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Materials Today: Proceedings XX (2016) XXX–XXX

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PMME 2016

LCC Analysis for Economic Feasibility of Rural Electrification by Hybrid Energy Systems ✩

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Abstract

Presently the most of the electricity generation is contributed by fossil fuel based conventional energy sources in the world. The increasing use of fossil fuels can deplete their resources in coming future and also increase put harm to the atmosphere by green house gas emissions. So, it is becoming necessary to conserve the fossil fuels and find some alternative sources. The renewable energy sources like solar energy, wind energy, small hydropower, biomass-biogas energy are available in ample amount throughout the world and have the potential to substitute the use of fossil fuels. In this study, economic feasibility of rural electrification is presented through various energy sources like solar energy alone, diesel engine generator alone, solar-diesel hybrid system and utility grid based system for the selected rural area. It has been found that the hybrid SPV-DEG system is the most economically feasible option for the selected area.

Selection and Peer-review under responsibility of International Conference on Processing of Materials, Minerals and Energy (July 29th – 30th) 2016, Ongole, Andhra Pradesh, India.

Keywords: renewable energy; economic analysis; LCC; COE; hybrid energy system

1. Introduction

Many isolated rural areas of the developing countries are still not having access to electricity. Such areas are mostly found in the hilly terrain and the main reason of unavailability of electrical supply is uneconomical grid extension due to uneven terrain, poor load density and poor load growth. Such areas can also be electrified by using

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Selection and Peer-review under responsibility of International Conference on Processing of Materials, Minerals and Energy (July 29th – 30th) 2016, Ongole, Andhra Pradesh, India.

some conventional fossil fuel (like diesel) which is costlier and emits the green house gases (GHG) into the atmosphere [1].

Nomenclature:

LCC_t	total life cycle cost	LCC_{DEGS}	total LCC for DEG system
LCC_{sic}	LCC of system installation cost	C_{DEGS}	total capital cost of DEG system
LCC_r	LCC of recurring cost	MC_d	total maintenance cost of DEG system
LCC_{nr}	LCC of non-recurring cost	C_{fd}	cost of fuel for DEG system
$LCCF_f$	LCC factor for fuel	C_{deg}	capital cost of deg
$LCCF_m$	LCC factor for maintenance	C_{fsd}	cost of fuel system of DEG
FE	fuel escalation factor	C_{scd}	cost of system control for DEG system
GE	general escalation factor	COE_{deg}	cost of energy of DEG system
DR	discount rate factor	LCC_{HPDS}	LCC for hybrid system
n	years	C_{HPDS}	total capital cost of hybrid system
LCC_{SPVS}	total LCC for SPV system	MC_h	total maintenance cost of hybrid system
C_{SPVS}	total capital cost of SPV system	C_{fh}	cost of fuel for hybrid system
MC_s	total maintenance cost of SPV system	C_{sch}	cost of system control for hybrid system
C_{fs}	cost of fuel for SPV system	COE_{hpd}	cost of energy for hybrid system
C_{spv}	capital cost of SPV panel	LCC_{UGS}	LCC for utility system
C_{bb}	capital cost of battery bank	C_{UGS}	total capital cost of utility system
C_i	capital cost of inverter	MC_u	total maintenance cost of utility
C_{sc}	capital cost of system control	C_{tl}	capital cost of transmission line
C_{bs}	capital cost of building structure	C_{fu}	cost of fuel for utility system
COE_{spv}	cost of energy for SPV system	COE_u	cost of energy for utility system
E_t	total energy generated throughout system lifespan	C_{tpd}	capital cost of transformer and protective and control device

Such areas can be enriched with various renewable energy sources like solar, wind, small hydropower (SHP) and biomass. Use of single or more locally available renewable energy sources (RES) can mitigate the issue of electrification. Renewable energy (RE) sources are environmental benign and buoyant sources which are almost free from carbon. The green house gas emission of solar photovoltaic (SPV), wind energy and biomass resources are 100 gram/kWh, 25 gram/kWh and 90 % less compared to conventional gasoline respectively [2].Utilizing locally available energy sources, GHG emission can be reduced. It will also improve the educational and socio-economic status of rural population by offering employment opportunities to the local people through small scale industrial development [3].

In this study, life cycle cost (LCC) analysis of rural electrification considering different energy sources such as SPV, diesel engine generator (DEG), conventional utility grid and hybrid SPV-DEG based systems is presented. Section-2 briefly discuss about methodology of LCC analysis. Load estimation of the study area is carried out in section-3. Calculation of LCC and cost of energy (COE) for various system configurations considered are presented in section-4. Finally results & discussion, and conclusions are discussed in section-5 and 6 respectively.

2. LCC analysis methodology

Life cycle assessment (LCA) facilitates the framework that consist the total estimated incremental development cost, production cost, utilization cost, and retiring cost of a particular item. LCA focuses on the entire life cycle of all items from development stage to final utilization stage through its useful life span. It usually produces a feasible but not always optimal solution, and are used for specific situation [4]. In this study, the LCC analysis is carried out by considering (1) system installation cost which is the capital cost of the different system components (2) recurring cost and (3) non-recurring cost. Recurring cost mainly consist the operation and maintenance (O&M) cost, where operation cost is generally fuel cost. It also includes taxation and insurance cost. Maintenance cost includes expense occurred for the pre and post maintenance activities of different system components. Non-recurring cost consist replacement cost of the system components. In SPV, DEG or hybrid of both system; battery and DEG with fuel system are considered to be the components requiring replacement after an interval of their useful life, throughout the system's life. In order to maintain the accuracy, escalation and discount rate factors are considered in calculation.

2.1. Mathematical modeling for LCC analysis

In order to perform the economic analysis, the mathematical model of the system is defined to find out the total system LCC throughout its lifespan. The total system LCC is determined considering the LCC of various cost components like system installation cost, recurring cost and non-recurring cost corresponding to the various system components. The total system LCC is given by equation (1). After getting total LCC of the system, cost of energy (COE) is determined by dividing total LCC by total energy generated throughout the system useful life span, which is given by equation (2).

$$LCC_t = LCC_{sic} + LCC_r + LCC_{nr} \quad (1)$$

$$COE = \frac{LCC_t}{E_t} \quad (2)$$

Where LCC_{sic}, LCC_r, LCC_{nr} and LCC_t are life cycle cost for the system installation cost, recurring cost, non-recurring cost and total respectively. E_t represents total energy generated by the system throughout its useful life span and COE indicates cost of energy.

LCC factor (LCCF) is specified considering the escalation factor and discount rate factor for calculating LCC_r and LCC_{nr}. The LCC factor for recurring expenses (fuel and general maintenance) and LCC for non-recurring (replacement) expenses (LCC_{nr}) are given by equation (3), (4) and (5) respectively [5].

$$LCCF_f = \left[\frac{1+FE}{DR-FE}\right] * [1 - \left(\frac{1+FE}{1+DR}\right)^n] \quad (3)$$

$$LCCF_m = \left[\frac{1+GE}{DR-GE}\right] * [1 - \left(\frac{1+GE}{1+DR}\right)^n] \quad (4)$$

$$LCC_{nr} = \sum \text{Item cost} * \left(\frac{1+GE}{1+DR}\right)^n \quad (5)$$

3. Load estimation for study area

In order to perform economic analysis of rural electrification project through various system configuration, Khatisitara village of Banaskantha district of Gujarat state in India is considered as study area. This village have 101 households with population of 562. The load demand for such community is estimated based on their daily needs. The load demand is estimated as 391 kWh/day with peak load of 49 kW.

4. LCC analysis for energy systems considered

In the present study, the LCC analysis is carried out for the various system configuration considering SPV, diesel engine generator (DEG), hybrid SPV-DEG and conventional utility grid are worked out. From the analysis, most economically feasible resource is identified for rural electrification. The economical parameters considered in the analysis are given in Table 1. The various resource options and their configurations are detailed subsequently.

4.1. SPV based system

To calculate LCC for the SPV based system, the components of the system considered are SPV panel array, battery bank, inverters, charge controllers and building structure [6,7].The annual operation and maintenance cost is considered as 2 % of the capital cost. The battery selected is having a rating of 200 Ah, 12 volt. The annual operation and maintenance cost of battery is considered as 5% of its capital cost. The annual O&M cost of inverter

Table 1. Economical parameters.

Parameters	Value
Capital cost of SPV panel array (C_{spv})	Rs. 90000/ kW_p
Capital cost of battery bank (C_{bb})	Rs. 19000/battery
Capital cost of inverter (C_i)	Rs. 8000/kW
Capital cost of system control of SPV (C_{scs})	Rs. 1500000
Capital cost of building structure of SPV (C_{bs})	Rs. 500000
Capital cost of DEG (C_{deg})	Rs. 100000/10kW unit
Capital cost of fuel system of DEG (C_{fsd})	Rs. 300000
Capital cost of system control of DEG (C_{scd})	Rs. 400000
Capital cost of system control of hybrid PV-DEG (C_{sch})	Rs. 1500000
Cost of transmission line (C_{tl})	Rs. 1500000/km
Cost of transformer (C_{tpc})	Rs. 1000000
Maintenance cost for oil & filter change	Rs. 5000/event
Frequency of oil & filter change	40 event/year
Maintenance cost for DEG decoke	Rs. 10000/event
Frequency of decoke	10 event/year
Maintenance cost for DEG overhaul	50000/event
Frequency of overhaul	2event/year
Fuel (diesel) cost	67 Rs./Litre
Fuel consumption rate for DEG	1.25 Litre/hour
General escalation factor (GE)	7.5 %
Fuel escalation factor (FE)	5 %
Discount rate	10 %
Economic evaluation period	25 years
Currency consider during analysis	Indian rupees (Rs. or INR)

is taken as 2% of its capital cost [8]. The annual operation and maintenance cost of chare controller is taken as 0.5 % of its capital cost. The replacement cost of all items are considered same as its capital cost. The useful life span of SPV panel array, charge controller, inverter, battery and building structure are considered as 25, 25, 25, 10 and 25 years respectively. In SPV based stand alone system, the component which needs frequent replacement is the battery. In order to meet the estimated load demand, 149 kW of SPV panel array, 450 battery and 48 kW inverters are considered and the HOMER software is used for analysis. The SPV panel array de-rating factor and ground reflectance are considered as 80 % and 20 % respectively. The solar radiation potential of selected site is taken as 5.48 kWh/m^2/day from the NASA through HOMER software. The LCC and COE of the SPV based system is calculated using equation (6), (7), (8) and (9).

$$LCC_{SPVS} = C_{SPVS} + C_{fs} * LCCF_f + MC_s * LCCF_m + LCC_{nr} \quad (6)$$

$$C_{SPVS} = C_{spv} + C_{bb} + C_i + C_{scs} + C_{bs} \quad (7)$$

$$LCC_{nr} = [C_{bb} * \left(\frac{1+GE}{1+DR}\right)^n], n \neq 0 \quad (8)$$

$$COE_{spv} = \frac{LCC_{SPVS}}{E_t} \quad (9)$$

4.2. DEG based system

The diesel engine generator is used some times to electrify the semi-isolated rural areas in case other renewable energy systems are not available and the conventional diesel fuel is easily available. For LCC analysis of the DEG based system, the system components considered are; DEG, fuel system, system control and building structure. The annual O&M cost of DEG is considered as 10 % of its capital cost [9].The O&M cost of fuel system is taken as 5 % of its capital cost. The O&M cost of system control is taken as 3 % of its capital cost. The replacement cost of each system components are considered same as its capital cost. The useful life span of the whole system is considered as 25 years. The DEG with fuel system life span is considered as 7 years. So, the system components which need replacements are DEG and fuel system. In order to meet the estimated load demand, 45 kW of DEG is considered from the HOMER software analysis. The lifetime operating hours and minimum load ratio of DEG are considered as 62000 and 100 % respectively. The LCC and COE of DEG based system is calculated using the equations (10), (11), (12) and (13).

$$LCC_{DEGS} = C_{DEGS} + C_{fd} * LCCF_f + MC_d * LCCF_m + LCC_{nr} \quad (10)$$

$$C_{DEGS} = C_{deg} + C_{fsd} + C_{scd} + C_{bs} \quad (11)$$

$$LCC_{nr} = [(C_{deg} + C_{fsd}) * \left(\frac{1+GE}{1+DR}\right)^n], n \neq 0 \quad (12)$$

$$COE_{deg} = \frac{LCC_{DEGS}}{E_t} \quad (13)$$

4.3. Hybrid SPV-DEG based system

In this system both SPV and DEG configurations are considered for the purpose of rural electrification. The life span of the hybrid system is considered as 25 years. So, the system components which needs replacement are battery bank and DEG with fuel system at an interval of 10 years and 15 years respectively. In hybrid system, the replacement frequency of DEG is less because it gets the benefit of integrated operation. In order to meet the estimated load demand, 50 kW_p SPV panel array, 20 kW of DEG, 120 batteries and 15 kW of converter are considered in the analysis by using HOMER software. The LCC and COE of the hybrid SPV-DEG system is calculated using equations (14), (15), (16) and (17).

$$LCC_{HPDS} = C_{HPDS} + C_{fh} * LCCF_f + MC_h * LCCF_m + LCC_{nr} \quad (14)$$

$$C_{HPDS} = C_{spv} + C_{deg} + C_{bb} + C_i + C_{sch} + C_{fsd} + C_{bs} \quad (15)$$

$$LCC_{nr} = [C_{bb} * \left(\frac{1+GE}{1+DR}\right)^n] + [(C_{deg} + C_{fsd}) * \left(\frac{1+GE}{1+DR}\right)^n], n \neq 0 \quad (16)$$

$$COE_{hpd} = \frac{LCC_{HPDS}}{E_t} \quad (17)$$

4.4. Utility grid based system

In this case the rural electrification is worked out through utility grid option. The grid extension distance for the utility is considered as 10 km. The fuel cost is considered in terms of electricity price, which is taken as Rs. 5 per unit, and the consumption is considered as four unit per hour throughout the year. The maintenance cost of utility grid is taken asRs.8000/km and the frequency of maintenance is considered as one time per year. As lifespan of system components of the utility grid based system is long, no replacement of item is required, so non-recurring expenses will be zero. The LCC and COE of the utility grid based system is calculated using equations (18), (19) and (20).

$$LCC_{UGS} = C_{UGS} + C_{fu} * LCCF_f + MC_u * LCCF_m \quad (18)$$

$$C_{UGS} = C_{tl} + C_{tpc} \quad (19)$$

$$COE_U = \frac{LCC_{UGS}}{E_t} \quad (20)$$

5. Results and discussion

The LCC analysis for rural electrification through various system configurations has been carried out and COE of each system configuration is determined. The economic analysis is performed for the period of 25 years. LCC factors for fuel and maintenance are calculated considering escalation and discount rate.

5.1. LCC factor

The LCC factor for the fuel is calculated for the each year considering the fuel escalation factor and discount rate factor throughout the system life span and shown in Fig. 1(a). From the calculation, cumulative LCC factor for the fuel is found to be 15.43. From Fig. 1 (a), it is seen that the LCC factor for the fuel is decreasing smoothly with system life span. Its value is higher during the initial period and then decreases. The lowest value of the LCC factor for fuel is found as 0.31.

The LCC factor for the maintenance is also calculated for the each year considering the general escalation factor and discount rate factor and shown in Fig. 1(b). From the calculation, cumulative LCC factor for the general maintenance is found to be 19.8. From Fig. 1(b), it is seen that the LCC factor for the maintenance is decreasing smoothly with system life span. Its value is higher during the initial period of life span and then decreases. The lowest value of the LCC factor for maintenance is found as 0.56.

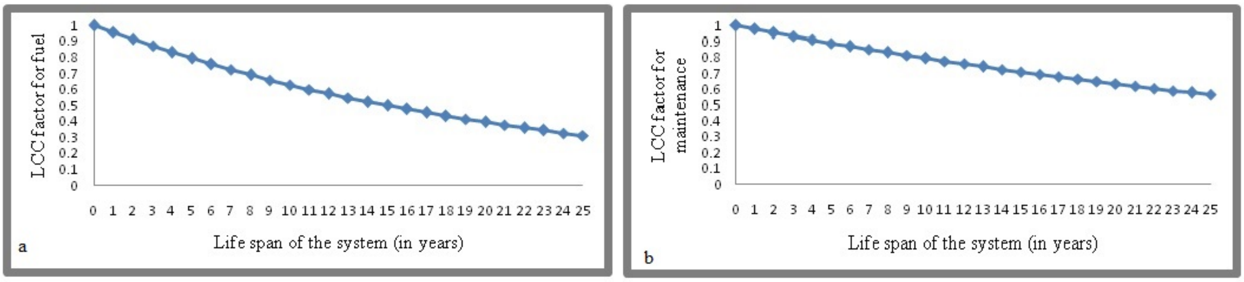

Fig. 1 (a) LCC factor for fuel versus system life span
(b) LCC factor for maintenance versus system life span

5.2. Cumulative cost

The cumulative cost of the system is also analysed for the different system configurations by performing the cash flow study. Fig. 2(a), shows the variation of cumulative cost of the system with system life span for all four configurations considered. From the Fig. 2(a), it is seen that SPV system alone and utility based system needs huge amount of capital investment and solar energy being stochastic in nature, the single SPV based system is not reliable. In order to have reliable SPV based system, cost of the system increases drastically due to large amount of storage requirements. Similarly for remotely located rural areas, the grid extension is also becoming uneconomical, mostly due to uneven terrestrial surface, poor load density and poor load growth. The DEG generator based system needs minimum initial investment, but the cost of operation and maintenance is high. Also single DEG based system is not preferable from environment point of view, as it releases higher amount of GHG into the atmosphere. Hybrid system is found more economical and reliable compared to other system configurations.

5.3. LCC versus COE

The LCC cost for all different system configuration is calculated and COE (Rs./kWh) is determined. The COE of different system configuration with respect to their LCC is shown in Fig. 2(b). From Fig. 2(b), it is found that COE for the hybrid SPV-DEG system is lowest.

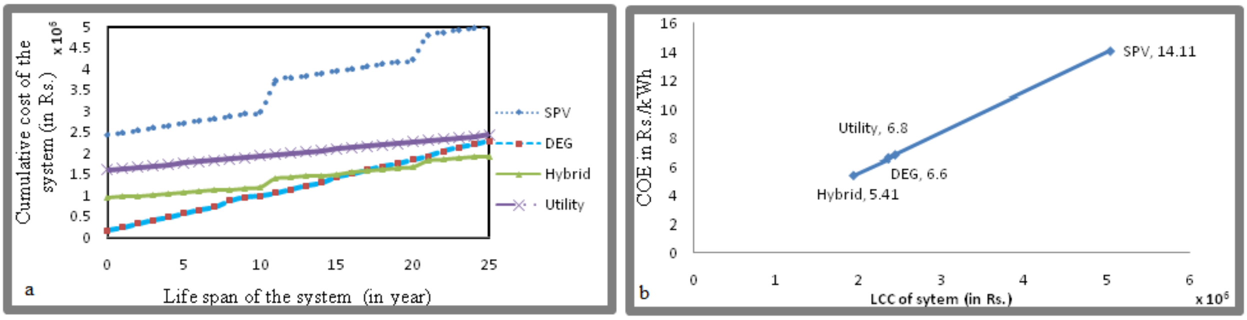

Fig. 1 (a) Cumulative cost versus system life span
(b) COE versus LCC of different systems

6. Conclusions

In this study, LCC analysis has been carried out to find out economic viability of rural electrification project for the remotely located village. Four various configuration of the systems were considered in the LCC analysis and COE is determined for each system configuration. From the LCC analysis, it is found that the hybrid SPV-DEG system is the most economically viable option for the area.

Acknowledgements

The authors thankfully acknowledge the Alternate Hydro Energy Centre (AHEC), IIT Roorkee and Quality Improvement Program (QIP) centre, IIR Roorkee, India for providing research facilities. Sincere thanks are also to All India Council for Technical Education (AICTE), New Delhi, India for providing financial support in the form of research scholarship. Authors also wish to express gratitude to Government Engineering College, Palanpur, Gujarat state, India and Commissioner of Technical Education, Gujarat state, India for financial support to conduct this study.

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