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# Sustainable bioenergy for India: Technical, economic and policy analysis

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ABSTRACT

India's energy challenges are multi-pronged. They are manifested through growing demand for modern energy carriers, a fossil fuel dominated energy system facing a severe resource crunch, the need for creating access to quality energy for the large section of deprived population, vulnerable energy security, local and global pollution regimes and the need for sustaining economic development. Renewable energy is considered as one of the most promising alternatives. Recognizing this potential, India has been implementing one of the largest renewable energy programmes in the world. Among the renewable energy technologies, bioenergy has a large diverse portfolio including efficient biomass stoves, biogas, biomass combustion and gasification and process heat and liquid fuels. India has also formulated and implemented a number of innovative policies and programmes to promote bioenergy technologies. However, according to some preliminary studies, the success rate is marginal compared to the potential available. This limited success is a clear indicator of the need for a serious reassessment of the bioenergy programme. Further, a realization of the need for adopting a sustainable energy path to address the above challenges will be the guiding force in this reassessment. In this paper an attempt is made to consider the potential of bioenergy to meet the rural energy needs: (1) biomass combustion and gasification for electricity; (2) biomethanation for cooking energy (gas) and electricity; and (3) efficient wood-burning devices for cooking. The paper focuses on analysing the effectiveness of bioenergy in creating this rural energy access and its sustainability in the long run through assessing: the demand for bioenergy and potential that could be created; technologies, status of commercialization and technology transfer and dissemination in India; economic and environmental performance and impacts; bioenergy policies, regulatory measures and barrier analysis. The whole assessment aims at presenting bioenergy as an integral part of a sustainable energy strategy for India. The results show that bioenergy technology (BET) alternatives compare favourably with the conventional ones. The cost comparisons show that the unit costs of BET alternatives are in the range of 15–187% of the conventional alternatives. The climate change benefits in terms of carbon emission reductions are to the tune of 110 T C per year provided the available potential of BETs are utilized.



## 1. Introduction

India is emerging as one of the fastest growing countries in the world with a GDP growth exceeding 8% consistently for the past couple of years and this trend is expected to continue. Energy being the driver of this growth its availability is of the utmost importance to sustain this level of growth. The official projections show that the energy demand is expected to be more than three to four times the current level in another 25 years [1]. With this kind of phenomenal growth India is expected to face formidable challenges in meeting its energy needs and providing adequate energy of the desired quality in modern forms to users in a sustainable manner and at reasonable costs. Broadly speaking this boils down to ensuring energy security to the large population, both urban and rural, of India.

However, careful analysis of the current energy scenario and future plans suggests India has a long way to go in ensuring energy security to the people. Some of the following summarized statistics clearly establishes this fact:

- Per capita energy consumption at 520 kgoe in 2003 is one of the lowest in the world and compares badly with world average of 1688 kgoe and 1090 kgoe for China [1].
- Though 74% of Indian villages were electrified as of March 2005 [2] only 54.9% of households had access to electricity [3,4]. Still 44.4% of rural households depend on kerosene lamps for

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lighting. In comparison, about 92% of urban households had access to electricity for lighting in 2005.

- About 42% of people had access to clean LPG for cooking as of January 2005. With respect to the rural–urban divide, in 2005, 9% of rural households had access to LPG whereas about 57% of urban households had access [4,5].
- About 75% of rural households still depend on fuel wood (in traditional stoves) for their cooking energy needs [3,4] with only 3% having access to kerosene for cooking.
- Rural households spend about 10% of total household expenditure on energy for cooking and lighting whereas this is 9% for urban households [6].
- For this level of energy demand, $CO_2$ emissions are expected to rise from the current level of 1 billion tonnes to 5.9 billion tonnes per year by 2031–2032 [1].

About 70% of the population in India lives in rural areas. The rural energy scenario is characterized by inadequate, poor and unreliable supply of energy services and large dependence on traditional biomass fuels. Non-commercial energy sources, predominantly fuelwood, chips and dung cakes, contribute around 30% of the total primary energy consumed in the country. Biomass is primarily used for meeting the cooking and heating requirements through traditional stoves and furnaces that have very low efficiencies, of the order of 10%.

About 74% of villages, as per the 2001 census, in India are deemed to have been electrified, based on earlier definitions of rural electrification, that is, lines have been laid [2]. In other words, about 150,000 villages still remain to be electrified, though their number is likely to be higher going by the latest definition which requires at least 10% of the total number of households in a village to be electrified. There is a large section of the rural population without access to electricity. Even in the villages already electrified, the electricity supply position remains highly unsatisfactory. Power cuts and load-shedding are the order of the day. However, given the current constraints in the electricity supply with a peaking shortage of nearly 14% and energy shortage of 10% [7], it is doubtful that the newly electrified villages will get adequate electricity supply in the foreseeable future.

The above discussion clearly indicates that there is an urgent need to focus the whole issue of energy planning, policy, investment and establishment of energy infrastructure on creating access to modern cooking fuel and electricity for the large section of deprived population in the rural regions of India. This paper presents the case of bioenergy technologies as sustainable alternatives for creating this access. The techno-economic and environmental assessments, combined with the discussion on technology transfer and commercialization status, barriers and their removal strategies and policy and institutional mechanisms, attempts to present the case of bioenergy technologies as a strategic alternative to create access to modern energy.

## 2. Bioenergy potential

Biomass is renewable organic matter derived from trees, plants, crops or from human, animal, municipal and industrial wastes. Biomass can be classified into two types, woody and non-woody. Woody biomass is derived from forests, plantations and forestry residues. Non-woody biomass comprises agricultural and agro-industrial residues, and animal, municipal and industrial wastes.

### 2.1. Bioenergy for power

India has a large biomass resource base, which is currently being utilized inefficiently. In addition, there are large tracts of wastelands that can be used for growing of biomass. An area of about 107 million hectares has been estimated to be degraded with 64 million hectares categorized as wasteland, which includes degraded forests [8]. The minimum wasteland area that might be available is about 35 million hectares. If about 5 million hectares of land by the side of highways and rail tracks is added to this, the total land available for raising plantations becomes 40 million hectares. In addition, there would be significant potential from farm forestry with farmers raising trees on bunds and in fields. Agro-forestry can also be promoted through contract farming whereby corporate bodies can organize groups of farmers to produce the required biomass under contract through development of wastelands.

Apart from plantations, surplus agricultural wastes and agro-industrial residues can also be utilized for thermal or electrical energy generation. About 450 MT (million tonnes), including sugarcane bagasse and leaves, of these resources are generated every year in the country (Table 1). About half of the surplus residues are burnt in the fields causing serious air pollution. The potential for additional generation of woody biomass in the country has been estimated at 255 MT. Out of this, forests wastelands are estimated to contribute 171 MT and the marginal cropland to contribute the remaining 84 MT.

**Table 1**
Bioenergy potential.

| Land category | Sub category | Area (Mha) | Biomass resource with energy potential | Potential energy end-use | Physical quantity (MT $year^{-1}$) | Energy potential |
|---|---|---|---|---|---|---|
| Crops | Rice | 46.1 | Straw + husk | Gasification for power | 41 | 4700 MW |
| | Maize | 6.6 | Stalk + cobs | | 6.2 | 700 MW |
| | Cotton and others | 16.8 | Stalk, coconut shells, fronds | | 240 | 28000 MW |
| | Sugarcane | 5.5 | Bagasse + leaves | Cogeneration for power | 163.5 | 8900 MW |
| Crop land | Marginal crop land | 14 | Woody biomass | Gasification for power | 84 | 9700 MW |
| Waste land | High potential | 28.5 | | | 171 | 20000 MW |
| MSW | | | Combustible organic matter | Biomethanation for power | 56 | 6500 MW |
| Forest | *Jatropha curcas* | 65 | 1.50 MT of oil seeds | Bio diesel for transportation fuel | 3.23 | 34.11 PJ |
| | Rice Bran | | 0.47 MT of oil seeds | | | |
| | Neem | | 0.40 MT of oil seeds | | | |
| | Sal | | 0.72 MT of oil seeds | | | |
| | Karanja | | 0.14 MT of oil seeds | | | |
| Crop land | Marginal crop land | 13.4 | Oil from *Jatropha curcas* | Bio diesel for transportation fuel | 16.08 | 530.6 PJ |
| Waste land | Marginal potential | 9.4 | | Bio diesel for transportation fuel | 11.28 | 372.24 PJ |
| Crops | Sugarcane | 5.5 | Ethanol | Transportation fuel | 20.9 | 562.2 PJ |
| Dung | Cattle | | Dung | Biogas for cooking | 344 | 336 PJ |
| | Buffalo | | | | 315 | |

Source: [29–32].

### 2.2. Bioenergy for heat

Cooking, bath-water heating, and operation of kilns are the most dominant activities which require heat energy. They require heating at low, medium and very high temperatures respectively. There are three bioenergy options for meeting the dominant cooking energy needs, namely shifting to efficient cookstoves, biogas and methanol. The biogas option uses cattle dung as the feedstock, and India has the highest bovine population that produces a total recoverable dung of 458 MT per year. If all the 458 MT of dung is used for biogas, it is possible to produce 16,030 million $m^3$ of biogas per year, which can generate 336 PJ of energy per year. The biogas generated will be 43,900 million litres per day, which is adequate to meet the cooking energy requirements of 219.5 million people (Table1).

Another choice for cooking from bioenergy, other than gaseous fuel would be liquid fuels like ethanol and methanol and more so methanol, as ethanol finds more use as a transportation fuel. Both ethanol and methanol can be produced from dedicated biomass plantations [9].

### 2.3. Bioenergy for transport

Oil bearing seeds from plants like *Jatropha curcas*, Neem, Mahua and other wild plants can be used to produce biodiesel which can be blended with diesel/petrol and used as transport fuels. In India, only non-edible oils can be considered for producing biodiesel. Even though both edible and non-edible oils can serve the purpose, edible oils are mostly confined to domestic use. Of all these wild plants *Jatropha curcas* (Ratanjoth) is a hardy plant which can grow in both good as well as adverse soil and climatic conditions.

India has total cropland of 140 Mha, even if 10% of this land is used for growing Jatropha it can produce 530 PJ of energy in the form of biodiesel. The wasteland with marginal agro-climatic conditions can produce 372 PJ of energy. The energy potential in forestry from Jatropha and other non-edible oil seeds accounts for 34 PJ (Table 1).

From a planning and subsequent implementation perspective, the estimates of bioenergy potential for power generation, heating energy and transport presented in Table 1 can be treated as an ultimate potential that is available from bioenergy. However, the actual realizable potential depends on many practical considerations, namely, alternative use of biomass as fodder or industrial raw material, collection efficiency, availability of so-called waste lands, availability of water, geographical and weather conditions. Thus, the influence levels of these factors determine the quantity of ultimate realizable bioenergy potential.

## 3. Bioenergy; a dominant renewable energy option

Biomass is the dominant source of energy in rural regions of most developing countries for cooking, water heating, etc. In these countries, the energy required for cooking often constitutes the biggest share of the total national energy consumption and is mainly met by biomass [10]. It is estimated that about 83% of total household energy consumption is derived from biomass with fuelwood having a dominating share (Table 2). Even the forecast shows that this domination is expected to remain significant at 52% in 2031–2032 with the remainder share contributed mainly by fossil fuel-based energy carriers. A pertinent question is how much of this 52% bioenergy share can be routed through the modern bioenergy technology (BET) path and how much of the 48% fossil fuel share can be shifted to modern BETs. It is an established fact that both are possible.

Modern BETs aim to use the same biomass as input and transform it into higher-grade energy carriers like electricity, gas, biofuel, etc., which can provide a wide variety of services (heating, lighting, motive power, audio/video, etc.). The advantage of these BETs is that they use a significantly smaller amount of biomass resources as input for providing higher quantity as well as quality of energy services for a greater number of people compared to the conventional process. They are environmentally friendly and reduce indoor pollution significantly while improving the living standards of the rural poor. BETs produce the same energy carriers that are produced by the fossil fuel technologies and any possibility of replacement of these with BETs will result in climate change mitigation.

## 4. Bioenergy technologies: technical potential and achievement

### 4.1. Bioenergy technologies for cooking

The traditional use of biomass to meet heating energy needs such as cooking, water heating and rural industrial applications has a large amount of potential for biomass conservation. Fuelwood consumption, estimated at about 205 MT a year, is the dominant bioenergy source used in India, followed by cattle dung (107 MT $year^{-1}$) and agro-waste (57 MT year) in 2003–2004 (Table 2).

#### 4.1.1. Improved cookstoves

The use of fuelwood for cooking in traditional cookstoves is characterized by low efficiency of use, in the range of 10–14%. Scientific and systematic approaches in the traditional cookstove design to improve combustion efficiency and reduce fuelwood consumption were introduced for the first time by Raju in 1953 [11]. The average thermal efficiency of the improved cookstoves (ICS) ranges between 15 and 35%. Currently three types of improved cookstoves are being promoted, which include fixed-type cookstoves, portable cookstoves and high-altitude metallic cookstoves, with an efficiency of over 20% for fixed cookstoves and over 25% for portable ones. The improved cookstove programme initiated in 1984–1985 with 2000 stoves built during the year reached a peak dissemination rate of 2.9 million during 1995–1996. The aggregate

**Table 2**
Current and expected future energy consumption in households.

| Source | Consumption 2003–2004 MTOE (%) | Consumption | Projections 2031–2032 MTOE (%) |
|---|---|---|---|
| Fuelwood | 92.57 (57.82) | 205.71 (MT) | 106.39 (37.44) |
| Agro waste | 17.12 (10.69) | 57.1 (MT) | – |
| Dung cake | 22.62 (14.13) | 107.7 (MT) | 40.47 (14.24) |
| Biogas | 0.71 (0.44) | 1.51 (million $m^3$) | – |
| Kerosene | 10.69 (6.68) | | 15.12 (5.32) |
| Electricity | 7.72 (4.82) | | 69.72 (24.53) |
| LPG | 8.68 (5.42) | | 52.49 (18.47) |
| Total | 160.11 | | 284.19 |

Source: [1].

number of improved cookstoves disseminated by 2003 was around 35.2 million [12].

The design of an ICS involves the application of heat transfer, combustion and fluid flow principles in order to attain complete combustion of the fuel with a minimum amount of excess air, maximum transfer of heat from the flame and the flue gases to the cooking vessel, and a minimum loss of heat to the surroundings. Fuel wood used in the above stoves comes from forest, forest tree twigs, forest wastes, plantation, farmlands, homesteads, degraded lands and shrubs. Animal waste, viz., dung pellets is substituted in many fuelwood scarce areas [13].

#### *4.1.2. Biomass gasifier stoves*

Cookstoves based on the biomass gasification process is another technology option for efficient cooking. Gasification is the process of converting solid fuels, such as wood, agricultural residues and coal, into a combustible gas, mainly a mixture of carbon monoxide and hydrogen. Gasifier stoves, which are basically compact gasifier–gas burner devices, have been tried since the mid-nineties for cooking applications. There a number of biomass gasifier cookstoves already in operation in countries such as China and India [14]. Similar to improved cookstoves, the efficiency of these gasifier stoves is in the range of 25–35%. Though the spread of these stoves is yet to take off in rural households, larger stoves have found applications in hotels, hostels, marriage halls, etc. One drawback of these stoves is that producer gas which is a mixture of carbon monoxide and hydrogen is poisonous and hence dangerous in the confined spaces of rural households. High cost is another barrier which needs to be overcome.

#### *4.1.3. Biomethanation*

Biogas (a mixture of about 60% methane and 40% carbon dioxide) is a combustible gas, which is the product of anaerobic fermentation of cellulosic materials such as animal dung, plant leaves and waste from food processing and households. Biogas can be combusted directly as a source of heat for cooking or used with internal combustion engines for mechanical or electrical power applications. The slurry produced after digestion can be used directly as valuable fertilizer.

A typical biogas plant has a digester in which the slurry (dung mixed with water) is fermented, an inlet tank used to mix the feed and let it into the digester, a gas holder/dome in which the generated gas is collected, an outlet tank to remove the spent slurry, distribution pipeline(s) to take the gas into the kitchen, and a manure pit, where the spent slurry is stored. Two popular designs of digester have been developed; the Chinese fixed dome digester and the Indian floating cover biogas. The digestion process is the same in both digesters but the gas collection system is different in each. In the floating cover type, the water sealed cover of the digester is capable of rising as gas is produced and acting as a storage chamber, whereas the fixed dome type has a lower gas storage capacity and requires good sealing if gas leakage is to be prevented [15].

In India, several types of biogas plant design have been promoted of which the two most widely promoted are the floating drum (KVIC design) and the fixed dome (modified Chinese design). Biogas plants are designed for operation at either the household or the community level as an ideal fuel for meeting cooking energy needs in rural areas. At the household level, the cumulative number of biogas plants built from 1982 to 2006 is estimated to be 3.83 million [12] against a potential of 12–17 million. The total number of large community and institutional biogas plants installed until 2006 was about 3902, and only 1228 plants were built during 1999–2006. This is a small achievement compared to the potential for a community biogas plant each in the majority of the 500,000 villages.

### *4.2. Bioenergy technologies for electricity*

A number of modern biomass conversion technologies are now available, which allow for conversion of biomass to modern energy forms such as electricity or gaseous (biogas, producer gas), liquid (ethanol, methanol), and solid (briquette) fuels. Biomass conversion technologies can help in meeting different types of energy needs, particularly electricity. Key technologies for power generation that have been promoted in India are gasification, combustion, cogeneration and biomethanation.

#### *4.2.1. Biomass gasification*

Biomass, particularly woody biomass, can be converted to high-energy combustible gas for use in internal combustion engines for mechanical or electrical applications. Biomass gasifiers are devices performing thermo-chemical conversion of biomass through the process of oxidation and reduction under sub-stoichiometric conditions. Gasifiers are broadly classified into updraft, downdraft and crossdraft types depending on the direction of airflow.

Gasifier systems with various capacities in the range of 1 kg $h^{-1}$ to about 500 kg $h^{-1}$ are presently in use. These systems are used to meet both power generation using reciprocating engines or for direct usage in heat application. The prime movers are diesel engines connected to alternators, where diesel savings up to 80% are possible [16]. Among the biomass power options, small-scale gasifiers (of 20–500 kW) have the potential to meet all the rural electricity needs and leave a surplus to feed into the national grid.

Indigenously developed technologies for biomass gasifiers, which are readily available from a few manufacturers, have been demonstrated successfully for their rural electrification potential, though on a relatively smaller scale [17]. The total installed capacity of biomass gasifier systems as of 2006 is nearly 76 MW [12].

#### *4.2.2. Biomass combustion*

The combustion technology is similar to coal-based thermal power generation technology, in which the biomass is burnt in a boiler to generate steam, which is used to drive a turbine to generate electricity. The spread of biomass-based combustion systems is low with only about 466 MW installed until 2007 [12].

#### *4.2.3. Biomethanation*

The technology of biogas production through biomethanation is as explained in the section biomethanation for cooking. The only difference here is that the biogas thus produced is supplied to a diesel engine, which is connected to an alternator. Except for a few demonstration projects hardly any potential has been exploited until now. At the national level, the Ministry of New and Renewable Energy (MNRE) has started a new initiative biogas-based power generation programme (BPGP) in 2006 to accelerate the spread of biogas power projects in the range of 3–250 kW as part of the rural electrification programme.

### *4.3. Medium-term potential and achievements*

India has a large potential to meet the energy needs of cooking, electrification for lighting and shaft power needs and liquid fuels for transport (Table 3). These estimates of potential are typically medium term (2031–2032), and are technically and economically feasible. India has implemented a large number of programs to promote bioenergy technologies. However, it can be observed from Table 3 that the spread of bioenergy technologies is marginal compared to the potential, except probably in improved cookstove technology.

**Table 3**
Bioenergy technology potential and achievements.

| Item | Potential | Energy potential | Cumulative achievements (as of 30-09-2006) |
|---|---|---|---|
| *Bioenergy power generation (MW)* | | | |
| Waste land | 20 million hectares | 45,000 MW | 0 |
| Surplus biomass | 120–150 MT $year^{-1}$ | 16,000 MW | 466.50 MW |
| Sugar cogeneration | 163.5 MT $year^{-1}$ | 5,000 MW | 571.83 MW |
| Waste to energy | | 7,000 MW | 34.95 MW |
| *Bioenergy for cooking/heating* | | | |
| Cattle dung | 510 MT $year^{-1}$ | 17.8 billion $m^3$ $year^{-1}$ | 1.12 billion $m^3$ |
| Leafy biomass | | | |
| No. of family type biogas plants | 12 million | | 3.89 million |
| No. of community/institutional biogas plants | Several hundred thousand | | 3902 |
| No. of improved chulha | 120 million | | 35.2 million[a] |
| *Bioenergy for transport* | | | |
| Bio-diesel | | 20 MTOE $year^{-1}$ | |
| Ethanol | | 10 MTOE $year^{-1}$ | >1 MTOE $year^{-1}$ |

Source: [1,12,29,33].
[a] Cumulative achievement refers to 31 March 2003.

## 5. Technology transfer and commercialization

Technology transfer, demonstration and dissemination leading to commercialization have been the cornerstones of the renewable energy technology deployment strategy of the Ministry of New and Renewable Energy (MNRE, changed from MNES). The technology transfer is facilitated with major considerations being performance and costs. While joint venture is considered the most desirable route, in many cases, there have been technical collaboration, funding, capacity building, equipment imports, etc. This section looks briefly at the technology transfer and diffusion experience of key bioenergy technologies.

### 5.1. Cookstoves

In 1983, a demonstration project on improved cookstoves took off in India and was later transformed into a fully-fledged project, the National Programme on Improved Chulha or Stoves (NPIC), by MNRE to function as a platform for the spread of improve cookstoves (ICS). The programme perceived multiple objectives like: fuel efficiency; reductions in indoor pollution, drudgery to women and cooking time; and creating employment opportunities for the poor. The stoves were usually built by entrepreneurs trained by professional institutions and were supported through MNRE incentives. The technology was made easily accessible to any interested stove builder. MNRE evaluates the improved stoves for efficiency and then certifies them for dissemination. As of 31 March 2003 over 35 million stoves had been built across the nation (Table 3). However, the NPIC was found to be ineffective over the long term in promoting a fundamental shift to improved stoves in India [18]. In 2002, MNRE deemed NPIC a failure and funding was stopped and the responsibility of continued ICS dissemination was passed to the states. Since then, a small number of state governments and NGOs have continued ICS dissemination; however, with the lack of central government support and limited funding the success rates are negligible [18].

### 5.2. Biogas/biomethanation

The principle of a cattle dung-based biogas unit was first evolved in India at the Indian Agricultural Research Institute, New Delhi in 1939. Dr S.V. Desai devised a simple gas plant and his work was followed by Prof. N.V. Joshi and was improvised as the first workable prototype of biogas plant by Jashbhai Patel, a Ghandhian worker from the early 50s [19–21]. The biogas plant was named Gramalakshmi III, which was later improved and known as the Khadi and Village Industries Commission (KVIC) floating drum in the early sixties. The technology was one of several designs approved by the MNRE under the National Programme on Biogas Development (NPBD). Though KVIC design has been very popular, it had some drawbacks. Firstly, the plant cost was very high, and secondly, the metal gasholder had to be painted regularly for protecting it against corrosion. These were overcome with the introduction of Deenbandhu biogas plants (Janata model) developed by Action for Food Production in 1984. Later, in 1987, another model known as Pragati was designed by the United Socio-economic Development and Research Programme (UNDARP), an NGO based in Pune. The Pragati model was approved under NPBD in 1987. This model is a combination of KVIC and Deenbandhu designs.

Under the NPBD programme, various biogas plant models have been approved by MNRE for dissemination. Some of the MNRE approved models include KVIC floating drum, Deenbandhu, Pragati, KVIC plant with ferrocement digester, KVIC plant with fibre reinforced plastic gas holder, and FLEXI. All these models are based on one of the two basic designs available: fixed masonry dome type; floating metal drum type including FLEXI, a portable model made of rubberized nylon fabric. The latest in the R&D is the development of biogas plants with leafy biomass as feedstock. Experimental biogas plants have been set up to demonstrate this technology [22].

### 5.3. Biomass gasifiers

The technical feasibility of biomass gasifier was proven long ago as gasifiers existed even during World War II. But the commercial potential of biomass gasifiers as a renewable energy technology was established recently. The national programme on biomass power was launched in 1985. A phased commercialization is being attempted through focused R&D, pilot testing and evaluation including prototype production, demonstration and evaluation, capacity building and manufacturing. A number of R&D groups are working on the programme and a number of designs of varying capacities have been developed. There are eight manufacturers of biomass gasifiers, although the technology is still evolving. The designs are approved by the ministry for the technologies to be able to utilize the benefits. Licensing is a major mode of transfer of the technologies.

The demonstration programme disseminated about 800 small wood gasifiers for irrigation water pumping with a total capacity of 6.5 MW until 1992. Later, from decentralized stand-alone systems, the focus shifted to application of biomass gasifiers for power generation. Five gasifier action research centres have been set up in selected technical institutions to provide technical support. As of the present date there are about 1700 gasifiers of different unit capacities (3–500 kW) aggregating 53.17 MW. While a majority include the stand-alone systems, a 5 × 100 kW biomass gasifier installation on Gosaba Island in Sunderbans area of West Bengal is being successfully run to provide electricity to the inhabitants of the island through a local grid. MNRE is currently supporting R&D for indigenous technology development and adaptation for advanced biomass gasification involving gas turbines in the combined cycle mode.

### 5.4. *Lessons learned*

Within the broad framework of R&D, and technology development, MNRE has strategized their interventions differently for different technologies. While the policies and programmes envisaged closer industry participation, the extent of their involvement varied from technology to technology. By and large, the industry involvement has been lower for most BETs except for cogeneration where the technologies existed in the private sector. Demonstration, dissemination, risk sharing (subsidy), technical assistance and awareness are a few elements of technology transfer.

Despite the best intentions of following a demand and market driven approach, most markets got created due to the technology push approach of MNRE. Lack of institutional networking for R&D and lack of coordinated efforts in solving R&D problems remain to be tackled. The distinct stages of technology transfer that could be broadly observed in MNRE programmes are: (1) R&D by technical institutions; (2) establishment of specifications and standards; (3) testing and certification; (4) demonstration; (5) dissemination; and (6) accelerated diffusion through other policy measures and incentives.

Dissemination of technologies was central to the technology transfer mechanisms facilitated by MNRE. Demonstration and targets along with favourable policies set by MNRE triggered the process of technology transfer. However, the effectiveness and efficiency of technology transfer varied and to some extent linked to the nature of the programmes and approaches. The dissemination of technologies focused on maximization of social benefits and a government supported subsidy driven path was adopted. This created many hurdles on the path of dissemination and failed to create successful self-sustaining replications.

The technical feasibility could be proven under ideal conditions for these technologies. However, under practical situations, the institutional challenges for ensuring technology performance were greater than the technologies per se. It was difficult to standardize the technology due to "software–human" and "hardware–materials" elements in the same technology. This also posed problems in setting standards and monitory quality. Examples include biogas or improved chulhas. While the components – burners, pipes, etc. – could be standardized, the process of construction of biogas or improved chulhas is dependent on so many factors, from materials to skills and use and maintenance of the systems.

While the latent demand existed, subsidy was mainly responsible for the real demand and initial market penetration of the technologies. Subsidies by and large could not ensure replicable demand. The NGOs and local institutions remained the agents of transfer with the private sector only getting involved indirectly. The diffusion rates of these technologies only confirm that technology transfer faces constraints and barriers that need to be addressed.

## 6. Economic feasibility

The above discussion clearly indicates that the technical potential of modern BETs in contributing to the energy system is indisputable. Even in terms of economic comparisons, the modern BETs outperform conventional fossil fuel-based technologies [23]. The life cycle cost (LCC) of installing and operating various types of BET for cooking and power generation is used for this comparison. The paper also reports the unit cost of energy or annualized levelized cost (ALC), which is estimated by annualizing the total life cycle cost and dividing it by the annual gross energy production. In this paper the same methodology is used with updated data (wherever relevant) for comparing with conventional alternatives.

**Table 4**
Life cycle cost estimates of bioenergy technologies for power generation and a comparison with grid electricity.

| | Total life cycle cost (Rs $kW^{-1}$) | Unit cost of energy (Rs $kWh^{-1}$) |
|---|---|---|
| Biomass gasifier + diesel | 218920 (5356) | 6.09 (0.149) |
| Biomass gasifier | 149150 (3649) | 4.17 (0.102) |
| Biomass combustion | 116430 (2849) | 2.15 (0.053) |
| Biogas + diesel | 183170 (4482) | 5.15 (0.126) |
| Diesel | 523140 (12800) | 14.44 (0.353) |
| Grid electricity (coal-based) | 174310 (4265) | 3.25 (0.080) |

Source: Adopted from [23] with revisions. The numbers in bracket are costs in US$ at an average exchange rate of Rs40.87 per US$ in May 2007.

In the case of BETs for electricity generation, four technologies, namely biomethane electricity, biomass gasifier (gas and dual fuel mode), biomass combustion, and cogeneration, are compared with diesel electricity and grid power based on coal thermal systems. The LCC and ALC estimates are presented in Table 4. From the table we may observe that the cost of electricity based on BETs varies from Rs2.15 to Rs6.09 $kWh^{-2}$ (US$0.053 to US$0.149 $kWh^{-1}$). In comparison, the cost of coal-based grid electricity is at Rs3.25 $kWh^{-1}$ (US$0.080 $kWh^{-1}$), and diesel generation is at Rs14.44 $kWh^{-1}$ (US$0.353 $kWh^{-1}$). The estimated cost of Rs3.25 $kWh^{-1}$ for grid electricity includes the cost of the transmission system. In the case of BETs and diesel power, it is assumed that this cost is equal to zero because these are basically decentralized systems and located near the consumption points (villages).

Efficient cookstove and biogas (cattle dung and leaf litter) are the three BETs considered for cooking applications and are compared with traditional wood and kerosene stoves. The costs are estimated per unit of heat output to overcome the inconsistency in terms of different quantities of fuel inputs. The costs estimated for biogas cooking include cost of production, distribution and utilization of fuel. The cost of energy from efficient cookstoves at Rs163.9 $GJ^{-1}$ (US$4.01 $GJ^{-1}$) of heat output compares favourably with that from traditional cookstoves at Rs271 $GJ^{-1}$ (US$6.63 $GJ^{-1}$). Similarly costs of energy from both the dung-based and leaf litter-based biogas systems are cheaper compared to Rs460 $GJ^{-1}$ (US$11.26 $GJ^{-1}$) for kerosene stoves (Table 5).

**Table 5**
Life cycle cost estimates of bioenergy technologies for cooking and a comparison with kerosene cooking (Rs $GJ^{-1}$ of heat output).

| | Total life cycle cost (Rs $GJ^{-1}$ of heat output) | Unit cost of energy (Rs $GJ^{-1}$ of heat output) |
|---|---|---|
| Traditional fuelwood stove | 674.27 (16.50) | 271.13 (6.63) |
| Efficient fuelwood stove | 713.78 (17.46) | 163.89 (4.01) |
| Dung-based biogas plant/stoves | 3572.4 (87.41) | 393.56 (9.63) |
| Leafy biogas plant/stoves | 2469.7 (60.43) | 272.07 (6.66) |
| Kerosene stove | 1743.1 (42.65) | 459.82 (11.25) |

Source: Adopted from [23] with revisions. The numbers in bracket are costs in US$ at an average exchange rate of Rs40.87 per US$ in May 2007.

**Table 6**
BETs' greenhouse gases reduction potential in India.

| Biomass technology | Technical potential | Global environmental benefit (million T C $year^{-1}$) |
|---|---|---|
| Biogas | 17 million | 5 |
| Community biogas | 150000 villages | 10.8 |
| Improved stove | 120 million | 4 |
| Biomass | 57000 MW | 89 |
| Cogeneration | 3500 MW | 6 |
| Urban wastes | 1700 MW | 3 |

Source: [17].

## 7. Environmental and climate change benefits

Biomass has traditionally been used in rural areas, particularly by the poor. The air pollution within rural households resulting from inefficient cookstoves has not yet received the attention that it deserves [24]. The poor's dependence on natural resources such as land, water and fuelwood could be further enhanced if biomass systems are holistically implemented. Land reclamation, soil conservation, and watershed development are the inherent benefits of biomass energy sources.

Environmental considerations compel greater use of sustainable technologies. One of the major environmental threats is energy induced global warming and associated impacts. BETs are uniquely placed in this context as they could mitigate the climate change impacts by preventing emissions and also absorb emissions by sequestering carbon through the photosynthesis process. A quick estimate of GHG reduction potential from BETs is shown in Table 6. A comparison of carbon emissions from alternative and baseline technologies is presented in Table 7 (third column). The estimates clearly show the emission reduction potentials of suggested alternative technologies.

BET-based power generation substitutes conventional grid electricity, which is based on fossil fuels, and mainly coal. It thus reduces $SO_2$ and $NO_x$ emissions and ash production. Sustainable biomass supply additionally contributes to reclamation of degraded lands estimated at 16–32 million hectares.

### 7.1. Cookstoves

The carbon emissions from combustion of fuelwood coming from sustainable sources do not make any net contribution to global carbon build up. However, incomplete combustion of fuelwood in traditional stoves is a cause of concern. The products of incomplete combustion are more powerful greenhouse gases (GHGs per gram as the global warming potential of these products, mainly, CO and $CH_4$ and other non-methane hydrocarbons is in the range of 20–110% as much as that of $CO_2$ itself). If fuelwood is obtained from a non-sustainable source, there will be a net emission of $CO_2$, in addition to non-$CO_2$, trace gases. In India 40% of fuelwood use is from non-sustainable extraction [9]. The exposure of women and children to pollutants during cooking exceeds the ambient air quality standards established.

### 7.2. Biomass gasifier

Biomass gasifier-based power generation technology has the potential to provide multiple environmental benefits: greenhouse gas (carbon) emission reduction, land reclamation and soil and water conservation in degraded lands. Potentially, they could substitute conventional fossil fuel-based electricity or supplement the conventional fossil fuel dominated sources for meeting the electricity demand supply gap. This avoids equivalent capacity addition of the conventional power supply and its associated environmental implications.

$CO_2$ emission reduction per unit of electricity generated through gas engines (without diesel use) is about 0.4 kg $kWh^{-1}$. In addition to $CO_2$ emission reduction due to substitution of fossil fuel electricity, $CO_2$ sequestration occurs in soil and standing vegetation. The $CO_2$ abatement potential has been shown to be high for gasifier-based power generation systems in India [9]. The total carbon abatement potential of total biomass power including combustion, and gasification based on the technical potential is estimated at 89 MT C at 45% capacity factor. The projected environmental impact at the current rate of spread of gasifier systems is estimated to be 0.7 MT C annually by 2012. Thus there is a large gap in the technical carbon mitigation potential and the expected achievements.

In the case of gasifiers on dual mode, $NO_x$ measurements would be 20% of the estimated 1.4 g $MJ^{-1}$ for Indian diesel engine systems. The significant reduction in the $NO_x$ levels in dual fuel and also in the gas alone operation is related to the peak temperatures that are achieved in the engine. The flue gas composition is CO = 1–2%, HC $\sim$30 ppm, Smoke $\sim$40 HSU, $NO_x < 200$ ppm, $O_2$ $\sim$4%, $CO_2$ $\sim$15–18%. The levels of total tar and particulate are in the range of $80 \pm 20$ mg $m^{-3}$. The gas quality in terms of particulate content at the hot end is about 180 ppm. In the cold gas the particulate

**Table 7**
Annualized levelized cost (ALC) of energy and $CO_2$ emissions from BETs and conventional systems per kWh or per GJ of heat output.

| Items | ALC (Rs $kWh^{-1}$ or Rs $GJ^{-1}$) | $CO_2$ emissions (kg $kWh^{-1}$ or g $MJ^{-1}$) | Abatement cost (Rs $T^{-1}$ $CO_2$)[a] |
|---|---|---|---|
| *Cooking technologies (MJ or GJ)* | | | |
| Traditional fuelwood stove | 271.13 (6.63) | 101.36 | – |
| Efficient cookstoves | 163.89 (4.01) | 43.44 | −1851.52[b] (−45.30)<br>−3098.74[c] (−75.82) |
| Dung-based biogas plant/stoves | 393.56 (9.63) | 0 | −476.90 (−11.67) |
| Leafy biogas plant/stoves | 272.07 (6.66) | 0 | −1351.30 (−33.06) |
| Kerosene stove for cooking | 459.82 (11.25) | 138.94 | – |
| *Electricity generation technologies (kWh)* | | | |
| Diesel generator for electricity | 14.44 (0.35) | 0.756 | 42873.56 (1049.02) |
| Biogas electricity system | 5.15 (0.13) | 0.15 | 2191.46 (53.62) |
| Biomass gasifier system (dual fuel mode) | 6.09 (0.15) | 0.15 | 3275.66 (80.15) |
| Biomass gasifier system (gas mode) | 4.17 (0.10) | 0 | 904.62 (22.13) |
| Biomass combustion power system | 2.15 (0.05) | 0 | −1081.61 (−26.46) |
| Grid electricity | 3.25 (0.08) | 1.017 | – |

Adopted from [23] with revisions. The numbers in bracket are costs in US$ at an average exchange rate of Rs40.87 per US$ in May 2007.
[a] Abatement costs have been estimated assuming a shift from kerosene stove and grid electricity for cooking and power generation alternatives respectively.
[b] Shift from traditional to efficient cookstoves.
[c] Shift from kerosene to efficient cookstoves.

content is much below 50 ppm. The tar content in the hot gas is about 120–170 ppm, where as in the cold gas it is less than 40 ppm. This is a function of the biomass used. In the case of wood, the ash is less than 1% and in case of agri-residues (mulberry) it is 2.8%. Rice husk has about 20% ash, which is basically silica. The carbon content in the refuse is ∼30–40%, and nitrogen is ∼0.2%. Thus the emission of pollutants from biomass combustion in a gasifier is lower than that in a diesel engine.

Energy plantations for sustainable supply of woody biomass as the feedstock act as carbon sinks as at any given time there would be standing biomass. Analyses show that the per capita woody biomass requirement for power generation using gasifiers would be lower than the current per capita fuelwood use of 0.29 T per capita per year for cooking alone. This would further imply that nationally the total wood required for producing electricity for rural needs is 122 MT, which is equal to about 67% of the fuel wood presently used in the rural domestic sector for cooking. Degraded lands could be ideally adapted for growing energy plantations. Biomass gasifier projects could thus also be equated to land reclamation projects, which could also incorporate biodiversity implications.

### *7.3. Biogas*

Biogas technology when used for cooking or electricity generation provides multiple environmental benefits. The most important benefits are:

- Use of biogas for cooking eliminates smoke in the kitchen resulting in indoor pollution reduction.
- Production and use of biogas for cooking can drastically reduce the depletion of natural resources like forests and village trees.
- The biogas slurry used as farm manure could improve soil conditions and enrich it with organic matter and nitrogen. This can boost agricultural production and conserve soil from erosion losses, while decreasing the use of chemical fertilizers. Due to anaerobic digestion of the cellulose biomass materials, the nitrogen loss due to aerobic fermentation is totally avoided; the biogas route is considered as an efficient method in producing best quality manure and a bonus of obtaining gaseous fuel for energy. In addition, the digested biomass would have killed pathogens and weed seeds because of anaerobic digestion and the gestation period in the digester, which when used as manure has an added advantage to farmers.
- The estimated fuelwood conservation potential of biogas technologies is 79 MT annually. The corresponding carbon emissions avoided would be 15.8 MT annually assuming 40% of the fuelwood requirements are from non-sustainable sources and at 0.5 T C of dry wood [17]. If biogas is used for electricity generation at the decentralized (village) level, it could substitute fossil fuel electricity (diesel or coal-based) leading to carbon mitigation.

## 8. Barriers to spread and performance

India has implemented a large biomass energy program, which involves the promotion of several BETs through several policy, institutional and financial incentives and interventions. Most of the BETs were implemented with direct capital subsidy support from the MNRE. Other policy incentives such as income tax holiday, accelerated depreciation, concessional duty/custom duty free import, soft loans for manufacture and state level policies on wheeling and banking, etc., were also used to facilitate market development.

Despite a number of supportive policies and incentives, the rate of spread of bioenergy technologies has remained low. The slow rate of spread has been attributed to the existence of several barriers, which have been identified in several studies [25–28]. To improve the spread of BETs it is essential to address the most important of the barriers and develop appropriate measures to overcome them.

### *8.1. Limited capacity to assess, adopt, adapt and absorb technological options*

These technologies are primarily targeted at rural areas or poor customers, who have limited capacity to absorb these technologies. There is a general resistance to change, which is magnified due to lack of capacity to understand, adopt and adapt the technologies for greater benefits. The capacity constraints are not only linked to its use but in its production. There is limited manufacturing capacity and as a result not much innovation has taken place. Scale-up of manufacturing and thereby reduction in the associated costs has not taken place.

### *8.2. Inadequate information to assess the technological needs*

Information needs vary from one stakeholder to another. A user of a cooking stove might have different information needs as compared to a manufacturer of stoves. The generic information dissemination approach has had only limited impact, as the access to information also remains a key issue.

### *8.3. Weak institutional infrastructure for diffusion*

There are no institutional mechanisms to provide after sale support to these technologies. Limited private sector participation and target linked programmes have not been able to infuse motivation to the existing institutional mechanisms to be able to cater to the new markets.

### *8.4. Lack of access to financing*

High first costs and investments associated with mass manufacturing remain as barriers. Both the users and the manufactures have very a low capital base. This problem is further accentuated by the rigid lending procedures that limit access to financing even when financing is available on standard norms.

### *8.5. Limited R&D funding*

Technical and performance standards are laid down by the MNRE and incentives are made available to only those systems that conform to MNRE standards. Manufacturers do not take any initiative to alter these standards, as they, in any case, are conforming to the specifications drawn up by the MNRE.

### *8.6. Subsidies*

Subsidies for new or conventional technologies seriously distort markets. Since the conventional technologies are supported by subsidies, there is no level playing field for the new technologies competing with them.

### *8.7. Lack of motivation and incentives*

The technologies promoted under this category are primarily for consumptive purposes. The poor families with low incomes do not see any difference in their economic conditions, as fuels that are replaced are available either at subsidized rates or free. The improved living conditions are not enough incentive for their spread.

### 8.8. Difficulty in mainstreaming environment into development plans

Economic and other development priorities precede environmental objectives. Even in countries like India, which has an exhaustive regulatory and policy framework for protecting the environment and sustainable development, have difficulty in their enforcement or implementation. The institutional set up – multiplicity of institutions, overlapping roles, etc. – further acts as a barrier.

### 8.9. Lack of direction and transparency

There is reluctance to transfer the technologies by the research institutions. The fear of failure and the risks associated with the transfer being high due to low confidence levels, information sharing is limited.

### 8.10. Lack of private sector participation

In the case of BETs, there have been hardly any partnerships with the private sector in the process of technology development. Few private sector companies were involved in production of systems such as biomass gasifiers under a licensing agreement. These enterprises were mainly first generation entrepreneurs with very weak financial and technical resource bases and as a result dependent on the research institutions for any major technological breakthrough.

## 9. Institutional and policy framework

BETs are still considered as the most complex cluster of technologies for transfer or diffusion. First of all, BETs are still in an evolving phase, which makes it difficult to decide what exactly should be diffused in terms of knowledge, techniques and hardware. Second, it requires a series of difficult technological choices concerning biomass sources, production, transportation, conversion and end-use. Finally, there are a multitude of actors who potentially could become crucial players. In the above context, policies, institutions and financing play catalytic roles in technology transfer and diffusion of BETs.

### 9.1. Partnerships and institutions

Technology deployment involves multi-stakeholders and is not limited to two entities – the technology supplier and the recipient. It requires a collaborative partnership among key stakeholders. To sustain this partnership a proper institutional mechanism needs to be established. Institutional mechanism at national level, which focuses on transfer of BETs is essential to coordinate and engage in dialogues with stakeholders. The whole process needs to be properly designed by including institutions and individuals from central and state governments, industry, legal, financial sectors, academic, NGOs and community organizations. Their roles, responsibilities, authorities, contributions and activities have to be well defined. This effective stakeholder partnership should result in the emergence of innovative mechanisms related to regulatory policies, finance, marketing, incentives and implementation.

### 9.2. Plans and policies

Detailed specific technology transfer and diffusion assessment needs to be carried out through participatory approaches. Technology push approaches are difficult to penetrate and sustain the markets. This approach is even riskier when the given technology is not an off-the-shelf product. An example here would be LPG vs. biogas plants. The latter still require more institutional support and perhaps of different nature. Continuous stakeholder dialogues will facilitate the identification of the country's technology priorities in a correct way. For this, the approach that has to be followed should be "bottom up". Broadly, at the first level, the technology needs can be ascertained by having objectives like GHG mitigation, economic development, improving living standards and increased access to quality energy. The needs assessment has to establish technology evaluation on various criteria, the diffusion potential, acceptability by the users, ability to meet the developmental goals, impacts on the conventional technologies, commercialization possibilities, etc.

Technology information is an important issue for successful technology transfer and diffusion. If complete information on BETs like technology sources, technical details, costs, licensing procedures, patenting requirements, financial support available, etc. are available at one place, the transfer process can be smooth. For this, a technology database exclusively for bioenergy can be created on the lines of technology clearing houses. In addition, simplified prototype business plans for the chosen BETs can be developed and included in the technology database. This would help mainly the small-scale entrepreneurs in establishing the commercial viability of various technologies and also enable them to plan their venture into bioenergy. The business plan can include techno-economic analysis, profitability analysis, possible financial arrangements, available government and international incentives, market potential and human resource requirements for prominent technologies.

It is essential to change the misconception of bioenergy technologies being not commercially viable and markets do not readily accept them. For this, the suggested approach is market transformation. The approach is basically to change the types of products or services that are offered in the market and with that tune the purchase and behavioural decisions of the consumers and thereby ensure the sustenance of new products. A market transformation approach can promote replicable, ongoing technology transfers rather than one-time transfers. For such an approach to be effective, the role of government policies is important. With appropriate policy measures it is possible to end the reign of the traditional technologies and give way to that of a new and alternative technology. Some of the important public policy measures to help market transformation are technology adaptation, enterprise technological capability, incentive measures, command and control measures, consumer education, and marketing. In addition to these holistic policy measures, successful deployments require some targeted technology/end-use specific policy prescriptions.

### 9.3. Cookstoves

To achieve large-scale diffusions, the devices need to be robust enough to function under varying conditions. Towards this, the first step is to promote R&D to improve stove designs which are superior in efficiency and performance, reduce smoke emissions and ensure long life. Quality certification by the Bureau of Indian Standards is an essential step in this direction. Quality control and user education is a must to ensure high performance and to motivate them to switch to improved stoves.

### 9.4. Biomass gasifier and biogas technologies

Compared to cookstoves, these are a more complex class of technology and need different kinds of policy prescriptions for their spread. From an implementation perspective, the policy instruments required for these two technology types are likely to be similar because of similar complexities. The requirement is to frame targeted policies to address issues related to the following:

- Structured training programs to create a pool of skilled personnel and developing entrepreneurship development programs.
- Facilitating design change and innovative loan schemes to reduce cost.
- Creating effective monitoring and evaluation systems to take care of lack of quality control problems.
- Information campaigns and widespread demonstrations for information diffusion.
- Building economic/financial viability through transparent feasibility studies, pilot projects and prototype business plans.
- Reviewing the existing R&D policies and projects, and develop programmes to promote coordinated R&D projects for cost reduction and performance enhancement under practical or field conditions.
- Creating incentives for enhanced private sector participation.
- Developing information packages on various aspects of the technologies to policy makers, manufacturers, entrepreneurs and end-users.

## 10. Conclusion

India's energy supply system dominated by traditional biomass, centralized grid electricity and petroleum products has failed to meet the growing energy needs of the nearly 700 million rural population and at the same time has contributed significantly to local and global environmental degradation. It has been proved time and again that advanced bioenergy technologies have the potential to produce sufficient quantum of modern energy carriers to meet the heating, lighting, shaft power and motive power needs, particularly of the rural population. Further, bioenergy technologies are the prime candidates aimed at mitigation of climate change apart from land reclamation through growing energy plantations and reduction in domestic indoor pollution. Though India is a pioneer in establishing one of the most comprehensive programmes in bioenergy, the success rates in terms of number of installations, self-sustaining replications and creating access to modern energy carriers in rural regions are marginal. Against this backdrop an attempt has been made here to reassess bioenergy technologies keeping in mind the goal of meeting the prioritized energy needs of the rural population rather than contributing to bridging the demand–supply gap.

The Planning Commission forecast shows that the biomass energy share in total household energy consumption would be 52% even in 2031–2032. The assessment attempted here establishes the fact that much of this 52% bioenergy share can be routed through the modern bioenergy technology (BET) path and a substantial share of the 48% fossil fuel share can be shifted to modern BETs. This can be achieved with less overall economic cost and higher climate change benefits. The results show that the cost of electricity based on BETs varies from Rs2.15 to Rs6.09 $kWh^{-1}$ compared to the average cost of grid electricity at Rs3.25 $kWh^{-1}$, and diesel generation at Rs14.44 $kWh^{-1}$. For cooking energy needs, the cost of energy from efficient cookstoves at Rs163.9 $GJ^{-1}$ of heat output compares favourably with that from traditional cookstoves at Rs271 $GJ^{-1}$. Similarly costs of energy from both the dung-based at Rs393.56 $GJ^{-1}$ and leaf litter-based biogas systems at Rs272.07 $GJ^{-1}$ are cheaper compared to Rs460 $GJ^{-1}$ for kerosene stoves. The climate change benefits in terms of carbon emission reductions are to the tune of 110 T C $year^{-1}$ provided the available potential of BETs are utilized.

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