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Bioenergy technologies for carbon abatement

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Abstract

In this paper, bioenergy technologies (BETs) are presented as potential carbon abatement opportunities substituting fossil fuel or traditional (less efficient) biomass energy systems. Cost of energy (produced or saved) of BETs is compared with fossil fuel and traditional biomass energy systems to estimate the incremental cost (IC). The IC of carbon abatement for each of the selected BETs (in $\$\,kWh^{-1}$ or $\$\,GJ^{-1}$) is estimated using the carbon emission ($tC\,kWh^{-1}$ or $tC\,GJ^{-1}$) reduction obtained by substituting fossil fuel and traditional biomass alternatives. The abatement costs are estimated and compared for ten combinations of BETs (with seven technology alternatives) substituting conventional technologies. The analysis indicates that out of the ten project cases six have negative ICs in the range of -37 to -688 $\$\,tC^{-1}$ and four have positive ICs in the range of 52–162 $\$\,tC^{-1}$ mitigation. The negative ICs indicate that the suggested alternatives are cheaper than the original technologies. Thus, results indicate that the chosen BETs are cost-effective mitigation opportunities and are currently aggressive candidates under Clean Development Mechanism.

Keywords: Bioenergy technologies; Incremental cost; Carbon abatement; CDM

1. Introduction

With the ratification of Kyoto Protocol, Clean Development Mechanism (CDM) has become a reality. The CDM Executive Board is already in place and the guidelines and methodologies are also available to operationalize CDM. In this context identification of appropriate carbon abatement technologies and analysis of their cost effectiveness becomes critical to promote them as CDM projects. There is a need to analyze the potential and costs of modern bioenergy technologies (BETs) to substitute greenhouse gas (GHG) or carbon-emitting fossil fuel (FF) and even the less efficient traditional biomass energy systems (TBES) (significant share of firewood used for cooking is procured through unsustainable means) for reducing GHG emissions [1].

In India, biomass accounts for about a-third of primary energy supply and is projected to account for a significant component even in the future [1]. Traditionally, biomass energy is used in cookstoves with an efficiency level ranging between 10% and 15%, thus providing opportunity to increase efficiency levels to the extent of 30–35% with the adoption of improved cookstoves and conserve biomass and thereby reduce the adverse impacts on the environment. However, the versatility of biomass resource is not just limited to meeting cooking energy needs; there are technological opportunities to transform this resource into modern energy carriers (e.g., electricity, gas) for other energy end-uses. Vast degraded lands in India also provide excellent opportunity to produce biomass sustainably for modern BETs, particularly, for power generation [2].

In this paper, an attempt is made: (i) to consider various modern BET options available for substituting FF and low-efficiency TBES; (ii) to compare the cost of energy service among the FFs (and less efficient biomass energy) and modern bioenergy system; (iii) to compare the carbon abatement potential of bioenergy systems on the basis of per unit of energy; and (iv) to estimate the incremental costs (ICs) of per tonne of carbon abatement. The databases for comparison of FF, TBES and modern BETs are from the reports of a research project carried out by the

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authors [3,4] and the summarized input data are presented in the paper as tables (discussed later in the paper).

2. Primary energy use and GHG emissions in India

2.1. Primary energy use in India

The total primary energy [5,6] use in India is dominated by coal accounting for about 36% of the total, followed by oil for about 24% and fuelwood accounting for 20% (Table 1). Fossil fuels, including coal and oil, account for nearly 67% of total primary energy use and biomass accounts for 31%. Projections for future show that consumption of all energy sources will increase and FFs will continue to dominate by accounting for approximately 77% by 2010, and the share of petroleum products is likely to be close to 24% in the final energy consumption [5,6]. Dependence on biomass will continue, due to increase in rural population and continued lack of access to FFs in rural areas, particularly for cooking [2]. However, these projections show a possible decline in the relative share of biomass in total energy. Possible reasons could be a shift to other energy carriers for meeting cooking needs and efficient use of biomass energy.

2.2. GHG emissions from energy sector in India

The CO_2 equivalent GHG emissions from energy sector in India during 1990 were estimated to be 508 Mt CO_2, with coal dominating the emissions (Fig. 1). The GHG emission is projected to continue to increase in the early decades of the current century. The total energy sector emissions are projected to increase by over 5 times to 2862 Mt CO_2 by 2020.

Thus, in the present scenario countries such as India may have to consider options to reduce CO_2 emissions, without affecting economic development. Among the carbon abatement options, indications are that BETs provide large and relatively low-cost mitigation opportunities [1,8]. The estimated renewable energy potential of India is quite high and if exploited can meet significant proportion of projected energy needs (Table 2). For example, a comparison could be made between total renewable energy-based power generation potential of 82 GW (excluding solar PV and ocean thermal-based potential) with a projected total additional generation capacity of 100 GW required by 2012 [9].

3. BETs for substituting fossil fuels and traditional biomass energy systems

There are mitigation opportunities in every energy subsector: transportation, residential, energy supply, industrial, etc. [8]. The mitigation opportunities could be created either through environmental friendly energy supply technologies or through technologies for efficient utilization of energy. Among the abatement technologies, renewable energy and particularly BETs are shown to have significant opportunity to mitigate climate change and promote sustainable economic development. In this paper, a set of BETs with a potential to substitute FF or TBES are evaluated for carbon abatement. There are a large number of abatement opportunities but only 10 opportunities as project cases are explored based on the following

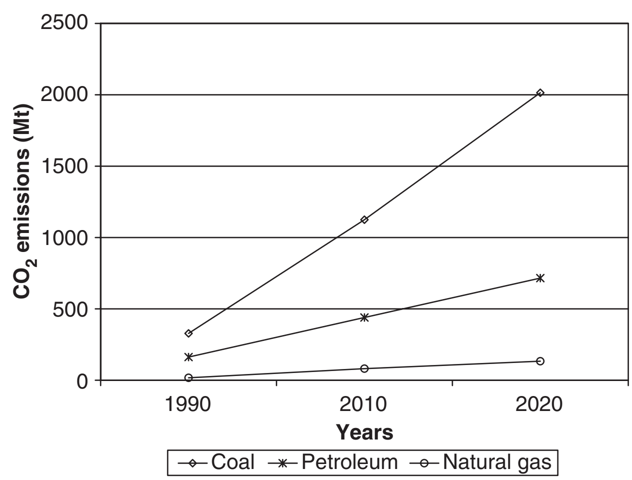

Fig. 1. GHG emissions from energy sector (in Mt CO_2) in India [7].

Table 1
Current and projected energy consumption pattern in India

Energy sources	Energy consumption in 1998–1999		Energy consumption in 2010–2011	
	PJ	%	PJ	%
Coal	5775.27	36.36	12,267	46.37
Petroleum	3868.60	24.36	6,322	23.90
Natural gas	983.90	6.19	1,758	6.65
Hydroelectricity	262.51	1.65	628	2.37
Nuclear energy	35.17	0.22	—	—
Fuelwood	3199.97	20.15	3,660	13.84
Crop residue and dung	1758.46	11.07	1,816	6.87
Total	15,883.88	100	26,453	100

Source: [5,6].

Table 2
Technical potential of renewable energy in India

Sources/systems	Potential I	Potential II
Biogas plants (No.)	12 million	17 million
Improved cookstoves (No.)	120 million	120 million
Solar water heating	140 million km^2 collector area	140 million km^2 collector area
Power generation		
Solar energy	20 $MW km^{-2}$	20 $MW km^{-2}$
Biomass	16 GW	57 GW[a]
Wind energy	45 GW	45 GW
Small hydro power	15 GW	15 GW
Ocean thermal energy	50 GW	50 GW
Cogeneration	3.5 GW	3.5 GW
Waste to energy	2.5 GW	2.5 GW

Source: Potential I is based on MNES estimates [9].
Potential II is based on Ravindranath and Hall [2] for biogas and biomass power.
[a]Biomass power of 41 GW from dedicated plantation + 16 GW from crop residue [9].

criteria—locally available energy resources, indigenous technological capabilities, abatement potential, cost effectiveness, compatibility to national priority and feasibility for large-scale spread (dissemination/marketing) in India. These project cases have been chosen with a goal of providing better quality and efficient alternatives for meeting the energy needs of rural India. Also, it is expected that these projects to the maximum extent possible depend only on the locally available/grown biomass resources. Specifically, the project cases on BETs for power generation (except for sugar cogeneration) are expected to be de centralized and village centric.

For the purpose of analysis, the emissions of CO_2 and CO_2 equivalent (21 times for CH_4 and 310 times for N_2O of CO_2 potential) have been considered. This paper assesses the abatement cost of CO_2 using annualized (or levelized) life cycle cost (ALC) method (refer Appendix for the details on LCC method).

3.1. Annualized life cycle cost method (ALC)

The abatement cost of a particular BET to save a tonne of carbon is determined as follows:

$$\text{Cost Rs./tC} = \frac{\text{Incremental ALC of BET in (Rs. kWh}^{-1}\text{ or Rs. GJ}^{-1}) \times 1000}{\text{Incremental GHG abatement in kg kWh}^{-1}\text{ or kg GJ}^{-1}}.$$

$$\text{Incremental ALC of BET (Rs. kWh}^{-1}\text{ or Rs. GJ}^{-1}) = [\text{ALC of BET (Rs. kWh}^{-1}\text{ or Rs. GJ}^{-1})] - [\text{ALC of FF (Rs. kWh}^{-1}\text{ or Rs. GJ}^{-1})]$$

$$\text{Incremental GHG Abatement (kg/kWh or GJ)} = [\text{Emission from FF in kg kWh}^{-1}\text{ or kg GJ}^{-1}] - [\text{Emission from BET in kg kWh}^{-1}\text{ or kg GJ}^{-1}]$$

$$\text{ALC} = \text{life cycle cost (LCC)} \times \text{capital recovery factor (CRF)},$$
$$\text{LCC} = \text{PV[capital cost + replacement cost + O\&M cost + fuel cost]},$$
$$\text{CRF} = 1/[\text{PV(1 rupee annuity, interest rate, period)}].$$

The data inputs in the form of capital, fuel and operations and maintenance costs, and technical factors such as capacity of the plant, plant load factor, fuel types, fuel consumption norms and plant life are presented for BETs as well as coal thermal-based grid electricity in Table 3. Similar information for cooking technologies is given in Table 4. The estimates of costs and carbon abatement potentials are made for the fixed performance levels (Tables 3 and 4). It is true that these estimates are sensitive to the changes in input parameters like, cost of fuel, capital cost, discount rates, plant load factors, etc. However, the attempt here is to compare any given two technology alternatives (conventional technology and BET) based on their field-level potential/capacity to deliver the desired energy output. If a technology has a capability to perform better it will be an advantage for that particular technology (e.g., coal-based thermal power plant has a plant load factor of 75% as against 45.66% for biomass gasifier).

A set of 10 promising options of BETs substituting FF or TBES are presented as project cases (Box 1). The bio-energy technologies considered here are efficient cook stoves, biogas using bacterial conversion, producer gas using thermo-chemical conversion and combustion technologies. These are compared with the TBES like

Table 3
Basic data inputs for the life cycle cost estimates of various power generation alternatives

	Biomass gasifier + diesel	Biomass gasifier	Biomass combustion	Biogas + diesel	Diesel	Sugar cogeneration	Grid electricity (coal based)
Capacity of the plant (kW)	20	20	10,000	120	20	10,000	500,000
Initial capital cost (Rs. million)	0.883	0.950	350	4	0.403	420	43,800[a]
Engine life with three overhauling (hours)	20,000	20,000	—	20,000	20,000	—	—
Cost per overhauling (Rs.)	37,950	45,000	—	120,000	37,950	—	—
Engine overhauling and replacement cost (Rs.)	568,600	674,200	—	1,798,000	568,600	—	—
Gestation period (years)	0.5	0.5	1.5	1.5	0.5	1.5	3.25
Life time (years)	25	25	25	25	25	25	30
Discount rate (%)	10	10	10	10	10	10	10
O&M cost (Rs. y^{-1})	37,735	37,735	—	701,000	21,735	—	—
O&M cost (Rs. million y^{-1})	—	—	41.25	—	—	21.90	1128.44[b]
Working hours per year	4000	4000	5974	4000	4000	4380	6570
Plant load factor (%)	45.66	45.66	68.20	45.66	45.66	50	75
Primary fuel used	Biomass	Biomass	Biomass	Dung	Diesel	Bagasse	Coal
Primary fuel cost (Rs. kg^{-1} or Rs. l^{-1})	1	1	0.99	0	19	0.66	1.42
Primary fuel consumption (kg kWh^{-1} or l kWh^{-1})	1	1.4	0.820	0.583	0.4	1.147	0.745
Secondary fuel used	Diesel	—	—	Diesel	—	—	—
Secondary fuel cost (Rs. l^{-1})	19	—	0	19	19	—	—
Secondary fuel consumption (l kWh^{-1})	0.08	—	—	0.056	—	—	—

Note: Excluding the grid electricity, all the data were obtained from live projects (primary data from project documents). For grid power, most of the data are from the proposed thermal power plant at Bellary, Karnataka (http://www.karnatakapower.com/_private/vijay.asp).

[a]The capital cost for grid power based on coal thermal includes the following:

- Rs. 17,960 million of initial capital cost and Rs. 4060 million of interest during construction for the thermal power plant;
- Rs. 17,960 million of initial capital cost and Rs. 3837 million of interest during construction (for 3 years) for the equivalent transmission system.

[b]The O&M cost for the grid power includes operation and maintenance cost of power plant and transmission system.

Table 4
Basic data inputs for the life cycle cost estimates of various cooking alternatives

	Traditional firewood stove	Efficient firewood stove	Community biogas plant/stoves[a]	Kerosene stove
Capacity of the plant ($M^3 d^{-1}$)	—	—	3875	—
Initial capital cost for biogas Plant (Rs. million)	—	—	41.65	—
Initial capital cost for distribution system (Rs. million)	—	—	4.945	—
Gestation period (years)	—	—	0.5	—
Life time of the plant (years)	—	—	25	—
Discount rate (%)	10	10	10	10
Initial capital cost for single stove (Rs.)	50	250	500	250
Life time of the device (years)	3	6	10	5
Device efficiency (%)	15	35	55	49.5
O&M cost (Rs. million y^{-1})	—	—	1.90	—
Working hours per year	—	—	5,974	—
Primary fuel used	Firewood	Firewood	Dung	Kerosene
Primary fuel cost (Rs. kg^{-1} or Rs. l^{-1})	0.6	0.8	0.99	7.60
Primary fuel consumption per year ($kg\,y^{-1}$ or $l\,y^{-1}$)	2000	950	0.820	180
Total annual heat energy output (GJ)	4.50	4.99	17,892	3.12

Source: The data have been obtained from various field studies conducted by the Indian Institute of Science, Bangalore, India.
[a]Community biogas plant meeting the cooking needs for 5000 households.

Box 1
Bioenergy mitigation options substituting fossil fuel and traditional biomass energy systems

Energy service or end-use	Fossil fuel/traditional biomass energy system	Potential bioenergy technology
Cooking energy	1. Traditional fuelwood cookstove	Efficient cookstove
	2. Traditional fuelwood cookstove	Community biogas plant/stove
	3. Kerosene stove for cooking	Community biogas plant/stove
Rural electricity supply/captive requirements/export to grid		
	4. Diesel generator for electricity	Biogas electricity system
	5. Diesel generator for electricity	Biomass gasifier system (dual fuel)[a]
	6. Grid electricity	Biomass gasifier system (dual fuel)
	7. Grid electricity	Biomass combustion power system
	8. Grid electricity	Bagasse cogeneration
	9. Grid electricity	Biomass gasifier system (Gas mode)[b]
	10. Grid electricity	Biogas electricity system

[a]Biomass gasifier system with 80% producer gas and 20% diesel as fuel input.
[b]Biomass gasifier system with 100% producer gas as fuel input.

traditional fuelwood cookstove, kerosene stove, diesel generator for power and coal-based grid electricity. It may be observed from the list that the chosen technologies are mostly appropriate for meeting the village energy needs and use locally generated biomass resources. The basic data on these technologies are presented in Tables 3 and 4. The case descriptions, mitigation potential and costs are presented and discussed in the following sections.

3.2. Project case 1: efficient cookstove substituting traditional fuelwood cookstove

Fuelwood is the dominant cooking fuel in rural India with a consumption of about 212 Mt annually [2]. Significant part of the fuelwood consumed comes from unsustainable extraction leading to GHG emissions, tree resource degradation and low quality of life to women.

In rural India, cooking is primarily performed using inefficient traditional fuelwood stoves without any proper chimney or ventilation. The result is over use of fuelwood along with severe indoor pollution affecting health of women. Thus, opportunity exists to replace traditional stove by improved and efficient stove, to conserve fuelwood, not only to reduce pressure on forests, but also to reduce domestic pollution and GHG emissions. The efficient cookstoves having efficiency levels of 35% are being considered as replacements for traditional stoves with about 10% efficiency. The efficient stoves, which are, in addition to being fuel-efficient, are also known to provide other benefits to rural households such as reducing indoor pollution and saving in cooking time as well as fuelwood gathering time. The technology of efficient cookstoves is proven and these stoves have penetrated into significant number of Indian households [9].

Till now, in India about 34 million efficient cookstoves have been built. However, the estimates show that there is a potential for 120 million stoves [9]. Thus, a large potential exists to conserve fuelwood through spread of efficient cookstoves.

3.3. Project case 2: community biogas plant substituting traditional fuelwood cookstoves

Biogas is a process by which the cattle dung and other biomass is converted to methane and CO_2 by bacterial action. For cooking, biogas supply from family as well as community biogas plants based on cattle dung and leafy biomass feedstock is an attractive option to substitute traditional wood-based cookstoves because it is a clean and efficient fuel. Considering the cattle population in the country and availability of suitable biomass, the potential to substitute fuelwood, and thereby conserve forests is large. The use of biogas for cooking improves the quality of life of women; even the fertilizer benefit of dung is not lost in the process. Biogas replacing fuelwood is a mitigation option as fuelwood coming from unsustainable source could potentially be fully conserved leading to reduction in GHG emissions.

In India, the total potential for family biogas plants is estimated to be 12–17 million numbers and in over 20 years only 3.4 million biogas plants have been built. There is a potential to build community biogas plants possibly in majority of 0.5 million villages. However, till 2002 only 3901 community biogas plants are built [9]. Thus, there is a large potential to build both family and community size biogas plants to conserve fuelwood and forests, to reduce GHG emissions and improve quality of life of rural women.

3.4. Project case 3: community biogas plant substituting kerosene stove for cooking

In rural India use of kerosene for cooking is increasing. The government policy of providing subsidies on kerosene prices also encouraged this process. Biogas is of a better quality and more efficient fuel for cooking apart from reducing GHG emission by substituting FF (kerosene). Unlike kerosene, biogas is of a renewable option and it is produced from locally available dung/biomass resources. A shift from kerosene to biogas can promote self-reliance. Rural households who use kerosene could be motivated to shift to biogas. A community-based biogas plant at the village level, using locally available cattle dung, along with an integrated gas distribution mechanism would provide an inexpensive energy supply at the doorsteps of rural households. This facility is expected to provide similar levels of service standards as that of bottled LPG supply in urban areas.

3.5. Project case 4: biogas electricity system substituting diesel generator for electricity

Diesel generators sets are becoming increasingly popular in rural areas for mechanical and electrical applications, due to low reliability of grid electricity. Village community-scale biogas plants can provide a renewable energy alternative for reliable electricity for lighting and other shaft power activities. Biogas used in internal combustion engines replacing diesel would lead to CO_2 emissions reduction. The estimation of potential for biogas electricity in India is difficult because biogas is preferred mostly as an effective cooking fuel. However, this technology could be adopted in meeting energy needs of villages where there is no or unreliable electricity supply. A few field projects have been implemented in India showing feasibility of biogas electricity for rural electrification [1].

3.6. Project case 5: biomass gasifier (dual fuel) electricity system substituting diesel generator for electricity

Gasification is a thermo-chemical process, converting the biomass to producer gas to be used in an internal combustion engine [10]. The producer gas can be used to generate power using a diesel engine with gas and diesel. This mode of operation is known as dual fuel. Diesel savings of up to 85% is possible. Gas and air mixture is drawn into the engine cylinder and the diesel is regulated by the governor to maintain the frequency. It is also possible to operate a spark-ignited engine on producer gas alone without any support of FF (gas mode). The use of producer gas in the diesel engine on dual fuel mode reduces the exhaust emissions by about 1/6th and by 1/10th in comparison to gas-alone engines.

Village-scale (20–500 kW) biomass gasifier (dual fuel)-based decentralized power generation is one of the BETs with maximum potential in India for meeting rural electricity demands and could become an effective replacement for diesel generator sets. Even these systems can be considered as effective alternatives for small-scale captive diesel generator sets installed in industries and commercial establishments. In this system, the diesel replacement is to the extent of 80%. Biomass gasifier system based on sustainable biomass production leads to global benefits through substitution of diesel and ultimately reducing GHG emissions. Captive biomass plantations can be raised to provide regular fuel supplies to these gasifier plants in a sustainable manner. Biomass plantations in degraded land lead to carbon sequestration in soil and standing vegetation in sustainably managed energy forest plantations. Further, the biomass gasifier systems can also use agro-residues as fuel.

3.7. Project case 6: biomass gasifier (dual fuel) replacing grid electricity

In India, nearly 70% of electricity is from coal-based power plants. Rural areas account for nearly a-third of electricity consumption in India. Studies have shown that decentralized biomass gasifier-based power generation systems have a large potential to meet rural electricity needs. The GHG or carbon mitigation benefits will accrue as mentioned earlier. The potential for biomass-based power generation systems (the technologies could be either biomass gasifier or combustion) is estimated to be about 57 GW in India [1]. A few field projects have shown the feasibility of the technology in India [1].

3.8. Project case 7: biomass combustion power replacing grid electricity

Large biomass combustion-based power generation systems based on agro-residues or wood are being increasingly considered as a potential renewable energy option for power generation for feeding to the grid. In India, 300 MW of biomass combustion-based power generation systems have been installed. As mentioned earlier, the potential is large. The estimated potential for crop-residue-based power generation alone is about 16 GW, through combustion route [1]. The GHG or carbon abatement is as described above for other biomass based power generation systems.

3.9. Project case 8: cogeneration in sugar mills for electricity replacing grid electricity

In India, cogeneration in sugar mills is estimated to have a potential of 3.5 GW of installed capacity and currently only about 350 MW capacity is installed [9]. The electricity generated from bagasse, a by-product in sugar mills could be used to generate electricity for in-house consumption and feeding surplus to the grid. Thus, there is a large potential for using bioenergy (cogeneration technology) through a commercial approach.

3.10. Project case 9: biomass gasifiers (gas mode) supplementing grid electricity

Unlike the dual fuel biomass gasifier-based power generation systems, wholly (producer) gas systems have the potential to generate electricity without using diesel [10]. Electricity from such systems could substitute grid electricity coming largely from coal-based power plants (in India, about 70% of the electricity is generated from coal-based thermal power plants) leading to net CO_2 emission reduction.

3.11. Project case 10: biogas electricity for supplementing the grid electricity

India faces a huge energy demand–supply gap with around 20% of peak power deficits. In addition to the shortages, there are high transmission and distribution losses resulting in high delivery costs of energy at rural areas. This makes decentralized energy supply systems comparatively more economical than grid extension for supply to remote areas or villages. The Indian government has identified about 18,000 villages, where grid extension is not feasible due to difficult terrains and vulnerable ecosystems [9]. Thus, there would be a need for locally based decentralized energy supply and in this context; biogas electricity would be ideal for meeting the base load requirements at village level.

4. Annualized cost of energy and CO_2 emissions of bioenergy technologies and fossil fuel/traditional biomass energy systems

4.1. Cost of energy; bioenergy technologies, fossil fuel and traditional biomass energy systems

The LCC estimates of installing and operating various types of power plants and cooking stoves have been made using the discounted cash flow approach. Further, the unit cost of energy or ALC is estimated by annualizing the total LCC and dividing it by the annual gross energy generation. The basic cost data, assumptions and other information for BETs and TBES are presented in Tables 3 and 4. In the case of BETs for electricity generation, five technologies, namely, biogas electricity, biomass gasifier (gas and dual fuel mode), biomass combustion, and cogeneration are being considered to replace the grid power based on coal thermal systems. The LCC and ALC estimates are presented in Table 5. From the table we may observe that the cost of electricity based on BETs varies from 2.15 to 5.05 Rs. kWh^{-1}. Among the FF options for power generation, the cost of coal-based grid electricity is the lowest at 3.25 Rs. kWh^{-1}, and diesel generation is the highest at 9.24 Rs. kWh^{-1}. The estimated cost of 3.25 Rs. kWh^{-1} for grid electricity includes the cost of transmission system. In the case of BETs and diesel power, it is assumed that this cost to be equal to zero, because

Table 5
Life cycle cost estimates of bioenergy technologies for power generation and a comparison with grid electricity

	Biomass gasifier + diesel	Biomass gasifier	Biomass combustion	Biogas + diesel	Sugar cogeneration	Diesel	Grid electricity (coal based)
Life cycle capital cost (Rs. kW^{-1})	44,150	47,500	35,000	33,300	42,000	20,150	87,600
Life cycle engine overhauling and replacement cost (Rs. kW^{-1})	28,400	33,700	—	14,980	—	28,430	—
Life cycle O&M cost (Rs. kW^{-1})	17,120	17,120	37,400	53,020	19,870	9,860	20,310
Life cycle fuel cost (Rs. kW^{-1})	91,400	50,830	44,030	38,630	30,090	275,900	66,400
Total life cycle cost (Rs. kW^{-1})	181,070	149,150	116,430	139,930	91,960	334,340	174,310
Unit cost of energy (Rs. kWh^{-1})	5.05	4.17	2.15	3.90	2.31	9.24	3.25

Notes: 1. The life of all the power generation systems is assumed to be equal to 25 years. Wherever the life of an individual device or even a whole system is less than 25 years then replacement cost of such device is considered.
2. A discount rate of 10% is used for the life cycle estimates.
3. Grid electricity is from the load center coal thermal power plants and the estimated present value includes the delivery cost (capital and O&M cost of transmission and distribution system). The unit cost of Rs. 3.25 kWh^{-1} has been adjusted for auxiliary consumption.

Table 6
Life cycle cost estimates of bioenergy technologies for cooking and a comparison with kerosene cooking (Rs. GJ^{-1} of heat output)

	Traditional fuelwood stove	Efficient fuelwood stove	Community biogas plant/stoves	Kerosene stove
Life cycle capital cost	11.11	50.13	2,625.7	80.2
Life cycle O&M cost	0	0	946.7	0
Life cycle fuel cost	663.16	663.66	0	1,662.9
Total life cycle cost	674.27	713.78	3,572.37	1,743.1
Unit cost of energy	271.13	163.89	393.56	459.82

Notes: 1. The lives of traditional stove, efficient stove, community biogas plant, biogas stove and kerosene stoves are 3, 6, 25, 10 and 5 years, respectively.
2. A discount rate of 10% is used for all the life cycle estimates.
3. Life cycle capital cost of community biogas plant/stoves includes replacement costs of biogas stoves.

these are basically decentralized systems and located near the consumption points (villages). However, the local distribution costs for both BET and grid electricity (they are likely to be same for all technologies because the distribution system needed is limited to a village) are ignored for the present analysis.

Efficient cookstove and biogas are the two BETs considered for cooking applications as a replacement for traditional wood and kerosene stoves. The costs are estimated per unit of heat output to overcome the inconsistency in terms of different quantity of fuel inputs. The cost of energy from efficient cookstove is 163.9 Rs. GJ^{-1} of heat output and that from community biogas system is 394 Rs. GJ^{-1} of heat output (Table 6). The unit cost of energy for the traditional stove is 271 Rs. GJ^{-1} and for kerosene stove, the cost is 460 Rs. GJ^{-1}. BET has lower cost per unit of energy output than the FF option in the case of biogas replacing kerosene stove or efficient cookstoves replacing traditional cookstove. In the case of BETs for power generation, the cost of energy based on biomass combustion is lowest at 2.15 Rs. kWh^{-1}. However, all BETs have unit cost of energy lower than diesel generation costs. The diesel prices are escalating, and therefore, the proposed BET options could be even more attractive for replacement in the future.

4.2. CO_2 emissions comparison; bioenergy technologies, fossil fuel and traditional biomass energy systems

Table 7 compares the ALC of the combinations of technologies and respective CO_2 emission levels. In this paper, BET options are considered as potential mitigation activities to address climate change. From the table we may observe that a shift from traditional fuelwood stove to efficient fuelwood cookstove will result in CO_2 emission reduction from 101 kg GJ^{-1} to 43 kg GJ^{-1} of heat output. The CO_2 emissions from fuelwood (for cooking) include the CO_2 equivalent emissions of CH_4 and N_2O, and CO_2 emissions of firewood from unsustainable source [2] (40% of firewood is assumed to be from unsustainable source). Biogas plants have no net GHG emissions as it is from sustainable source. However, if a biogas plant is operated on dual fuel mode with diesel for electricity, then the CO_2 emissions would be 0.15 kg kWh^{-1}. Similarly, biomass

Table 7
Annualized levelized cost (ALC) of energy and CO_2 emissions from BETs and FF/TBES systems per kwh or per GJ of heat output

FF/TBETs	ALC in Rs. kWh^{-1} or Rs. GJ^{-1}	CO_2 emissions (kg kWh^{-1} or g MJ^{-1})	Substituting BETs	ALC in Rs. kWh^{-1} or Rs. GJ^{-1}	CO_2 emissions (kg kWh^{-1} or g MJ^{-1})
Cooking technologies (*output is in MJ or GJ*)					
Traditional fuelwood stove	271.13	101.36	Efficient cookstoves	163.89	43.44
Traditional fuelwood stove	271.13	101.36	Community biogas plants	393.56	0
Kerosene stove for cooking	459.82	138.941	Community biogas plants	393.56	0
Electricity generation technologies (*output is in kWh*)					
Diesel generator for electricity	9.24	0.756	Biogas electricity system	3.9	0.15
Diesel generator for electricity	9.24	0.756	Biomass gasifier system (dual fuel mode)	5.05	0.15
Grid electricity	3.25	1.017	Biomass gasifier system (dual fuel mode)	5.05	0.15
Grid electricity	3.25	1.017	Biomass combustion power system	2.15	0
Grid electricity	3.25	1.017	Bagasse cogeneration	2.31	0
Grid electricity	3.25	1.017	Biomass gasifier system (gas mode)	4.17	0
Grid electricity	3.25	1.017	Biogas electricity system	3.9	0.15

Notes: 1. Grid electricity is from the load center coal thermal power plants and the estimated annualized cost includes the delivery cost (cost of transmission and distribution system is assumed to be equal to Rs. 1.10 kWh^{-1}).
2. The cost differences due to the different levels of T&D losses between grid electricity and electricity from BETs is not accounted.
3. 1 US\$ = Rs. 47.

gasifiers have no net CO_2 emissions if operated on gas mode, but under dual fuel mode, the net emissions would be 0.15 kg kWh^{-1}. CO_2 equivalent emission for diesel generation system is 0.75 kg of CO_2 kWh^{-1} and for electricity from coal plants is 1.01 kg kWh^{-1} (Table 7). Thus, biogas for cooking and electricity from bioenergy systems based on sustainable biomass resources are carbon neutral eliminating CO_2 emission from power generation.

5. Abatement cost of BETs

5.1. Incremental cost of CO_2 abatement of bioenergy technologies over fossil fuel and traditional biomass energy systems

One of the important factors contributing to the spread of BETs is their cost effectiveness compared to FF systems. A comparative assessment and ICs of CO_2 abatement are given in Table 8. The IC of abatement using BETs for cooking in place of traditional alternatives is negative for efficient cookstove and biogas replacing traditional fuelwood and kerosene stove, respectively. It is positive for replacement of traditional wood stove by biogas plant. A negative IC indicates that the shift is advantageous both in terms of economic and environmental benefits. On the other hand, positive IC indicates the need for additional cost inputs in order to implement the BET alternative and thereby achieve the required CO_2 abatement. The CO_2 emission reduction potential is in the range of 58–139 kg GJ^{-1} of heat output for cooking applications.

The IC of shifting from FF/TBES is negative for four BET options (Table 8). The IC for BETs is positive for biomass gasifier and biogas power systems compared to coal grid-based electricity. The CO_2 emission reduction potential is in the range of 0.60–1.01 kg of CO_2 kWh^{-1} for BET options for electricity generation. The IC is negative for BETs replacing diesel-based power generation systems.

Thus, from Table 8 and Fig. 2 we may observe that out of the ten CO_2 abatement BET alternatives, six have negative and the remaining four have positive incremental abatement costs. In other words, the replacements of the conventional alternatives with BETs provide significant financial returns (in terms of reduced costs) to the investors. Practically speaking, these shifts may not encounter any financial barriers except may be for high initial cost sensitiveness. Appropriate financial mechanisms, which convert the one-time cost into recurring costs, may provide impetus for shift to BET alternatives. The abatement alternatives with positive IC may require financial support to overcome the investment cost barrier. For example, biomass gasifier system (gas mode) substituting grid electricity requires only marginal incremental financial support to make it economically viable and attractive.

Table 8
Incremental cost of CO_2 abatement through BETs substituting fossil fuel and traditional biomass energy technologies

BET substituting FF/TBETs alternatives	Incremental cost of BET (Rs. kWh^{-1} or Rs. GJ^{-1})	CO_2 emission reduction potential (kg kWh^{-1} or g MJ^{-1})	Cost of CO_2 abatement (Rs. kg^{-1} CO_2)	Cost of CO_2 abatement (Rs. t^{-1} CO_2)	Cost of CO_2 abatement (\$ t^{-1} CO_2)
Cooking technologies (output is in MJ or GJ)					
1. Efficient cookstoves substituting traditional fuelwood stove	−107.24	57.92	−1.85	−1851.52 (−6,789)	−39.39 (−144.4)
2. Community biogas plant substituting traditional fuelwood stove	122.43	101.36	1.21	1207.87 (4,429)	25.70 (94.23)
3. Community biogas plant for cooking substituting kerosene stove	−66.26	138.941	−0.48	−476.89 (−1,749)	−10.15 (−37.20)
Electricity generation technologies (output is in kWh)					
4. Biogas electricity system substituting diesel generator for electricity	−5.34	0.606	−8.82	−8818.95 (−32,336)	−187.64 (−688)
5. Biomass gasifier system (dual fuel mode) substituting diesel generator for electricity	−4.19	0.606	−6.92	−6919.73 (−25,372)	−147.23 (−539.8)
6. Biomass gasifier system (dual fuel mode) substituting grid electricity	1.80	0.867	2.08	2076.16 (7,613)	44.17 (162)
7. Biomass combustion power system substituting grid electricity	−1.10	1.017	−1.08	−1081.63 (−3,966)	−23.01 (−84.4)
8. Bagasse cogeneration substituting grid electricity	−0.94	1.017	−0.92	−924.30 (−3,389)	−19.67 (−72.1)
9. Biomass gasifier system (gas mode) substituting grid electricity	0.92	1.017	0.90	904.63 (3,317)	14.23 (52.2)
10. Biogas electricity system substituting grid electricity	0.65	0.867	0.75	749.72 (2,749)	19.25 (70.57)

Note: 1 US \$ = Rs. 47
Values in parentheses are in Rs. t^{-1}C and \$ t^{-1}C, which is converted from CO_2.

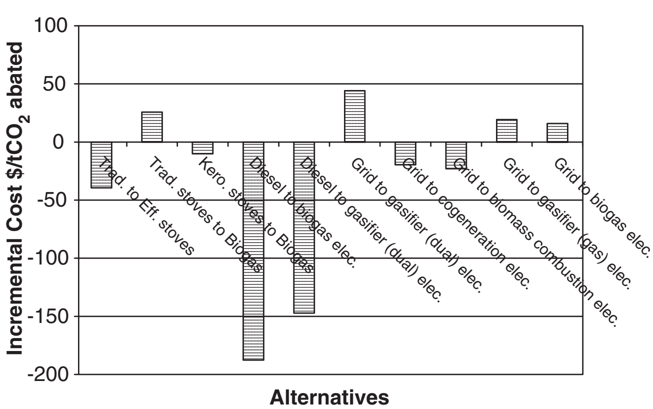

Fig. 2. Incremental cost of carbon abatement for the selected BETs substituting fossil fuels or traditional biomass energy technologies.

5.2. Incremental unit cost of carbon abatement

The IC of unit cost of abatement of BET replacing FFs/TBES is given in Table 8 (47 Rs. USD^{-1}). The unit IC of carbon abatement is negative for the following technology combinations.

- Efficient cookstoves substituting traditional fuelwood stove.
- Community biogas plant/stove substituting kerosene stove.
- Biogas electricity system substituting diesel generator for electricity.
- Biomass gasifier system (dual fuel mode) substituting diesel generator for electricity.
- Bagasse cogeneration substituting grid electricity from coal thermal power plants.
- Biomass combustion power system substituting grid electricity from coal thermal power plants.

Among the BETs with negative values, the most promising are biogas electricity substituting diesel electricity at—688\$ tC^{-1} abated and biomass gasifier (dual fuel) electricity substituting diesel electricity at—540 \$ tC^{-1} (Table 8). The cost of diesel, which is very high in India compared to no fuel cost for biogas plants generating electricity and very low wood fuel cost (at 12\$ t^{-1} of wood), is the main reason for this very high negative abatement costs. Biomass combustion and bagasse cogeneration power are very attractive mitigation opportunities with negative costs and with large commercial potential.

Incremental unit abatement cost is positive for the following technology combinations.

- Biogas plant substituting traditional fuelwood stove.
- Biomass gasifier system (dual fuel mode) substituting grid electricity.
- Biomass gasifier system (gas mode) substituting grid electricity.
- Biogas electricity system substituting grid electricity.

Biogas substituting traditional cookstove has positive IC due to high investment cost for community-sized biogas plants compared to insignificant investment cost for traditional cookstoves. Biomass gasifier (dual fuel as well as gas mode) systems have positive ICs over grid electricity due to economies of scale, as the comparisons are made between kilowatt-scale gasifier systems with hundreds of megawatts of capacity grid system. This holds good even for biogas plant substituting grid electricity.

It is important to note that BETs, which have negative IC of abatement, are not spreading in India or other developing countries due to technical, financial (high initial capital sensitiveness), institutional and other barriers [11]. Removal of these barriers involves ICs. These technologies, which have negative IC of abatement, may become eligible for CDM, if the revenues from certified emission reductions (CERs) can meet the barrier removal costs.

Further, the technologies, which have positive IC (of investment, operation and maintenance costs), are likely to face barriers to their spread, in addition to the technology costs. These technologies can also become part of CDM provided the unit CO_2 abatement costs fall within the range of prevailing market prices (5–10 $\$\,tCO_2^{-1}$) for emission reduction in carbon trading market.

6. Conclusions; CDM opportunity for BET

The Annex-I or industrialized countries are exploring cost-effective carbon abatement options under CDM. It is unlikely that Annex-I countries will initially use high-cost renewable energy or energy efficiency options under CDM. Thus, developing countries will be competing for CDM projects and cost-effectiveness criterion will determine which projects will be funded under CDM. Generally, it is assumed that BETs are higher-cost options compared to FFs, and thus are not spreading. A comparative analysis of a number of BETs and FF/TBES showed the majority of BETs to have lower unit cost of energy (per GJ or kWh) compared to FF/TBES. Further, the IC of adoption of BETs is negative for majority of BETs. This results in the negative IC of carbon abatement for majority of BET abatement options. Thus, BETs such as efficient stoves for cooking, electricity from biomass gasifiers and biomass power combustion systems substituting diesel and grid electricity are attractive CDM opportunities. With the continuing R&D on BETs, it would be possible to increase conversion efficiency and further bring down the costs.

The question that arises is that if BETs are already cost effective compared to FFs and even TBES, why they are not spreading or the rate of spread is low. Studies have shown that the cost-effective BETs are not spreading due to technical, financial, market and institutional barriers [1,11]. The Global Environment Facility (GEF) has dedicated operational programs for funding activities to overcome barriers to the spread of renewable energy technologies particularly BETs. Similarly, CDM revenues for BETs are likely to assist overcome barriers to BETs, which are already cost effective. The developing countries facing financial or resources barriers to promote BETs could potentially use global mechanisms such as GEF and CDM to promote BETs, which provide global environmental benefits and more importantly provide co-benefits, socio-economic and local environmental benefits.

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Appendix:. Life cycle costing

The present value (PV) of the costs incurred throughout the project life are estimated with respect to a reference year (say year of commissioning) with following steps.

PV of investment: annual investments (K_g) made during the construction or gestation period (g) are future valued to the commissioning year using discount rate of 'd'.

$$\mathrm{PV}(I) = \mathrm{PV}(FV = K_g, d, g) = \sum_{g=1}^{G} K_g(1+d)^g.$$

PV of other capital costs (*after commissioning*): Capital costs (K_u) incurred after the commencement of the project are discounted to the commissioning year.

$$\mathrm{PV} = (K_u)\sum_{n=1}^{L} K_{un}/(1+d)^n$$

PV of replacement cost: Some of the equipments associated with the project will be of shorter life compared to the project life. They need to be replaced periodically. The PV of the cost of replacements (K_R) is estimated as follows:

$$\mathrm{PV}(K_R\mathrm{Ann},\ d_{\mathrm{eff}},\ N_R) = K_R \sum_{N_R=1}^{N_R} 1/(1+d_{\mathrm{eff}})N_R,$$

where $d_{\mathrm{eff}} = (1+d)^{L_e} - 1$ is the effective discount rate, $N_R = (L/L_e)-1$, L, the life of the project and L_e, the life of the replacement device.

PV of operation and maintenance cost: PV of annual operations and maintenance costs are given by

$$\mathrm{PV}(\mathrm{O\&MAnn}, d, n) = \sum_{n=1}^{L} \mathrm{O\&MAnn}_n/(1+d)^n.$$

If the O&M costs are constant, then

$$\mathrm{PV}(\mathrm{O\&MAnn}, d, n) = \mathrm{PV}(1\mathrm{Ann}, d, L)\ \ \mathrm{O\&Mann}.$$

PV of fuel cost: PV of annual fuel cost for a given level of capacity utilization are estimated as follows:

$$\mathrm{PV}(F\mathrm{Ann}, d, n) = \sum_{n=1}^{L} F\mathrm{Ann}, d, n/(1+d)^n.$$

If the fuel costs are constant, then

$$\mathrm{PV}(F\mathrm{Ann}, d, n) = \mathrm{PV}(1\mathrm{Ann}, d, n)\ \ * \mathrm{Fann}.$$

Life cycle cost (*LCC*): All the above PV of different cost components is summed up to obtain the LCC of installing and operating the project. The cost of disposal also can be included depending on the type of projects and the needs of decision making.

$$\mathrm{LCC} = \mathrm{PV}(I) + \mathrm{PV}(K_u) + \mathrm{PV}(K_R) + \mathrm{PV}(\mathrm{O\&M}) + \mathrm{PV}(F).$$

Annualized life cycle cost (*ALC*): The annual cost of installing and operating a project is given by

$$\mathrm{ALC} = \mathrm{LCC}/\mathrm{PV}(1\mathrm{Ann}, d, L).$$

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