-PVHS) feeding to a house located in remote area. The reminder of this paper is organised as follows. Second section presents the historical data of CO_2 emission and daily residential power demand. Section III estimates the emission factor and energy cost of Main Interconnected System (MIS) feeding to the residential sector. Section IV describes the potential of renewable energy in the Oman. The model development is described in Section V. The application of this case study is explained in section VI. Results and discussion are described in section VII while conclusions of the study are presented in section VIII.

2. CO_2 EMISSIONS & RESIDENTIAL LOAD

The rapid growth in population, urbanization, and industrialization are the major driving force for utilities to increase the power generation. To keep a balance in supply

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and demands, utilities are putting more efforts to generate the electricity by combustion of subsidized fossil fuels. Around 95% of total electrical power in the country is generated by combustion of fossil fuels which are having significant contribution in production of CO_2 and other pollutants.

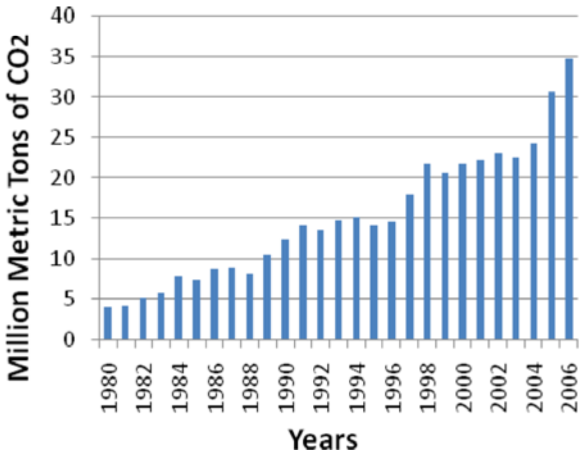

Fig. (1). Total CO_2 emission in Oman.

The international energy statistics [3] show that total CO_2 emission as well as per capita emission in the Oman is on rising trend and shown in Figs. (**1**) and (**2**) respectively. It can be seen from Fig. (**1**), the total CO_2 emission has increased by more than 41.21% during 2006 compared to the level of 2004.

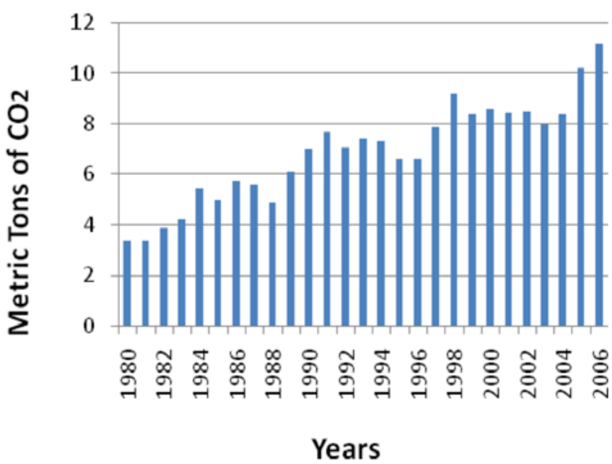

Fig. (2). Per capita CO_2 emission.

The largest part of total electrical power in the country is consumed by residential, commercial, government and industrial sectors. Residential sector is largest among all energy consumers [4]. The hourly load of the residential sector depends on many factors like home occupancy, life style, ownership of appliances, summer/winter season etc. The load data from 226 houses in rural and urban area were collected to analyze the load pattern and demand. An average hourly load profile of a typical house is shown in Fig. (**3**). It can be seen from profile that average energy demand is around 78 kWh per day.

For reducing the GHG emissions, it is essential to gradually diversify the fossil fuel based power generation with more environmentally friendly renewable energy resources. The Distributed Generation Technology (DGT) using solar or wind power along with conventional sources can be a viable solution [5, 6] to develop the hybrid system.

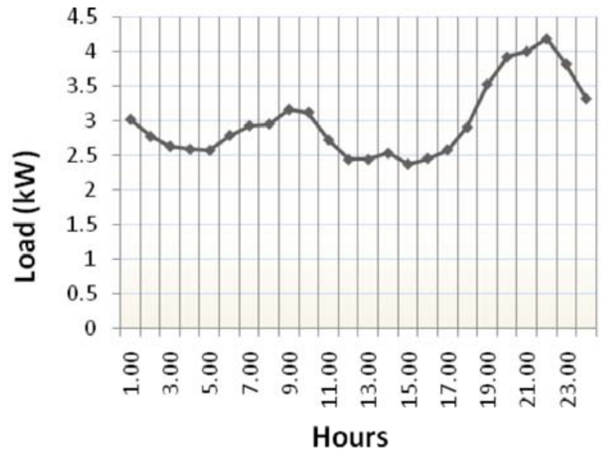

Fig. (3). Average power demand of a house.

3. CO_2 EMISSION & COST OF ENERGY FOR MIS

Majority of urban and rural residential area in the Oman are powered by low voltage distribution networks through MIS which is an integral part of national power grid connected to 8 power generating stations [7]. About 80% of electrical power injected to MIS is produced by combustion of Liquid Natural Gas (LNG) while remaining generation is dependent on diesel and other resources [8]. The total CO_2 emission (ton) on power grid is calculated by the following equation

$$Total\ CO_2\ Emission = \sum_t Output \times P_t \times CEF_t \qquad (1)$$

Where, $\sum_t Output$ is the total generated electricity output at grid (MWh), P_t is the percentage contribution to grid, CEF_t is Carbon Emission Factor for specific technology and or fuel type (tons CO_2/MWh).

Fuel type used and percentage share of generation at power plant with corresponding emission factors are shown in Table **1** [9, 10]. It can be seen that CO_2 emission of LNG is 22.05% lower compared to diesel which eventually reduce the overall emission factor of MIS to a level of 0.700 kg CO_2 per kWh.

Table 1. Emission Factor for Power Plants

Fuel Type Used	Emission (kg CO_2/kWh)	Share (%)	Emission Factor
LNG	0.661	80	0.529
Diesel	0.848	15	0.127
Other	0.928	5	0.046

The evaluation of actual data of energy cost at MIS is highly complex due to different operating conditions, plant load factor, efficiency and subsidies on fossil fuel of each connected power station. The data are assumed based on local utilities information to calculate the approximate cost of energy produced by gas based power plant at zero subsidy and international market price of LNG are shown in Table **2**. The energy conversion factor for LNG is assumed to be 3.601 MJ per kWh.

Table 2. Input Data for Energy Cost Estimation

Particulars	Value
LNG fuel cost($/ liter)	0.750
All other cost ($ / liter)	0.050
Energy density of LNG(MJ/liter)	25.480
Plant efficiency (%)	33

4. POTENTIAL OF RENEWABLE ENERGY

There are various renewable energy resources (e.g. solar, wind, and tidal etc.) available across the country which required attention to explore the resources for distributed generation at domestic and commercial level. The information on solar radiation and wind speed at various locations is updated by meteorological department while adequate information on tidal waves is yet to be explored.

(i) Solar Energy

The solar insolation varies from year to year and location to location, therefore to estimate the long term average solar energy potential it is essential to use the data of past several years. A study on renewable energy resources by COWI & partners [5] has collected the solar radiation data from 1987 to 1992 for six different locations across the country. The study shows that Oman is blessed with abundant direct solar radiation. The most parts of country bear clear sky (except some part of southern Oman) with annual average sunshine duration of 3708 hours per year [11]. The solar radiation of Muscat area based on five years data (2002 to 2007), ranging from 4.232 to 8.011 kWh/m^2 per day with overall average of 6.383 kWh/m^2 per day [12]. The monthly average solar radiation incident in the region is shown in Fig. (**4**). It can be seen that solar energy incident is very high during May and June which is observed as high summer season across the country. These conditions are very much favourable to use the available solar potential as source of clean energy to meet high demands on MIS.

The solar technologies are broadly characterized as either passive solar or active solar depending on the way they capture, convert and distribute sunlight. Active solar techniques include the use of photovoltaic panels and solar thermal collectors while passive solar techniques include orienting a building to the sun, selecting materials with favorable thermal mass or light dispersing properties, and spaces that naturally circulate air.

The following systems are more commonly used [13, 14] for the application of solar technology:

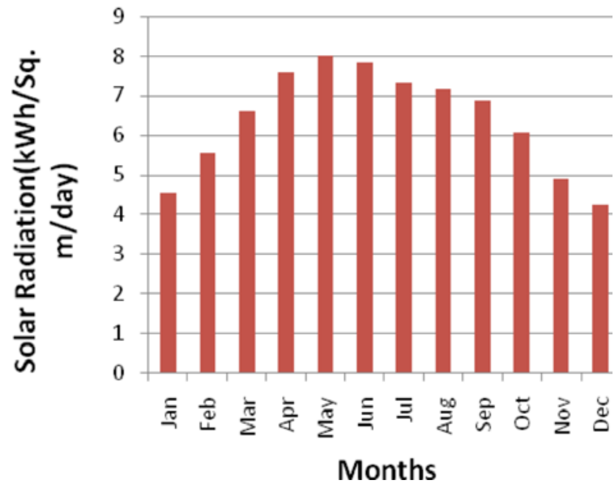

Fig. (4). Average solar radiation in Muscat area.

- PV-system: This convert sunlight directly to electricity by means of PV cell made of semiconductor materials.
- Concentrating Solar Power System: This concentrate the sun's energy using reflective devices such as troughs or mirror panels to produce heat then is used to generate electricity.
- Solar Water Heating System: This contain a solar collector that faces the sun and either heats water/ working fluid directly.
- Transpired Solar Collectors or Solar Walls: In this system solar energy is used to preheat ventilation air for a building.
- In remote rural sites the PV modules can facilitate the primary power source for applications like traffic signalling and data acquisition.

(ii) Wind Energy

The high wind speeds are observed along the coast from Masirah to Salalah in Oman [5, 6]. The highest wind speeds are in the Dhofar region while the wind speed remains at moderate and low in north and western part of the country. Geographically Muscat lies at 23.61^0 latitude north and 58.54^0 longitudes east which is not a favorable location for good wind speed.

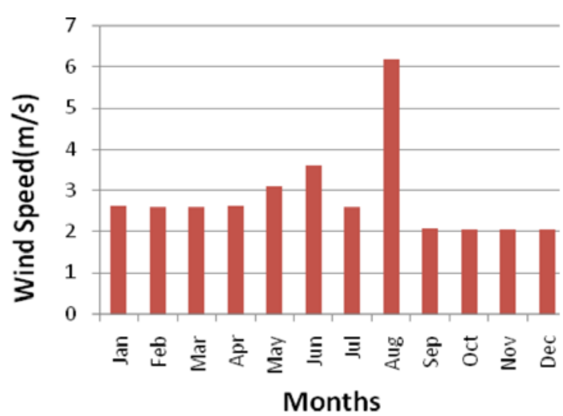

Fig. (5). Average wind speed in Muscat area.

The average wind speed in the region is about 2.830 m/s and becomes more eminent (around 2.182 times) when southwest monsoon winds prevailing during August is shown in Fig. (**5**). The intermittent nature and the class of low wind speed is neither commercial nor for residential sector is much encouraging to extract the electrical energy.

5. MODEL DEVELOPMENT OF D-PVHS

To determine the reduction in carbon emission and longer run economic feasibility, a D-PVHS is proposed along with Diesel System Alone (DSA) to feed a typical house located in remote area.

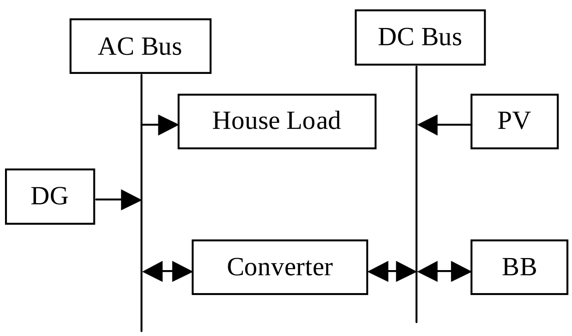

Fig. (6). Proposed diesel-PV hybrid power system.

The model consists of Diesel Generator (DG), PV modules (PV), Battery bank (BB), Converter, AC and DC busbars. The block diagram of proposed model is shown in Fig. **(6)**. Monthly average insolation data and average residential load are used as input parameters.

The Hybrid Optimization Model for Electricity Renewables (HOMER) [15] software is used for energy simulation, economic analysis and calculation of GHG emissions. The major components and economic modeling of hybrid system is described as follows:

(i) Description of Major Components

PV Array: A device that produce dc electricity in direct proportion to the global solar radiation incident upon it.

The power output of the PV array is simulated by using the expression

$$P_{pv} = f_{pv}\, Y_{pv} \left(\frac{I_T}{I_S}\right) \tag{2}$$

Where, f_{pv} is the PV derating factor, Y_{pv} is the rated capacity of the PV array (kW), I_T the global solar radiation incident on the surface of the PV array (kW/m^2), and I_S is 1kW/m^2, which is the standard amount of radiation used to rate the capacity of the PV array.

The rated capacity also known as peak capacity of a PV array is the amount of power it would produce under test conditions of 1000 W/m^2 irradiance and panel temperature of 25^{0}C and 1.5 air mass. The software calculates the global solar radiation each hour of year, incident on the PV array using Hay, Davis, Klucher, and Reindl (HDKR) model [16]. The derating factor is a scaling factor meant to account for effect of dust on the panel, wire losses, elevated temperature etc. that would cause the output of the PV array to deviate from the expected under test conditions.

The approximate roof area required [17] for standard PV module having efficiency of 12% is given in Table **3**.

Table 3. PV Module Capacity and Approximate Area

PV-Module Capacity(W)	Approx. Roof Area Required (m^2)	Approx. Cost ($/W)
4000	37.160	8 to 10
10000	92.900	6 to 8
100000	929	5 to 6

Battery Bank: The battery bank is a collection of one or more individual batteries capable of storing a certain amount of dc electricity at fixed round-trip energy efficiency. To calculate the battery's maximum allowable rate of charge or discharge, the kinetic battery model [18] is used.

The life of the battery bank is determined by the following equation

$$R_{batt} = min\left(\frac{N_{batt} Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right) \tag{3}$$

Where, N_{batt} is the number of batteries in the battery bank, $Q_{lifetime}$ the lifetime of throughput of a single battery, Q_{thrpt} the annual throughput (the total amount of energy that cycles through the battery bank in one year), and $R_{batt,f}$ the float life of the battery (the maximum life regardless of throughput).

The wear cost (the cost per kilowatt-hour of cycling energy through the battery bank) of the battery is determined by using following equation

$$C_{bw} = \frac{C_{rep,batt}}{N_{batt} Q_{lifetime} \sqrt{\eta_{rt}}} \tag{4}$$

Where, $C_{rep,batt}$ is the replacement cost ($) of the battery bank, N_{batt} the number of batteries in the battery bank, $Q_{lifetime}$ the lifetime throughput of a single battery (kWh), and η_{rt} is the round-trip efficiency.

Converter: It is a device that converts electric power from dc to ac in a process called inversion, and/or from ac to dc in process called rectification. The converter size which is decision variable, refers to the inverter capacity, meaning the maximum amount of ac power that the device can produce by inverting dc power. It is assumed that the inversion and rectification efficiency of the device is to be constant.

Generator: A diesel generator is considered as a basis of conventional source to generate the electrical power. It is assumed in model that the fuel curve is a straight line with a y-intercept and uses the following equation for the generator's fuel consumption

$$F = F_o\, Y_{gen} + F_1\, P_{gen} \tag{5}$$

Where, F_o is the fuel curve intercept coefficient, F_1 is the fuel curve slope, Y_{gen} the rated capacity of the generator (kW), and P_{gen} the electrical output of the generator (kW). The unit of F is litres/hour (L/h) and for F_o, F_1 L/h. kW.

The following equation is used to calculate the fixed cost of the energy of a diesel generator

$$C_{gen.\,fixed} = C_{om,gen} + \frac{C_{rep.gen}}{R_{gen}} + F_0 Y_{gen} C_{fuel,eff} \tag{6}$$

Where, $C_{om,gen}$ is the Operation and Maintenance (O&M) coast in $/ h, $C_{rep,gen}$ is the Replacement Cost (Rep. Cost), R_{gen} is the generator lifetime in hours, F_o is the fuel curve intercept coefficient in quantity of fuel per hour per kW, Y_{gen} is the capacity of the generator (kW), and $C_{fuel,eff}$ is the effective price of fuel in $/ litre.

The marginal cost of the energy of generator is calculated by the equation

$$C_{gen,mar} = F_1\, C_{fuel,eff} \tag{7}$$

Where, F_1 is the fuel curve slope in litre of fuel per hour per kWh and $C_{fuel,eff}$ is the effective price of fuel in $/ litre of fuel.

(ii) Economic Modeling

Economics play an important role to identify the system to minimize total net present cost and its optimization process. Total Net Present Cost (NPC) includes the costs of initial construction, component replacements, maintenance, fuel, plus the cost of buying power from grid and miscellaneous costs and hence is used to represent the life-cycle cost of a system, and determined by the following equation

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{8}$$

Where, $C_{ann,tot}$ is the total annualized cost, i is the annual real interest rate, R_{proj} the project lifetime, and CRF is the capital recovery factor which represent the % of initial capital cost to recover the cost of capital investment.

To determine the net present cost, the CRF is calculated by the equation

$$CRF_{(i,N)} = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{9}$$

Where, i is the annual real interest rate and N is the number of years.

The average cost per kWh of electricity produced by system is known as levelized cost of energy or Cost of Energy (COE) and is determined by following equation

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \tag{10}$$

Where, $C_{ann,tot}$ is the total annualized cost, E_{prim} and E_{def} are the total amounts of primary and deferrable load respectively that the system serves per year, and $E_{grid,sales}$ is the amount of energy sold to the grid per year. In this case study last two factors are out of scope, as the calculations are limited to off grid system.

6. APPLICATION OF D-PVHS IN CASE STUDY

The electricity demand of residential sector is having significant impact on total generation. The majority of houses are reliant on local distribution network which is integral part of MIS. In this case study a typical house located in remote area is considered to determine the potential of reduction in GHG emission and the economic feasibility when it is powered by D-PVHS, DSA and MIS. Some miscellaneous input parameters and analysis related data used for case study are shown in appendix-A. The cost of major components considered for D-PVHS and DSA are shown in Table **4** and **5** respectively.

Table 4. Cost of D-PVHS Components

System Comp.	Capital Cost ($)	Rep. Cost ($)	O&M Cost ($/yr)
Generator	1500/kW	1200/kW	438
PV Array	5000/kW	4500/kW	25
Converter	1000	1000	100
Battery	300	300	20

Table 5. Cost of DSA Components

System Comp.	Capital Cost ($)	Rep. Cost ($)	O&M Cost ($/yr)
Generator	1500/kW	1200/kW	438
Converter	1000	1000	100
Battery	300	300	20

(i)Assumptions

The following assumptions are considered in the case study to determine the optimised cost of the D-PVHS:

- The power output of PV array is independent of panel temperature.
- Maximum power point tracker is present in the system to maintain the voltage equal to the maximum power point.

- Properties of the batteries remain constant throughout its lifetime and are not affected by external factors such as temperature.
- Project life is 20 years and bank interest rate is 7%.

7. RESULTS AND DISCUSSION

The GHG emissions for three systems feeding to a typical house located at remote area in Muscat region are calculated and the results obtained are shown in Table **6**.

Table 6. GHG Emissions for a House

Emissions (kg/yr)	DSA	D-PVHS	MIS
CO_2	29882	18526	19035
CO	73.801	45.710	47.011
SO_2	60	37.210	38.220
NO_X	658	408	419.150

It can be seen from Table **6** that employment of D-PVHS is enable to mitigate 38% CO_2 emission compared to DSA and around 2.67% to MIS. There are 462117 residential customers accounted [8] across the country in urban, rural and remote locations out of them 30% are residing in Muscat region alone which are connected to low voltage distribution network. Therefore the effective implementation of D-PVHS in the region has the potential of 72609 metric tons of CO_2 reduction.

During summer season the residential load is highest due to maximum use of air-conditioners which accelerate the peak demand on MIS. The amount of average power produced per month by diesel generator and PV module in a distributed hybrid system is shown in Fig. (**7**).

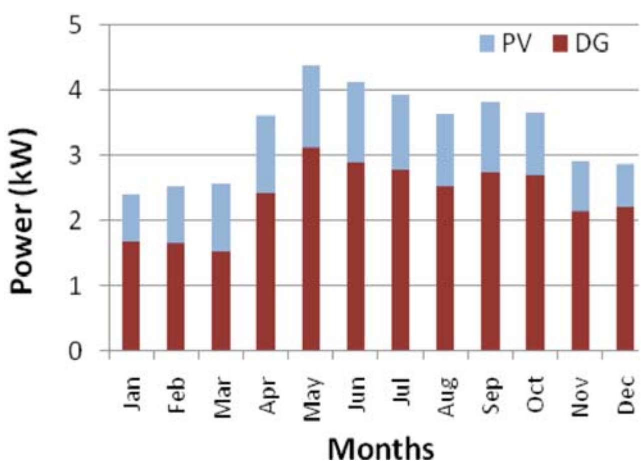

Fig. (7). Output of PV module and DG in hybrid system.

It can be seen that during summer, power produced by PV system is high which enhance the possibility to limit the additional demands. Further it can be observed from Fig. (**7**), that around 30% of the total power is produced by PV system which may considerably curb the operating reserves of conventional power generation if PV system is extended to entire residential sector.

The various significant costs are involved in power generated by DSA and D-PVHS. The HOMER software is used to optimise the proposed hybrid system design for cost effectiveness. The various costs are calculated by software embedded with equations described in section 5. The approximate cost of energy for MIS is determined using data collected from local utilities as shown in Table **2**. The results of optimised cost obtained for DSA and D-PVHS are shown in Table **7**.

Table 7. Comparison of Optimised Cost & Other Factor

Particulars	DSA	D-PVHS
Initial cost($)	16095	39800
COE($/kWh)	0.472	0.415
Operating cost($/yr)	11568	8162
Total NPC ($)	163971	144141
$C_{gen,fixed}$ ($/hr)	1.250	0.664
$C_{gen,mar}$ ($/kWh)	0.112	0.112
C_{bw} ($/kWh)	0.032	0.303
F (liter/yr)	11348	7035
R_{batt} (yr)	10.802	4.041

It can be seen from Table **7** that initial cost of D-PVHS is 2.47 times higher than DSA, but per unit energy cost and operating costs are 12.08% & 29.44% lower than DSA. The life time operation of D-PVHS may be capable to compensate the higher initial cost difference in longer run.

The power supplied by MIS is more cost effective compared to both DSA and D-PVHS due to bulk production and big size of power plants connected to national grid. The obtained per unit cost of energy for MIS is 0.380 $/kWh which is 19.49% lower than DSA and 8.43% lower than D-PVHS.

The other parameters like net present cost, fixed cost of energy produced by generator, marginal cost of energy of generator and fuel used are also calculated.

8. CONCLUSIONS

The following conclusions have been drawn from the work presented in paper:

- The proposed D-PVHS is attractive to reduce CO_2 emission by about 38% compared to DSA and 2.67% compared to MIS.
- While keeping the GHG at lower level, the proposed hybrid system is also a cost effective option for off-grid remote locations to meet demands in residential sector. The operating cost of D-PVHS is 29.44% less compared to DSA while per unit energy cost is 12.08% lower.

- The per unit energy cost from MIS is cheaper by 19.50% compared to DSA and 8.43% to D-PVHS respectively. However, MIS is not attractive in terms of CO_2 emission.

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APPENDIX A: Miscellaneous data used in model

(i) House Powered by D-PVHS

- House Load: 78 kWh/day, 27819 kWh/yr and 8.300 kW peak load demand.
- Diesel Generator: 5 kVA, 0.8 pf.
- PV Array: 6 kW, 80% derating factor, 20 year life time.
- Converter: 5 kW, efficiency = 90%, 15 year life time.
- Battery Bank: comprises of 16 batteries, each of nominal voltage of 6V & capacity of 360 Ah respectively, η_{rt} =85 %.
- Fuel cost: $0.45 per litre, ± 11.11%.

(ii) House Powered by DSA

- House Load: 78 kWh/day, 27819 kWh/yr and 8.3 kW peak load demand.
- Diesel Generator: 9.5 kVA, 0.8 pf.
- Converter: 2 kW, efficiency = 90%, 15 year life time.
- Battery Bank: comprises of 6 batteries, each of nominal voltage of 12V & capacity of 200 Ah respectively, η_{rt} = 85%.
- Fuel cost: $0.45 per litre, ± 11.11%.

(iii) Analysis Related Data

Description	Value
$C_{rep,batt}$ ($)	300
F_o (L/hr/kW)	0.080
F_1 (L/hr/kW)	0.250
Y_{gen} (kW)	7.530
P_{gen} (kW)	3.801
$C_{om.gen}$ ($/hr)	0.051
$C_{rep.gen}$ ($/kW)	1200
R_{gen} (hour)	15000

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