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Research Article

Comparison of Technological Options for Distributed Generation-Combined Heat and Power in Rajasthan State of India

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Distributed generation (DG) of electricity is expected to become more important in the future electricity generation system. This paper reviews the different technological options available for DG. DG offers a number of potential benefits. The ability to use the waste heat from fuel-operated DG, known as combined heat and power (CHP), offers both reduced costs and significant reductions of CO_2 emissions. The overall efficiency of DG-CHP system can approach 90 percent, a significant improvement over the 30 to 35 percent electric grid efficiency and 50 to 90 percent industrial boiler efficiency when separate production is used. The costs of generation of electricity from six key DG-CHP technologies; gas engines, diesel engines, biodiesel CI engines, microturbines, gas turbines, and fuel cells, are calculated. The cost of generation is dependent on the load factor and the discount rate. It is found that annualized life cycle cost (ALCC) of the DG-CHP technologies is approximately half that of the DG technologies without CHP. Considering the ALCC of different DG-CHP technologies, the gas I.C. engine CHP is the most effective for most of the cases but biodiesel CI engine CHP seems to be a promising DG-CHP technology in near future for Rajasthan state due to renewable nature of the fuel.

1. Introduction

In centralized generation(CG), electricity is generated in large remote plants. Power must then be transported over long distances at high voltage before it can be used. Distributed generation (DG) can be defined as electric power generation within distribution networks or on the customer side of the network [1]. DG is referred to as the use of small, modular power generation at or near the point of consumption irrespective of size, technology, or fuel used—both off-grid and on-grid as an alternative to large power generation and electricity transport over long distances [2].

The performance of the small power technologies (i.e., reciprocating engine and gas turbine) has improved remarkably over the last decade. In the last decade, technological innovations and a changing economic and regulatory environment have resulted in a renewed interest for distributed generation [3]. This is confirmed by the five major factors that contribute to this evolution; these are developments in distributed generation technologies, constraints on the construction of new transmission lines, increased customer demand for highly reliable electricity, the electricity market liberalization, and concerns about climate change [4]. This has aroused the interest of operators, regulators, and legislators in distributed generation. Three independent trends, first, increasing system capacity needs, second, utility industry restructuring, and third, technology advancements are concurrently laying the groundwork for the possible widespread introduction of DG. DG at the customer's site can also provide benefits to the electric utility that include reduced T&D electric losses, T&D upgrade deferrals, transmission congestion relief, and peak shaving [5]. The potential positive effects of distributed generation for improving tail-end voltages and power factor corrections were mentioned by Dondi et al. [6]. The IEA [7] recognizes the provision of reliable power as the most important future market niche for distributed generation.

Cogeneration, or combined heat and power (CHP), is defined as the simultaneous generation of heat and power in a single process. The power output is usually electricity but may include mechanical power. Heat outputs can include steam, hot water, or hot air for process heating, space heating, or absorption chilling [2]. Distributed (co)generation (DG) represents an alternative paradigm of energy supply and the opportunity for significant CO_2 emission reductions [8]. It is very reasonable to expect that DG will play a role in reducing local, regional, and even global air pollution [9]. One of the keys to the success of fossil-fuelled DG in Europe is the ability to use the waste heat from electricity generation, that is, CHP, raising total system efficiencies up to 90% (higher heating value (HHV)) in the best applications. Overall efficiencies of CHP system can approach 90 percent (considering both power and heating), a significant improvement over the 30 to 35 percent electric grid efficiency and 50 to 90 percent industrial boiler efficiency when separate production is used [5].

The high efficiencies of such applications, that is, CHP, offer both reduced costs and significant reductions of CO_2 emissions. Other factors which are enhanced reliability and security, reduced need for transmission and distribution upgrades, and easier plant siting may also drive increased deployment of DG in the future [10]. DG holds the promise of improved environmental performance of energy sectors due to higher efficiencies (using CHP) and the use of low-carbon fuels, for example, natural gas or carbon-free fuels, for example, hydrogen [11].

DG provides low-cost electricity and gives access to liberalizing generation markets for distribution utilities. DG also offers the potential for improved network management. This network management requires knowledge of projected electricity production and is greatly enhanced by distribution utilities having some control over electricity exports [8]. Distributed energy resources (DER) technologies, such as gas-fired reciprocating engines and microturbines, can be economically beneficial in meeting commercial sector energy loads. Even with a lower electric-only efficiency than that of traditional central station coal steam turbines (CST) and centralized combined cycle gas turbines (CCGT) combined with on-site gas-fired heat boilers (DH), combined heat and power (CHP) applications can increase overall system energy efficiency. From a policy perspective, it is useful to have good estimates of penetration rates of DER under different economic and regulatory scenarios [12]. Banerjee [13] analyzed the different technological options available for DG, their status and evaluated them based on the cost of generation and future potential in India. Narula et al. [14] studied DG technology options motivated by the goal of achieving "universal energy access" by 2030 and looked at electricity access for rural households in the South Asian region. They developed a model which was employed to assess the cost effectiveness of centralized and decentralized distributed generation (DDG) technologies.

There is increased interest in renewable fuels in present time and in Rajasthan, being mainly the dessert land, scope of renewable fuel like biodiesel obtained from the nonedible vegetable oil sources is great. Depleting oil reserves, increasing oil prices, lack of availability of the mineral oil, and the problem of environmental pollutions have prompted research worldwide into alternate fuels for internal combustion (IC) engines. Vegetable-oil-based fuels have been proved as potential alternative greener energy substitute for fossil diesel in compression ignition (CI) engines. The vegetable oils are renewable in nature and have comparable properties with fossil diesel. These are biodegradable, nontoxic and have potential to reduce the harmful emissions [15–18]. Diesel vehicles remain a major cause of street-level air pollution in many cities. For new diesel vehicles, increasingly stringent emissions standards have been imposed to reduce the pollutants emitted by them. Gasoline- and diesel-driven automobiles are the major sources of greenhouse gases (GHG) emission [19–22]. In this century, fuels derived from crude oil have been the major source of the world's energy as well as transportation sector. Future projections indicate that economics and energy needs will increase the focus on the production of synthetic fuels derived from nonpetroleum sources, including biomass and waste products [23, 24].

There is a need for examination of cost effectiveness of various DG-CHP technological options for Rajasthan considering its local requirement and potential within the framework of existing DG technologies. The earlier studies have been related to DG technological options for particular countries without taking the CHP options. But in case of our research study, the comparison for only DG technologies with DG-CHP has been analyzed with selected DG technologies, for example, IC engines fuelled by diesel and biodiesel, microturbines, and so forth for Rajasthan state only. These various DG-CHP technological options are proposed for Rajasthan state where there is mostly desert land and where the population is also scattered. The large distances between the villages and the cities prompt the use of DG technologies. So it is considered that if DG-CHP is used instead of only DG technology, then significant benefits can be achieved. This paper examines the cost effectiveness of the different DG-CHP technological options including biodiesel-fuelled CI engine CHP and evaluates them based on the cost of CHP generation.

2. Power Sector Status in Rajasthan State

Rajasthan state has low population density and people lives in remote places. Mandatory electricity requirement as insured by Rajasthan government for these villages has not been fulfilled by present supply of electricity through transmission lines due to lacking of transmission lines availability and shortage of electricity generation. Rajasthan government is lagging behind their schedule for providing electricity for all villages and hamlets as mentioned in the central government's 11th five-year plan to be implemented by the states. This shortage can be fulfilled by distributed generation of electricity.

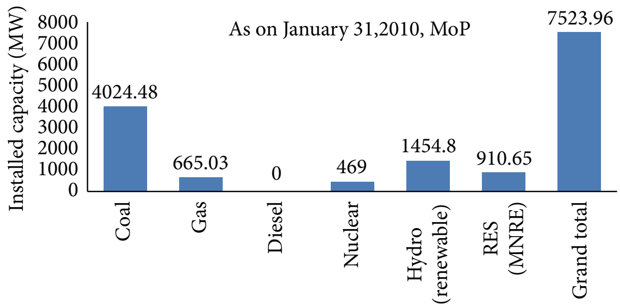

Figure 1: Installed capacity of power utilities in Rajasthan.

In Rajasthan, in 1949, the total installed capacity of power houses was 13.27 MW. Total circuit length of 33 kV lines was 137 Km and that of 11 kV was 193 Km. Total consumers were 34518. During first five-year plan in 1951–1956, 15 crores were spent on power development which resulted in an increase in installed capacity to 34.90 MW. The number of villages electrified was 36, wells electrified was 47 and there were 51205 consumers with per capita consumption of energy 2.8 unit.

The Rajasthan State Electricity Board was constituted with effect from July 1, 1957, by government of Rajasthan under the Electricity (Supply) Act, 1948, whose enactment has for its object the coordinate development and rationalization of generation and supply of electricity on a regional basis throughout the country in the most efficient and economical way. Government of Rajasthan on July 19, 2000, issued a gazette notification unbundling Rajasthan State Electricity Board into Rajasthan Rajya Vidyut Utpadan Nigam Ltd. (RVUN) as the generation company; Rajasthan Rajya Vidyut Prasaran Nigam Ltd. (RVPN) as the transmission company, and the three regional distribution companies, namely, Jaipur Vidyut Vitran Nigam Ltd. (JVVNL), Ajmer Vidyut Vitran Nigam Ltd. (AVVNL), and Jodhpur Vidyut Vitran Nigam Ltd. (JdVVNL).

The generation company owns and operates the thermal power stations at Kota and Suratgarh, gas-based power station at Ramgarh, hydel power station at Mahi, and minihydel stations in the state. The transmission company operates all the 400 kV, 220 kV, 132 kV, and 66 kV electricity lines and system in the state. The three distribution companies operate and maintain the electricity system below 66 kV in the state in their respective areas mentioned in their license.

Rajasthan state fulfills its electricity requirement mainly from CG (centralized generation) which includes thermal, hydro, nuclear, and renewable energy sources. Rajasthan had an installed capacity of 7523.96 MW in the centralized power utilities on January 3, 2010. Of this 4689.51 MW is accounted for by thermal power plants, 1454.80 MW by large hydro plants, 910.65 MW by renewable energy sources, and 469.0 MW of nuclear power plants as shown in Table 1 and Figure 1 [25].

Rajasthan state has seen remarkable development in the recent past decade and is in developing stage also. It means energy requirement in the state will be more than that predicted. In this context consumption of diesel and gas will increase in the coming years.

3. Relevance of Distributed Generation in Rajasthan

In Rajasthan, distributed generation has found three distinct markets which are given below where CHP can be used as per requirements:

(i) back-up small power generation systems including diesel generators that are being used in the domestic and small commercial sectors,

(ii) stand-alone off-grid systems or minigrids for electrification of rural and remote areas. The units will be located at dispersed rural locations, which reduces the transmission and distribution (T&D) losses to some extent. The T&D losses in Rajasthan were about 28% in 2002 [26],

(iii) large captive power plants such as those installed by power-intensive industries.

However before going to these three markets, it is necessary to study the government policy about the generation of electricity. A comprehensive electricity bill was drafted in the year 2000 following a wide consultative process. After a number of amendments, it sailed through the legislative process and was enacted on June 10, 2003. It is known as Electricity Act 2003. It replaces the three existing legislations governing the power sector, namely, first, Indian Electricity Act, 1910, second, the Electricity (Supply) Act, 1948, and third, the Electricity Regulatory Commissions Act, 1998. The policy in section 3 (3.3) of the Electricity Act 2003 identifies decentralized distributed generation of electricity by setting up of facilities together with local distribution network based on either conventional or nonconventional resources methods of generation.

Also to promote distributed generation, the government of India has announced many schemes. Two specific schemes of the government of India, the RGGVY (Rajiv Gandhi Grameen Vidyutikaran Yojana) and the RVE (Remote Village Electrification) scheme, provide up to 90% capital subsidy for rural electrification projects using DDG (decentralized distributed generation) options based on conventional and nonconventional fuels, respectively.

Keeping all above factors in mind it seems that DG can be an additional method of electricity generation. Therefore in this paper economic comparison has been made between various technological options of DG. The various technological options selected for this study are reciprocating diesel engine, biodiesel CI engine, reciprocating gas engine, microturbine, small gas turbine, and low-temperature fuel cell.

4. Comparison Methodology

In order to compare the costs of generation of electricity from each of the above technological options, when these options are used as CHP supply, the annualized life cycle cost (ALCC) [13] is used. The annualized life cycle cost represents the annual cost of purchase of the system and its operation. The amount of fuel consumed annually in producing electricity only by DG-CHP option is obtained by subtracting the

Table 1: Installed capacity of electricity generation in Rajasthan state.

Sector	Thermal Coal	Thermal Gas	Thermal Diesel	Total thermal	Nuclear	Hydro (renewable)	RES** (MNRE)	Grand total
State	3240.00	443.80	0.00	3683.80	0.00	987.96	30.25	4702.01
Private	135.00	0.00	0.00	135.00	0.00	0.00	880.4	1015.40
Central	649.48	21.23	0.00	870.71	469.00	466.84	0.00	1806.55
Subtotal	4024.48	665.03	0.00	4689.51	469.00	1454.80	910.65	7523.96

**Renewable energy sources (RES) include SHP, BG, BP, U&I, solar, and wind energy.
Abbreviation: SHP: small hydro project, BG: biomass gasifier, BP: biomass power, U&I: urban and industrial waste power.
Source: [25].

Table 2: Heat-to-power ratio (HPR) values.

DG-CHP technology outputs	HPR
Microturbines	2.6
Reciprocating diesel engines	1.6
Reciprocating gas engines	2.1
Low-temperature fuel cells	1.4
Small gas turbines	2.0
Biodiesel CI engine	1.6

Note: heat distribution losses are not included in this table.
Source: [10].

amount of fuel consumed in producing heat from the total amount of fuel consumed annually in DG-CHP technological options. The amount of fuel consumed in producing heat in DG-CHP option is calculated with the help of heat-to-power ratio (HPR) [8] of each technology given in Table 2:

$$\text{HPR} = \frac{\text{Energy produced (or consumed) as heat}}{\text{Energy produced (or consumed) as electricity}}. \tag{1}$$

In this study, it is considered that there is a heating requirement for domestic purposes or for processes in small industries, and so forth. Loads are not proposed for any particular case; it is considered that there is always almost a heating requirement locally and this local requirement can be fulfilled by using DG-CHP technologies (as per the heat-to-power ratio) and a separate boiler will not be needed for heating purpose hence saving fuel cost. The annualized loads are considered in the study mainly concentrating on the variation of load factor and its effect on the life cycle cost of the technologies. In centralized generation of electricity, if heat is produced separately, a boiler will be required. Here in DG-CHP the cost of boiler is saved but it is not subtracted from the cost of the technological option and considered heat will be used locally and heat distribution losses are not taken into account. The cost of generated electricity is obtained by dividing the ALCC by the annual generation of electricity.

The ALCC is computed as

$$\text{ALCC} = C_0\text{CRF}(d, n) + \text{AC}_f + \text{ACO}\,\&\,\text{M}, \tag{2}$$

where C_0 = the initial capital cost for the technological option, $\text{CRF}(d, n)$ = capital recovery factor for the technological option based on the discount rate "d" and the life of the option "n" in years, AC_f = the annual fuel cost to produce electricity only for the technological option, and ACO & M = the annual operating and maintenance cost for the technological option.

The capital recovery factor (CRF) is computed using the equation

$$\text{CRF}(d, n) = \frac{[d(1+d)^n]}{[(1+d)^n - 1]}. \tag{3}$$

The annual generation of CHP is dependent on the load factor. The cost of generation of CHP is dependent on the size of the equipment and the application load factor. In this paper based on the typical unit size range given in Table 2, a 50 kW peak rating is used as the basis of calculation except for small gas turbine (500 kW). Tables 2, 3, and 4 are used for the ALCC calculations of the selected technological options. The calculations are done with existing Rajasthan state's fuel and equipment prices. Other data used are diesel fuel costs Rs. 42.06 per liter in June 2011 and Rs. 49.30 per liter in January 2013 in Rajasthan. Natural gas price is Rs. 18/sm^3 in June 2011 and Rs. 22.5/sm^3 in January 2013.

In the case of technologies not commercially available in Rajasthan or India the existing international prices in US $ have been converted to Indian rupees (Rs.) at the prevalent exchange rates (1 US$ = 52.5 Rs. in January 2013). An idea of the comparative costs of technological options, when these are used as only power and as CHP, and impact of the load factor will provide an idea of the viability of the DG-CHP option. The status of each option in Rajasthan is discussed along with some of the issues relevant to its adoption.

5. Cost of Generation

To make the comparison between the various technological options, load factor and ALCC are used. Load factor represents the operation of engine in fraction of hours in one day. ALCC for various technological options is calculated using (2) and (3). Graphs between ALCC and load factor are drawn at two interest rates 10% and 30% with and without heat power ratio obtainable for a particular technological option for the months of June 2011 and January 2013.

Figures 2 and 3 show the annualized life cycle costs of the diesel engine, gas engine, microturbine, small gas turbine, and fuel cell options, as a function of the load factor with a societal discount rate of 10% for the months of June 2011 and

Table 3: Technologies: markets and performance.

	Residential	Commercial	Industrial	Grid distributed	Remote/off-grid distributed	Typical unit size range (installation size can be larger)	2010 Installed capital cost (Rs/kW)	Electric conversion efficiency (%)	Commercial availability	Application
Microturbines[a]		1	1	1	2	25–300 kW	20000	28	Yes	CHP
Reciprocating CI engines	1	1	1	1	1	5 kW–20 MW	7100	35	Yes	Standby services/CHP
Reciprocating gas engines	1	1	1	1	1	5 kW–20 MW	16000	40	Yes	CHP
Low-temperature fuel cells	1	1	2	1	1	2–250 kW	80000	35	Yes	CHP
Small gas turbines[b]			1	1	2	500 kW–20 MW	17000	40	Yes	CHP

[a]Recuperated microturbine.
[b]Forty percent efficiency achieved with advanced turbine cycle.
1: Primary target market.
2: Secondary target market.
Source: table constructed on the basis of information found in [4, 5] and data available in Rajasthan.

Table 4: Distributed generation technologies and characteristics.

DG-CHP technologies	Life in years	*O&M* cost (Rs/kWh)	Fuel used
Microturbines	20	0.30	Generally uses natural gas, but flare, landfill, and biogas can also be used
Reciprocating CI engines	20	0.30	Diesel, also heavy fuel oil and biodiesel
Reciprocating gas engines	20	0.30	Gas, mainly natural gas; biogas and landfill gas can also be used
Small gas turbines	20	0.30	Gas, kerosene
Low-temperature fuel cells	10	0.30	Hydrogen or natural gas. Reforming of CH_4 to H_2 leads to decreased efficiency

Source: table constructed on the basis of information found in [4] and data available in Rajasthan.

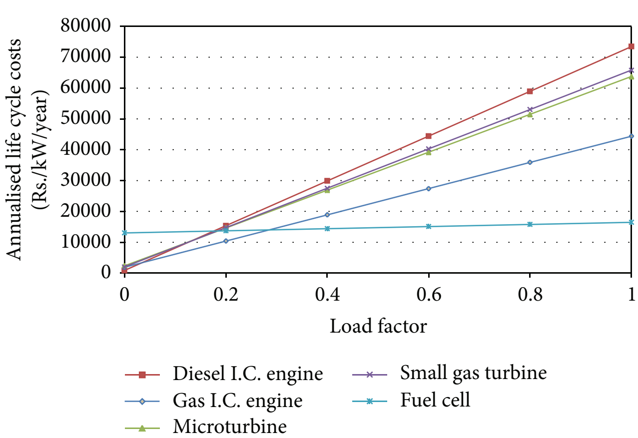

Figure 2: Comparison of annualised life cycle costs for different technological options, when only DG is considered (discount rate (d) = 10%) for the month of June 2011.

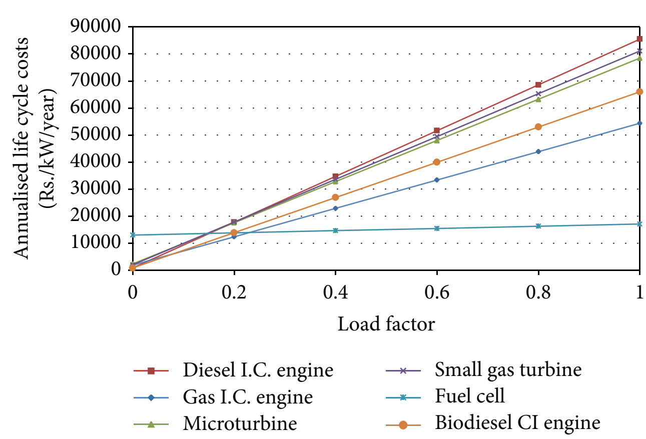

Figure 3: Comparison of annualised life cycle costs for different technological options when only DG is considered (discount rate (d) = 10%) for the month of January 2013.

January 2013, respectively, for DG only, that is, not as DG-CHP. Data for biodiesel CI engine is taken in January 2013 only.

It is seen from Figure 2 that fuel cell is the cheapest option at load factor more than 0.3 in June 2011 and from Figure 3 at load factor more than 0.24 in the month of January 2013. It

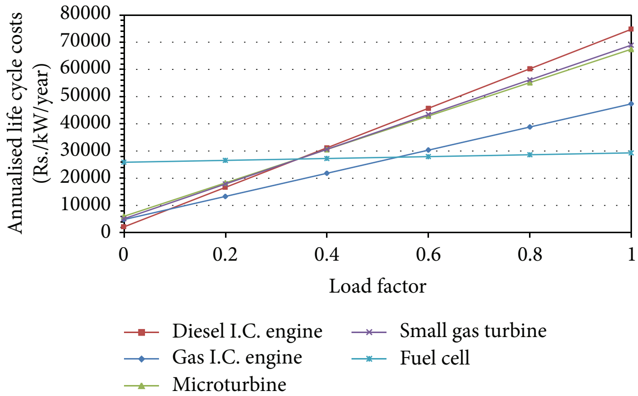

FIGURE 4: Comparison of annualised life cycle costs for different technological options when only DG is considered (discount rate (d) = 30%) for the month of June 2011.

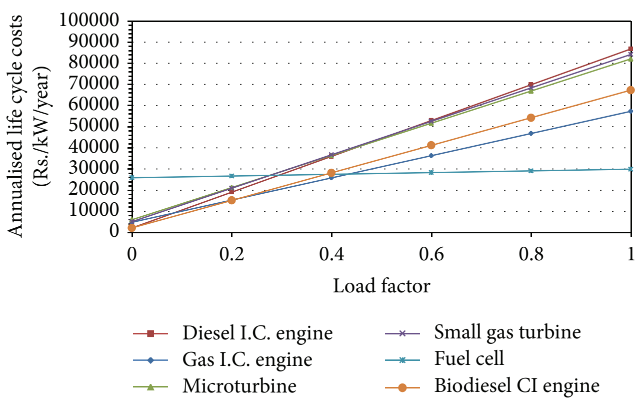

FIGURE 5: Comparison of annualised life cycle costs for different technological options when only DG is considered (discount rate (d) = 30%) for the month of January 2013.

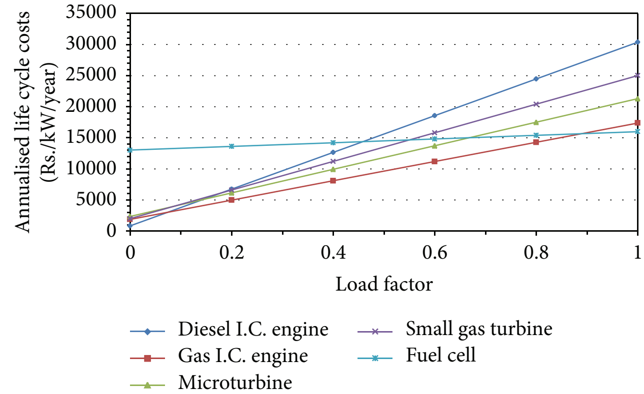

FIGURE 6: Comparison of annualised life cycle costs for different technological options when DG-CHP is considered (discount rate (d) = 10%) for the month of June 2011.

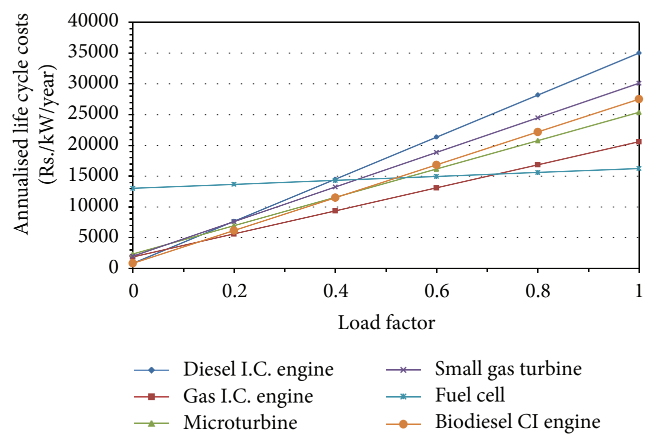

FIGURE 7: Comparison of annualised life cycle costs for different technological options when DG-CHP is considered (discount rate (d) = 10%) for the month of January 2013.

shows that fuel cell is becoming more favorable at low load factor during the passage of time; it is because that cost of diesel is increasing. But technical expertise for fuel cell is not available in the state. Therefore fuel cell is not possible in the present scenario in Rajasthan state but it seems the better option for the future.

From Figures 2 and 3 it can be analyzed that the gas engine is the next cheaper option but the ALCC of gas engine has increased from June 2011 to January 2013 remarkably as compared to fuel cell. The gas engine is less popular in the state due to higher initial capital cost and poor distribution system of gas as a fuel. The improvement in natural gas availability and the presence of gas distribution companies in the state are likely to see an increase in gas engine option. However at low load factor diesel engines are used as a back-up power. Figure 3 shows that at low load factor biodiesel CI engines are better option than diesel engines. Also biodiesel CI engines have better environment-friendly characteristics.

It is seen from Figures 4 and 5 that at high load factors fuel cell is cheaper than other options. Gas engine is the next cheaper option at high load factors. Diesel engine is the costliest at high load factor. At low load factor biodiesel CI engine is the cheapest.

In Figures 4 and 5 (d = 0.3) with comparison to Figures 2 and 3 (d = 0.1), ALCC of fuel cell is increased from Rs. 14000 to Rs. 26000 due to increase in discount rate from 0.1 to 0.3. The possible reason for this increased cost is high initial capital cost of the fuel cell. Because of high initial capital cost, the interest amount will be high which increases the ALCC.

Figures 6 and 8 show the ALCC for societal discount rates of 10% and 30%, respectively, for DG-CHP in the month of June 2011. Here also, except at very low load factors, the gas engine option is cheaper than the diesel engine.

Figures 7 and 9 show the ALCC for societal discount rates of 10% and 30%, respectively, for DG-CHP in the month of January 2013. Here also, except at very low load factors, the gas engine option is cheaper than the diesel engine.

It is noticed from Figures 6–9 that the gas engine is the most favorable option in DG-CHP consideration. That is, ALCC of gas engine is the lowest at almost all the load factors. In case of DG alone, it was seen that ALCC of fuel cell was the lowest but in case of DG-CHP it is more than all other options at low loads and more than gas engine with d = 0.3 at high load factors. With DG-CHP the diesel engine is found as the most expensive option at all load factors. The biodiesel CI engine is always more favorable than diesel engine.

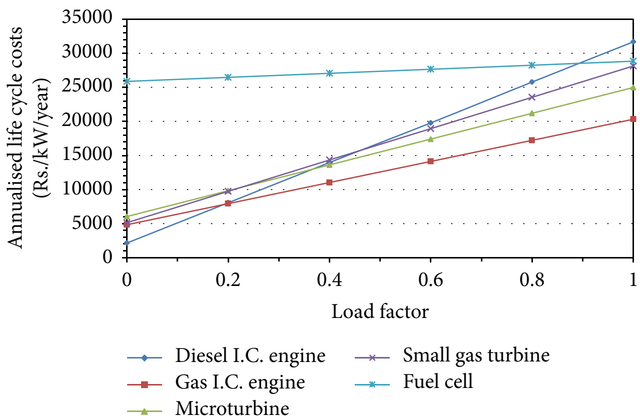

FIGURE 8: Comparison of annualised life cycle costs for different technological options when DG-CHP is considered (discount rate (d) = 30%) for the month of June 2011.

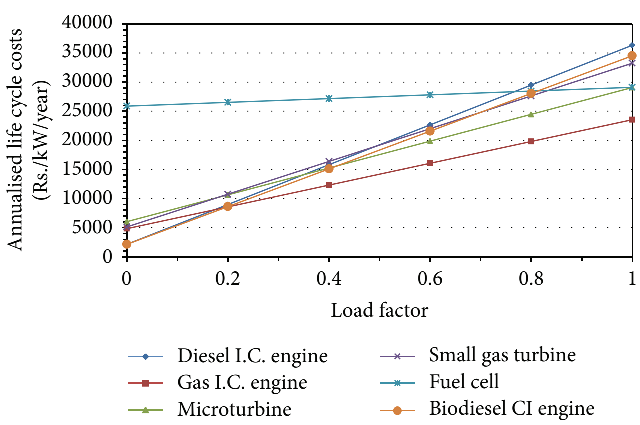

FIGURE 9: Comparison of annualised life cycle costs for different technological options when DG-CHP is considered (discount rate (d) = 30%) for the month of January 2013.

As seen in Figures 8 and 9, except at very low load factor, gas engine is cheaper than diesel engine. Fuel cell is costlier than other options at almost all load factors. Reason for this high cost of fuel cell is that its HPR value is low in comparison to other options. It means useful heat generation is very low which does not contribute towards the cost saving. Initial setup cost of fuel cell is also very high which increases the ALCC.

Figure 9 shows that biodiesel CI engine is more favorable than diesel engine at almost all load factors. It can be seen from the figure for the month of January 2013 and for the month of June 2011 that ALCC of different options has been increased in different manners for the options with the passage of time. Rising trend of ALCC of different options for different years can be observed by comparing Figures 2, 4, 6, and 8 with Figures 3, 5, 7, and 9.

6. Conclusions

DG and DG-CHP are compared for the various technological options at two different discount rates and at two different timings to find out the most suitable option. The following conclusions are drawn from the study.

(1) The fuel cell is found to be very economical but it is not possible to implement the fuel cell due to technical facilities presently in the state.

(2) In case of DG the ALCC for most of the options is found to be more than twice that for the DG-CHP. Therefore DG-CHP may be more beneficial compared to only DG.

(3) In case of DG-CHP the cost for gas engine is found to be the lowest which shows that gas engine is the most effective option in the future when more knowhow about the gas engine will be available in the state.

(4) The biodiesel CI engine-based CHP is found to be very attractive as the ALCC is lower than that for diesel engine CHP and more competitive compared to other options for most of the cases and additionally due to its renewable nature it may emerge as the most effective option considering the local conditions in Rajasthan.

Hence from the above study, it can be concluded that the DG-CHP technologies may be proved as better option for energy sustainability as compared to only DG technologies and the most effective DG-CHP can be selected depending upon the local conditions and availability of fuel sources.

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